Adding a Q-Multiplier to a "Zero Power Receiver."

Wes Hayward, w7zoi, Oct 3, 2007; Updated Oct 17, 2007.

Abstract

Experiments are presented dealing with a simple "*crystal set*" with one resonator, first using a diode detector and then a MOSFET. Traps are added to enhance selectivity. The radio is then converted to a "regenerative receiver" through the addition of a single transistor operating as a Q-Multiplier. The resulting design can still be used as a crystal set, but can hear some other signals with the flip of a switch and the adjustment of a pot. The active device consumes 1 mA from a 9 volt battery.

A ZPR built in an old BC-221 chassis.

Introduction

The term "Zero Power Receiver" (ZPR) applies to a radio circuit that receives AM broadcasts to generate an audio signal in headphones while consuming absolutely no external power. In earlier times, we would use the less pretentious term *crystal set* to describe such a receiver. But this term may no longer fit for our contemporary ZPR might not even use a crystal. No matter what we call it, we are concerned here with primitive, simple receivers, and simple ways to expand their performance.

I became re-interested in modern crystal sets after discussions in 2006 with a good friend, Bob Culter, N7FKI. Bob steered me toward web sites that presented some of the many interesting aspects of the contemporary crystal receiver. A central one is the home page of the Birmingham, Alabama, Crystal Radio Group. See http://www.crystalradio.us/ Within this site you will find a list of interesting links. I especially recommend the site of Ben Tongue at http://www.bentongue.com/ I urge you to follow the links within these links, and to do your own searching through Google or other search engines. There is a wealth of information out there.

A landmark paper recently appeared: Bob Culter, N7FKI, "High Sensitivity Crystal Set," QST, pp31-33, January, 2007. This paper can be downloaded from the ARRL web site. Bob's design replaces the traditional semiconductor diode detector of a classic crystal radio with a zero-voltage-threshold MOSFET. The result is a receiver with good sensitivity and even better selectivity. Bob's effort produced an immediate interest among the crystal set crowd, as evidenced on the web in the "Rap 'n Tap" discussion group found at http://www.midnightscience.com/rapntap/default.asp The response to Bob's paper was so strong that Mouser sold their complete stock of the parts that Bob used in his receiver shortly after publication. (They are now available again.) My reaction was not as quick, but it was still firm – I had to build one of these receivers.

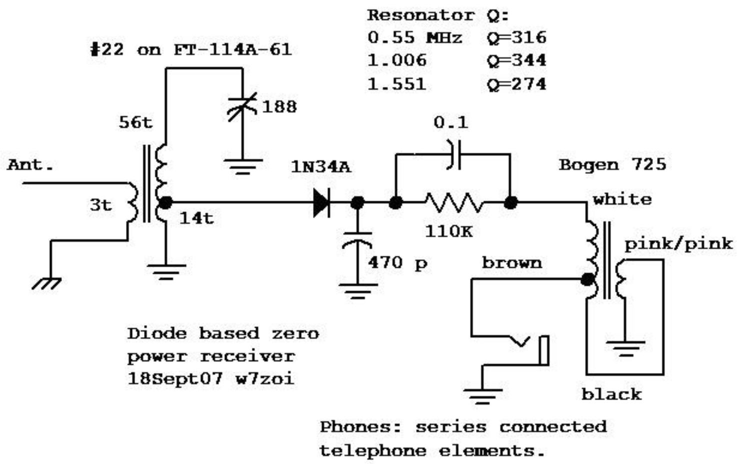
It took a while, but I finally got around to the project in September of 2007. I ordered some ferrite toroids and Litz wire and jumped into the crystal set game. It's been a lot of fun so far.

Coils and their Q

One of my first realizations about the modern crystal set was that the quality of components, especially the inductors, was a vital part of a successful design. Accordingly, I started my efforts by building several coils. I measured their inductance and Q, and often the self resonant frequency which allowed calculation of a parallel capacitance. This information is summarized in a companion document titled **Experiments with Coils and Q-Measurements**, which is also posted on my web page at http://w7zoi.net/tech.html

A First ZPR

I wanted to start with a receiver that was somewhat compact. Still, it was clear from the websites that vernier tuning and some logging accuracy would be of great value in a modern crystal set. So the chassis and tuning capacitor of an otherwise empty BC-221 Frequency Meter was elected to form a first receiver. The tuning capacitor had a range of 13 to 188 pF. So a higher than normal inductance would be required. I filled a fairly large ferrite toroid with #22 wire to yield an inductance of 449 uH. A crystal tap was placed at 14 turns from ground. The first receiver is shown below:



A first receiver using a diode detector.

The basis for this design was the “Progressive” design offered by Jack Bryant, KE4ID, one of the gang from Birmingham. I had the pleasure of meeting Jack at the Dayton Hamfest in May of 2007.

The receiver shown above was used with a typical ham antenna consisting of a pair of dipoles for 40 and 20 meters that were fed with a single piece of coax cable. For receiving the lower frequencies, the feeders were tied together and fed against the station ground, which was far from good. It still worked well enough.

A Bogen 725 audio transformer matched the diode detector audio output to the available low impedance phones that I had. Initially I used the phones from my ham gear, currently a pair of TDK MP-100s. These were inexpensive, but are adequate for normal use. Shortly after building the first receiver I converted a couple of telephone handsets (about 25 years old) that N7FKI had contributed to become a pair of higher sensitivity phones. The sensitivity improvement was dramatic.

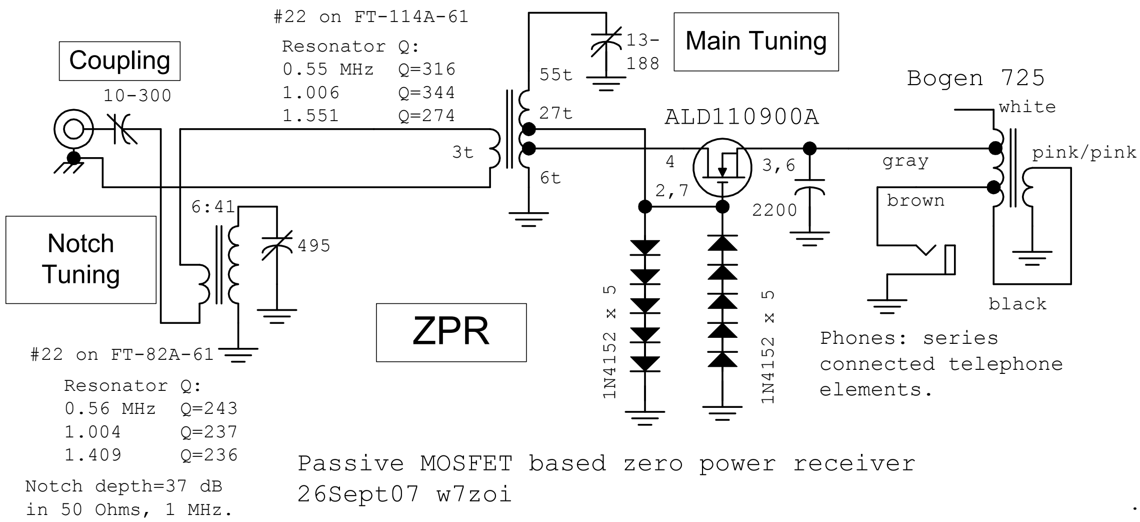
The signals from a few of the local stations were quite strong. However, distortion was severe until the “Benny” was added. This is a parallel RC, 110K and 0.1 uF in this example. This circuit is a creation of Ben Tongue, which accounts for the name. The high DC resistance reduces the detected DC current flowing in the diode. But the parallel capacitor routes the audio past the resistor to the transformer. The circuit improved selectivity and reduced the distortion on the local blockbuster station.

Selectivity was poor with this receiver. It was better than I had ever experienced with a crystal set, but it was still compromised.

Switching to a MOSFET Detector

The next receiver, shown below, used one of the MOSFETs that Bob had used in his receiver. I started immediately to protect the gate with back-to-back catch diodes, for some other builders had reported damaging the FETs with large signals. I had just a single pair of diodes in the circuit from gate to ground, and the MOSFET gate was attached to the top of the tuned circuit. The results were confusing at best. There was audio output, but the tuning had little to do with it. I attenuated the input RF signal and the circuit started to behave.

At this point it appeared that the signal level across the resonator was already too large for a single diode. I temporarily returned the receiver to the crystal detector mode shown above and started placing series strings of diodes across the total resonator. I was amazed. Even a string of 5 diodes degraded the performance. Considering the implied high signal voltage, I moved the MOSFET gate and related diodes to a center tap on the coil. The result is shown below where 5 diodes no longer caused problems. The number of diodes will, of course, depend on the environment and antenna system used with the receiver. (I can only guess at the signal levels that some folks must encounter with their much larger antenna systems!)



A modified ZPR using a MOSFET detector.

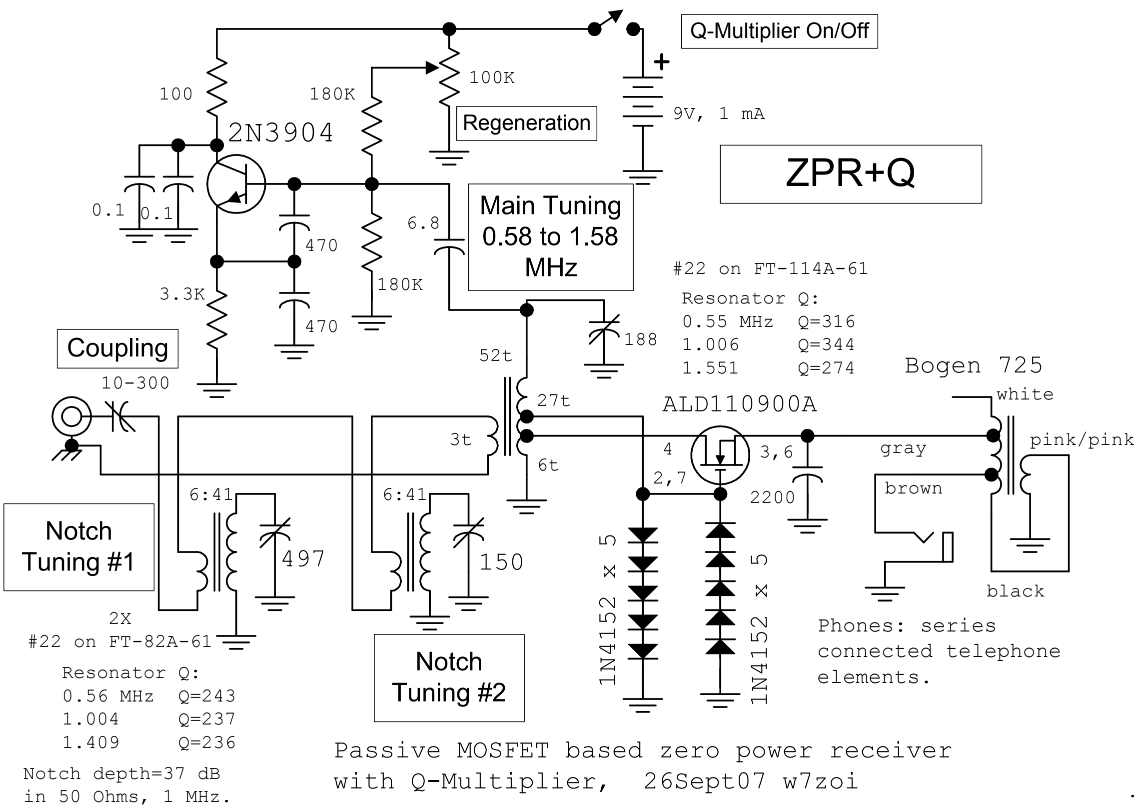
This receiver was now beginning to function like the one that Bob had built. I was able to receive a number of the local stations over the entire tuning range. The selectivity was aided with looser coupling to the antenna afforded by an impedance transformation provided by a series variable capacitor. A link coupled trap was added. There is no need to float the notch generating resonator above ground.

I had a variable capacitor with plastic insulated mounting hardware, so used a floating capacitor for the variable coupling. However, a traditional grounded capacitor could be used in the ground return lead from the main resonator link.

Adding a Q-Multiplier

While crystal sets were fun, I have also always enjoyed regenerative circuits. I was tempted to move on to a regen in this BF-221 format, but did not want to dismiss the crystal set just yet. Among other things, I had not yet heard anything outside of the greater Portland, Oregon area. I wanted to at least hear some "DX." Signal strength measurements with a general coverage receiver indicated that I was within 10 dB, so I was close. While thinking about the problem, the approach taken by a friend in the UK came to mind. (George Dobbs, G3RJV, "A Stable Regenerative Receiver," SPRAT 105, Dec 2000. Also see Fig 1.16 in EMRFD.) He had built a great shortwave regenerative receiver by attaching a Q-Multiplier circuit to a simple JFET detector.

Some computer simulations proved to be both useful and interesting although they brought some irony to the project. Somehow it does not seem proper to design a crystal receiver based upon computer simulation. It appeared that a suitable circuit could be built with either a FET or a bipolar transistor. I ended up using a common 2N3904 bipolar, although about anything would work. The transistor is biased to about 1 mA maximum, with net current controlled by a regeneration control. A pair of capacitors are added to generate positive feedback in the manner of a Colpitts oscillator. This feedback creates a negative resistance in parallel with some capacitance when looking into the transistor base. This is loosely coupled to the hot end of the tuned circuit through a small capacitor. The final circuit is shown below.



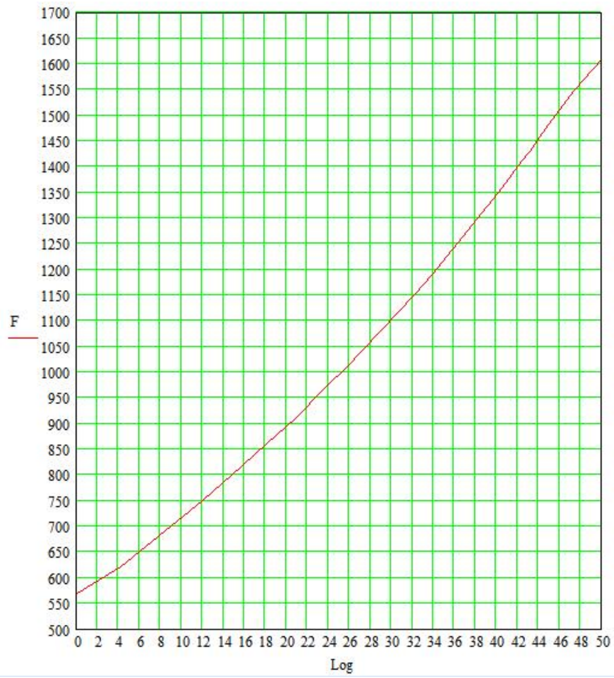
The ZPR is converted to a regenerative receiver with the addition of a Q-Multiplier.

This design includes some additional refinements. A second trap was added, allowing me to attenuate two of the local rock crushers at one time. (A third might be appropriate!) A few turns were removed from the coil to allow tuning to 1600 kHz.

The computer simulations had shown that the Q-multiplier would enhance selectivity and provide a little bit of gain. The gain was not excessive though; usually about 20 dB maximum. This is different than a typical regenerative detector. On the other hand, this might be just right for a receiver in the broadcast band. This is exactly what I observed. Switching the Q-Multiplier on produces no change unless the coupling capacitor is near minimum C. Then advancing the regeneration will allow oscillation to occur. Tuning then produces a signal in about every 10 kHz slot. Many of them can be copied by dropping the regeneration just below oscillation. Advancing the coupling will make the signals louder, but excessive coupling may inhibit oscillation completely. This is all related to the impedance of the antenna system and the way it interacts with the receiver tuning.

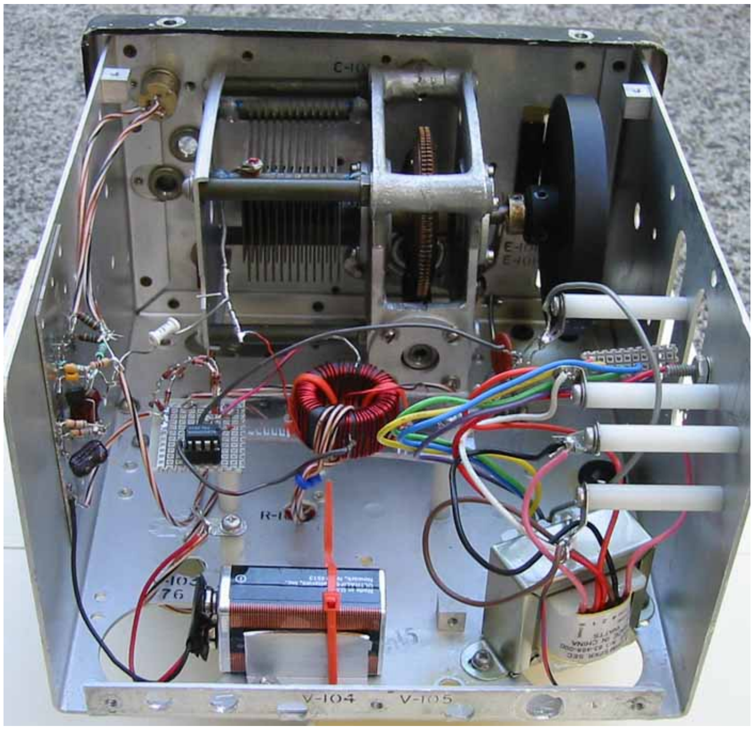
It seems to be very effective to let the Q-multiplier oscillate. When this happens, tuning to zero beat seems to cause the oscillation to lock to the carrier, producing clean audio without any whistles. As with any regenerative receiver, the operation of this one is itself an experimental experience. This is the characteristic that makes a regenerative receiver so much fun and so instructive.

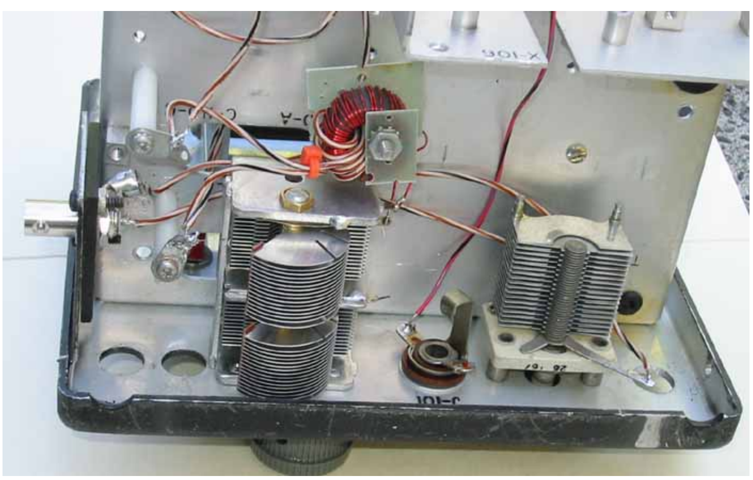
The best part of this circuit is that the system is returned to a more ideal crystal set status merely by turning the Q-Multiplier off. Virtually no retuning is required. It is important to keep the coupling capacitor between the main resonator and the Q-multiplier as low as possible. If this C becomes large, it will compromise the tuning range, especially at the high frequency end of the BC band. The 6.8 pF value seemed optimum in my receiver.



Tuning Curve for our receiver.

The tuning is wonderful with this receiver, as you would expect with this tuning mechanism. There are 50 full turns of the dial to cover the BC Band, and each turn can be resolved into 1000 positions.


This view shows the top of the chassis with the tuning coil mounted on a strip of scrap Plexiglas. The MOSFET, which is actually a dual pair in parallel, is in a DIP-8 package and is mounted in a socket. The protection diodes can be seen looping around to the gate connection from a grounded point. The battery is held to the chassis with a cable-tie, with the audio transformer to the right. The Q-multiplier circuitry is build "ugly" on a scrap of PC board mounted to the left chassis wall. The many standoff insulators on the right wall hold solder lugs with some of the transformer taps that were used. Others that were not used are soldered into a scrap of vector board.


Bottom view of the receiver. Only one trap had been installed at this stage in the construction. The right hand variable capacitor is the coupling adjustment. A BNC input connector goes to the antenna. This connector is insulated from ground, although that is not necessary.

First Conclusions and Results—Oct. 3, 2007

This has certainly been an unusual project, one totally different than any crystal set I built in my youth. I've received things that I never dreamed of hearing on that first crystal set. Two stations out of the greater Portland, OR, area have been logged while operating in the crystal-set mode. One is KOMO in Seattle while the other was CKMX in Calgary, Alberta. Activating the Q-multiplier has allowed me to hear stations all over the western US and Canada.

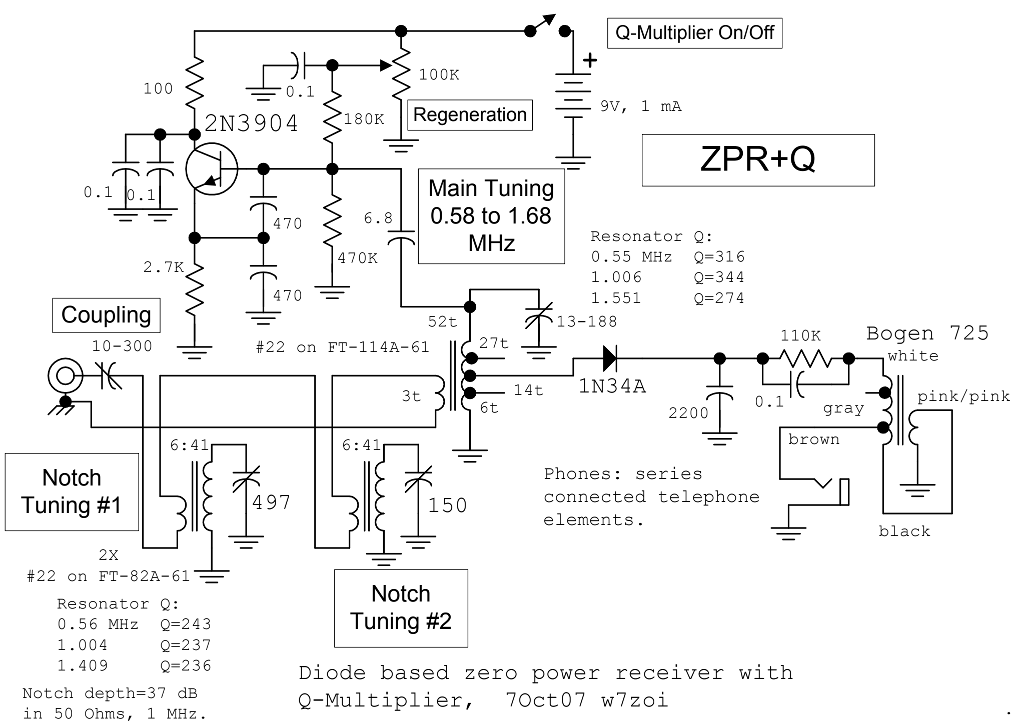
The MOSFET based detector is certainly more selective than that using a diode detector. While not tried, the Q-multiplier should function with the diode detector.

One downside is the nature of the program material. I must admit that the endless talk show format is something of a bore. What ever happened to the music, or programs like the Whistler of the good ole days. (Yea, this is showing my age.)

Update, Oct. 17, 2007.

Although fun, the previous receiver didn't perform as expected. The MOSFET detector was selective, but not as sensitive as it should have been.

A diode detector was inserted in the receiver and used for a while. This circuit is shown below.



Diode based zero power receiver with
Q-Multiplier, 7Oct07 w7zoi

Zero Power Receiver using a Diode detector.

The performance of this receiver was reasonable, and produced some additional "DX" reception, where we here define DX as a signal from outside the greater Portland, Oregon, area. The experience with this receiver was especially interesting with the Q-Multiplier. We found that the Q-multiplier was very well behaved when using a diode detector. Regeneration was smooth and it was easy to operate while the circuit oscillated and was tuned to zero beat.

Q-multiplier operation was not, however, as clean when the receiver used a MOSFET detector. It was then difficult to maintain a stable sine wave oscillation. Instead, we observed a pulsed oscillation, akin to super regeneration. This behavior is known here as *squegging* (See the classic text by Clarke and Hess, Communication Circuits: Analysis and Design, Adedison-Wesley, 1971, pp255-261) In this case, we observed that the normal sine wave turned off and on at about a 200 Hz rate, much slower than we normally encounter with a "super-regen" receiver. The signal sounds "ratty" when observed with an external communications receiver. Oscilloscope measurements were done with a 10X probe attached to the 6 or 14 turn taps. Further investigation revealed that the squegging was a direct result of the back to back diodes used to protect the MOSFET gate. Squegging was observed with a diode detector when the protection diodes were added. The diodes should not be eliminated in a MOSFET detector receiver, for the oscillation may be strong enough to destroy the FET.

The question remained: Just how poor was the MOSFET performance and how did it compare with the diode? We put some numbers with the performance observations by measuring receiver sensitivity. A signal generator (HP-8640B) was set up for 30% amplitude modulation with a 1 kHz tone. This was injected into the receiver with the coupling set at maximum. We then listened to the output in our "hottest" headphone, which were built from old telephone handsets. The level from the generator was reduced until we could no longer hear anything in a quiet room. We then increased the level until we could barely hear the tone. Measurements were done in both modes, without (X) and with (Q) the Q-multiplier. The Q case used a regeneration setting just prior to oscillation.

The initial results were very interesting. The X mode operation (crystal set) was about 5 dB more sensitive with the diode detector. But why? The MOSFET detector was in an 8 pin DIP IC socket, so I replaced the integrated circuit. The improvement was immediate and dramatic. The MOSFET #2 detector was now 5 dB better than the diode and 10 dB above the original MOSFET #1. The results are shown below for three different frequencies.

Minimum Detectable Signal Levels, dBm
(Measurements with coupling at Maximum C)

Freq. MHz	MOSFET#1	1N34A	MOSFET#2
0.6	-37/-53	-42/-58	-44/-56
1.0	-39/-56	-44/-59	-49/-68
1.5	-39/-55	-46/-59	-50/-72

Zero power receiver without and with
Q-Multiplier, X/Q, 17Oct07 w7zoi

MDS Measurement Results

One might question the accuracy of using simple audio earphone detection as a means of evaluation. Ideally, I should have set up an audio termination and an audio voltmeter. But I've had a lot of experience in listening to CW and SSB receivers while doing MDS measurements with the meters, so my ears are partially "calibrated." I will eventually refine the measurement.

I also observed that the Q-multiplier behavior was different with the new detector, MOSFET #2. It now took less current in the multiplier circuit to produce oscillation, suggesting reduced loading by the MOSFET. I now suspect that one of the two parallel FETs was bad. In all cases, the FET channel was attached to turn number 6 while the gate was driven by the 26 turn tap.

The results "on the air" were also dramatic. The first hour of use yielded several new "DX" stations in the log. Of course, as a beginner in this game, there is a lot of room in my log book.