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Improved rejection of transmitter noise: a convenient scheme with resonant crossed diodes

Daniel W. Sinkovits, Mark S. Conradi*

Department of Physics, Washington University, 1105, One Brookings Drive, St. Louis, MO 63130-4899, USA

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Abstract

A method is presented for improved rejection of transmitter noise in the duplexer (transmit–receive switch). The capacitance of a set of crossed diodes forms a resonant circuit with a length of coaxial cable. The rejection of our resonant design is 60 dB, compared with only 12–15 dB for the usual method, all measured at 175 MHz. Tuning the entire duplexer to different frequencies is convenient, requiring only two new lengths of cable. The scheme is most useful with ungated linear rf power amplifiers at very high frequencies (above 100 MHz), where transmitter noise can be a severe problem.

Keywords: Noise; Duplexer; Transmit–receive switch

1. Introduction

Single-coil NMR circuits employ the same coil for receiving and transmitting and are widely used. A duplexer or transmit–receive switch is required; a commonly used approach relying on the non-linear I–V behavior of semiconductor diodes [1,2], the design of Lowe and Tarr, is displayed in Fig. 1. The crossed (anti-parallel) diode sets are *approximately* zero impedance for large voltages during the transmitter rf pulse and infinite impedance for the very small voltages during reception of the nuclear spin signal. The diodes serve to limit (clip) the voltage to the receiving preamplifier during transmitter pulses to about 1–V peak and to prevent part of the spin signal from being wasted by going back into the transmitter output port.

A third and important role of the diodes is to prevent noise from the transmitter from entering the receiver, which would degrade the signal-to-noise ratio (SNR). The diodes appear as capacitances C in the off-state, with impedance magnitude $1/\omega C$ (ω is the angular operating frequency). Thus, the transmit diodes in Fig. 1 are increasingly *leaky* at higher frequencies.

There are many ways to reduce the leaked transmitter noise. One can use a non-linear amplifier as the final stage of the transmitter, such that it is biased-off in the absence of an input rf pulse (e.g., Class C). Transmitter amplifiers with external gating or blanking ports reduce the noise by disabling one or more stages of gain. One can use diodes with smaller capacitances. For example, the Schaefer group at Washington University uses Agilent Technologies (formerly Hewlett–Packard) PIN diodes, 1N5179 (Schaefer and Potter, private communication). These diodes are 0.5 pf at zero bias, substantially smaller than the usual small-signal silicon junction diodes that we use (e.g., 1N4151 at 2 pf per diode). Here, the PIN diodes are driven only by the rf, with no dc bias voltage or current [3]. The only disadvantage of the PIN diodes is their price ($5–10 versus $0.15 per diode). The most common approach to the problem is to simply string transmit diodes in series [4] until the desired noise rejection is obtained (but see below).

* Corresponding author. Fax: +1 314 935 6219.
E-mail address: msc@wuphys.wustl.edu (M.S. Conradi).

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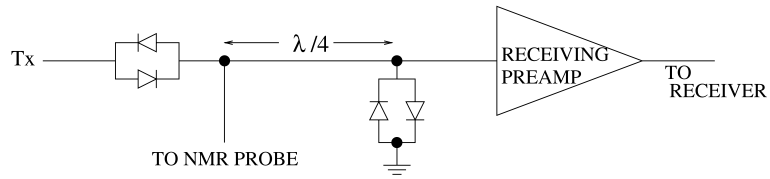

Fig. 1. Standard duplexer (transmit–receive) circuit using crossed diodes as switches. Tx is the transmitter.

In terms of transmitter noise during NMR signal reception, the worst offenders are ungated, linear (Class A or AB) power amplifiers; many of these are in use in NMR labs. An amplifier that can generate 100 W from a 1 mW rf input has 50 dB of gain; with a typical 5 dB input noise figure, the amplifier's output is 55 dB hotter than k_BT (thermal energy at room temperature). To prevent this noise from reducing the received SNR requires a rejection of 60 dB or better in the transmit–receive switch. A pair of anti-parallel diodes with 2 pf capacitance (each) has an impedance of 250 Ω at 175 MHz. In a 50 Ω system, the rejection of the transmit diodes in Fig. 1 would be about 5:1 in voltage, or 14 dB; this is far short of the required performance.

2. Resonant design

The root of the problem is the capacitance of the diodes. Our approach is to resonate this capacitance with a length ℓ of coaxial transmission line as presented in Fig. 2A. The length ℓ, a bit shorter than $\lambda/4$ (λ is the wavelength in the cable, typically 2/3 the free-space value), is chosen so that the diode capacitance C is transformed to zero impedance at the cable's upper end [5–7]. A related approach was used to remove the lead inductance of receiving (voltage clipper) diodes [8]. We note the previous use of $\lambda/4$ diode-stubs in a duplexer [9].

To understand this approach, we start by assuming perfect crossed diodes ($C = 0$) and $\ell = \lambda/4$. In receive, the infinite impedance of the diodes is transformed by ℓ to appear at the junction (dot in Fig. 2A) as zero impedance, shorting the transmitter noise to ground. In transmit, the zero impedance of the diodes is transformed by the $\lambda/4$ cable to infinite impedance (current node) at the junction, so the transmitter is not loaded by this shunt stub.

The small capacitance C of the diodes in their off-state can be compensated by shortening the cable length ℓ. A simple view is that C is equivalent to the capacitance of the few centimeters of cable length that are to be removed. With the length ℓ chosen this way, there

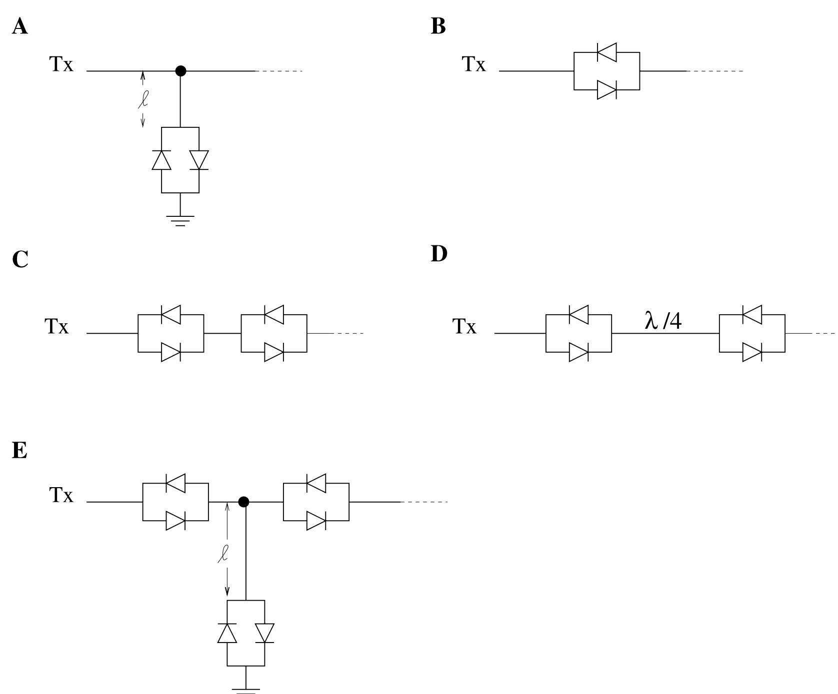

Fig. 2. Several diode elements and combinations of elements for rejecting transmitter noise. Each of these can be used in the standard duplexer design of Fig. 1, replacing the transmitter diodes there, with the exception of scheme (A). Each circuit is tested by putting it between an rf generator and an rf receiver. All diodes are silicon PN junction diodes, IN4151. The length ℓ of (A) and (E) is selected to transform the diodes' capacitance to zero impedance; ℓ is a bit shorter than $\lambda/4$.

is very high rejection of noise with C transformed by the cable to be zero impedance at the junction. Because ℓ is no longer *exactly* $\lambda/4$, during transmit this shunt stub presents an inductive and large impedance at the junction [5]. Generally, this is of little impact, but could be corrected with a small capacitance to ground located at the junction, possibly in the form of a very short length of cable on a Tee. We have not pursued this small correction of the impedance in transmit-mode.

We note that an alternate resonant scheme uses an inductor in parallel with a set of transmitter crossed diodes, forming a parallel tuned circuit (high impedance) with the diodes in their off-state [9,10]. The advantage of the present design is one of convenience for use at multiple frequencies, as discussed below.

3. Results

Several crossed diode elements and combinations are presented in Fig. 2. Each of the schemes B, C, D, and E are suitable for use in the standard duplexer of Fig. 1, replacing the transmitter diodes there. The single element of scheme A is not suitable for such use by itself, but is presented for evaluation of its noise attenuation and because it is one element in the ultimately chosen scheme of Fig. 2E. The performance of all five designs in attenuating transmitter noise is presented in Fig. 3. The measurements were made with an rf signal generator with a calibrated output attenuator, H–P 608E, and an NMR receiver. When the diode element or elements were installed (in place of direct connection from the generator), the generator output was increased to obtain the same signal in the receiver. The increased generator output (in dB) is the rejection of the diode network reported in Fig. 3.

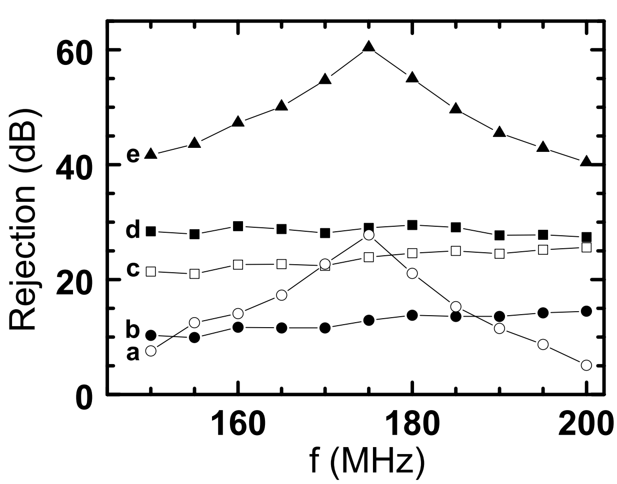

Fig. 3. Rejection in decibels of the circuits of Figs. 2A–E, as functions of frequency in a range centered on the desired operating frequency of 175 MHz.

Single diode elements (Fig. 2B) show rejections of 12–15 dB, depending on the brand of diodes. Two diode sets coupled directly together (Fig. 2C) should have half the capacitance, twice the series impedance, and 6 dB better rejection than a single set. Simply stringing diode sets in series produces only modest improvements in rejection; in voltage ratio units, the rejection factor increases only linearly with the number of diode sets. Without going into details, one is better off to separate the diode sets by lengths of cable, so that each diode set, together with the following cable length, forms a voltage divider. Used this way, the attenuation of the elements combines multiplicatively (additively in dB units). The optimum cable length ℓ is not critical and is approximately $\lambda/4$; in particular, integer multiples of $\lambda/2$ (including zero) should be avoided. In practice, the diode sets of Fig. 2C had about 5 cm of rf connector between them, so the increase in attenuation compared to the single diode set was about 10 dB, somewhat greater than the 6 dB expected from the above reasoning. With a $\lambda/4$ cable between the diode sets, as in Fig. 2D, the performance was improved, as expected. The circuit of reference four uses resistors-to-ground between diode pairs, yielding cascaded attenuation, but at the cost of reduced transmitter power delivered to the probe.

Clearly, the shunt stub of Fig. 2A shows the best rejection for a single element. Combined with two diode sets as in Fig. 2E, the rejection in Fig. 3 reaches 60 dB at the resonance frequency of 175 MHz. The bandwidth of the design indicates that, to lose no more than 5 dB of the rejection possible, one has a ±5 MHz out of 175 MHz or ± 3% bandwidth. The length ℓ should be cut to this accuracy.

Selecting the correct length ℓ can be done with an assortment of cables with lengths ℓ'. The circuit of Fig. 2A is connected, using a sweep generator for source and an amplifier and diode detector for receiver. The generator level must be kept low to avoid conduction in the diodes. The frequency f of greatest rejection is plotted as a function of ℓ'. Interpolation of the data allows the correct length ℓ for the desired frequency to be selected. In practice, this is easy and needs only two lengths, one a bit shorter and one a bit longer than the correct length ℓ.

The result is a particularly convenient scheme: for each NMR operating frequency, one needs a cable to use as ℓ in Fig. 2E and another to serve as $\lambda/4$ in Fig. 1. Thus, changing frequency of the duplexer involves changing only two cut-to-length cables. We prefer this method over tuning of crossed diodes with an inductor, as has been reported [9] and as commercially available [10]. The inductively tuned diode method requires there be many diode boxes, one resonated at each desired operating frequency.

Wideband linear transmitter amplifiers require one more consideration. In addition to rejection of noise *at* the NMR frequency, the huge burden of wideband noise must be reduced, so that it does not overload the receiving preamplifier and/or generate intermodulation noise products at the NMR operating frequency. Thus, one needs moderate rejection of noise across the entire spectrum of transmitter noise as well as deep rejection at the NMR frequency. One would not want to rely exclusively on resonant schemes such as Fig. 2A; the design of Fig. 2E incorporates both resonant attenuation (as in 2A) and wideband attenuation (as in 2C and 2D). With one of our power amplifiers, the output noise extends well beyond 500 MHz. We use a 200 MHz lowpass filter in the transmitter output; the diode sets are leakiest at high frequencies so the lowpass filter eliminates the most offending part of the transmitter noise spectrum.

At frequencies substantially above the 175 MHz used here, the performance of the simple crossed diode set of Fig. 2B will be even poorer. By contrast, the performance of the shunt stub of Fig. 2A should only improve: although the loss per unit length of transmission line increases approximately as $\sqrt{\omega}$, the loss on length ℓ will be reduced because ℓ varies approximately as $1/\omega$. We note that attenuation on this line prevents the impedance at the junction of Fig. 2A from going fully to zero [5]. Thus, the shunt stub is expected to show even more performance advantage over simple crossed diodes (Fig. 2B) at higher frequencies.

A duplexer was constructed with the network of Fig. 2E replacing the single set of transmitter diodes in Fig. 1. The NMR performance is excellent. The noise at the phase-detector output of the receiver does not change visibly (less than 0.5 dB change) with the rf transmitter power amplifier turned on and off. Using a signal generator in place of the NMR probe, the received signal/noise is virtually identical with the generator directly driving the preamplifier or with it routed through the duplexer.

4. Conclusions

A resonant scheme is presented for use with crossed diodes, providing greater rejection of noise from the transmitter power amplifier. The scheme is especially useful with ungated linear amplifiers at very high frequencies (above 100 MHz), where the problem of transmitter noise leakage is most severe. Frequency changes require only the change-out of two cut-to-length coaxial cables.

Acknowledgments

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