# The Crystal Set

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In past issues of this journal, the late H. R. Crane wrote a long series of articles under the running title of "How Things Work." In them, Dick dealt with many questions that physics teachers asked themselves, but did not have the time to answer. This article is my attempt to work through the physics of the crystal set, which I thought I knew, but actually did not.

In an age of almost instant personal communication, it seems anachronistic to talk about the crystal radio receiver. But this device, dating from the years before 1920, is easily built and demonstrates some basic principles of physics. Unlike all other radios, it does not require an external source of power; the energy in the radio wave is sufficient to produce an acoustic signal.

Crystal sets were built commercially and by amateurs to receive the first commercial amplitude modulation (AM) radio station signals. Figure 1 shows some of the crystal radios in my collection, some antique and some built by me over the last 50 years. On the left is a home-built one using a tuning coil from a broken transistorized radio and a variable capacitor with a maximum value of about 300 μF; the detector is a 1N34 diode. The large set in the middle was home-built, probably in the 1930s, and has a crystal with a cat's whisker (see below) as a detector. Tuning is done by varying the number of turns on the air-core coil, and the (fraying) capacitor is made of alternating layers of tinfoil and paper. The set on the right is commercial and cost $4 in 1924. In the middle is my 1970 attempt at miniaturization; inside the matchbox is a fixed capacitor and a coil in which a ferrite slug is moved in and out to change the inductance of the coil and so tune the receiver.

The signal transmitted by a North American AM radio station has a carrier wave in the range of 540 KHz to 1610 MHz. Superimposed on this is the audio signal in the range of about 100 Hz to 10,000 Hz. An actual AM signal is shown in Fig. 2, but with the ratio of the radio to audio frequencies much higher. Here you can see a high-frequency carrier signal (the closely spaced oscillations) with an audio frequency producing the envelope (the larger-scaled undulations). The modulation of the high-frequency carrier signal by the audio-frequency information signal is produced by multiplying the two signals together. The composite signal in Fig. 2 was produced with a PASCO Dual Function Generator, model WA9301A. Circuits in the receiver must first tune the system to the proper carrier frequency, and then recover the audio signal from the composite waveform.

The circuit may be split into four parts [Fig. 3(a)]: (a) the passing electromagnetic wave impinges on the antenna, sending oscillations up and down it between the tip of the antenna **A** and ground **G**; (b) a parallel resonant circuit formed by a coil **L** and a capacitor **C** is tuned to the frequency of the carrier wave; (c) a rectifier **D** removes the negative-going portion of the signal; (d) a pair of earphones **E** eliminates the carrier signal (see below for more detail) and serves as a transducer to turn the electrical signal into an acoustic signal.

The first problem is to tune to the wanted carrier frequency. This is done with the parallel resonant circuit formed by the coil and the capacitor. The analysis is very much like that of two resistors in parallel, except that in this case the resistances are replaced by the *impedances*, $Z_L$ and $Z_C$ of the coil and capacitor.[1] For the coil, the impedance is given by $Z_L = 2\pi fL$, where $f$ is the frequency of the signal, and $L$ is the


**Fig. 1. A collection of new and old crystal radios in the Greenslade Collection.**

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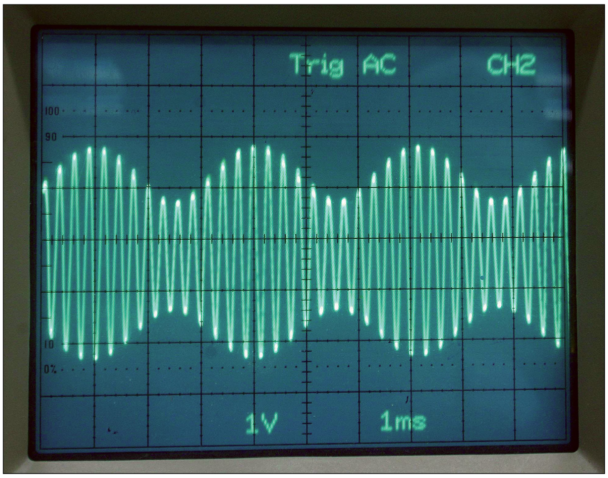


**Fig. 2. An amplitude-modulated signal.**

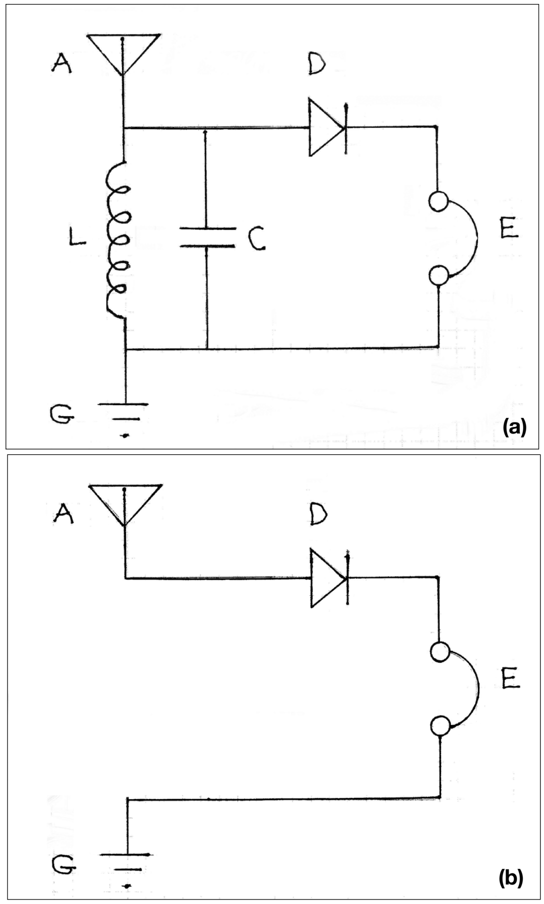


**Fig. 3. (a) The basic crystal radio circuit. (b) The crystal radio circuit with the parallel LC circuit at resonance.**

inductance of the coil, given in henries. This impedance has the units of ohms. The impedance of the capacitor is given by $Z_C = -1/(2\pi fC)$, where $C$ is the capacitance of the capacitor, measured in farads. Once more, the unit of $Z_C$ is the ohm. The minus sign reminds us that the signals across the two components are 180° out of phase.

Since two impedances in parallel act like two resistors in parallel, the coil and capacitor combination have an effective impedance of

$$1/Z = 1/Z_L + 1/Z_C.$$

When the equation is inverted, we get

$$Z = Z_L Z_C/(Z_L + Z_C).$$

The denominator of this expression is given by

$$Z_L + Z_C = 2\pi fL - 1/(2\pi fC).$$

This expression is zero when $f = 1/[2\pi(LC)^{1/2}]$, which is the condition for resonance in a parallel LC circuit. Curiously enough, this is also the condition for resonance for a series LC circuit. There is a difference, however. At resonance the impedance of the series circuit is zero, but the impedance of the parallel circuit is infinity. Thus, at resonance, the parallel LC circuit appears to vanish electrically [and the circuit of the radio is that of Fig. 3(b)].

The AM signal is then passed on to the diode rectifier (recall that a diode only allows current to pass in one direction), which cuts off the bottom half of the signal in Fig. 2, and the information-bearing signal appears across the top of the high-frequency peaks. The earphones have a mechanical iron diaphragm that is driven back and forth by the electric current passing through a nearby coil. The mechanical system cannot respond to the high-frequency carrier signal, but is driven by the audio-frequency signal. The earphones thus act as a low-pass filter.

The diode rectifier was originally called a "detector." In the early crystal sets, the rectification was done with a metal-semiconductor junction. The semiconductor was a crystal of galena (lead sulphide), often potted in a circular base of lead-tin solder for stability. The junction was formed by the pointed end of a metal wire, usually called a "cat's whisker," held in a jointed base that enabled it to be moved around until a sensitive spot on the semiconductor was found. This was the basis for the fixed-diode detectors used in radar sets during the 1939-45 war. A variation of this was the 1N34 germanium diode. My father brought one home for me about 1947, and no longer did I have to search about the surface of the crystal before listening to "The Lone Ranger" and other radio shows.

1. Raymond A. Serway, Robert J. Beichner and John W. Jewett, Jr., *Physics for Scientists and Engineers,* 5th ed. (Saunders College Publishers, Fort Worth, 2000) pp. 1048-1051.

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