Time Domain Modeling of MR Linear Balanced Duplexers Switched with Low Magnetic Moment PIN Diodes

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ABSTRACT: A linear balanced duplexer (LBD) is shown as a viable means for implementing a transmit-receive RF switch for MR systems. In Transmit mode it must exhibit very low loss from the transmitter port to RF coil port and high isolation from transmitter to receiver. In Receive mode it must have very low loss from RF coil to preamp and high isolation from transmitter to receiver and coil. This simple design achieves this with minimum components and is scalable in frequency and power. Ultra Low Magnetic Moment (ULM) PIN diodes are used to switch between states; the ULM devices also reduce possible magnetic artifacts in high field MR Imaging. Designers of MR scanners often use CAD packages to simulate their designs but up until recently, there have been no models available that show the behavior of the PIN diode in its ON and OFF state as well as in the switching transition between states. Previously discussed models for PIN diodes were used to simulate the behavior of the LBD for use in a 3T system at 128 MHz and has shown good agreement with experiments. Both fast rectifier and higher power PIN diodes are simulated. The model accurately predicts the operation of the LBD using industry-standard simulators such as SPICE as well as it variants.

MATERIALS & METHODS: Theory for the Linear Balanced Duplexer (LBD) is well described by Zabel in the classic 1948 MIT Rad Lab Series [1]. Fig. 1 shows two quadrature hybrids connected in series (C3, C5, C6, T1-T4) with the ports defined as shown (vin-transmit port; vout-RF coil/antenna port; vpreamp-receive/preamp port; vidle-idle port). PIN and PIN1 are shunt PIN diodes used as switches. In transmit mode, PIN and PIN1 are closed (forward biased) and in this case all transmit power is circulated in the left half and reflected to the RF coil (vout in Fig. 1). In receive mode, the PIN diodes are open (reverse bias) and the coil signal is split into 90 degree components passed through PIN and PIN1 then recombined at the preamp port. The idle port absorbs RF leakage or unbalanced power. Fig. 2 shows an example implementation.

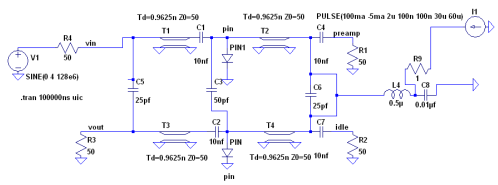

Figure 1: Spice schematic of LBD.

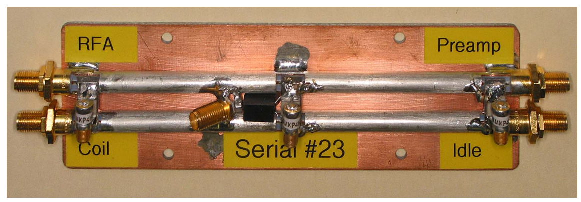

Figure 2. Hybrid implementation of an LBD

Glass-encapsulated SOGO passivated [2] ULM PIN diodes exhibit low lead inductance and contact resistance, low magnetic moment, and metallurgical bonds to attach the silicon chip to the pins on the cathode and anode sides of the chip, and have been extensively modeled using a novel SPICE-based based on the underlying physics governing the switching behavior [3]. To show the important utility in MR applications and for MR instrumentation engineers, the SPICE models were used to simulate the transient response of the LBD for thin (6 micron), medium (40micron) and thick (250micron) I-region PIN diodes and to compare these simulations with measured results. As shown in the example (Fig. 3), the model accurately characterizes the level of blocking in the Preamp port in the LBD as well as the dynamic LBD turn-on and turn-off characteristics for a medium thickness PIN diode. For the example shown in Fig. 3, the LBD switches in less than 20us in simulation in both switching states, consistent with less than 50us measured. High power devices modeled include the UM7200 series of higher power devices (I-region widths greater than 2 MIL) and the UMX9989AP, a single (for ease of assembly in MR coils) anti-parallel pair of fast switching rectifier diodes with narrow I-regions (approximately 6 microns). The table also shows the results of switching speed for a number of different PIN diode geometries and electrical characteristics.

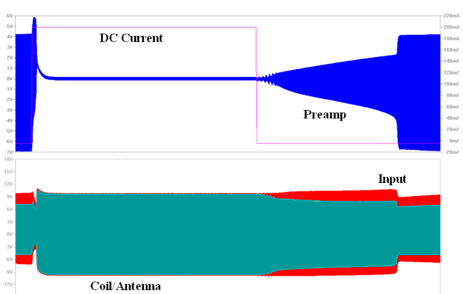

Figure 3 (at left). Example SPICE dynamic simulation. The table shown at right summarizes the results of a number of SPICE simulations on the LBD with PIN diode switches of various I-region thicknesses and carrier lifetimes.

W(um)	6.0	40	175
τ (us)	0.012	2	26
I_{DC} mA (on/off)	10/-1	100/-5	400/-40
ON delay	7us	2us	4us
OFF delay	7us	20us	29us

RESULTS & DISCUSSION: A SPICE-based model is shown that accurately models ON, OFF and transient state behavior of ULM PIN diodes in linear balanced duplexers for MR scanners. Higher power thick I-region UM7200 series diodes are shown to exhibit extremely low resistance values at high currents, providing low insertion loss at the high RF powers in transmitting, active detune and block switching applications as well as robust blocking/detuning functions, but at a somewhat slower switching rate compared with thinner devices due to the I-region stored charge. Thinner I-region UM9989 series diodes, used in higher field (B_o) scanners for passive coil detune and blocking functions in surface coils (i.e., diodes turned on by the applied RF signal), shows less blocking capability but higher speeds. The PIN diodes used must be chosen to handle the peak RF current and carrier lifetime depending on the frequency and power level desired. At low frequencies, lumped element equivalent circuit can be used to replace the transmission lines for a more compact circuit. Each quad hybrid can be designed using branched, lumped, or quasi-lumped element designs

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