Phil Anderson, W0XI

4620 Harvard Rd, Lawrence, KS 66049; aldenmcduffie@sunflower.com

A Great Teacher: The Crystal Set

Many have built crystal sets, but few have analyzed them in this much detail!

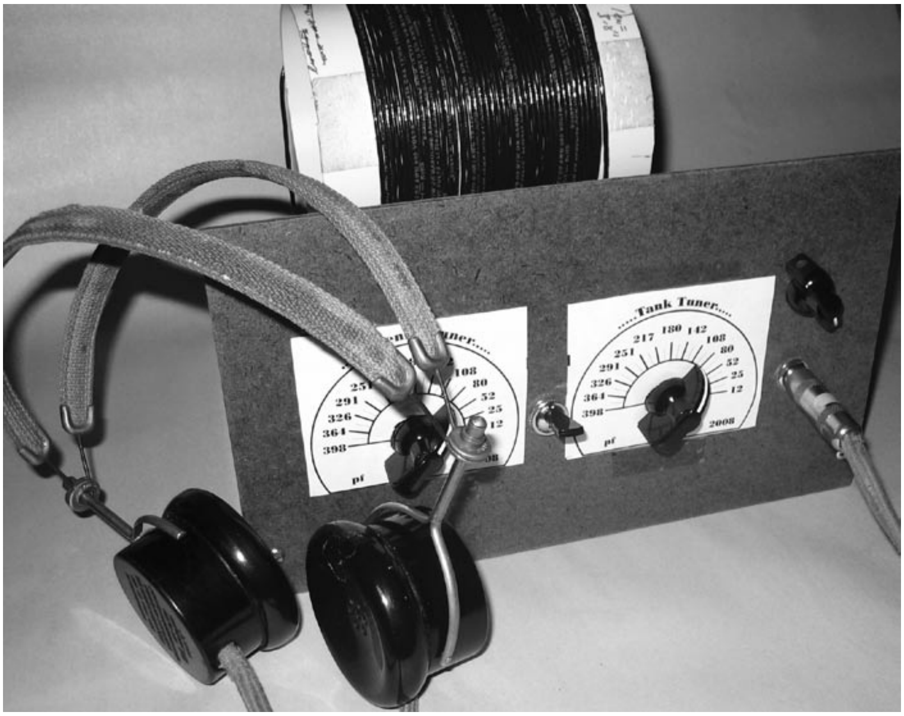

Figure 1 displays the schematic of a typical AM broadcast band crystal set system. The antenna is assumed to be an end-fed vertical or "L," the tuner consists of a simple parallel tuned circuit featuring a multi-tapped coil, and the detector assembly uses a germanium diode with blocking capacitor and headphones. The job of the antenna is to capture the radio waves passing by. The tuner — or tank — is added to select a desired station from the many captured. The detector assembly works triple-duty, accommodating the tank, stripping audio from the AM modulated radio frequency (RF) signal, and producing audio (pressure waves). Yes; the lowly crystal set system does all that!

As TV ads are noted to say, "But wait, there's more!" The *more* in this case is sometimes less. Unless the antenna, tank, and detector assembly are purposely designed to work together, results are often disappointing. Moving the antenna tap along the coil may not provide a good impedance match. Using small wire for the coil will limit Q, and hence selectivity. Ignoring the impedance match between the antenna-tank system and the diode can also reduce results.

Fortunately a number of architectures/systems have evolved that are capable of producing satisfying results with just a few inexpensive parts. The antenna can be inductively or capacitive-coupled to the tank; the tank coil can be wound on a low-loss solenoid or toroid form; the coil wire can be Litz or large single or multi-strand; a diode with favorable characteristics can generally be selected; and a tap on the coil or a transformer can be used to match the tank and diode with phones or other loads.

Today's Crystal Set

I've picked a low-cost architecture to investigate in some detail: a crystal radio system consisting of a capacitive-coupled end-fed antenna, a solenoid coil design with moderate Q and output tap — an autotransformer, if you will — and a germanium diode for the detector, with a resistor and earpiece load. As you'll see, decent crystal-set performance can be had with such a simple design and inexpensive set of parts.

The schematic for such a set is shown in Figure 2 and a front shot of the bench model is pictured in the lead photo. At first glance the schematic looks like the one given in Figure 1, but let's look more closely. A matching air variable capacitor, C_m, is inserted between the end-fed antenna and the tank. A fixed capacitor, C2, is placed in parallel with the air variable tank capacitor, C1, to extend tuning to the bottom of the band (525 to 800 kHz). The headphones denoted in Figure 1 are replaced by a high impedance ear piece and 32 kΩ resistor. Note that the ear piece is designated as a 25 nF capacitor.

Our approach shall be as follows: analyze and model the antenna match; design, simulate and bench test the tapped coil; investigate the antenna-tank match with the detector assembly using *Spice*; and estimate power

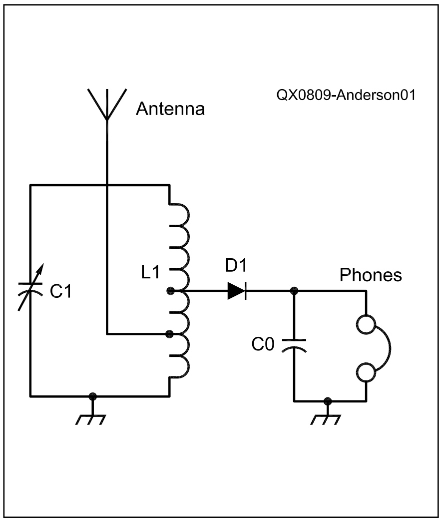

Figure 1 — This schematic diagram represents a generic crystal set

dissipation in the detector and load given varied signal levels at the antenna input.

Matching the Antenna

With inductively coupled (double-tuned) sets, one resonates the antenna with an inductor to maximize current and adjust coupling for selectivity. With this set, the object is to convert the resistance of the antenna to a very high value and connect the antenna assembly to the top of the tank.[1] Any capacitance left over will be added in parallel with the tank. As such, *we're not really matching the antenna to the tank, but striving for step-up transformer action of the voltage and resistance.*

A 50 to 150 foot end-fed antenna for the AM band can be modeled as shown in Figure 3A. It has a voltage source, an antenna and ground system resistance of 20 to 50 Ω, and a distributed capacitance of 100 to 500 pF. Using an antenna bridge, the impedance of my antenna, 30 feet up and 60 feet horizontal to the west, measured 32 Ω with 400 pF at 400 kHz and 30 Ω with 501 pF at 1 MHz.[2] The following analysis shows how the added series capacitor, C_m, provides the voltage step-up desired.

The voltage source, in the circuit of Figure 3A, can be converted into a current source — a source substitution — by shorting its output and calculating the resulting current. The initial impedance is then placed in parallel with the current source, as shown in Figure 3B.

$$I_a = \frac{V_a}{R_a - jX_a} \quad \text{[Eq 1]}$$

where R_a is the resistance and X_a is the capacitive reactance of the antenna model.

The series impedance of the current source can, in turn, be converted, *at one frequency*, into a parallel combination, R_{ap} and C_a, without changing the circuit operation. This substitution is called "a series-to-parallel equivalent," using the following equations:[3]

$$R_{ap} = \frac{R_a^2 + X_a^2}{R_a} \approx \frac{X_a^2}{R_a} \quad \text{[Eq 2]}$$

$$X_{ap} = \frac{R_a^2 + X_a^2}{X_a^2} \approx X_a \quad \text{[Eq 3]}$$

This conversion results in the circuit shown at Figure 3C. Pushing capacitor C_a aside, let's convert the remaining current source and resistor R_{ap} back into a voltage source.

$$V_1 = I_a R_{ap} = \frac{V_a}{X_a}(R_{ap}) = V_a \frac{X_a}{R_a} \quad \text{[Eq 4]}$$

Note that the new voltage source, at Figure 3D, less any capacitance, is equal to the original antenna source times the ratio of the antenna's reactance to its resistance. Since the reactance is much larger than the resistance for the AM broadcast band, the voltage presented to the tank circuit, now including C_a, has been stepped up substantially. *In effect, the RC series circuit of the antenna acts like a voltage step-up transformer.* Rearranging Equation 4 and substituting X_a from Equation 2, we rediscover a transformer-like turns ratio:

$$\frac{V_1}{V_a} = \frac{\sqrt{R_a R_{ap}}}{R_a} = \sqrt{\frac{R_{ap}}{R_a}} = n \quad \text{[Eq 5]}$$

That leaves us with a simple voltage source, which has a resistance that can be used in simulation with the tank circuit and detector assembly.

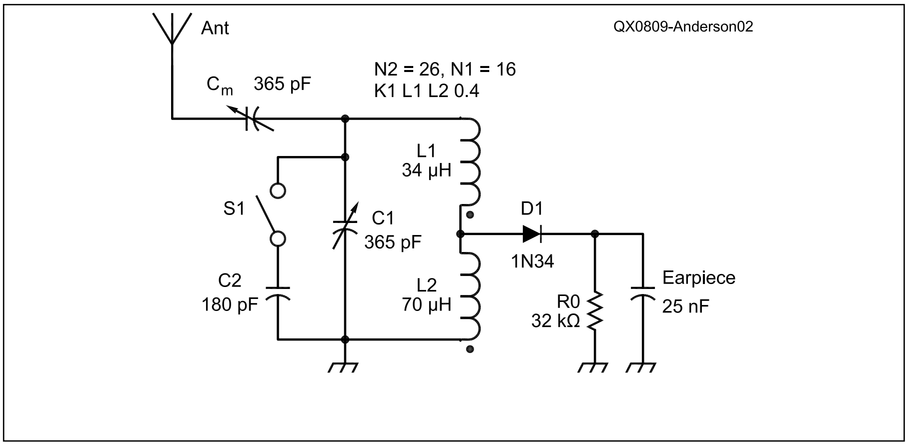

Figure 2 — This schematic diagram shows the capacitive-coupled, coil-tapped crystal set we will analyze in this article, and as shown in the lead photo.

Parts List

Qty	Name	Value	Designations
2	variable capacitors	365 pF	Cm, C1
1	ceramic cap	180 pF	C2
1	SPST Switch		SW1
1	coil	133 µH	L1
1	germanium diode	1N34	D1
1	resistor	32 kΩ or 47 kΩ	R_0
1	ear piece	Hi-Z	CO

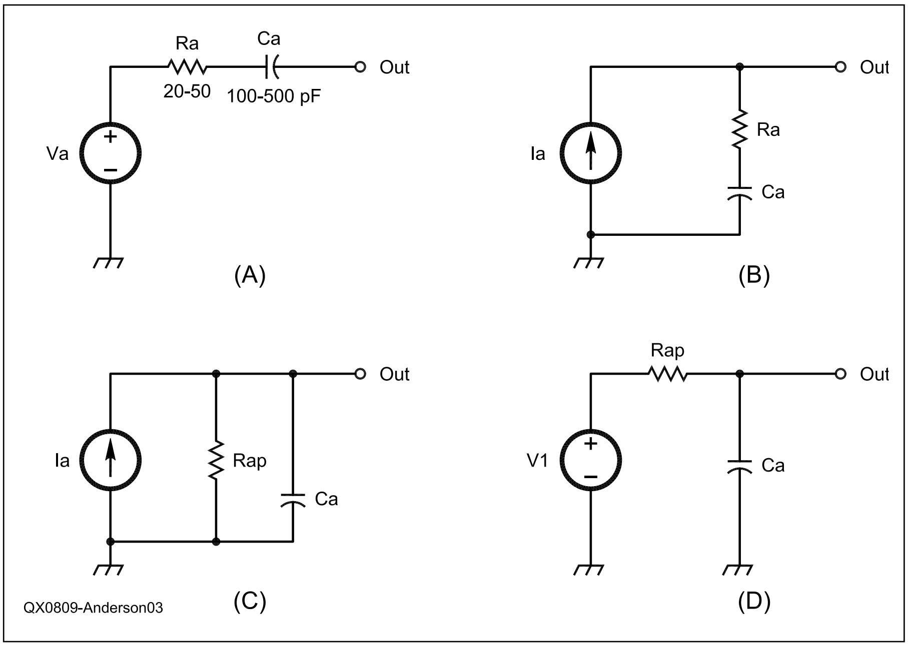

Figure 3 — Parts A through D show antenna equivalent circuits.

Building the Tank Circuit

Regarding the best energy transfer from the tank circuit to the detector assembly for weak signals, current thinking is to match the effective resistance of the tank and antenna in combination with the detector diode's crossover resistance.[4] Intuition leads us to think that this process is like optimizing the flow of power to a resistive load driven by a battery with equal source resistance. The situation turns out to be a bit more subtle at RF, with a detector circuit involved, but let's start with this thought. We will show with the simulation example that our intuition is heuristic!

After fiddling with the design — simulating, building, and bench testing several tanks — I arrived at a workable solution for the tank circuit, given the matches desired. I can now present it as if it were a derivation (kind of like in a textbook where derived equations precede the examples).

Initially, I chose to build the tank circuit with a 140 µH coil with an output tap, an inexpensive 365 pF air variable capacitor, and a 180 pF disc capacitor, switched in to enable coverage of the band from 525 to 800 kHz. The lower inductance value somewhat avoids the problems of bunching up tuning and lowering tank Q because of using an inexpensive air variable capacitor at the top end of the band. I chose to build the coil on a thin-walled 4.2 inch diameter length of PVC sewer pipe, using No. 18 stranded wire. While Litz or solid wire provide for a higher Q, there are advantages to using stranded wire: it's cheaper, easier to wind and solder and the jacket expands the winding pitch to 0.09 inches. In addition, I chose to set the tap so that the impedance looking into the tap would match the ubiquitous 1N34 diode. This arrangement avoids the use of expensive inter-stage audio transformers, which allow diode attachment at the top of the tank circuit. You give up a bit of performance with this arrangement. With these ideas in mind, let's look at the coil.

To match the diode, we need to know its crossover resistance, R_X. While diodes vary from batch to batch and by manufacturer, let's assume a 1N34 has a saturation current of about 1000 nA, operation at room temperature, and an m factor of 1.3. Hence:

$$R_x = \frac{0.025m}{I_0} \approx 32\ \text{k}\Omega \qquad \text{[Eq 6]}$$

In addition, when the coil is wound with 42 turns and tapped at 26 turns, as noted in Figure 6, the output to input turns ratio (of this auto-transformer) is

$$N = \frac{N_1}{N_1 + N_2} = \frac{26}{26+16} = 0.61 \qquad \text{[Eq7]}$$

This calls for an antenna and tank total resistance match of

$$R_{\text{tank}} = \frac{R_X}{N^2} = \frac{32k}{0.38} \approx 84\ \text{k}\Omega \qquad \text{[Eq 8]}$$

For a simple starter set, this value is reasonable. For a high performance set, DXers would strive for 500 kΩ to 700 kΩ perhaps.

Modeling and Checking the Tank Coil

Since our coil is an air solenoid, wound on a thin form, coupling between the windings is not as tight as it would be on a ferrite toroidal core, for example. We can still model the total coil as an auto-transformer by measuring the mutual inductance between the portions of the coil on each side of the tap. Figures 4 and 5 denote the measurement setup at 580 kHz. A 4017B B&K RF generator was used to drive a launch coil with 12 turns of No. 22 wire wound on a 3.5 inch ABS form. The resulting signal was inductively coupled to the coil assembly under test. The coil, at that time, consisted of 12 turns for L2 and 30 turns for L1, all close-wound in the same direction.

The tank circuit was resonated at 580 kHz by adjusting C1, an air variable capacitor. C1 was then disconnected and its value measured with an 810C B&K capacitance meter. Total inductance, with coils aiding (dots in same direction), was calculated to be 142.5 µH. Coil L2 was then unwound, rewound in the opposite direction (on the same form), the circuit was again resonated, C1 was measured, and the total inductance calculated to be 78.1 µH. Mutual inductance was then estimated to be:

$$M = \frac{L^+ - L^-}{4} = 16\ \mu\text{H} \qquad \text{[Eq 9]}$$

The individual inductances of the coils were then calculated, using a modified Wheeler's equation:[5]

$$L_{22} = \frac{r^2 N^2}{10Np + 9r} = 21\ \mu\text{H},\ \ L_{11} = 86\ \mu\text{H} \qquad \text{[Eq 10]}$$

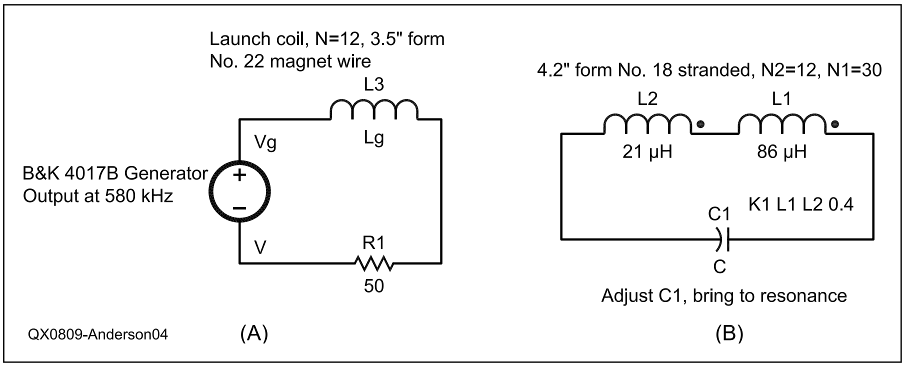

Figure 4 — These schematic diagrams show the connections for the mutual inductance test setup.

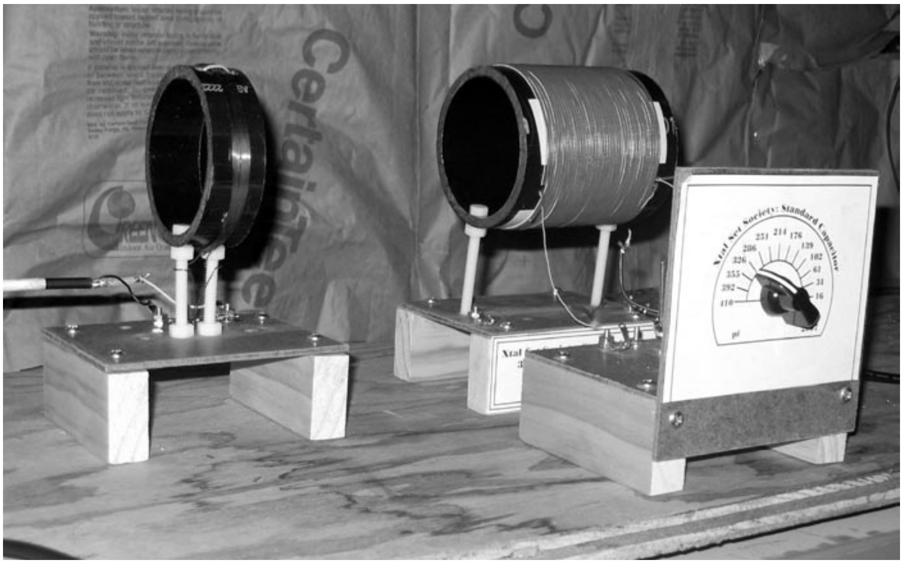

Figure 5 — This photo shows the mutual inductance test setup.

where:

r is the radius of the coil

N is the number of turns

p is the winding pitch, in this case 0.09 inches.

Hence, the coupling coefficient for the two sections is:

$$k = \frac{M}{\sqrt{L_{22} L_{11}}} = 0.4 \qquad \text{[Eq 11]}$$

To check the coil model and to prepare for a full simulation of our crystal set, I carried out a *Spice* simulation, as denoted in Figure 6.[6] I am happy to report that the results agree with the measurements made on the bench! Our coil is modeled as an autotransformer with the *Spice* declaration "K1 L1 L2 0.4" — it says that L1 and L2 are combined and have a coupling coefficient of 0.4. Note that the effective turns ratio is:

$$N = \frac{N_2}{N_1 + N_2} = 0.28 \qquad \text{[Eq 12]}$$

As noted in Figure 6B, a frequency sweep simulation of the circuit is in agreement, stepping the primary voltage down from ~53 to 15 mV at 580 kHz, a ratio of 0.283. This is simply another confirmation of Clarke's derivation that high-Q RF tank circuits, at the point of resonance when properly tapped, act like a transformer.[7] Hence, the load seen by the transformer primary is:

$$R_{primary} = \frac{R_{tap}}{(N)^2} = \frac{6.53\ \text{k}\Omega}{(0.28)^2} = 83.3\ \text{k}\Omega \qquad \text{[Eq 13]}$$

This is further confirmed by calculating the tank Q from the sweep graph, Figure 6B:

$$Q = \frac{f_0}{bandwidth} \approx \frac{580\ \text{kHz}}{7\ \text{kHz}} = 82 \qquad \text{[Eq 14]}$$

Therefore, the *effective* parallel resistance of the tank circuit, with the given load is:

$$R_p = QX = Q(2\pi f_0 L) = 82(2\pi \times 0.580)(140) = 41.8\ \text{k}\Omega \qquad \text{[Eq 15]}$$

Clearly, the Q has been halved by the effective reflection of 6.5 kΩ of resistance from the secondary into the primary, in parallel with its inherent antenna and coil losses modeled by ~82 kΩ. Flipping it around — reflecting the primary impedance into the secondary, the diode "sees" roughly 6.5 kΩ.

Thinking about "Today's Crystal Set," shown in Figure 2, if we wish to use a 1N34 detector that has a crossover resistance of about 32 kΩ, *we'll have to change the turns ratio of our example above*. We need to match (or transfer to the primary if you will) 32 kΩ to 80 kΩ. A turns ratio of 0.62 does the trick.

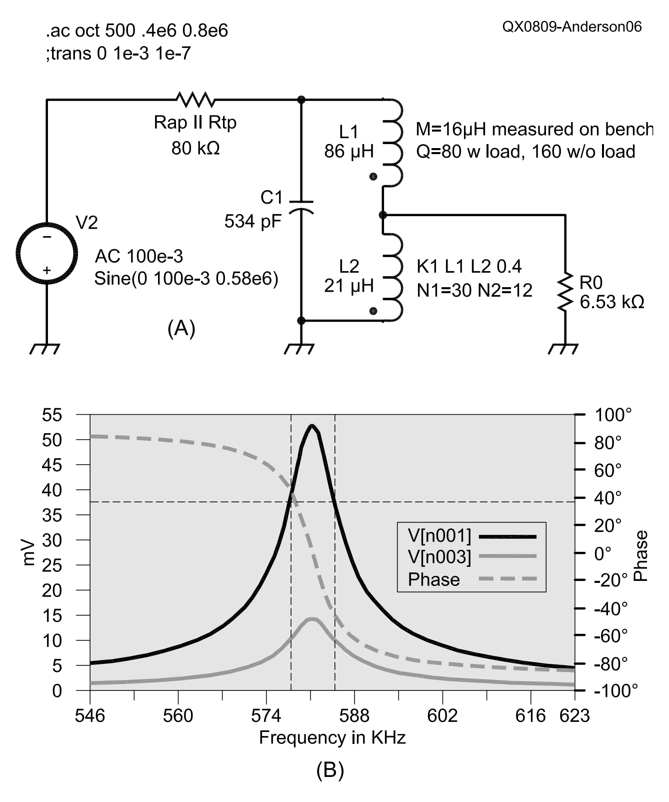

Figure 6 — Part A shows the *Spice* model for the tuned circuit autotransformer. Part B shows the *Spice* output results of the tank Q measurement.

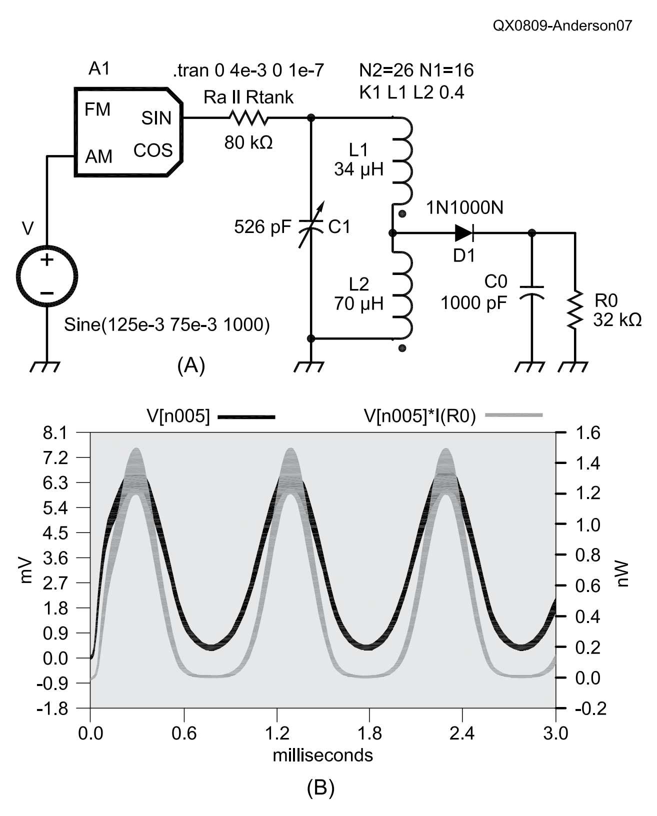

Figure 7 — Part A shows the *Spice* crystal set circuit simulation. Part B shows the *Spice* output waveform and power dissipation results.

Simulating the Full Crystal Set

We've finally arrived at the best part — simulating the full crystal set. The *Spice* schematic for doing so is shown in Figure 7A, with the results shown in Figure 7B. Let's do a bit of housekeeping first. Sources V and A1 combined simply generate an AM signal and together with resistor Ra replace our antenna and ground source presented in Figure 3D. Our tank circuit has been updated to provide an input-to-output turns ratio of 0.61. The 1N1000N diode is fictitious in name; I simply give my *Spice* diode models a part number that names their saturation current value. You can't buy a 1N1000N diode. As noted earlier and in Table 2, the crossover resistance of a diode with an I_O of 1000 nA has a crossover resistance of about 32 kΩ. As per our earlier discussion, the turns ratio now provided will reflect a resistance of 32 kΩ into the primary of the tank of about 80 kΩ, matching the loss there. We'll now run a series of simulations to show that, approximately, *the maximum peak power of the audio signal obtained at the output occurs when the total antenna and tank resistance matches the crossover resistance of the diode, given that the output load is roughly the same value, too.*

Table 1
RF Voltage In — Power Out

V_{tap} (mVp-p)	*V_O (mVp-p)*	*Peak Power Out (nW)*	*Average Power Out (nW)*	*Peak Power Out (dBm)*
600	350	6300	2900	–22.01
300	157	1150	463	–29.39
150	74	170	62	–37.70
75	21.5	18	6.3	–47.45
37	6.5	1.4	4.7	–58.54

Table 2
Tank – Diode Matching for Maximum Power

Io (nA)	*Peak Power Out (nW)*	*Rx at Peak (kΩ)*	*Power Out (nW)*
600	1.06	54	1.06
700	1.28	46	1.28
800	1.37	41	1.37
900	1.44	36	1.44
1000	1.7	33	1.7
1100	1.74	30	1.74
1200	1.74	27	1.74
1300	1.7	25	1.7
1400	1.7	23	1.7
1500	1.63	22	1.63
1600	1.5	20	1.59

Voltage source V in Figure 7 sets the RF carrier level, modulation level, and audio frequency. For example, the directive "sine(125e-3 75e-3 1000)," noted on the drawing, sets the RF level at 125 mVpeak, the modulation at 75 mVpeak, with an audio frequency of 1000 Hz. The ratio of the RF and audio levels sets the modulation percentage; hence, 75/125 provides for 60%. This statement is varied to produce more or less drive. Source A1 determines the RF frequency and is set to 580 kHz. You may wonder why I chose 580 kHz instead of the usual standard of 1 MHz. It's simply because WIBW, a 5000 W station 20 miles from me, broadcasts on 580, and can be used as a real comparison to the simulation.

A tabulation of five simulation runs is noted in Table 1. Each run notes the drive level at the tap output and resulting audio voltage, peak power across the load, R_O, in nW and dBm. With each succeeding run the drive voltage is reduced by ½. The first three entries are certainly very strong signals, producing loud copy in my Baldwin headphones or a Hi-Z ear piece. Once the tap voltage level drops below 74 mVp-p, listening level begins to drop. Note that the output voltage, V_O, at first drops by ½ in concert with the tap voltage. At a diode input drive of 75 mVp-p, V_O drops to ⅓, from 74 to 21 mVp-p. In the last entry, V_O drops from the last entry to near ¼, from 22 to 6 mVp-p. Peak power out, of course, drops even faster. With the tap at 37 mVp-p, peak output is at –58 dBm. Our basic set gives up at about this point; at least I noted that when using Baldwin phones and a matching Bogen transformer in place of the 32 kΩ resistor. In comparison, very high impedance DX sets report minimum discernable signal levels at around –67 dBm or lower. (See Note 4.)

We finish by looking at what happens when the resistance at the tap (from the antenna and tank circuit) does not match the crossover resistance of the diode installed. I simulated this by leaving the tank circuit and load constant and substituting various diode models, 1N1000N, 1N900N, and so on. These results are tabulated in Table 2. Note that the match is very broad except when diodes with an Rx much larger or smaller than the antenna tank resistance are used. *Maximum power at the load, R_O, is noted as 1.7 nW when the diode's resistance of about 32 kΩ matches that of the tap output and load.*

We've just brushed the surface here. The *Spice* simulation circuit of Figure 7 could be used to generate volumes of data. We could look at the relatively high currents circulating in the tuned tank circuit. We could crank up the Q of the tank and run the simulations again, thereby investigating weak signal reception. We could investigate what the current spikes in the diode look like at the peak of each RF cycle for heavy and weak signal drives. We'll save these investigations for another time.

Notes

[1] Ed Richley, "The Design of Unpowered AM Receivers Using Detectors Made From Rocks (Part 2 of 3)," *The Xtal Set Society Newsletter*, Vol 5, No. 2, March 1, 1995. Available at **www.midnightscience.com.**

[2] Phil Anderson, "XS-800 Antenna Measurement Bridge," **www.midnightscience.com/article2.html**.

[3] H. Skilling, "Electrical Engineering Circuits," "Series & Parallel Equivalent Circuits," p 97, Wiley, 1959.

[4] B. Tongue, **http://www.bentongue.com/**.

[5] "Inductance of a Single Layer Solenoid," **www.midnightscience.com/formulas-calculators.html**.

[6] There are many variations of the *Spice* circuit simulation program. One convenient version, available for free download is the Linear Technology *LTSpice*. See **www.linear.com/designtools/software/index.JSP**. The author's *Spice* files are available for download at the ARRL Web site. Go to **www.arrl.org/qexfiles** and look for the file **09x08_Anderson.zip**.

[7] Kenneth Clark, *Communication Circuits: Analysis and Design*, p 38, Addison-Wesley, 1978.

Phil Anderson, WØXI, was first licensed as a teenager in 1953 as KNØHSB. He graduated from the University of Kansas in 1963 with a BSEE, and then earned an MSEE from Syracuse University in 1967. He added a DocEng degree from the University of Kansas in 1971. He was an engineer at IBM in Poughkeepsie, NY between 1963 and 1969. Phil founded Kantronics in 1971, and retired in 2002. He founded the Xtal Set Society in 1991, and is still playing with crystal sets!

In 1969 Phil took (and passed) the Novice through Amateur Extra Class license exams in one sitting at the FCC Field Office in Kansas City. He is co-inventor of the GTOR communications protocol and co-designer of the Kantronics KPC-2, KPC-3, KPC-4, KPC-9612, KAM, KAM-XL and several pager controllers as well as 144, 220 and 440 MHz RF amplifiers. His current technical interests include ultrasonics, QRP, powerless devices, mm waves and radio astronomy. Phil is also a proud grandfather!