High-Power T/R Switches with 350 ns Rise Time for Zero Echo Time Imaging

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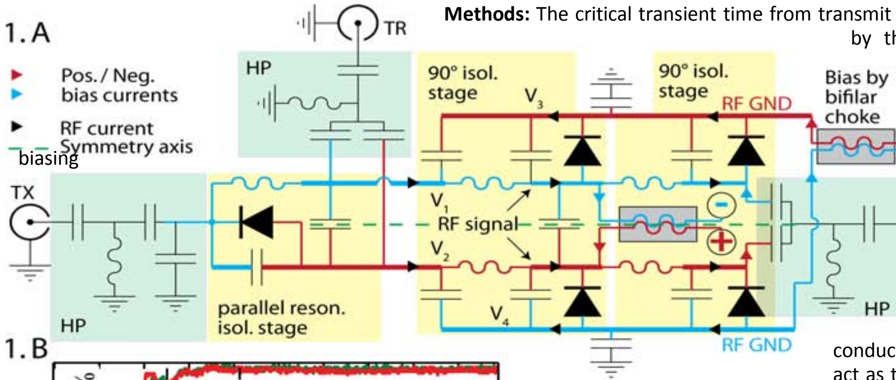
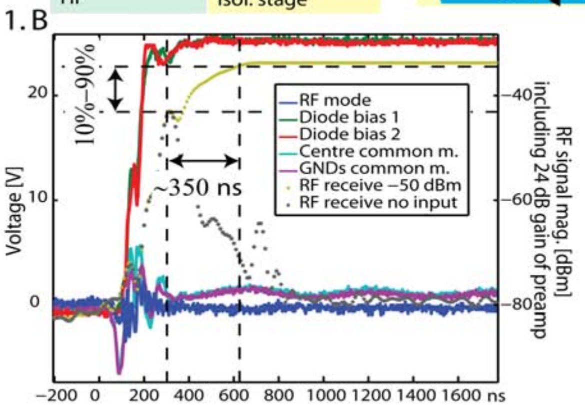
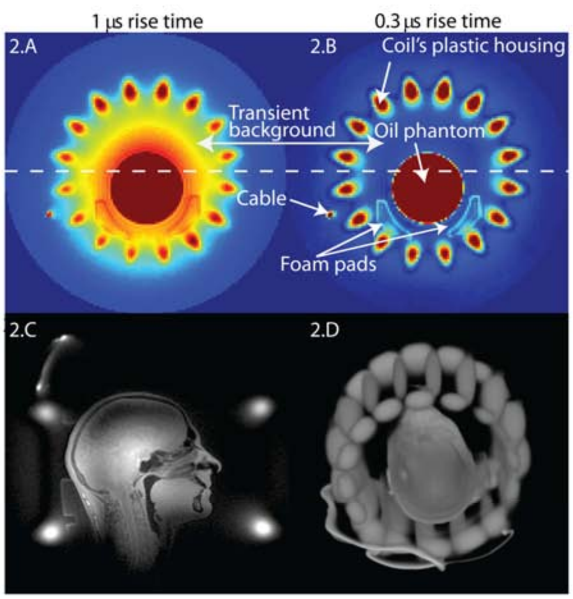
Introduction: High-power transmit-receive (T/R) switches are a core component of pulsed NMR and MRI spectrometers. The usually employed PIN diodes offer low losses and high power handling capabilities, but are inherently slow semiconductors and let switches usually transit within 5-20 µs from transmission to reception. For liquid state NMR methods, this dead-time is mostly not a big caveat, however with the advent of novel techniques for imaging of ultra-short T_2^* species such as UTE[1], SWIFT[2], ZTE[3] and others the need for switching in a microsecond and less has been set. This however necessitates the diode biasing being itself an actual high-bandwidth (few MHz) RF design with considerable power to swiftly drive the diodes. But the strong switching transients must be well isolated from the RF signal paths of the NMR signal in order not to hamper the high-gain, low-noise amplification chain joining the receive (RX) port of the switch which is very difficult in most traditional topologies. In this work we will present an approach to design high power RF T/R switches with RF signal rise times in the realm of 300 ns with low glitches (video leakage) from the switching bias at the outputs and demonstrate an implementation for 7 T proton ultra –short T_2^* imaging (f_0=298 MHz) with zero echo time (ZTE) and up to 650 kHz bandwidth.





Methods: The critical transient time from transmit (forward biased) to receive state (reverse biased) is determined by the PIN diode's charge carrier lifetime in the intrinsic layer, however it can be significantly accelerated by higher biasing voltages and transient bias currents. But swiftly switching several 10 V with high inrush currents causes strong glitches and spikes in the order of the biasing voltages on the RF lines at RF frequencies which can be very detrimental for the preamplifier (LNA) leading to long recovery dead-times (~µs) or even destruction of the input gate. To intrinsically isolate the biasing signal from the TX and RX RF signals, the novel design (Fig. 1) guides the biasing and the RF signals on two orthogonal modes on four conductors. For the RF signal the middle two (AC coupled) conductors act as the centre conductor of a coplanar strip line and are hence kept on an even symmetric mode ($V_{\text{RF mode}} = V_{Center\,cm} - V_{GND\,cm} = (V_1 + V_2) - (V_3 + V_4)$). The biasing signals run on a double-balanced, anti-symmetric mode ($V_{Bias,1,2} = V_{1,2} - V_{3,4}$), thus decoupled from the RF signals. Also spikes and glitches from the switching diodes are cancelled out of the RF mode by the pair wise anti-symmetric arrangement. Further, the topology allows biasing the MA4P (Macom, Lowell, Ma. USA) PINs via bifilar wound (toroidal) transformers (attached to the centre and AC ground conductors) choking the RF (common) mode from the bias lines by its common mode inductance but not introducing a high inductance for the differential biasing signals which would limit the switching bandwidth. The diode driver was a custom, high current (1.2 A) differential amplifier providing 27 V reverse bias. The remnant biasing glitches are blocked by high-pass filters (HP, 50 MHz) at all ports.

Results: Although the reverse-bias voltages on the pin diodes rises with about 270 MV/s (Fig. 1B) only a 3 $V_{pk\text{-}pk}$ transient appears in the relevant RF signal mode at the diodes. At the input of the preamplifier (LNA) the video leakage signal was accordingly only 150 $mV_{pk\text{-}pk}$, hence below any problematic level. The 10%-90% RF rise time was measured by a time resolved through (TR→RX) measurement with 18 MHz bandwidth being about 350 ns amounting to a total settling time of about 700 ns (including 100 ns biasing propagation delay). All transient signals rang down within 800 ns below measurable levels after preamplification with 24 dB gain. Insertion losses (TR-TX, TR-RX up to LNA) where found to be 0.5 dB with an isolation in TX mode of 67 dB and 40 dB in RX mode. TX powers up to 1.5 kW peak have been tested with switch rates up to 10 kHz (T_R=100 µs) and duty cycles of 10%. Further, images of an oil phantom (Fig, 2.B) and in-vivo (2.C&D) have been acquired by the ZTE technique [3] with 500 kHz bandwidth taking the digitized samples 1 µs after the 3 µs excitation pulse has been sent to a quadrature Birdcage coil (Nova Medical, Wilmington, MA, USA). The comparison to the same acquisition employing a T/R switch with 1 µs rise time (2.A equally scaled as B to 30% of the maximum signal) shows clearly the substantial suppression of halo-like artefacts attributed to the switching transients in the centre of the k-space. The in-vivo data with the new switch even allowed 3D rendering of the subject and the proton containing coil by simple intensity based alpha blending (no segmentation applied).



Conclusions: The proposed topology for T/R switches allows biasing PIN diodes with high RF bandwidths (10-20 MHz), high voltages and intrinsically decoupling the biasing signals from the transmission and receptions paths in principle with very high bandwidth resulting in very low glitches (video leakage) not perturbing/saturating the preamplifier. The switching bandwidth is thereby not limited by the bias choke inductance–being practically zero for the biasing signal-nor by the spike sent to the receive line which can be controlled by the bias balancing providing a high rejection to the signal carrying mode as opposed to traditional designs where the biasing and the RF signal share the same mode and can only be separated by their different realm of frequencies. The proposed design resulted in high-power tolerant (>1.5 kW) switches with about 350 ns rise times which was found to be fast enough to render the achieved bandwidth of ZTE acquisitions being limited by the gradient system and coil ring-down times. The double-balanced biasing scheme can equally be employed for detuning circuits of dedicated transmit or receive coils, which is expected to reduce the ring-down times of the applied coils. Further, the presented approach can also be applied with similar expected benefits when using different switching elements than PIN diodes such as Schottky diodes or transistors further improving speed.

References: [1] Bergin, Radiology (1991), [2] Idiyatullin, JMR (2006), [3] Weiger, MRM (2011)