A Passive Dual-Circulator Based Transmit/Receive Switch for Use with Reflection Resonators in Pulse Electron Paramagnetic Resonance

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ABSTRACT: To protect the low-noise amplifier (LNA) in the receive arm of a pulsed 250 MHz EPR bridge, it is necessary to install as much isolation as possible between the power exciting the spin system and the LNA when high power is present in the receive arm of the bridge, while allowing the voltage induced by the magnetization in the spin sample to be passed undistorted and undiminished to the LNA once power is reduced below the level that can cause LNA damage. We discuss a combination of techniques to accomplish this involving the power-routing circulator in the bridge, a second circulator acting as an isolator with passive shunt PIN diodes immediately following the second circulator. The low resistance of the forward biased PIN diode passively generates an impedance mismatch at the second circulator output port during the high-power excitation pulse and resonator ring down. The mismatch reflects the high power to the remaining port of the second circulator, dumping it into a system impedance matched load. Only when the power diminishes below the diode conduction threshold, the resistance of the PIN diode will rise to a value much higher than the system impedance. This brings the device into conduction mode. We find that the present design passively limits the output power to 14 dBm independent of the input power. For high-input power levels, the isolation may exceed 60 dB. This level of isolation is sufficient to fully protect the LNA of a pulse EPR bridge. Concepts Magn Reson Part B (Magn Reson Engineering) 35B: 133–138, 2009

KEY WORDS: transmit/receive switch; passive receiver protection; EPR instrumentation; low-field EPR; EPR imaging

INTRODUCTION

In conventional continuous wave (CW) electron paramagnetic resonance (EPR), the use of a balanced bridge and narrow band low-instantaneous power prevents saturation of the first stage of amplification in the detection chain. In time domain EPR, short duration radio frequency (RF) high power (hard) pulses are used to rapidly change the macroscopic spin system magnetization. Time domain EPR imaging techniques utilize simultaneous excitation of the whole EPR line broadened by the applied magnetic field gradient (*1*, *2*). This requires the application of tens of nanosecond long RF pulses that have broad bandwidth and kilowatts of incident power. The first stage in the detection of the response of the magnetization to the high-power RF pulses is a sensitive, low-noise amplifier (LNA). The amplifier can be destroyed by RF pulses of sufficient power. The output of the LNA is saturated and otherwise distorted

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by high-power pulses and recovers slowly from these pulses contributing to the dead time of an imager. This is exacerbated in the context of EPR imaging of large objects with size on the order of several centimeters that exhibit important spectral features separated by tens of Gauss. Under these circumstances, high-spectral bandwidth requires shorter pulses and, consequently, higher power.

Several strategies have been adopted to protect that LNA from the high-input power. One approach to isolation of the power from the LNA has been the use of bimodal resonators (*1*, *3*, *4*). Most versions use resonators whose excitation RF field B_1 is perpendicular to the readout RF field B_1 (*5*). This isolates the RF excitation power from appearing at the detector LNA by as much as 60 dB, obviating the need for a dedicated transmit/receive (T/R) switch. However, bimodal resonators typically suffer from geometric complexity that limits sample accessibility. They also suffer from a lower filling factor leading to lower $B_1/\sqrt{W}$ RF power-field conversion efficiency than that of a unimodal resonator (*6*, *7*).

Another approach has been the use of a single mode reflection resonator which uses a T/R switch to isolate the LNA from the excitation power (*2*). During the high-RF power application, a T/R switch directs RF power to the resonator and isolates the LNA from the excitation power. During the signal detection time the T/R switch directs signals from the resonator to the LNA. However, the RF power reflected from the resonator can still have considerable amplitude and additional protection is required. One can categorize two basic approaches to the design of T/R switches applied to EPR. The first is based on the time separation between the excitation and detection processes. At a predetermined time after the power from the RF amplifier pulse is delivered to the resonator/spin sample, the resonator is disconnected from the RF source and connected to the LNA detector using a high power RF switch (*8*). The connection direction of this switch can be defined externally, for example using an external gating pulse. The use of this external, carefully timed pulse is an active protection mode, in that it requires the active intervention to direct the power and signal pulses. This needs to be carefully synchronized with the applied power pulse to insure isolation of the initial power amplifier stage from the LNA. Available high-power PIN diode switches have nanosecond switching times and are capable of typical 50 dB isolation.

One serious limitation of an active T/R switch design is the difficulty finding a fast active RF switch capable of isolating kilowatts of RF power necessary to generate broadband RF pulses required for imaging. We present here a passive design based on RF devices which provide an intrinsic directionality, circulators. More than one circulator provides higher isolation at kilowatt power than a single circulator, alone. The design involves passively forward biasing shunt connected PIN diodes into a protect mode until the RF power has diminished to a safe level. In this way, the passive mode of operation involves using the level of the RF power itself to determine the need for protection.

The goal is to achieve an overall isolation of about 45–50 dB at a power level of 60 dBm, with an insertion loss during the signal acquisition of <1.5 dB. For the safe operation of the LNA, the power during the high-power application period needs to be brought down to a level of 15 dBm (31 mW, 1.8-V amplitude) or less.

MATERIALS AND METHODS

Overall Bridge Design

Figure 1 shows the overall bridge design, the context of the passive T/R switch. RF power (250 MHz) is provided by a Hewlett–Packard model 8662 RF power source. The pulsed RF amplifier (Tomco, Adelaide, South Australia) can reach 63 dBm (2 KW) instantaneous power with 12 ns rise and fall times and noise blanking (*9*). Thus, this amplifier can produce RF pulses as short as 25 ns. In practice, transients with amplitudes of tens of microvolts are present well after the amplifier ring down, during the noise blanking. This requires crossed blanking diodes, as shown after the power amplifier's output in Fig. 1, which eliminate these low-power artifact signals. After the crossed blanking diodes, the power is routed to the T/R switch.

T/R Switch

Figure 2 details the T/R switch. Two broadband (225–400 MHz) ferrite based circulators are shown, CR1 and CR2 (Renaissance Electronics, Harvard MA,

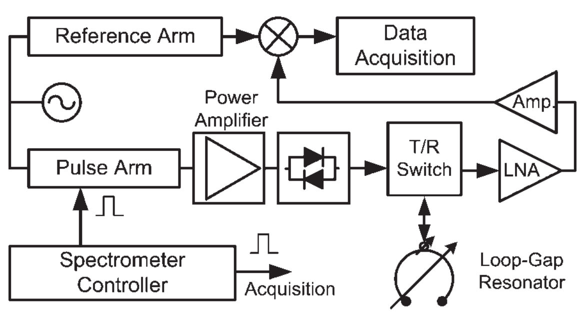

Figure 1 Block diagram of the pulse bridge.

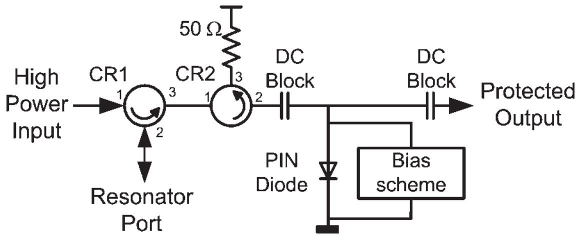

Figure 2 Schematic of the T/R switch. The configuration of the ACC diode limiter (PIN diode) and bias scheme is conceptual and does not reflect the actual wiring of ACLM4930-H-C25 limiter.

model 3A2BC). The isolation between Ports 1 and 3 of the circulators under CW conditions for a matched 50 Ω load at the center frequency is 23 dB. The loop-gap resonator connected to the Port 2 of CR1 is critically coupled at the central frequency and has the quality factor of about 14. For high-pulse power 40 ns pulses, the reflections from the unmatched frequency wings of the broadband pulses deteriorate the isolation of the resonator/CR1 circulator system. This decreases the isolation of the resonator/CR1 system to about 10 dB. The power emerging from the Port 3 of CR1 is fed to Port 1 of the circulator CR2.

CR2 forms the first part of the protection circuit, transmitting power reflected from Port 2 of the circulator to a high-power 50 Ω resistive load (system impedance, Z_0) at Port 3 while the level of the power is above 5 dBm (3 mW). This protects both the LNA and the high power amplifier.

The second part of the protection circuit is implemented with a shunt connected PIN diode limiter as shown in Fig. 2. The PIN diode is forward biased by high-input power/voltage reaching the indicated biasing system. The forward biased diode produces a low-resistance R_S of the order of 0.5 Ω. When the input power diminishes to a value below the bias threshold, the diode resistance rises. As an open shunt circuit, local impedance is then determined by downstream elements. The equivalent circuit in this state is a parallel combination of a high-PIN diode resistance R_P and a low-PIN diode capacitance C_T (1 pF typical). In the low-power situation when the T/R switch is conducting power to the LNA, the insertion loss is mainly determined by the PIN diode capacitance C_T which should be as low as possible.

The PIN diode and its biasing system are, thus, forward biased by the incoming power pulse itself, the basis of its passive mode. In principle, the biasing scheme can be as simple as a parallel inductor or a parallel Schottky diode. These biasing schemes maintain forward bias typically to a power level above to ~5 dBm or a voltage of ~0.6 V. In practice, we selected a commercially available PIN diode based device and built-in biasing system that has both low loss and turn on threshold. We used an Advanced Control Components (ACC, Eatontown, NJ) high-power limiter ACLM4930-H-C25. This has a conduction threshold of 5 dBm and a measured maximum flat leakage of 14 dBm at 60 dBm (1.03 KW) peak incident power level. Relevant pulsed measurements were performed at discrete center frequencies and power values. The DC block at the output of the T/R switch isolates the downstream components from the bias voltage generated by this scheme.

The LNA, downstream of the PIN diode limiter was an Advanced Receiver Research (Burlington, CT) P240-270 VDG-NMR-LoMag gallium arsenide FET amplifier custom tuned to 250 MHz center frequency with 20 dB of gain and a noise figure of 0.5 dB with a 1 dB bandwidth of 240–270 MHz and a 1 dB compression power of 12 dBm.

Determination of the T/R Switch Characteristics

Pulse High Power Measurements. The characteristics of the T/R switch were determined using both CW and pulsed inputs. The high-input power protection mode isolation of the T/R switch was measured using a digital oscilloscope, a Hewlett–Packard model 54616B with a 500 MHz bandwidth, capable of 2 GS/s acquisition. Measurements of the isolation, at high power, were made using 250 MHz, 40 ns RF pulses at 60 dBm incident power. These measurements were carried out by injecting the power amplifier output into Port 1 of the CR2. The digital oscilloscope was connected downstream of the T/R switch.

Low Power CW Measurements. The transmission characteristics of T/R switch in conduction state were measured using a network analyzer in a CW mode at low power. This allows continuous frequency sweeping at low power to show the frequency profile of the insertion loss of the T/R switch. A Hewlett–Packard Model 8753ES (Palo Alto, CA) network analyzer provided CW inputs and outputs at discrete powers. For measurement of the insertion loss, a power of 0 dBm (1 mW) was used. Typically the four circuit scattering parameters were measured but this article focuses on S_{21}, the insertion loss in the conduction state of the T/R switch.

RESULTS

The receiver protection scheme of the T/R switch includes the circulator CR2, the 50 Ω high-power

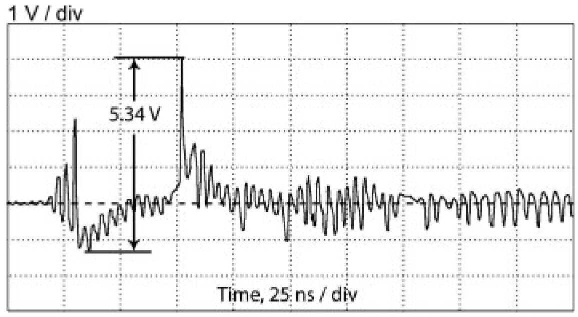

Figure 3 The oscilloscope trace downstream of the T/R switch. The 40 ns long 60 dBm (1.03 KW) RF pulse is applied to the Port 1 of CR2. The CR1 circulator and resonator are excluded from the scheme. The vertical scale values in this figure are 10.78 times the values recorded on the scope to account for a ~20 dB power attenuator on the scope input. The input power produces a 2 ns transient of just over 5 V, with insufficient power to damage the LNA.

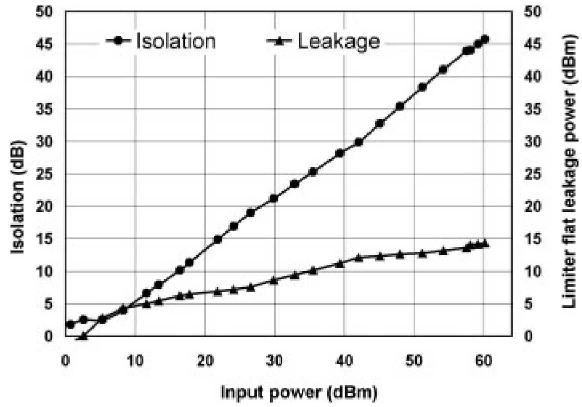

Figure 4 Isolation and leakage of the T/R switch. The CR1 circulator and resonator are excluded from the scheme.

termination at Port 3 of CR2, and the PIN diode shunting Port 2 of CR2 and its biasing system as well as the 50 Ω transmission downstream of the PIN diode. When a forward biased diode shunts a transmission line, the isolation in dB is

$$\text{Isolation} = 20\ \log_{10}\ [1 + Z_0/2R_S] \qquad [1]$$

where Z_0 is the system impedance and R_S is the diode resistance. A typical 0.5 Ω PIN diode forward bias resistance gives an isolation of 34 dB.

Figure 3 shows a digital oscilloscope trace at the T/R switch output. The 250 MHz, 60 dBm incident RF power, 40 ns RF pulse is applied to the Port 1 of CR2. Into 50 Ω, this pulse will have instantaneous amplitude of 310 V. For this measurement CR1 and resonator were excluded from the scheme because the isolation of CR1/resonator system is strongly dependent on the resonator loading, quality factor and matching. A 20 dB attenuator protects the oscilloscope input which is internally terminated with 50 Ω. A spike at the trailing edge of the pulse with 5.3-Vpp amplitude is seen with a width of <2 ns. Otherwise, the largest amplitude of variation of the scope trace (1/2 the peak-to-peak variation) is <1.5 V, a factor of 200 in voltage or 46 dB in power isolation. As indicated earlier, the isolation is sufficient to fully protect the LNA, at the 63 dBm maximum rating of the power amplifier.

Reversing Eq. [1], the R_S of 0.1 Ω can be calculated. From this, we can infer that ACLM4930-H-C25 high-power limiter has either a two stage diode cascade or a PIN diode with a much lower conduction resistance than the typical 0.5 Ω for a single PIN diode in the ACC switch. Details of the circuit and the biasing scheme are not available from the manufacturer.

Figure 4 plots the power leakage downstream of the limiting PIN diode switch as a function of power input to Port 1 of CR2, based on the scope trace amplitude. The difference between the input power and the leakage is the isolation which is also plotted. These are based on the maximum amplitude of variation in the scope trace shown in Fig. 3 excluding the 2 ns spike. The spike was not considered because we believe that the energy in the spike is insufficient to damage the LNA.

Figure 5 shows the total insertion loss (S_{21}) of the T/R switch as a function of frequency in the 60 MHz interval about the operating center frequency of

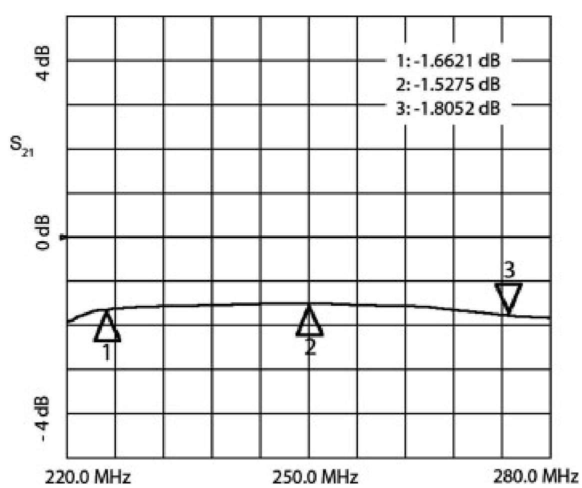

Figure 5 Low-power insertion loss as a function of frequency from 220 to 280 MHz. The broadband response is crucial to capture either a large spectral interval or as large as a spatial interval for imaging.

Table 1 Parameters of the T/R Switch

Maximum instantaneous power	60 dBm
Isolation at 60 dBm	47 dB
Excitation power (CR1 port 1 to port 2) insertion losses	0.8 dB
Total signal insertion losses, S_{21} in 60 MHz bandwidth	1.5–1.8 dB
Bandwidth	72 MHz
Imager dead time at 60 dBm input power	450 ns

250 MHz. Including the T/R switch internal connections and cables used, the measured insertion loss is seen in Fig. 5 to be ~1.5 dB at 250 MHz and almost flat for 72 MHz. This flatness of S_{21} curve over the large frequency range shown is of particular importance for time domain EPR imaging, where as large a bandwidth as possible is desirable. The parameters of the T/R switch are summarized in the Table 1.

Figure 6 presents the electron spin echo signal obtained using the 250 MHz imager (*2*) equipped with the described T/R switch. The echo was generated using 35 ns π/2- and π-RF pulses that had, correspondingly, 54 and 60 dBm of instantaneous power. The baseline signal is obtained by switching the magnetic field off-resonance by 10 gauss. The spurious signal denoted by in the figure originated from the circulator (*2*). The dead time of the imager is about 450 ns.

DISCUSSION

This is essentially a passive circuit using diodes biased by the input power. The advantage of this configuration is its independence of the need for an external biasing circuit for the PIN diode. Our design eliminates the need for a synchronous application of externally timed pulses as is the case with active systems. It provides fully reliable and simplified control. The overall isolation of our design is RF power dependent and grows with increasing input power. Although the first circulator provides some level of isolation, the overall isolation depends on the isolation of the CR2/limiter. For 60 dBm RF pulses, the overall isolation is 47 dB with 38 dB isolation provided by the CR2/limiter part of the T/R switch. Figure 4 demonstrates that isolation grows proportionally with the input power, whereas the flat leakage stays nearly constant. The power rating of the CR1 circulator prevented us from testing the overall T/R switch isolation at higher input power levels.

Other such designs have been published. A passive T/R switch similar to the present design was presented by Quine et al. (*10*) at 1–2 GHz. However, the present design exceeds the power handling capacity of the Quine et al. design by nearly two orders of magnitude and has wide band response at VHF frequency. The recently developed feedback type limiter used in our design has an incident power handling capacity in excess of 60 dBm and low-insertion loss of 0.4 dB. The power handling capacity of our design is limited by the circulators and expected to increase in the near future to at least 63 dBm.

The T/R switch designed by the NIH group makes use of active PIN diode switches separated by a quarter wave segment designated as a diplexer (*8*). This generates a high impedance and a low impedance in a push–pull configuration under the control of external biasing system. The system is an elegant example of an active system using two diode switches responding to the same control system in opposite directions. The reported power handling capacity of this system is 50 dBm. It is limited by power handling capacity of the active elements. Other parameters of this switch are similar to ours.

Monroe (*11*) have produced a design with some similarity to the one proposed here. It involves a circulator T/R switch with impedance at Port 2 determined by a PIN diode limiter. However, like the system of Murugesan et al. (*8*), the biasing system is not passive. Rather, it is under external control. This is a fundamentally different configuration from that presented here.

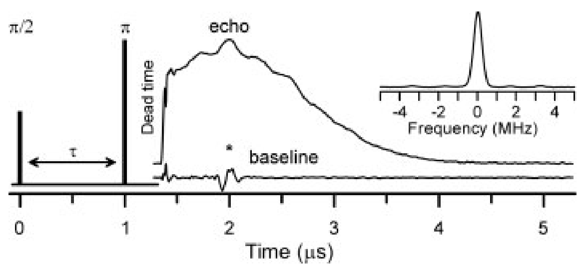

Figure 6 The electron spin echo signal of 1 mM OX063H spin probe obtained in 250 MHz pulse imager. The pulse π/2-τ-π sequence is schematically shown on the left. The echo was filtered using low-pass filter with 20 MHz cut-off and corrected for baseline. The baseline is obtained in the off-resonant magnetic field. The Fourier transformed signal is presented in the insert. Other parameters: loop-gap resonator with $Q = 13$; π/2-pulse 35 ns, 47 dBm; π−pulse 35 ns, 53 dBm; $\tau = 1$ μs; shot repetition time 20 μs; and 32,000 averages including phase cycling.

CONCLUSION

We have presented the wide band, high speed, high power, low-insertion loss T/R switch working at 250 MHz. This device uses only passive components for its operation and is failsafe. We expect that the present power handling capacity of the T/R switch (60 dBm) can be extended at least two to four times in the future. The response of the switch is flat for the bandwidth of about 60 MHz. This will enable the application of pulse EPR imaging to large objects.

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