High Sensitivity Crystal Set

Build a "crystal radio" that does not require an outside antenna or ground by using a new zero-voltage-threshold MOSFET.

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If you are like me, you may have been bitten by the "radio bug" while building an AM broadcast band crystal set. In my case, I was using a galena "cat's whisker" detector.[1] Such a radio typically required a long outside antenna and ground rod or water pipe ground connection to function, even with the use of a low-threshold (0.3 V) germanium detector diode such as the well-known 1N34A.

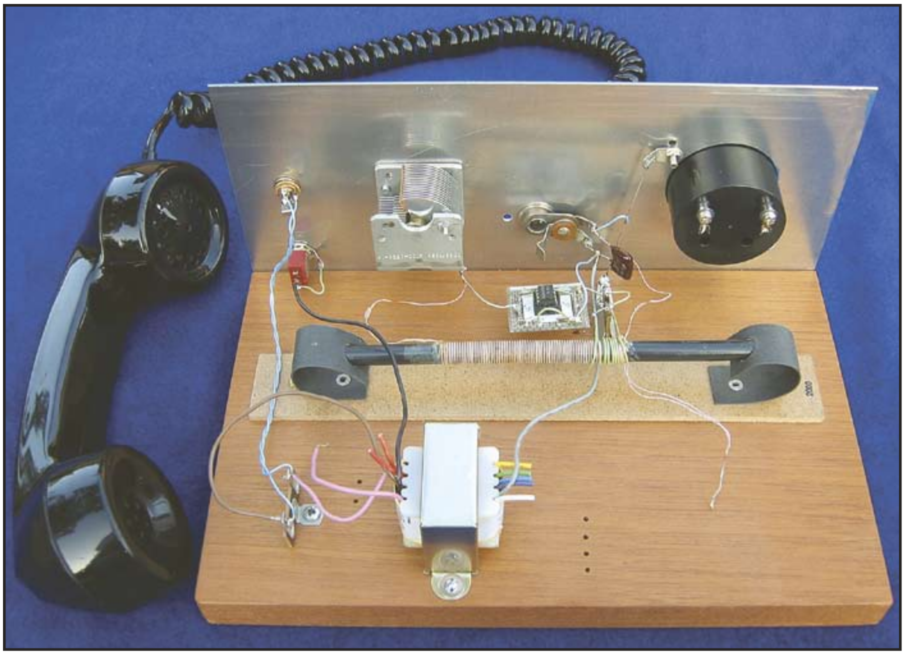
To rekindle the spark of your youth or to interest young people in radio, consider building a radio that doesn't need an outside antenna or ground that might be hard to come by with modern high-density housing, antenna restrictions, and the danger of power line proximity or lightning. Fortunately, a new detector has been developed that does just that.

Anyone who has experimented with simple crystal sets knows that there is a trade-off between sensitivity and selectivity, or the ability to separate stations that are close in frequency. To understand that, refer to Figure 1, the schematic diagram of a typical crystal set. For highest sensitivity, it is desirable to place the detector diode at the top of the LC resonator (which provides the means for selectivity) where the maximum RF voltage appears with the hope of exceeding the 0.3 V threshold of the detector diode. Placing the detector and headphone load at the top of the resonator at point A results in "de-Q-ing" the resonator, largely destroying selectivity.[2] Placing the detector at a tap point on the inductor, typically 10% of the way up from the ground end at point B, results in much less loading of the resonator and preserves selectivity. Unfortunately, the top of the resonator must now see 3 V peak in order for point B to provide 0.3 V to the detector, so sensitivity is severely affected.

Referring to Figure 2, it is possible to have your cake and eat it, too, with a circuit using the newly introduced ALD110900A zero-threshold-voltage MOSFET IC made by Advanced Linear Devices.[3] Figure 2 shows the circuit topology, which was motivated by a similar circuit using a JFET and battery gate bias configuration developed by David W. Cripe, NE4AM (formerly KC3ZQ).[4] The circuit is essentially a synchronous rectifier. It uses the high voltage end of the resonator formed by a ferrite antenna rod, L1, and tuning capacitor, C1, to drive the gate of the MOSFET, resulting in rectifier action from the channel. The MOSFET source and drain replace the anode and cathode of the usual 1N34A diode connected to a separate 8-turn winding on L1, which is equivalent to the 11% tap point on L1.

In a synchronous rectifier, the MOSFET acts like a switch, turning on during the positive half cycles of the applied RF voltage and off during the negative half cycles. The 2000 pF capacitor, C2, integrates the pulsating dc to create the audio modulation in the headphones. In this circuit, the gate voltages are not high enough to create a perfect switch, and so the MOSFET modulates the resistance of the source-drain channel over some impedance range whose average approximates the impedance of the headphone load for maximum energy transfer.

In the radio shown in Figure 2, both FETs of the dual-FET ALD110900A, U1, have a common-source connection and are connected in parallel to better match the headphone impedance. The resulting detec-



Rear view of the AM band high sensitivity crystal set showing a GTE telephone handset as the headphone. The panel meter is not used for this project.

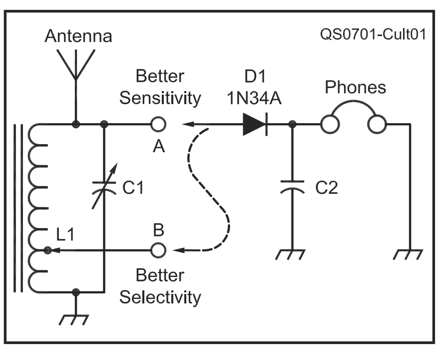


Figure 1 — Schematic diagram of a typical crystal set with diode connected to A for sensitivity and B for selectivity.

[1]Notes appear on page 33.

tor has an off resistance (0 V on the gate) of 52 kΩ and an on resistance of 250 Ω with a peak voltage of +5 V on the gate. In this radio, the maximum measured gate voltage is only 0.25 V peak, so the channel modulation creates an average source impedance to the headphones of approximately 25 kΩ. An antique pair of 25 kΩ headphones can be used directly if you have them, but most headphones will require an impedance transformer, in this case the multi-tapped Bogen T-725 public address matching transformer.

Most of the other parts are scarce or no longer in production. You may have to wind your own ferrite rod to emulate the J. W. Miller 2000 antenna rod or adapt the rod from an old AM transistor radio. To wind your own, obtain an Amidon Associates ferrite rod, part number R61-050-750, which is 7.5 inches long and 0.5 inch diameter.[5] Using 15/44 or 15/46 Litz wire, wind 70 turns in the center of the rod spaced to fill 3 inches.[6] The 8-turn secondary can be ordinary magnet wire wound over primary, on the lower end of the main coil. A high-quality 365 pF air variable tuning capacitor can be purchased or obtained from an old radio. A good junk box and resourcefulness are in order.

There is No Magic

Even though the zero threshold of the MOSFET detector greatly improves performance, the available power is low and the acoustic power from the headphones depends on extracting the greatest efficient from every component in the radio.

The use of high-sensitivity earphones is critical to the success of your radio. The best inexpensive stereo earphones have a sensitivity of 108 dB sound pressure level per milliwatt (SPL/mW), where 0 dB SPL is 20 microPascals SPL or the 0.0001 pW/cm² threshold of human hearing, and an impedance of 8 to 64 Ω. Although these can be matched to the radio with the Bogen T-725 transformer (which has a separate 8 Ω winding) and offer superior bass response, this is a very low sensitivity compared to what is desired. The receiver of an old dial type or early model tone access pad telephone may be a better choice. I have used an audio signal generator and RadioShack sound level meter to measure the sensitivity of telephone receiver elements such as the GTE D-51030A or Western Electric U-1 or LB-1, which can be obtained from old telephones in thrift shops for several dollars. The sensitivity is about 122 dB SPL/mW or 14 dB better than stereo headphones, although the response is limited to about 3 kHz. If we assume an earphone aperture of 1 cm², this is an efficiency of 16% in converting electrical power to sound power. The Knowles Acoustics CM-3152 balanced-armature element

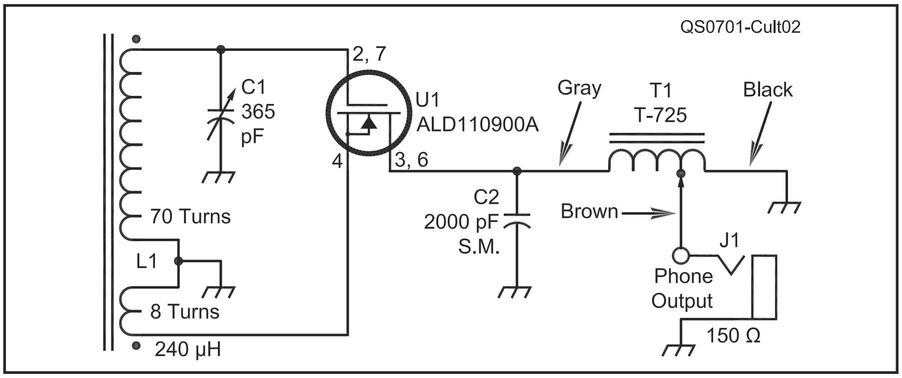


Figure 2 — Schematic and parts list for high sensitivity crystal set.

C1 — 15-365 pF air variable capacitor (www.midnightscience.com or see text).
C2 — 2000 pF silver mica or ceramic capacitor.
J1 — Mono headphone jack.
L1 — 240 μH, 7.5-inch ferrite loop antenna (J. W. Miller Model 2000 or see text). Eight turn secondary wound on lower end, over 70 turn primary winding.
T1 — Bogen T-725 public address matching transformer (www.schmarder.com or www.Grainger.com). Note: Only three of many taps shown to match 25 kΩ output to 150 Ω headphone impedance.
U1 — ALD110900A dual MOSFET (www.mouser.com, part number 585-ALD110900APAL for PDIP-8 or 585-ALD110900ASAL for 8-SOIC).
Headphones — See text.

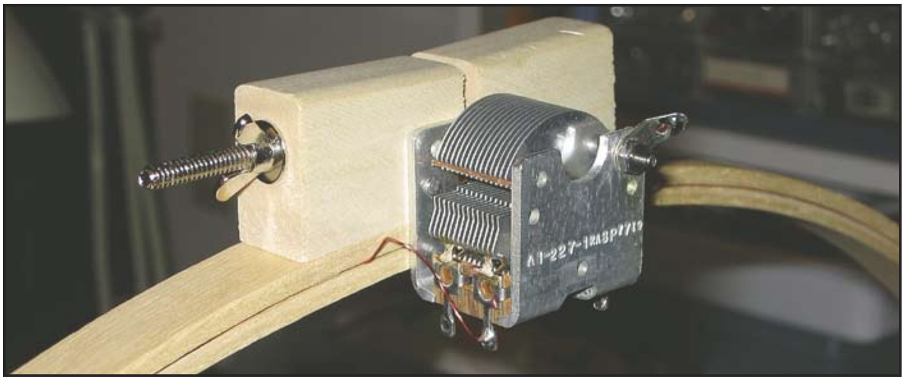


Figure 3 — Variable capacitor mounted on auxiliary quilting-hoop loop antenna.

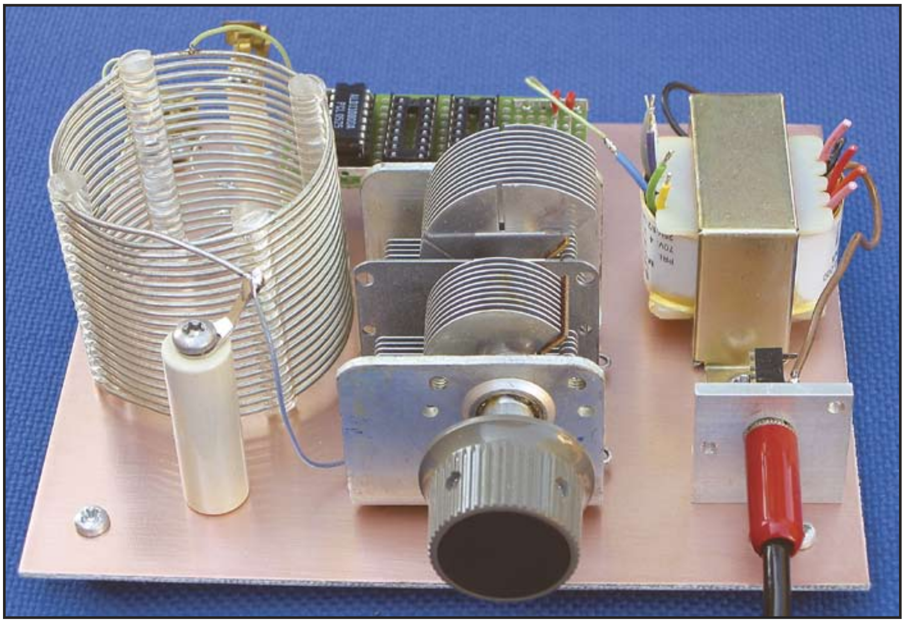


Figure 4 — This photo shows the 90 meter to 40 meter shortwave version of the high sensitivity crystal set.

should offer similar performance.[7] All of these elements have an impedance of 150 Ω at 1 kHz.

Making it Even Better

An additional improvement in received volume can be obtained by coupling a high-Q tunable loop antenna to the ferrite rod antenna in the manner of a "loose coupler." I have used an 11-inch diameter Select-A-Tenna loop to obtain 65 dB SPL A-weighted volume (about normal conversational volume with 3.3 µW electrical input) from a 5 kW station 3 miles away.[8] Replacing the MOSFET with a 1N270 germanium diode resulted in no discernable output. It has been possible to hear seven local stations in a 25 mile radius with no difficulty. You can search for your station locations on the FCC Web site.[9] Signals with 30 dB SPL (whisper level) volume are quite listenable with only 0.1 µW electrical input to the earphone. It only takes 5 to 10 mV peak-to-peak on the source of the MOSFET to provide an adequate volume level.

You can make your own "amplifying" tunable loop antenna with a 23 inch diameter wooden quilting hoop. This will come apart as an inner hoop and a split outer hoop with wooden ends and a tightening screw. Close-wind 12 turns of AWG no. 24 magnet wire in the middle of the outside surface of the inner hoop and tape the ends in place. Next, at about 2 to 3 inch intervals, carefully separate the turns to spread them evenly across the ¾ inch width of the inner hoop and tape in place as you proceed. Mount the outer hoop over the inner hoop and tighten in place using the long metal screw. Mount a 365 pF air variable tuning capacitor on the large wooden blocks as shown in Figure 3. It will be necessary to drill an additional hole in the mounting blocks to pass the shaft of the capacitor. Use a shaft extension with a knob to provide tuning ability. Solder the two ends of the coil to the stator and rotor of the capacitor.

The auxiliary loop that you have created has an inductance of about 240 µH and will tune the entire AM broadcast band with a 365 pF capacitor. Place the loop off the end of the crystal set's ferrite loop. A line across the diameter of the loop should point to the desired station. Tune in a station on the crystal set and peak the volume by tuning the large loop. The received signal strength will be dramatically increased. With this larger loop, the station previously mentioned increased in volume to 72 dB SPL using a GTE telephone receiver.

Shortwave Version

I have constructed a version of this receiver to cover the 90 to 40 meter shortwave spectrum. Figure 4 is a picture of this receiver and Figure 5 shows the schematic diagram and parts list. Shortwave performance is difficult, especially at my US West Coast location where few powerful shortwave stations can be heard and severe fading is evident. With this receiver I was able to reliably receive HSK9, Radio Thailand, broadcasting from the 250 kW International Broadcasting Bureau (IBB) transmitter in Delano, California on 5890 kHz. I was using an external 40 foot wire antenna.

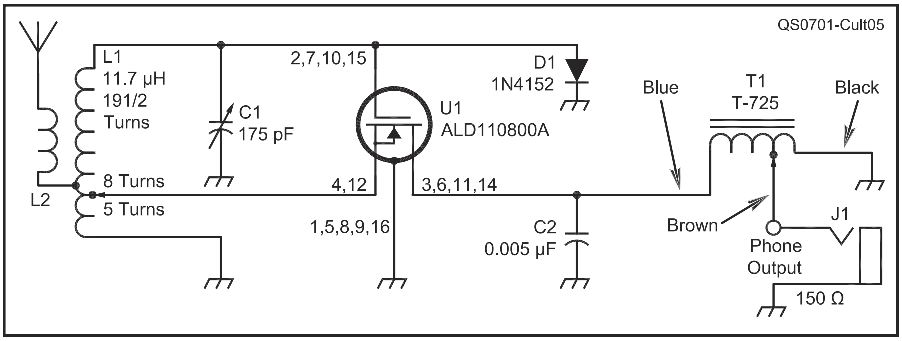


Figure 5 — Schematic and parts list for 90 meter to 40 meter shortwave version of high-sensitivity crystal set.

C1 — 175 pF air variable capacitor.
C2 — 0.005 µF ceramic capacitor (or two 0.0022 µF capacitors in parallel).
D1 — 1N4152 silicon diode (see text).
J1 — Mono headphone jack.
L1 — AirDux coil, 19.5 turns, 2 inch diameter, 10 turns/inch, tapped at 5 and 8 turns.
L2 — 9 turns FT 50-43 toroid (see text).
T1 — Bogen T-725 public address matching transformer. (Note: BLU tap, 5 kΩ, is different from AM version.)
U1 — ALD110800APCL Quad MOSFET (Mouser 585-ALD110800APCL).

The detector consists of four MOSFETs in parallel using the quad version of the detector IC in order to better match the lower resonator impedance. The source tap point was also changed to the 25% point on the inductor. The resulting loaded Q was 44 at 6 MHz compared to 53 for the AM receiver at 1 MHz. The integrator capacitor was changed to 0.005 µF and the transformer tap was changed to the 5 kΩ tap (BLU). In order to protect the gates of the MOSFET array, the V– and substrate diode connections were grounded and a 1N4152 silicon diode was placed from gate to ground. This diode does not participate in any detector action.

As with any crystal receiver, antenna matching is important to transfer as much power to the receiver as possible. I found that connecting the antenna to the eighth turn of the inductor was optimum. Substantial interference from local FM and TV stations can be greatly reduced by placing a 9 turn FT50-43 toroid in series with the antenna.

Make it Your Own

This article is intended to motivate experimentation in radio at the most fundamental level. If you build either of these sets, you will learn much about high-efficiency radio design and construction, and you will appreciate how the human ear can hear audio signals with energies much less than 1 µW. You will have to adapt the materials you have or can obtain. There is no joy in radio quite like listening to a radio where the only energy is being provided by the station itself, but you will have to cultivate the "art of listening." Hopefully, you can pass on this learning and joy to young people and help them catch the "radio bug." They may well become future hams and extend this wonderful hobby for some time to come.

I would like to thank Wes Hayward, W7ZOI, for valuable discussions during the development of these receivers.

Notes

[1]A. Morgan, *The Boy's First Book of Radio and Electronics*, Charles Scribner's Sons, New York, 1954, pp 126-159.
[2]W. Hayward, R. Campbell, and B. Larkin, *Experimental Methods in RF Design*, ARRL, 2003, pp 3.8-3.9.
[3]**www.aldinc.com/pdf/ALD110800.pdf**.
[4]D. W. Cripe, KC3ZQ, "Nostalgia For The Future," *73 Amateur Radio Today*, Dec 1995, pp 14-16.
[5]**www.amidoncorp.com**.
[6]**www.schmarder.com**.
[7]**www.digikey.com**, part number 423-1036-ND.
[8]**www.selectatenna.com**.
[9]**www.fcc.gov/mb/audio.amq.html**.

Bob has been licensed since 1983 and holds an Advanced class license and a General Radiotelephone Operator License. He has a BA in Physics from Portland State University and works as a design engineer at Phoseon Technology. Bob's interests include QRP, homebrewing, shortwave listening and musical instrument construction. Bob's wife Terry, KA7VAF, is a social worker and is very supportive of his many projects. You can contact Bob at 5860 SW 161st Ave, Beaverton, OR 97007; **n7fki@teleport.com**.