Some Thoughts on Electronic T/R Circuits

Wes Hayward, w7zoi, November 3, 2018

Abstract: *Several schemes have been used to switch an antenna between a receiver and transmitter. A popular scheme with low power (QRP) equipment uses shunt back-to-back diodes in the middle of a series tuned circuit. But this scheme sometimes fails, for it is misapplied within a filter and matching networks. The failure appears as high attenuation of the received signal. This paper analyzes this topology and proposes solutions to improve receiver performance. The basis for this work is LT-SPICE disturbed by Linear Technology, now part of Analog Devices.*

Introduction—The Classic QRP Transmit-Receive Scheme

We all have our personal lists of design projects that we want to do, someday. Typical are circuits with a known deficiency with a suspected easy solution. Rather than fixing the problem at the time, most of us add the project to ***the list*** with the thought that we will examine it someday. This is one of those things that was finally examined. A classic transmitter circuit including a T/R switch is shown in Fig 1. Circuit discussion follows.

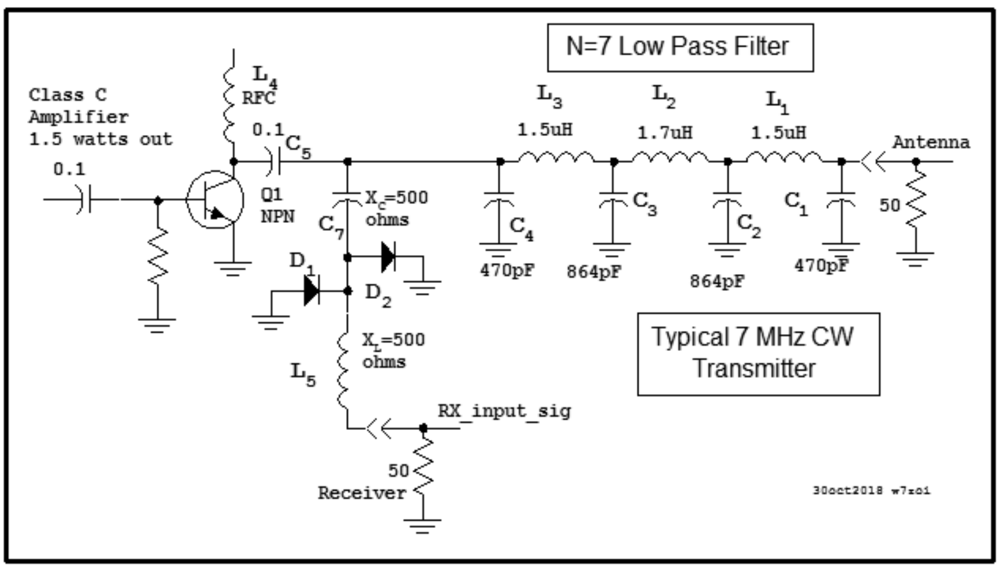

Fig 1. Schematic for the power amplifier in a QRP transmitter. This topology is a favorite classic circuit that many of us have built, perhaps too often. The 7th order low pass filter has a 3 dB cutoff near 8 MHz, presenting a flat response in the 40 meter band.

The low pass filter has a good input match. The 50 ohm load at the antenna port causes the input impedance to also be very close to 50 ohms. Imagine for the moment that C7 is eliminated, causing the low pass filter input to be presented directly to the NPN collector. There is now no connection to the receiver. A 50 ohm load presented to the collector can generate a transmitter output power of 1.5 watts with a 12 volt power supply.

Imagine now that C7 is present, but that the two diodes are missing. This capacitor has a high reactance of 500 ohms. C7 would be 45.5 pF at 7 MHz. We would probably use a standard value of 47 pF. The receiver is assumed to have an input impedance close to 50 ohms, R5 in Fig. 1. L5 is chosen to resonate with C7 at 7 MHz, so would be 11 uH. The series tuned circuit of L5 and C7 presents a low impedance, so the receiver is connected directly to the low pass filter input. The receiver functions well, with almost all available antenna signal presented to the receiver input, R5. The transmitter circuitry does not affect the receiver function, for the transmitter PA is off, causing it to look like a high impedance. Without the diodes, turning the transmitter on, even at 1 watt, would most likely destroy the receiver.

Diodes D1 and D2 are now reinserted in the circuit. These are silicon switching diodes, so they require a voltage of 0.6 or more applied before they will conduct. This level occurs when the transmitter is keyed, generating a much higher signal at the collector. The diodes then rectify the RF and conduct, acting as a shunt switch offering low impedance to ground of just a few ohms. The two diodes alternate, one conducting with each polarity of the applied RF voltage. The diode switching adds a capacitance of 47 pF to the filter input, but this is small compared with C4, so does not significantly alter the filter response. The signal present at the receiver input, R5, is less than a milliwatt when the key is down, so the receiver is not damaged. It may, however, be overloaded, so receiver muting is required. This T/R scheme first appeared in detail in the now classic work of W7EL. (See QST, August, 1980)

Analysis Methods, the N=7 Low Pass Filter

Some analysis techniques will be reviewed before attacking the central problem of this note. The schematic in Fig 2 below is a simulation in LT-SPICE with two parts. The left is the generator end of a **Vector Network Analyzer**, VNA. The right section contains the low pass filter from Fig 1 and a termination R1. R1 is not part of the filter. An output voltage is marked as **S21**. This is the output, forward scattering parameter. **S11**, the input scattering parameter is marked in the generator portion at the left.

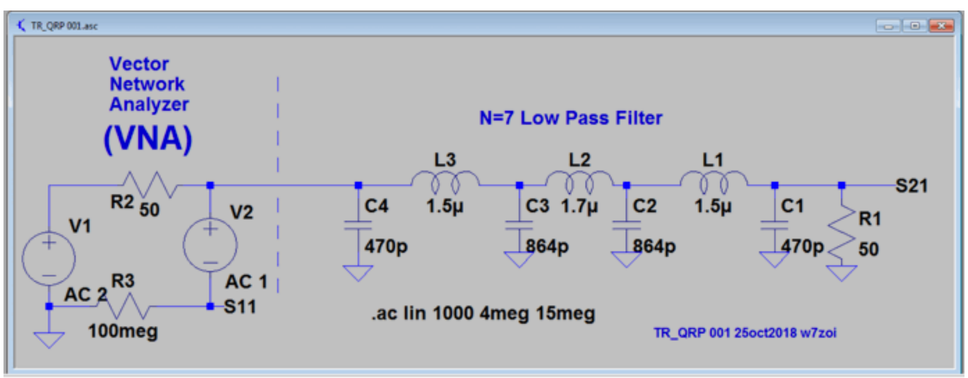

Fig 2.

The 7th order low pass filter is studied with a Vector Network Analyzer, producing a gain, S21, and an input *impedance* S11. The input topology with two generators of 2 and 1 volt strength is especially useful when using SPICE. R3 in this circuit merely keeps SPICE happy, for unterminated voltage sources can otherwise be a problem in some SPICE versions. (The origin of this SPICE topology is unknown, but was first shown to me by Thor Hallen, K5AGE, at Tektronix in the 1980s. I wrote more about it in QEX, Jan 1993.)

The point marked S11 in Fig 2 is the reflection coefficient usually plotted on a Smith Chart. Return loss or VSWR may be extracted from the amplitude. The S-parameters are vectors with both amplitude and phase. The results of this simulation are shown below in Fig 3.

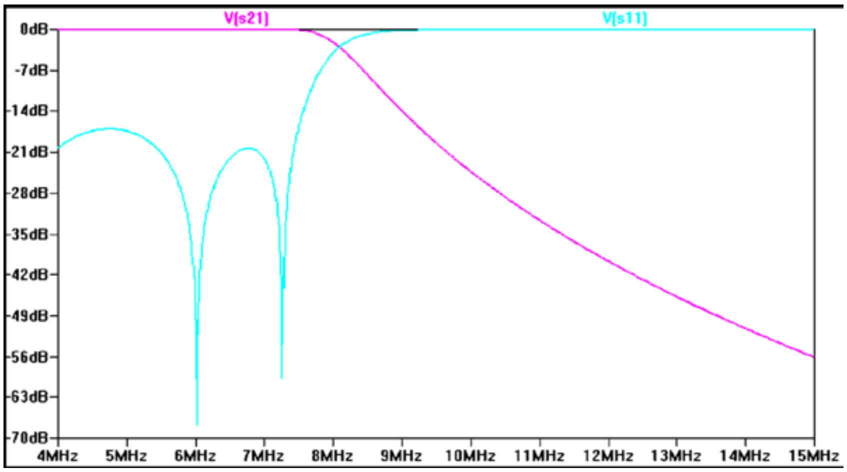

Fig 3. Gain (S21) and input match (S11) for the low pass. The values are show in dB. The S11 ripples are not equal, indicating a departure from the original Chebyshev filter design. This is a result of using practical (that is, junk box) values in the low pass filter.

Receiver Match with a 1.5 watt Transmitter

The next figures show the antenna port to receiver path gain and impedance match. We are now driving the antenna port with the **VNA**. The circuit is that of Fig 1.

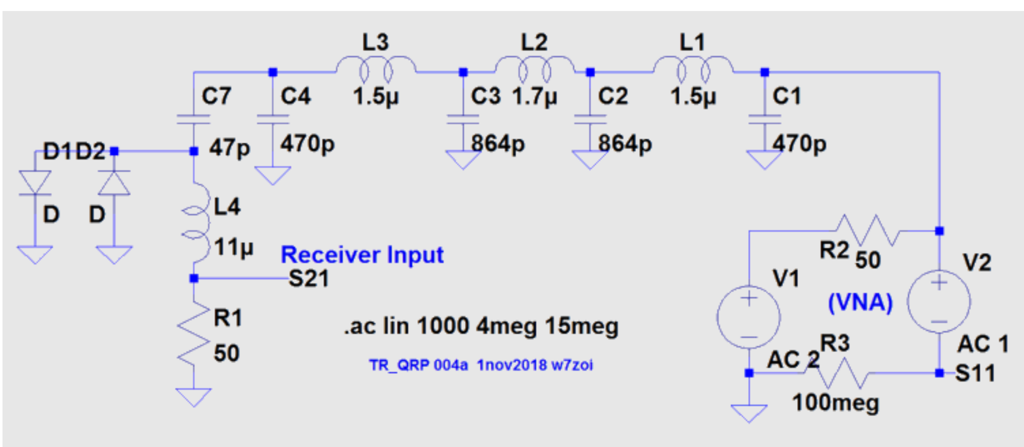

Fig 4. The receiver path for a 1.5 watt transmitter. Transmitter PA is not shown, but is essentially just a small capacitance in parallel with C4. This is the circuit of Fig 1

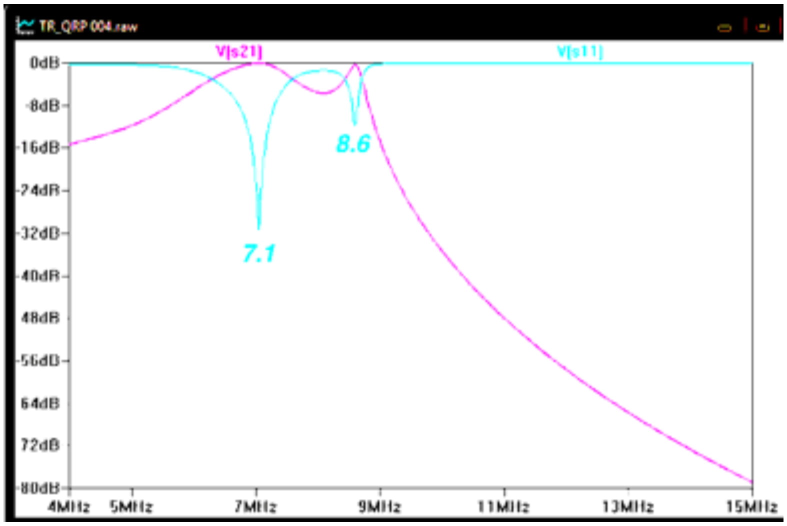

Fig 5. Impedance match looking into the antenna port for a 1.5 watt transmitter. The match at 7.1 MHz is very good with a return loss of better than 30 dB. Return loss is the negative of S11 in a measurement or calculation of this sort. Another response appears at 8.6 MHz. See text for a discussion.

The gain and match response shown for the receiver path in Fig 5 is mostly determined by the 47 pF and 11 uH series tuned circuit used in the T/R switch. The extra response at 8.6 MHz appears from over coupling between the series resonator and the elements of the low pass filter. It should not be a problem with this example, but might be for similar situations. Interaction of the series tuned circuit with a preselector filter in the receiver can be especially interesting. (See http://w7zoi.net/imtc/imtc.pdf)

The Problem

Having dispensed with the preliminary details, an initial example of the problem can now be presented. This is shown below in Figures 6 and 7. The circuit contains the same series tuned circuit and switching diodes and the same low pass filter. But an L-network has been inserted as a step down circuit to provide a 12 ohm load to the transmitter PA. Some SPICE versions become unstable when an open circuited inductor is included in a circuit, so a 1 megohm resistor is included. It is the shunt 788 pF capacitor that causes a problem.

The transmitter is off when the path from the antenna to the receiver is analyzed. Hence, the diodes are off and do not affect circuit behavior and are not included in Fig 6.

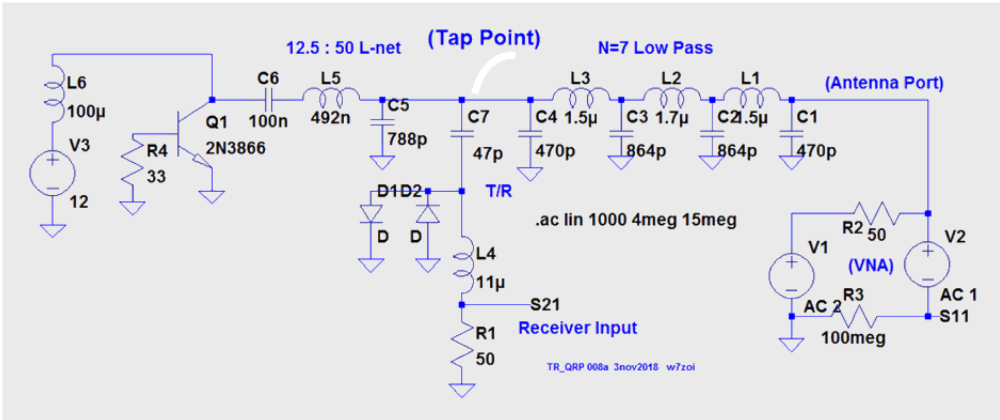

Fig 6. The "tap point" for the T/R switch is now buried within a complex filter. In this example, the 788 pF capacitor, C5, severely alters the receive path.

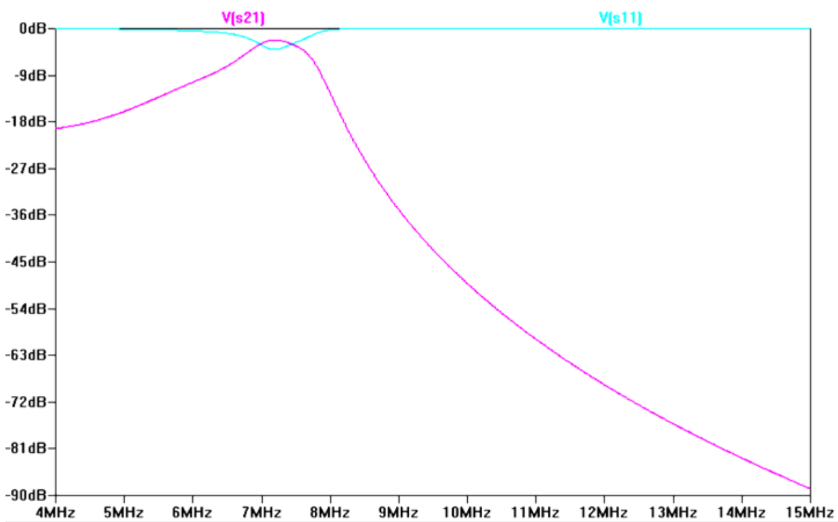

Fig 7. The response is severely compromised. There is a few dB loss in the signal path, S21. Equally bad, the return loss is only a few dB at 7 MHz. This is a reactive situation that will probably interact unfavorably with other filters or with stray elements in the circuit.

Performance is improved with a two step modification. First, the tap point is moved to the collector. Then the impedance is transformed from the 12 ohm environment back to 50 ohms at the receiver port. The transformation uses an L-network identical to that used for the transmit path. The circuit is shown in Fig 8 with the response in Fig 9.

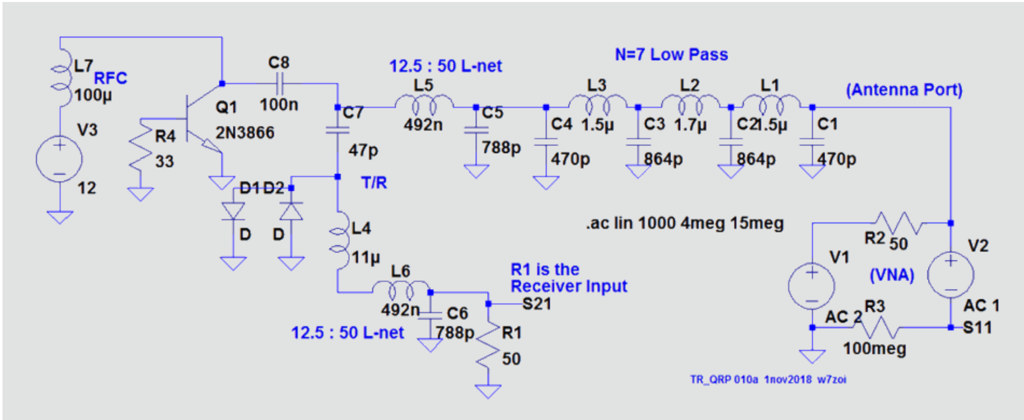

Fig 8. An improved T/R system using L-networks.

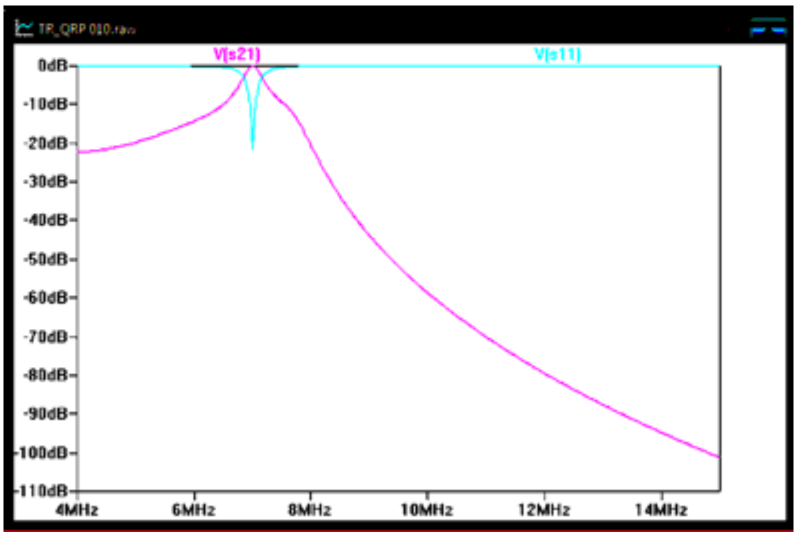

Fig 9. Both gain and match are now OK. The gain hits 0 dB at 7 MHz. It should be 0, for the models we have used have no loss elements.

The improvement is significant. There is no gain loss at 7 MHz, and the return loss is a comfortable 20 dB, a good match. Lossless components have been assumed for all inductors and capacitors, so the simulated insertion loss will be zero. In practice, practical components will produce a dB or so of IL, usually an acceptable tradeoff.

The same concepts can be simulated with wide bandwidth matching elements. A bifilar ferrite transformer can drop the impedance from 50 to 12.5 ohms. This is considered in the following figures.

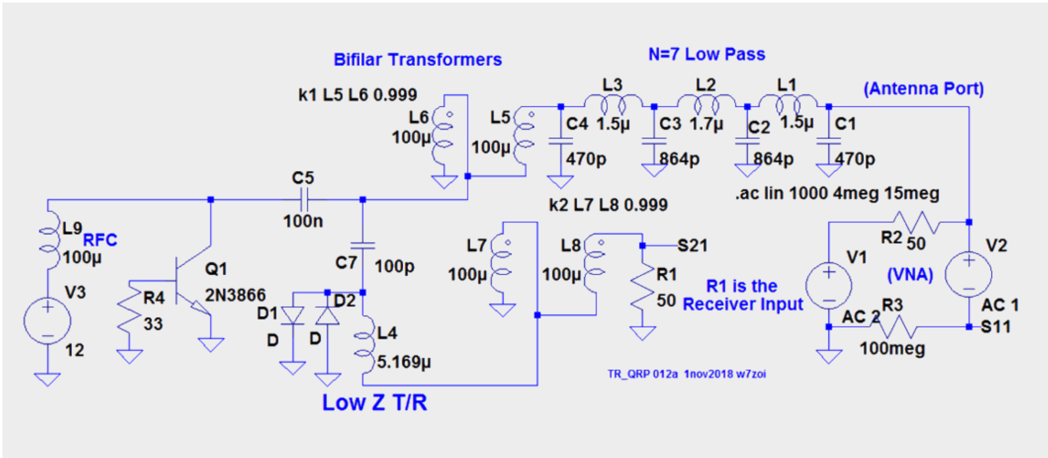

Fig 10. A higher power case with bifilar transformers on either side of the T/R diode network. A lower impedance is used in the T/R, resulting in improved bandwidth.

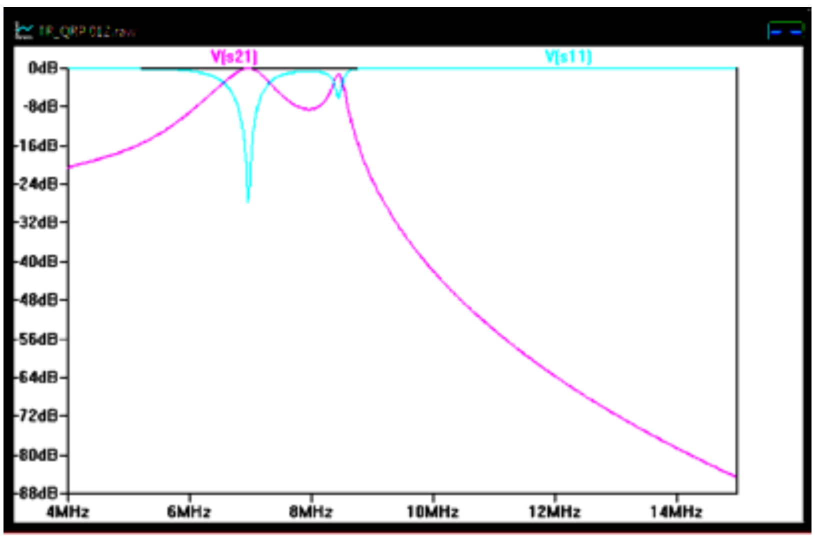

Fig 11. Gain and match for Fig 10.

Figures 10 and 11 depict a case with two changes. The impedance transformation is done with a wide bandwidth transformer. The other is new component values for the series tuned circuit surrounding the diodes. The original circuit used 47 pF and 11 uH. That worked here with good performance, but a narrow bandwidth. Changing to 100 pF and 5.17 uH yields greater bandwidth, but with higher peak current in the switching diodes. The new L and C values may also be worthwhile with L-network matching. For that matter, a mixture of methods should work well.

Diode Waveforms

What is the diode current? Figure 12 shows a **transient** rather than linear simulation intended to examine diode waveforms. The initial diode model, D, is just the default that comes up when a diode is inserted into a circuit. Fig 13 shows the related waveforms.

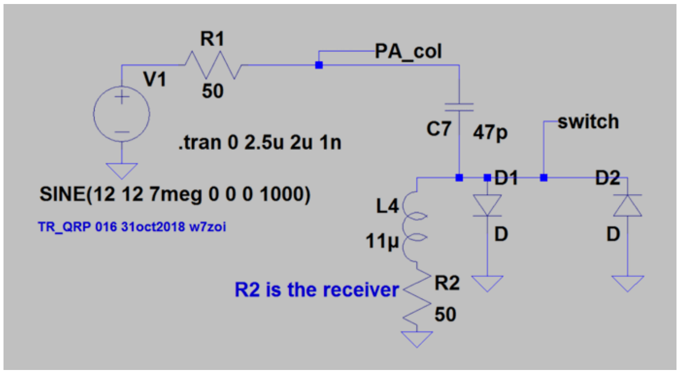

Fig 12.

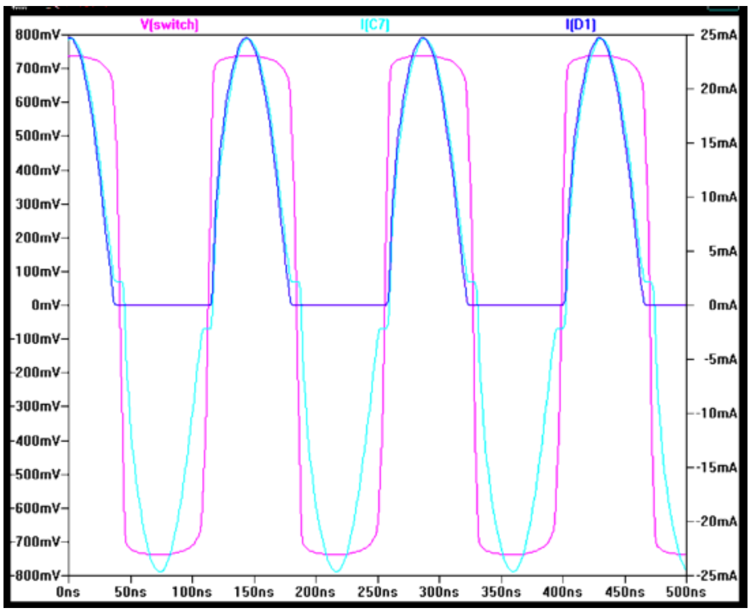

Fig 13. The diode current I(D1) overlaps I(C7), the capacitor current.

The diode model "D" is a simple, ideal Silicon diode that starts to turn on with the classic 0.6 volt. This model contains none of the real world charge storage effects. If the model is changed to a 1N4148, or example, the storage becomes apparent. These "glitches" do not seem to get in the way of the switching action.

The schematic of Fig 12 represents a 12 volt transmitter supply, so the voltage generator is set to have a 12 volt AC amplitude with a 12 volt DC offset. Hence, the applied voltage, PA_col, goes from 0 to 24 volts. This is **not** shown in the waveforms of Fig 13 for the figure is messy enough as shown. Fig 13 shows the voltage across the diode pair, the current in the capacitor, C7, and the current in one of the diodes. The reactance of 47 pF C7 at 7 MHz is 484 ohms. The applied voltage is 24 volts peak-to-peak, so the peak-to-peak capacitor current is, by Ohm's law, 50 mA. The peak current in each diode is half of this, 25 mA. Increasing the capacitor to 100 pF as was done in Fig 10 would increase diode current in proportion. A different supply voltage would also alter the peak diode current. A different transmitter power, however, would not change the peak diode current so long as the T/R series tuned circuit is attached to the PA collector or drain.

Single-ended power amplifiers with transformer collector matching sometimes work well with a tap point at the high impedance end of the transformer. (See EMRFD, Fig 2.112.) The core problem of this report is void, owing to the high impedance of the transformer with the transmitter off. However, the signal voltage can be much higher than twice the supply voltage. This must be taken into account when evaluating the peak-to-peak capacitor (C7 of Fig 12) current, and hence the peak diode current.

Additional Thoughts

The simulations presented here have all used diodes. Simple AC analysis was adequate to extract most of the salient detail. Other switches would also work. For example, a PIN diode switch could replace the diode pair. DC current would be applied when the transmitter was on, and a reverse voltage would be needed during receive intervals.

The diodes considered here could be replaced by three terminal devices. A saturated bipolar might work in some situations. Careful measurements are required. Some MOSFETs such as the BS170 look appealing, although low capacitance is preferred. Again, measurements are required.

This discussion has dealt with single ended power amplifiers. Balanced, push-pull amplifiers are much more common. The concept put forth in this note could certainly be applied to a push-pull design. Two series tuned circuits would be required with two diode pairs. The receiver side of these two switches would then be combined and impedance transformed in a balanced to unbalanced transformer (balun). The transformer on the receiver side of the T/R need not handle the power presented in the transmitter, so it could be modest in size.

The analysis examples presented here have been confined to 5 watt designs. That is certainly not required. There is nothing to preclude extending the methods to much higher powers.

The methods of this note are generally restricted to single band designs. Wide bandwidth is a greater problem.

Finally, all of the discussion here has used computer simulations. While I am certainly fan of such analysis, there is still nothing better than a pure measurement on physical equipment. The first, and most important measurement examines the power coming out of the T/R switch at the receiver port. Replace the receiver with a power meter or a 50 ohm terminated oscilloscope and measure the available power when the transmitter is at maximum. A power of a few milliwatts is usually not a problem, but much more could damage the receiver. Next, the net loss from the antenna port to the receiver port can be measured. Values of 1 or 2 dB are common. Always be very careful when attaching a signal generator to a transceiver.