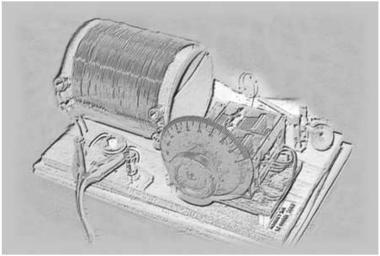
Crystal Radio Engineering

A web book by Kenneth A. Kuhn
updated Apr. 17, 2008



A SIMPLE CRYSTAL RADIO

ADVANCED TOPICS

A chapter on making various measurements of your system is planned. Some other chapters or additional information is planned to connect all the chapters together smoothly. Right now the connections are rough -- but this is a work in progress.

PREFACE

This is a collection of articles that form a text book on designing crystal radios. The primary focus is to illustrate to engineering students how to apply concepts of engineering to solve a problem. It takes a lot of in-depth research to be good at what one does. The main part of this book deals with understanding the required concepts to build a good basic crystal radio. Advanced concepts (to be written and posted last) will deal with a number of improvements that can be made to the basic design.

Here is a link to an excellent site for crystal radio information:
http://www.crystalradio.net/crystalplans/index.shtml

http://www.1n34a.com/ This is an excellent site with links to other crystal radio sites. Be sure to check the Ben Tongue link for a number of practical articles.

Here is a source for parts I found using a Google search http://www.midnightscience.com/catalog5.html#part2 This company specializes in parts for crystal radios and sells variable capacitors, diodes, crystal earphones, etc. I have not bought from them before so I do not know how good they are but I might try them someday.

The following are links to the pdfs for each chapter. If a link is not active then the chapter is not complete -- I am working as fast as I can to finish and post those so check back often. The following is only a guide for now. As the book develops I will likely add chapters or merge some chapters. Many of the chapters are still incomplete and more material will be added as I have time. I am trying to post all I have at the moment, however incomplete, so that students in the communications class, EE421, can use this to help with their crystal radio projects.

Original web location for book:
http://www.kennethkuhn.com/students/crystal_radios/designing_inductors.pdf

outside width of each piece. Some supporting structure (made of wood) connects this to a base for sitting the unit on a table – or sometimes it is just a handle to make it easier to hold. The wire (often 100 feet or more) is wound on the outside of the wooden cross. The tuning capacitor and radio circuit are often assembled either at the center of the cross or on the base. In operation, one must remember to orient the loop for maximum pickup –the plane of the loop should point to the station's antenna.

References

1. Ferromagnetic Core Design and Application Handbook, M. F. "Doug" DeMaw, Prentice-Hall, Inc. Englewood Cliffs, New Jersey 07632, 1981, p 49

2. Practical Antenna Handbook, second edition, Joseph J. Carr, TAB Books, 1994, p 301

The inductance of the loop in the previous example is 343 microhenries using a winding width (b) of 4 cm.

The length of wire required is 4 * a * N Eq. 3

Calculating the inductance of a ferrite rod antenna is a challenge. A rough estimate is provided below based on the author's notes. The constants shown below are selected to be representative of typical ferrite rods you might encounter –but significant variation is likely.

$L = k * \pi * \mu net * A * N2 / length$ Eq. 4

where
L is the inductance in microhenries
k is a constant (use 0.004)
μnet is derived (complicated) from rod initial permeability and geometry (use 50)
A is the cross section area in cm2 of the rod
N is the number of turns
length is the length of the rod in cm

The inductance of the ferrite rod antenna (length is 9.3 cm) in the previous example is

L = 0.004 * 3.14 * 50 * (3.14 * 0.92 / 4) * 1002 / 9.3 = 430 microhenries

Construction of air loops

Air loops are typically constructed using two equal lengths (typically two to three feet) of 1x2 or 1x3 wood. The center of each length is notched out so that the two pieces can be glued together as a cross so that the wire can be evenly wound on the

TABLE OF CONTENTS:

Each chapter of the book is a separate pdf to be assembled in the following sequence. This sequence may change as the book develops because of additional chapters or merged chapters.

INTRODUCTION

The purpose of this book is to illustrate applied engineering concepts and the associated thought process to electrical engineering students by using a project that is historical as well as fun. The goal is to learn engineering methods and then apply those to design and
build a working crystal radio.

A crystal radio receives amplitude modulated signals generally in the AM broadcast band and produces an audio signal to earphones or even a speaker using only the energy of the received signal –no external power source is required. These radios have sometimes been called free power radios. Crystal sets (another name they go by) were used in the early days of radio prior to the development of vacuum tube amplifiers. A crystal radio consists of the following components:

* A wire antenna, typically 8 to 40 meters in length at a typical height of 3 to 8
meters, and corresponding earth ground to receive radio frequency energy

* An antenna tuning or matching system to couple power from the antenna to the
first resonant circuit that is tuned to the desired station

* A resonant circuit (sometimes more than one) to select the frequency of the
desired broadcast station

* A crystal detector to demodulate the AM signal thus producing an audio signal
from the modulation

effective permeability will always be less and is a complicated function of rod geometry. The process for calculating that is beyond the scope of this chapter but a representative value is 50. The electrical height of this loop at 1 MHz is

he = 6.28 * 100 * (3.14 * 0.0092 / 4) * 50 / 300 = 0.0067 meters

With a resonant Q of 20 the effective value becomes 0.133 meters and the total received signal is 13.3 mV –over a factor of ten less than the large air loop. The conclusion here is to not waste time and effort with ferrite rod antennas unless you are in a very strong (i.e. 1000 mV/meter) signal area.

A square loop in the 40 to 50 cm range on a side is about the maximum practical for transporting. If transportation is not an issue then one can consider loops over a meter on a side for higher received strength. A larger loop requires fewer turns of wire to achieve a given inductance and is more efficient.

Inductance

Reference 2 provides an accurate equation for the inductance of an air-core square loop as follows.

L = 0.008*N2*a*{ln[1.414*a*N /((N+1)* b)] + 0.379 + 0.33*(N+1)*b/(a*N)}   Eq. 2

where
L is the inductance in microhenries
N is the number of turns
a is the length of a side in cm
b is the winding width in cm

not a physical dimension (although it is proportional to the loop area) but a characteristic.

Reference 1 provides the equation to calculate the electrical height of a loop antenna.

$$he = \frac{2 * \pi * N * A * \mu e}{\lambda} \qquad \text{Eq. 1}$$

where
he is the electrical height in meters
N is the number of turns
A is the area of one turn in square meters
μe is the relative permeability of the core (air = 1, ferrite is several 10s)
λ is the wavelength in meters

As an example, a practical air loop might be 18 turns of wire wound on a square with sides of 0.43 meters. The electrical height of this loop at a frequency of 1 MHz (300 meters) is

he = 6.28 * 18 * 0.432 * 1 / 300 = 0.070 meters

Thus, a strong 100 mV/meter radio signal will develop 7 mV across the loop. This calculation assumes the loop is not resonant. If the loop is resonant at 1 MHz then the 7 mV signal is multiplied by the net Q of resonance as loaded by the diode detector. That Q can typically be 20 or more for an effective height of 1.4 meters so the net signal developed could be in the range of 140 mV which will readily heard in headphones.

A ferrite loop might consist of 100 turns of wire around a 9 mm diameter rod with an initial permeability of 125 (Initial permeability is a term used by the manufactures). The real or

* An earphone or speaker to convert the audio signal to sound

The author has built a number of crystal radios over the years and it was a childhood quest to learn how to build the best crystal radio possible. In fact, an interest in crystal radios and radios in general led the author to become an electrical engineer. One of the radios built by the author could power a speaker such that the station could be readily heard on the opposite side of a quiet room –and it could be tuned to different stations with minimal interference. Although it was based on some good concepts, that event was blind luck in the author's youthbut it did establish a benchmark for later life. Over the years the author has spent many hours of engineering trying to determine and explain the conditions required to replicate that radio. This book is the result. If an experiment can be replicated then it is science –and the author strongly believes in science. Otherwise it is magic and of no use. This book explains how you can use science and engineering to replicate that radio.

A major error made by students and even practicing engineers is to skimp the proper research and design process and jump to building hardware as soon as possible –this process is known as hacking –with luck it works –but it is mostly a waste of time. Before you can do design engineering you must have data and mathematical models of what you are trying to do. Sometimes data is readily available. Other times such as when you are doing something that has never been done before, only minimal if any data exists. Mathematical models may have errors or be incomplete based on knowledge you do not yet know. Thus, it is not uncommon for an experimental system to be constructed on a small scale in order to obtain data and refine and prove the mathematical models prior to expending a lot of time and money on the real system. The key to successful engineering is proper research done prior to the design phase. A crystal radio is an excellent example to demonstrate this because if any step is not understood or engineered well then the radio will not work well. The following chapters will illustrate the process from beginning to end.

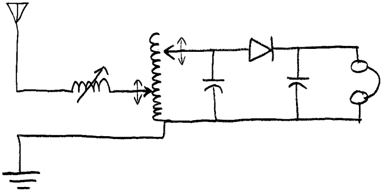


Figure 1 shows a simple crystal radio that will be discussed in great detail in this book. The circuit illustrates each of the bullet points above.

LOOP ANTENNAS

Introduction

An alternative to constructing a long wire antenna and ground system is to build the resonator as a large loop that picks up enough energy to power the radio. This approach is only useful in strong signal areas as the energy picked up by a loop is small in comparison to that of a long wire antenna.

A loop antenna responds to the magnetic field of the radio signal whereas a long wire antenna responds to the electric field. Unlike wire antennas that are less than a quarter wavelength and thus have little directional characteristics, loop antennas are very directional and the plane of the loop must be oriented towards the broadcast antenna to receive a signal.

Loop antennas can either be large air loops (with typical dimensions between 0.5 and 1 meter square) or small loops wound on a ferrite rod. Small ferrite rod antennas are very inefficient but are the only practical method to construct a small antenna for common purchased AM broadcast band radios. Large air loops can work as antennas for crystal radios but only in a strong signal area. A crystal radio can be built using a ferrite rod antenna but is only useful in a very strong signal area. This chapter will discuss both types but with an emphasis on the large air loop.

Electrical height

The signal voltage developed across a loop antenna is the strength of the radio wave in volts/meter multiplied by the electrical height in meters of the loop. The electrical height is

Although there may be exceptions, miniature (less than 4 inches across) speakers typically are very inefficient. You will probably find that the best speakers for crystal radio purposes are in the 4 to 8 inches across range. Larger speakers may work well too. It is important that the speaker be mounted in an enclosure designed to maximize the volume. Some designs that emphasize high fidelity are inefficient –which is not a consideration in the high fidelity business.

Do not waste time attempting to make a speaker work until you have very good volume in headphones. That is a clue that speaker operation can work.

COMPONENT SOURCES

The following are some sources for components for your crystal radio. Many sources have minimum handling and shipping charges so I suggest that a group of interested people pool their money and make a single order –one set of charges can be amortized over the group –everyone saves! Be sure to order extra parts to have to replace parts you accidentally break.

Antenna insulators and wire

Check with your local hardware store. You will probably not find insulators but there are all kinds of methods to improvise such as using plastic pipe. Some mail-order hobby electronics sources sell insulators made for wire antennas. The antenna wire can be #14, #16, or #18 stranded wire. Solid wire is fine but is harder to work with. I recommend the use of insulated wire.

Ground wire

Check with your local hardware store. The ground wire can be #14, #16, or #18 stranded wire. Solid wire is fine but is harder to work with. You may need a ground clamp if your are connecting to a metal water pipe.

Coil form

The coil form should be roughly two to six inches in diameter and can be plastic pipe, a cardboard tube, etc. An oatmeal box is a very good size although it is not very strong. Wire for coil

Check with your local hardware store. Use the chapter on winding coils to make the best decision about wire size for your particular coil form and desired inductance. For large diameter (six inches) coil forms, #14 insulated wire is a good choice. For small diameter coil forms (2 inches), #18 insulated wire is a good choice. Magnet wire (solid copper wire with a thin enamel insulation) has been popular over the years. Use as large a gauge (i.e. large diameter) as you can as that will have lower losses. See the chapter on winding coils –for best results the turns should not be packed together –that is hard to do which is why I recommend insulated wire instead as the insulation forms the spacing between turns.

Variable capacitor

Classic variable capacitors of the past are hard to find these days. You are generally looking for one with a maximum capacitance of around 365 pF. Some hobby electronics sources sell miniaturized versions using plastic film insulation and these are fairly inexpensive.

Detector diodes

I make reference to a 1N277 germanium diode. The following diodes are candidates. These are available from Mouser Electronics, http://www.mouser.com March 2008

Mouser # Description Price

* 526-NTE109 This is a generic germanium diode like 1N277 $1.31 This is the part the author uses and is probably the best.
* 610-CDSH270 This is a Schottky improved replacement diode $0.35 This part has higher conductivity at higher forward voltages but the author has not evaluated the part at very low forward voltages –it is not expected to be as good as

There is no rule that says you have to use the exact impedance each winding is designed for. You can generally go up or down a factor of two or more with little ill effect. If your impedance is lower than the winding is specified for then high frequency response will not be as good and losses will likely be higher. If your impedance is higher than the winding is specified for then low frequency response will not be as good and losses will likely be higher. Keep in mind that a few dB of extra loss will not stop your radio from working unless your signals are so weak that this extra loss makes them inaudible. What you want to do is to make the radio work however and then you can think about optimizations afterwards.

A typical speaker mounted in the proper enclosure will produce a sound level in the 85dBa for one watt of power at a distance of one meter. That is very loud. Humans can hear a much lower sound level. It would only take about 10 mW for this same speaker to produce the volume of normal speaking level. A power of only 100 uW would be definitely audible in a quiet room. Thus, if the signal strength of a station we want to pick up is in the 1 mW range then driving a speaker is practical. The following table shows some typical examples.

Power to Speaker	dBa @ 1 meter	Example volume level
1 Watt	85 dBa	Loud
100 mW	75 dBa	“Normal”volume on radio or TV
10 mW	65 dBa	Typical conversation
1 mW	55 dBa	Quiet conversation
100 uW	45dBa	Whisper
10 uW	35 dBa	Typical background noise level in a home

Table 1: Sound levels

A common speaker impedance is 8 ohms but other impedances exist between 2 and 16 ohms. The impedance of a speaker is not the DC resistance (ideally that would be zero) of its voice coil but is a complex relation involving the coupling of the speaker cone to the surrounding air. A back emf is generated by the moving coil and that forms an impedance that varies across the audio spectrum. The published impedance of a speaker is typically measured at a frequency of 1,000 Hz although other frequencies may be referenced if the speaker is intended for use at the very high or very low end of the audio spectrum.

A speaker has too low an impedance to directly connect to the detector of a crystal radio. A transformer must be used. The type of transformer you need is not easily found. You generally want a transformer that has is designed for a primary impedance of at least 5,000 but preferably 20,000 ohms or more. The specified secondary impedance should be reasonably close to that of the speaker you will be using. Miniature transformers are typically very inefficient and have a loss in the 3 to 6 dB range. Large transformers typically have a loss of 1 dB or less –that is what you want.

An “ideal” transformer would match about 20,000 to 50,000 ohms on the primary to 8 ohms on the secondary and would probably weigh a half pound or more (large size translates to low loss). However, the author has never found such a commercial transformer and plans someday to wind such a transformer. It is possible to find transformers to match 50,000 ohms to 1,000 ohms and other transformers to match 1,000 ohms to 8 ohms. This combination will work –not ideal –but much better than nothing.

a true germanium diode like the 1N277 but that experiment remains to be done.
* 630-1N5711 This is a Schottky diode that should work well $1.70 This is a good general purpose Schottky diode. The author has not evaluated this part for operation at very low voltages. It is not expected to be as good as a true germanium diode but that experiment remains to be done.

Audio Transformers
The following audio transformers are good candidates.
March 2008
Mouser # Description Price
42TM006-RC 20K –1K transformer $1.91
42TM117-RC 50K –1K transformer $1.91
42TU013-RC 1K –8 Ohm transformer $2.19
42TL017-RC 20K –600 Ohm transformer $1.86
Series secondary –600 ohms, parallel –150 ohms
This transformer may work very well with high impedance headphones -- most cheap headphones are low impedance in the 16 –33 ohm range.

Headphones

These are easily available from most any local electronics/audio store. You do not need expensive phones (those typically are inefficient –not suitable for crystal radios) –the cheap phones (under $20) can work very well for crystal radios. Most all common headphones are low impedance in the 12 to 33 ohm range and will need a transformer for matching to the diode detector. Look for a sensitivity of at least 95 dBa / 1 mW. The most sensitive headphones known to the author are rated at 108 dBa / 1 mW (Sony model MDR-ED12LP, ~$15 at Best Buy –each phone is 16 ohms –8 ohms when in parallel). Note that these are stereo headphones and the net impedance presented to your radio will be twice the stated impedance if the left and right sides are connected in series and half the stated impedance if connected in parallel. Use the series or parallel connection that best matches your transformer secondary rating. Sensitive headphones are a must –an excellent crystal radio will make no audible sound in insensitive phones –thus resulting in much frustration.

Speakers

Do not even think about a speaker until you have a working crystal radio that can drive loud volume in a headset. When you are ready, then you are looking for an inexpensive speaker in the four to eight inch diameter range that is mounted in an enclosure and that has an output of at least 85 dBa / 1 Watt (1 meter distance). If you look around you might find a speaker rated in the 90s which is significantly better. You are looking for efficiency, not fidelity. Often, high fidelity speakers are inefficient. The impedance of the speaker should be 8 ohms and you will need a transformer to match the speaker to the several thousand ohms impedance of the diode detector.

DRIVING SPEAKERS

Introduction

One of the high achievements in crystal radios is being able to drive a speaker and being able to hear the signal across the room. The sound will not be loud but will be definitely audible and even understandable if the room is otherwise quiet. The author has done this and it is a nice feeling of accomplishment. Driving a speaker is only possible if everything in the radio has been done in the best way and the antenna and particularly the ground system is decent. The radio station being received generally needs to be within 20 km and be operating at 50 kW. This will result in a whopping 10 to 100 microwatt audio signal to the speaker! Believe it or not, you can hear that in a quiet room. If you can get as much as a milliwatt to the speaker then everyone can definitely hear it.

Speakers

A speaker is typically constructed of a stiff suspended cone with a coil that is positioned inside a very powerful permanent magnet. Electrical current in the coil makes a magnetic field that reacts with the permanent field thus moving the cone in response. This process converts electrical energy to acoustical energy.

Speakers are typically rated in dBa acoustical output at a distance of one meter for one watt of applied electrical power. Typical speakers range from around 80 (inefficient) to over 90 (efficient) dBa at 1 meter for one watt. The electrical efficiency of a speaker has little if anything to do with its sound quality or price.

40	10 nW/m2	10 nW	very quiet whisper conversation
50	100 nW/m2	100 nW	
60	1 uW/m2	1 uW	quiet conversation
70	10 uW/m2	10 uW	typical office and normal conversation
80	100 uW/m2	100 uW	moderately loud radio
90	1 mW/m2	1 mW	loud radio
100	10 mW/m2	10 mW	very loud radio
110	100 mW/m2	100 mW	
120	1 W/m2	1 W e	xtremely loud dance club threshold of pain

Table 1: Acoustical data (headphones are 90 dBa for 1 mW)

RF FIELD STRENGTH

Introduction

The process of building a crystal radio begins with the transmitter. Without the transmitter there would be no point in building the radio.

AM Broadcast stations in the United States operate at 10 kHz intervals between 540 kHz and 1,700 kHz using double sideband amplitude modulation with a modulation bandwidth of 5 kHz (10 kHz total channel width) and a transmitted power ranging from around 1 kW to 50 kW. The broadcast antenna is generally some form of a one-quarter to over one-half wave vertical tower (the entire tower is the antenna) with numerous onequarter wave ground radials. A quarter-wave antenna at 540 kHz would be around 139 meters high!

A quarter-wave antenna is attractive because it has a low resistive (i.e. no reactive component) impedance of around 35 ohms. For a 50 kW transmitter the applied voltage to the antenna would be around 1,300 volts rms! This impedance is not the resistance of the tower –that needs to be as low as possible for high efficiency. The impedance of the antenna is the result of the fact that power leaves the antenna as a result of radiated electromagnetic fields –that is the purpose of the antenna.

If the electrical length of the antenna is not a quarter wave then there is a reactive component in the antenna impedance. This reactance is in the way of coupling power to the antenna. Various tuning schemes can eliminate the net reactance. Antenna designers are interested in maximizing the strength of the electromagnetic field emitted from the antenna. They also have to deal with other limitations such as maximum allowed antenna height, electrical characteristics of the soil around the antenna, and other factors. For these reasons the electrical height of the antenna may deviate from the seemingly ideal one-quarter wave. The result is an antenna that optimizes the broadcast range of the transmitter. Tuning networks can compensate for any antenna reactance.

The signal strength some distance from the transmitting tower is commonly measured in volts per meter. There is a corresponding current measured in amperes per meter obtained by dividing volts per meter by the impedance of free space, 377 ohms. There is no power dissipated in free space as the voltage and current are physically orthogonal. The voltage per meter is a cyclic gradient and is only meaningful over distances that are short (roughly 20 electrical degrees) with respect to a wavelength. Short antenna probes can measure this voltage. Amperes per meter is also a cyclic gradient and is a bit more difficult to visualize as it represents a magnetic field that would exist in response to an actual current. There is no actual current in free space which is an electrical insulator. The magnetic field can be measured using small (with respect to a wavelength) loop antenna probes in which a current is induced.

Thus, electromagnetic radiation is a combination of a cyclic voltage field and an orthogonal cyclic magnetic field. Either alone is just induction as opposed to radiation. As fields spread, the strength of an electromagnetic wave follows a one over distance law. Induction fields follow a one over distance cubed law. Thus, induction fields are useful only for very short distances.

In order to engineer a crystal radio we need to know the expected electromagnetic field strengths we intend to receive. Those strengths must be above some minimum or we will hear

as possible – that is what we need for a crystal radio. In the case of crystal radios the amount of available audio power is incredibly small –perhaps microwatts or less so highly efficient headphones are a necessity.

We should review some facts about acoustical power and decibels. Decibels always represent a power ratio. We might derive the value from a voltage or current ratio but it is always power that matters. When we speak of a sound level of 80 dBa, then we are referring to an acoustical power density relative to the zero dBa reference level which has been established at 1 pW per square meter (note: some sources state 2 pW). Acoustical levels are very commonly measured in dBa but unfortunately, the ‘a’ subscript which refers to the particular acoustic 0 dB reference level is often dropped. There is no such thing as absolute dB as the language often sounds like. The following table provides some examples. The headphones referenced are rated for 90 dBa / mW. This does not mean 90 dBa per milliwatt but that a sound pressure level of 90 dBa is produced by one milliwatt of electrical power. The sound pressure level produced by ten milliwatts would be 100 dBa. It is hard to hear sound pressure levels less than about 30 dBa because other low level noises are in that order of magnitude and mask the sound. Table 1 indicates that with ordinary headphones one should be able to detect an audio signal in the 1 nW range. That would barely be distinguishable from background noise in the room. However, a one-hundred nW level should readily be heard in the headphones.

dBa	Power	Headphones	Examples
0	1 pW/m2 a		accepted threshold of human hearing
10	10 pW/m2		
20	100 pW/m2		
30	1 nW/m2	1 nW	quiet room (background noise level)

these units ranges from around 30 to 150 ohms so some kind of transformer is always required to match into the much higher detector impedance (typically tens of thousands of ohms) of the crystal radio. If the left and right earpieces are connected in parallel then the impedance is halved. The impedance would be doubled if the units are connected in series. There is a slight issue with connecting the phones in series and that is that the phase is inverted from ear to ear –this really only matters for low audio frequencies. This would not be desirable from a high-fidelity standpoint but probably makes little, if any difference to most people particularly in a crystal radio setting as it is a thrill to hear anything at all.

Sensitivity

In modern society people are accustomed to high sound levels. People accustomed to this initially have difficulty in acclimating themselves to hear faint sounds. With practice and concentration, remarkably low sound levels can be heard. This is necessary to be able to use a crystal radio. Once you have adapted yourself to listen to weak signals the noisy world we live in will become very obvious.

It is very important to use headphones that are highly efficient. Audio quality is of no concern although just about all modern headphones have fine audio quality. A small amount of power produces a high volume in even inefficient headphones so few people care about efficiency and that data is rare. When you can find such data it is typically given in terms of dBa for one milliwatt with typical values ranging from the seventies (low efficiency) to over one hundred (high efficiency) dBa for one milliwatt. It does not make any sense to measure efficiency for this case in percent. What matters is how much acoustical power can be delivered to the ears for as little electrical power

nothing in our headphones. Data is readily available that gives us a reasonable expectation of the amplitude of a radio wave in terms of volts per meter at a given distance from the broadcast antenna. We must understand not to interpret such data too literally as there are always variables related to terrain and various structures that will affect the data –mostly negatively but sometimes positively.

Figure 1 shows typical signal strengths for a 50 kW station during daylight hours. The voltages will be about one-third for a 5 kW transmitter. The increased drop-off with distance is due to the curvature of the earth and varies at night and with weather conditions so a significantly greater range is possible at times. The typical atmospheric noise level for a 10 kHz bandwidth is also shown although this can vary significantly with location and season. Excellent reception is when the signal strength is 100 times the noise level. Poor, but usable, reception is when the signal strength is around 5 times the noise level. The noise floor is only shown for reference. Crystal radios are typically so insensitive that the minimum usable signal is around 1000 times the noise floor.

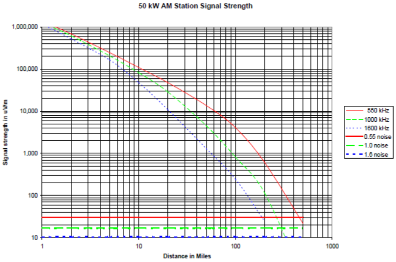


Figure 1: Signal strength with distance
adapted from Reference Data for Radio Engineers,
Howard W. Sams, Inc. sixth edition, pages 30-3 to 30-5

to using magnetic headphones (if you can find them –they are old and rare now). However, modern speaker phones generally are more sensitive and work better.

Crystal

These are based on the piezoelectric effect (piezo means force or pressure). A crystal physically expands or contracts in response to an electrical voltage applied across it. If the electrical voltage represents an audio signal then sound can be heard coming from the crystal. The process also works in reverse and the device is known as crystal microphone. Sound pressure causes the crystal to expand or contract which produces a voltage in proportion. Crystal earphones used to be very popular but are now rare as modern earphones work much better. Crystal earphones can be damaged by mechanical shock (such as dropping) and humidity. The sensitivity varies a lot – some are insensitive, others are fairly sensitive. Crystal earphones are high impedance (typically much greater than 50,000 ohms) devices and are ideal for use with crystal radios. DC voltages should not be applied so a coupling capacitor (typically in the 0.1 uF range) should be used to block the DC detected voltage from the rectifier diode. A resistor (often around 50,000 to 100,000 ohms) is placed across the output of the rectifier diode to ground to provide a required DC complete circuit.

Speaker

These headphones are built using a tiny speaker located close to the ear. The interest in using these with modern battery powered equipment has led to the development of units that require only a very small electrical power (on the order of a milliwatt) to produce a loud sound. The typical impedance of

HEADPHONES

Introduction

Headphones are made using small electrical to acoustical transducers that are located very close to the human ear so that very little electrical power is required for hearing a signal. With sensitive (i.e. high efficiency) headphones it is possible to hear audio signals in the nanowatt range! A milliwatt is a huge amount of power and makes a very loud signal.

Headphone types

There are three basic types of headphones as described below Magnetic These were the first headphones ever built and were popular for many years although modern headphones work better and have replaced them. Magnetic headphones are constructed by winding many turns of fine wire to form a coil around an iron core that includes a permanent magnet. A thin iron plate which makes the sound is held in place by the magnetic field. The center portion of the thin plate is pulled by the magnetism. As an audio (i.e. AC) current is passed through the coil the magnetic field increases or decreases in response. The variation in the magnetic field modulates the force of attraction of the iron plate which then moves slightly thus making a sound. Magnetic headphones generally have an impedance in the 2,000 to 20,000 ohm range. The impedance is not the DC resistance but is related to the inductance of the winding on the coil and the acoustical reaction of the iron plate. Some magnetic headphones are quite sensitive but others are only fair. Any old headphone set you find could vary considerably in impedance and sensitivity –you would have to make your own measurements with laboratory equipment to truly know what you have. For nostalgia there is an attraction

ANTENNA AND GROU ND SYSTEM

Introduction

This article explains the basics of the antenna and ground system for a crystal radio and the associated mathematical model. The mathematical model tells us how to design the antenna input section of the radio for optimum performance.

The passing RF wave induces an RF voltage across a length of wire referred to as an antenna. The induced voltage is the signal strength in volts/meter multiplied by the electrical (not the physical) height of the antenna in meters. For antennas that are shorter than one-quarter wavelength the electrical height is roughly the wire length (including lead-in wire) in meters. There are very little directivity effects for short antennas so orientation is not really a factor –i.e. the antenna is omnidirectional. The physical height of the antenna above the earth affects the signal amplitude as there is increased attenuation of the signal close to the ground.

The antenna should be as long as practical and as high as practical. A quarter wavelength for 540 kHz is (300,000/4)/540 = 139 meters. A quarter-wavelength at 1700 kHz is 44 meters. For a basic crystal radio there is little to be gained by an antenna longer than about 40 meters or higher than about 8 meters –that is a substantial antenna that few have the room to construct. A minimum antenna might be about 10 meters long and about 3 meters off the ground. Anything in-between can produce acceptable performance. Advanced crystal radio enthusiasts will construct bigger and more advanced antennas but that involves a degree of engineering beyond the scope of this article.

One advanced method that the author has not had the space to try is a true dipole antenna that is one-half wavelength long (in some cases longer). Such an antenna is balanced and so does not depend on a low-impedance ground for operation. The power received by the antenna would be significantly more than that of the simple long wire antennas described in this article. With such an antenna a local station could drive a speaker to significant volume. But, the antenna is only useful over a narrow band of frequencies and is also directive so it must be oriented properly relative to the transmitting antenna.

Figure 1 shows a typical antenna and ground setup for a crystal radio. The following sections discuss each attribute.

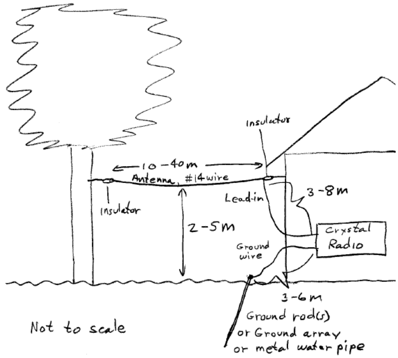


Figure 1: Basic Antenna System for a Crystal Radio

3000	________	________
4500	________	________

If the response data is plotted the curve should be generally smooth and will probably show drop-off at each end of the spectrum. It would not be unusual for the response at 100 Hz to be down by three or more dB. The response at 4500 Hz may be down by around one dB. You might see a broad dB or more increase in the response at some region (a sharp deviation at a single frequency is likely to be the result of an error). The standard method for rating the frequency response of a transformer is the band over which the response is within a +-3 dB variation from some norm. That coarse specification tends to hide the limited bandwidth that transformers can achieve.

Your transformer is suitable for a crystal radio if its frequency response over the 300 to 3,000 Hz range does not vary more than roughly 6 dB.

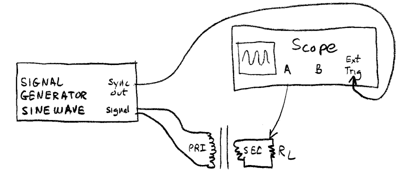


Figure 4: Measuring frequency response

Measure the amplitude across the load resistor at each of the following frequencies. The range shown is all you need to be concerned with for a crystal radio but if you are interested you might want to extend the range of test frequencies using the same coarse sequence of test frequencies. Compute the response (relative to 1 kHz) for each frequency using the following equation.

Response = 20 * log10(Vmeasured / Vref) Eq. 15

Test Frequency	Measured Amplitude	Computed Response
100	________	________ dB
150	________	________
200	________	________
300	________	________
450	________	________
650	________	________
1000	________	0.0 dB –by definition this point is 0 dB
1500	________	________
2000	________	________

Distal support

If available, a tree makes a convenient support for the antenna wire. Otherwise some kind of post will have to be constructed. Never use a utility pole or any other support that is not your property –your potential liabilities could be astronomical if some accident (lightning for example) or failure causes damage to someone else's property or person. An insulator typically made of ceramic or plastic is used to terminate the antenna wire and to connect to the antenna support usually via some kind of rope. These insulators are readily available from various hobby electronics sources. A large wood screw typically with a hook or eye end driven into a tree or other support is used as an attachment point for the rope. Do not wrap the rope around the tree as that will constrict growth in future years.

Antenna wire

The antenna wire is typically #14 AWG solid or stranded copper wire and may or may not be insulated. Insulation has no effect on reception but is an advantage to reduce corrosion effects. There is no advantage to using heavier wire such as #12 or #10 as the resistance of the wire is negligible compared to everything else and the added weight makes the end supports more challenging. Wire sizes of #16 and #18 also work well but are less strong –but are also lighter and will put less stress on the supports. Wire gauge sizes higher than 18 are not recommended because they are more fragile and are hard to see if they fall –you would like to not run over the wire with a lawn mower –could be very disastrous! Although low resistance is nice, it is a myth to go to great efforts for low resistance in the antenna wire as the resistance of the ground is going to be considerably higher.

The height of the antenna absolutely must be above head level for someone who might be standing on some vehicle (i.e. bicycle or motorcycle) that might possibly travel under the antenna to prevent what could be a horrible or even tragic accident –this means at least 3 meters. The antenna wire should not pass over anything such as a road or other wires such as electrical power such that if the antenna fell that a dangerous situation could result. Within practical limits the higher the antenna the more signal it will pick up. That does not extend indefinitely and there is a point of diminishing returns reached at roughly 5 meters. If it is easy for you to make the antenna higher then do so but there is little point in going to great effort to achieve that as you will only notice a difference in the
extreme small signal case.

Proximal support

This support is similar to the distal support and may be attached to either the dwelling or a convenient tree that happens to be close. An insulator supports the antenna and rope. The lead-in wire attaches to the antenna at the insulator. It is important to make sure that the support can break away without damaging the structure should something fall on the antenna wire.

Lead-in wire

The lead-in wire can be whatever is convenient and is often #18 wire. Since the antenna system is much shorter than one-quarter wavelength the lead-in counts as part of the antenna

$$Ploss = 10 * \log10(PRL/PRp) \qquad \text{Eq. 14}$$

Use the following chart as a guide to the suitability of your transformer for a crystal radio. Keep in mind that even an "awful" transformer is probably better than nothing so use that until you can obtain a better one.

Ploss	Quality
<1 dB	Excellent –few audio transformers achieve this
1 –2 dB	Good –most audio transformers achieve this
2 –3 dB	Fair
3 –5 dB	Poor
>5 dB	Awful –either a mistake or this transformer is not meant for audio

Measuring the transformer frequency response

The frequency response achieved by a transformer is influenced by the external circuit it is connected to. The most accurate way to measure the response is to use the actual circuit. This experiment shows a basic circuit that provides good results and forms the basis for comparing transformers.

Connect the transformer using the circuit in Figure 4. The load resistor is either that of your headphones or speaker. Connect an AC voltmeter or scope across the load resistor. Set the output of the signal generator to be a 1 kHz sine wave with an amplitude such that the voltage across the load resistor is easy to measure (for oscilloscope use a suggested value is 0.6 Vpp and the scope set on 0.1 volt per division). Measure this voltage and refer to it as Vref. Do not adjust the amplitude of the generator after this point –only adjust the frequency.

Set the signal generator to a 1 KHz sine wave and adjust the output amplitude for about 0.6 volts peak-peak as measured on the oscilloscope. Adjust R until the magnitude of the voltage on channel ‘B’ of the scope is roughly half the value of channel ‘A’. This provides the best resolution of the measurement. In measuring VA and VB you should note if the phase angle between them is close to zero. If not then there is a problem and the following calculations will be in error.

VB/VA = Rp / (R + Rp) = (Rp/R) / (1 + Rp/R)   Eq. 10

Solving for Rp gives

Rp = R * (VB/VA) / (1 –VB/VA)   Eq. 11

Measuring the transformer power loss

Without changing anything in the previous setup, measure the peak-peak voltage across RL using scope channel ‘A’ –you will probably have to adjust the vertical scale amplitude setting to measure the smaller signal. Call this voltage VLpp

Note that the power delivered to RL is

PRL = VLpp2 / (8*RL)   Eq. 12

Note that the power delivered to the primary of the transformer is

PRp = VBpp2 / (8*Rp)   Eq. 13

If things are going correctly, then PRL will be a little less than PRp because the transformer has power loss. The loss in db is

length. Thus, if the antenna wire was 25 meters and the lead-in wire was 5 meters, the total antenna length would be 30 meters.

Lightning arrestor

A lightning arrestor is an important part of the antenna system that is located outside the building and usually close to where the antenna and ground wires penetrate. A lightning arrestor consists of a spark gap that will arc when more than a few hundred volts exists across the points. Contrary to the name, a lightning arrestor will not protect you or the dwelling from a direct lighting strike. A lightning arrestor will reduce the probability of damage to your crystal set and anything nearby should lightning strike in the vicinity. A nearby strike can induce many hundreds or even thousands of volts on the antenna that could cause damage or injury. The lightning arrestor will then arc to limit the voltage to typically several tens of volts. You should never operate a crystal radio if there is any
possibility of a lightning strike. A number of people install shorting switches or connections to connect the antenna to ground when the radio is not being used. This provides some measure of safety but is not absolute. Nothing can protect you or your dwelling from a direct lightning strike.

Ground wire and ground system

The ground wire is typically #18 copper (because that is a convenient size) and should connect to either a nearby metal water pipe or some ground system –either buried pipe or ground rod(s). It is a myth to use wide braid or other large conductor for the ground wire as the resistance of a short length of #18 is negligibly small in comparison to the earth. It is nice for the wire to be no longer than necessary because inductive reactance in the wire can interfere with the operation of the radio –but that is a small point.

Most difficulties or frustrations with crystal radios can be traced to a poor ground system. Building a good ground system is the most labor intensive and even most expensive part of a crystal radio. If you are lucky then there is a long metal water pipe located just outside the window of your crystal radio. In that special case your ground system is easy and cheap.

If you are not so lucky then one alternative is to drive three or more 2.4 meter (8 foot) ground rods straight into the ground near the house. These should be spaced roughly 2 meters apart. The quality of this ground can vary a lot depending on soil conditions and it is not likely to be as good as that of a water pipe. At the easiest, this is a very labor intensive to even impossible job if the ground is very hard. A heavy duty hammer drill can make the job easier. Otherwise you will need a very heavy sledge hammer and strong and enduring muscles as well as significant patience.

An alternative is to dig a shallow trench at least 0.2 meters deep and bury a 10 meter or more length of copper pipe. It helps for the soil to be wet down to the level of the pipe when the radio is being used. This can make a decent ground for radio reception although it should in no way be considered a "safety" ground.

The following table provides a general idea of the quality of the ground system.

$$Ls = XL / (2 * \pi * 1000) \qquad \text{Eq. 8}$$

Given FLOW in Hz, the lowest audio frequency of interest and using the rough rule-of-thumb XL being three times the resistive impedance at the lowest frequency, the nominal load resistance for the transformer is

$$RLnom = 0.33 * XL * (FLOW / 1000) \qquad \text{Eq. 9}$$

For crystal radio use, choose an FLOW of around 100 to 200 Hz. The transformer will work well with any load resistance between about one half and twice this value.

Measuring the primary impedance

Refer to the circuit in Figure 3 and connect a load resistor, RL, across the secondary equal to the load impedance of the headphones or speaker that will be used. This assumes that your load impedance is roughly within a factor of two of RLnom calculated above.

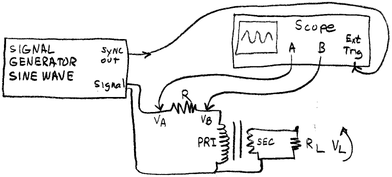


Figure 3: Measuring primary impedance

$$Zs = \frac{R * (VB * \cos(\theta) + jVB * \sin(\theta))}{(VA - VB*\cos(\theta)) - jVB*\sin(\theta)}$$

$$= \frac{R * (\cos(\theta) + j*\sin(\theta))}{(VA/VB - \cos(\theta)) - j*\sin(\theta)} \qquad \text{Eq. 6}$$

Multiply both numerator and denominator by the complex conjugate of the denominator to obtain Eq. 7a

$$Zs = R * \frac{\cos(\theta)*(VA/VB - \cos(\theta)) - \sin^2(\theta) + j*\sin(\theta)*[VA/VB - \cos(\theta) + \cos(\theta)]}{(VA/VB - \cos(\theta))^2 + \sin(\theta)^2}$$

After some simplification we have

$$Zs = R * \frac{\cos(\theta) - (VB/VA) + j*\sin(\theta)}{(VA/VB) - 2*\cos(\theta) + (VB/VA)} \qquad \text{Eq. 7b}$$

Note that Eq. 7b is of the form Zs = Rs + j*XL where Rs is the secondary AC resistance at the test frequency and XL is the secondary inductive reactance at the test frequency. Note that the first and last terms of the denominator are reciprocals. For a good transformer, Rs should be much less than XL.

Although all we really need to know is the inductive reactance, while we are at this point we can calculate the inductance of the secondary in henries as

Ground Quality	Resistance
Excellent	< 10 ohms
Good	10 to 20 ohms
Fair	20 to 40 ohms
Poor	40 to 100 ohms
Bad	> 100 ohms

A good question is how to measure the ground resistance. This is kind of hard to do since you have access to only one wire. Where is the other end that we measure with respect to? The answer is that it is nebulous but there does exist an effective point that completes the circuit for the radio signal. The effective ground resistance can be inferred from measurements using a received signal. The method is discussed in another chapter. Mathematical model of the antenna and ground system

A simple electrical model of a short wire antenna less than one-quarter wavelength is shown in Figure 2. It consists of a voltage source equal to the induced amplitude with a small series resistance and very large series capacitive reactance. A simple electrical model of the ground circuit is a series resistance that may range from single digit ohms (an excellent ground) to several tens of ohms. A poor ground may have a series resistance of over one hundred ohms.

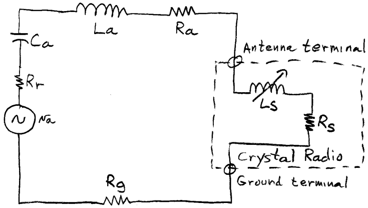


Figure 2: Simple Circuit Model for Antenna and Ground

Signal pickup

The radio frequency field strength is measured in volts/meter (or amperes/meter if you divide volts/meter by the free space impedance of 377 ohms). This is a cyclic voltage gradient. The voltage that will be induced in a conductor that is short in comparison to a quarter wavelength is roughly the RF signal multiplied by the length of the conductor. Proximity of the conductor to other conductive objects (such as trees and the earth) will reduce the induced voltage. This is one reason why it is desirable for the antenna to be as high as practical above the earth. There is no difference between the antenna proper and the lead-in so the total length is what counts. In Figure 2 this voltage is shown as va.

Radiation resistance

There is an effective radiation resistance associated with the total antenna length. For electrically short antennas this may only be a few ohms but can rise to several tens of ohms as the

accurate results. Record the following measurements on the oscilloscope:

* VA –the peak-peak applied voltage
* VB –the peak-peak voltage across the transformer
* θ–the phase angle of scope trace 'B' relative to scope trace 'A' (should be positive)

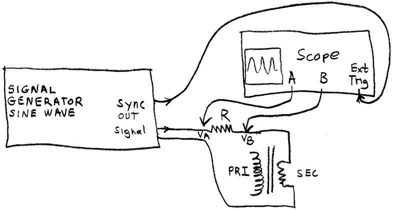


Figure 2: Measuring secondary impedance

We first analyze the circuit and then we can apply the results. We begin by noting that the current through the transformer winding is the vector voltage across resistor, R, divided by R.

$$I = \frac{(VA - VB*\cos(\theta)) - jVB*\sin(\theta)}{R} \qquad \text{Eq. 5}$$

The impedance of the secondary winding is the voltage across the winding divided by the current through it.

Figure 1: Cascading transformers

Characterizing your transformer

Before you use your transformer you should take some measurements to understand it. Basic characterization data for audio transformers is typically done at a test frequency of 1 kHz. You generally want to know what the nominal primary and secondary impedances are, the power loss, and the frequency response. The following sections describe how to make these measurements.

Measuring the secondary inductance

The first thing to do is to measure the inductance of the secondary winding. We measure the secondary because it is a lower inductance and is easier to measure without various errors creeping in. If we know the inductance of the secondary then we have a good idea of the resistive load impedance that will work best. Use the setup in Figure 2. Use a test frequency of 1 kHz and set the output amplitude of the generator to about 0.6 volts peakpeak as read on scope channel ‘A’. Adjust the value of R until the amplitude on scope channel ‘B’ is between about 40 and 75 percent of the amplitude on scope channel ‘A’. This range provides good measurement resolution and

antenna length approaches one quarter wavelength. In Figure 2 this resistance is shown as rr.

Antenna reactance

An antenna has both a series capacitance and series inductance that makes up a net reactance that varies with wavelength. Capacitive reactance dominates if the antenna is shorter than one-quarter wavelength and inductive reactance dominates between one quarter and one-half wavelength at which capacitive reactance dominates again for the next quarter wavelength, etc. Normal antennas for crystal radios are significantly shorter than one-quarter wavelength so there is a large capacitive reactance in series with the induced voltage. The inductive reactance reduces the net reactance somewhat for short antennas. At quarter-wave resonance the reactance terms cancel and the antenna is purely resistive. In Figure 2 these are shown as Ca and La.

Antenna resistance

The antenna wire has electrical resistance that is mainly due to the skin effect of the conductor since the frequency is high. This resistance is typically a few ohms and is often small in comparison with the ground resistance. In Figure 2 the antenna wire resistance is shown as Ra.

Antenna tuner inductance

The first element typically found in a crystal radio is an adjustable inductor to neutralize the capacitive reactance of the antenna thus maximizing the power transfer from the antenna to the receiver input resistance. This is known as conjugate matching where the sum of the positive inductive reactance of the inductor and negative capacitive reactance of the antenna is zero. In Figure 2 this inductance is shown as Ls for series inductance.

Crystal radio input resistance

The crystal radio generally appears as a pure resistance at resonance with a received signal. For optimum power transfer this resistance should be equal to the sum of the ground plus antenna plus radiation resistance. The ground resistance typically dominates this equation. The input resistance of the radio can be adjusted via taps on the tuning inductor or other matching network. For best performance it is important to match the radio to the antenna and ground system. Failure to do this results in an underperforming radio.

Ground resistance

The ground resistance completes the circuit back to the rather nebulous point that is the effective reference for the radio frequency signal. Ideally, this resistance is less than 10 ohms but typically is in the 10 to 100 ohm range.

A single short wire antenna is unbalanced and a low-impedance ground is required to complete the RF circuit. It is easy to set up a simple wire antenna that can work well but it is a challenge to construct a low-impedance ground. Without a low-impedance ground much of the signal picked up by the antenna will be wasted and the crystal radio will perform poorly if at all. Much frustration from poor performance of a crystal radio set is often caused by a high-impedance ground. An ideal situation is to connect the crystal radio set to a metal water pipe (either old-fashioned galvanized or preferably copper). The long exposure length to the earth produces a low-

which is in the range we are looking for. However, it is important that the transformer design impedance be similar to the impedance we will be working with –this means that the power rating of the transformer should be in a certain range. The typical load impedance for a speaker or headphones is in the 8 to 30 ohm range. Using a 6 volt secondary and a nominal load impedance of 16 ohms then the transformer should have a Volt-Amp rating of around 62 / 16 = 2.25. That is a very small transformer but they are available. This is not a number you have to precisely achieve – it is only a guide to choosing a transformer. Larger transformers in the 5 VA range will also work for this example. You prefer a transformer that will have no unused windings as those will have higher losses –but they are better than nothing so use what you have. At low audio frequencies an AC power transformer of the right size should work well.

At high audio frequencies the transformer will probably not work well because of losses. However, it only has to work good enough for the job –if it enables you to hear a signal then it is working alright.

Cascading transformers

You can cascade two transformers to obtain a higher impedance transformation than you might find in a single transformer. However, the losses are about double that of a single transformer. You could consider more than two transformers but be aware that losses increase with the number of transformers. One approach that can work is shown in Figure 1.

Hz and the number of primary turns would be optimized for that.

In the case of an audio transformer we are interested in a range of frequencies –typically from around 100 Hz to 5 kHz for simple systems. The issue for audio transformers is that the optimum number of turns for 100 Hz is too many turns for 5 kHz. The design of an audio transformer involves a complicated trade-off between low-frequency response and high-frequency response. A crude rule-of-thumb is that the inductive reactance of the primary should be around three times the operating primary impedance at the lowest frequency of interest. Then the number of secondary turns is calculated from the desired impedance ratio and then increased a little to compensate for losses.

Can AC power transformers work as audio transformers?

It is hard to find audio transformers with the right impedance ratio for use in crystal radios. It is tempting to look for other types of transformers that might be suitable. One concept is to consider the use of an AC power transformer. Although an AC power transformer is not optimum for audio it has the potential to work to some extent if the turns ratio is in the right range. The turns ratio needs to be in the 30 to 60 range in order to transform a 16 ohm headphone impedance up to several tens of thousands of ohms. This can be achieved with a 120 VAC primary and a 2 –4 volt secondary. Another possibility is a 240 VAC primary and a 4 –8 volt secondary. Dual primary/secondary power transformers are common. You might find a transformer with a 120/240 VAC primary with a secondary voltage of 12 if connected in series or 6 if connected in parallel. Use the series connected primary and parallel connected secondary. This provides a nominal turns ratio of 40

impedance ground in the low tens of ohms. The impedance is even lower if the soil is very organic and wet from a recent rain. Dry sandy soils are the worst. One common error is connecting to a metal water pipe assuming that there are no plastic pipe lengths involved.

If a metal water pipe is not available then it might be tempting to connect to the ground system of the electrical distribution in the house or building. For safety considerations I do not recommend this. In the vast majority of cases it may be alright but you never
know what errors or faults may be in the system that could result in a nasty or lethal surprise. Even if safety were not an issue, because of inductance the impedance of the ground system at radio frequencies will be much higher than the impedance at 60 Hz. So,
this practice is dangerous at worst or is not likely to work well at best. There are basically only two choices for constructing your own ground. One is to purchase several standard eight foot ground rods and laboriously install them spaced six or more feet apart. This can make a decent ground but is very difficult (impossible is probably more accurate) without the right equipment for installation. An easier
alternative that is fine for RF (although not recommended for 60 Hz systems) is to bury a length of bare copper wire or pipe perhaps six to twelve inches below the surface of the ground. Deeper is better but the incremental improvement is probably not worth the extra labor. The total length should be fifty feet or more and parallel runs spaced several feet apart can be used to accumulate effective length. AM broadcast stations use such a system with many buried radial wires from the tower. Each wire is typically a quarter wavelength and the total wire length of all the radials is often over a mile. Such extreme measures are necessary for a high power transmitter because otherwise

many thousands of watts could be wasted. The much more modest system described is fine for home use and a point of diminishing returns is quickly reached.

Figure __ shows the theoretical radiation resistance for a single wire antenna that is shorter than one-half wavelength calculated under the assumption that there are no nearby objects that interfere with the impedance. For most situations the antenna is not very far above the ground and the actual resistance will likely be somewhat less than shown. But this is a reasonable model to use for analysis.

Figure __ shows the theoretical series capacitive reactance

How much signal can be received? With a variety of impedance transformations we can obtain most any voltage or current we want but what really matters is how much power we can receive. It is power that will make audible sounds in our earphones. Assuming that there are no losses and that the load consists of an inductor with the same magnitude of reactance as the antenna capacitive reactance in series with a resistive load equal to the radiation resistance of the antenna, then the power delivered to the resistive load is:

P = (V/m/2 * L)^2 /(40*pi^2*L^2*FMHz^2 /300^2)

= (V/m)^2 *57 / FMHz^2

An important transformer parameter for crystal radios is the impedance ratio which by definition is the impedance on the primary divided by the impedance on the secondary. Using the above relations for a lossless transformer we can write

$$\frac{Vp}{Ip} = \frac{Vs * N}{Is / N} \qquad \text{Eq. 2}$$

which simplifies to

Zp = Zs * N2 Eq. 3

Thus, the impedance ratio is

Zp / Zs = N2 Eq. 4

Design of transformers

Although the design of a transformer is beyond the scope of this book, it is useful to be aware of the issues so that one understands how to choose and apply a transformer. The design of a transformer consists of determining the required number of turns for the primary for a given size and characteristics of a magnetic core and for a particular low frequency. The turns of wire on the primary forms an inductor whose reactance at the low frequency of interest should be negligibly high but not too high. There is not a single solution so a range of designs are possible with various trade-offs. A transformer with too few turns on the primary will have high core losses and a transformer with too many turns on the primary will have high ohmic losses. There is an optimum number of turns for a particular application. In the case of power transformers the low frequency would either be 50 or 60

AUDIO TRANSFORMER

Review of transformers

As applied to audio systems a transformer is used to transfer a signal at one impedance to another impedance with minimal loss of power. As applied to crystal radios the purpose of the audio transformer is to transform the low impedance of the headphones (typically in the 8 to 30 ohm range) up to the high impedance (typically in the 10,000 to 50,000 ohm range) required for the load on the diode detector.
As a quick review of transformers, the turns ratio, N, is the number of turns on the primary, Np, (or input side) to the number of turns on the secondary, Ns, (or output side). Expressed as an equation,

$$N = Np / Ns \qquad \text{Eq. 1}$$

The ratio of the voltage applied to the primary to the voltage developed (under no load and assuming no losses) on the secondary is also the turns ratio.

As a simple example, a certain 120 VAC power transformer might have 3000 turns on the primary and 150 turns on the secondary. The turns ratio is 20. The secondary voltage would be 6 volts and the voltage ratio is also 20. A real transformer has losses and would be designed such that the loaded secondary voltage is 6. The unloaded voltage is typically ten to twenty percent higher in small transformers.

The current ratio is the reciprocal of the voltage or turns ratio. Thus, the secondary current is N times the primary current for a lossless transformer.

SIMPLE RADIOS

The purpose of this brief chapter is to introduce you to what can be done prior to your efforts to build a good crystal radio. The simple receiver circuits here let you test your antenna, ground, diode, and headphones. There is little if any selectivity and you may hear several stations at the same time. But, and this is the important thing, if you hear anything then you can make a radio. If you hear little or nothing then you need to investigate why. The most common problem is a poor ground system. If this radio does not work then even the best crystal radio will probably not work either.

Build the circuit in Figure 1. You may hear little at first until your ears acclimate to hearing faint sounds. The volume will never be loud unless you are very close to the broadcast antenna. The inspirational thing here is hearing anything –for if you do then you are experiencing the same thing the very first pioneers in radio experienced over one hundred years ago. You are reliving history! The capacitor is theoretically needed but there might be little difference without it –tray that. The headphones should represent an impedance of several thousand ohms –use a transformer to match common lowimpedance phones. If you are in a strong signal area then you might try using a speaker with the appropriate matching transformer to produce a primary impedance of several thousand ohms. In a quiet room you should be able to hear something. You might try the diode in the opposite direction. It really should not make any difference but sometimes there are surprises.

If you do not have the exact parts illustrated in Figure 1 then use whatever you have. The circuit is not critical and a wide variety of sub-optimal components will work to some extent. The key thing is to try something. It does not have to be perfect. You can always improve upon it later. Having something that works at all is an inspiration to persevere.

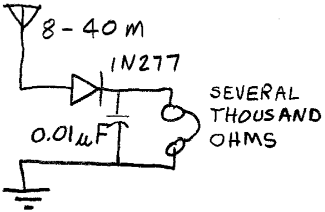


Figure 1: Simple Crystal Radio

The circuit in Figure 2 adds an inductor. The inductive reactance cancels part of the capacitive reactance of the antenna wire and enables a stronger signal to be received. Try whatever inductors you have in the 100 to 700 uH range. In theory the inductor could be variable and you could form resonance with a desired station. This would maximize the received signal strength. However, the overall operating Q of this is not going to be very high so selectivity will be poor. But it is a worthwhile experiment. This represents the beginnings of a good crystal radio and should build some excitement as to what ultimately can be achieved.

For best demodulation efficiency the diode (preferably germanium) should be connected to a high-impedance load and be driven from the highest RF voltage in the system.

References

1. Terman

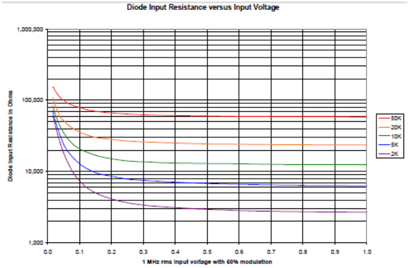


Figure 9

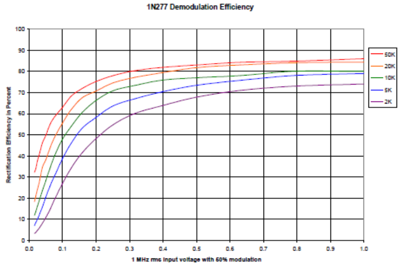


Figure 10: Diode Demodulation Efficiency

Conclusions

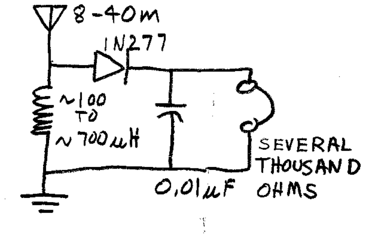


Figure 2: Improved Simple Crystal Radio

If you have made the circuits in Figures 1 and 2 work then you are on the road to success in building a real crystal radio. The next steps are optimal antenna impedance matching and a resonant circuit for tuning.

MATHEMATICAL MODEL OF A WIRE ANTENNA

Introduction

Although very simple in structure, the mathematical model of a wire antenna is extremely complicated. There are so many variables that it is basically impossible to accurately model. However, a reasonable model can be derived that provides useful information and understanding. That is essential for doing engineering. An imperfect model is far better than no model. We begin with the simplest possible model (that is always a good starting point!). Then, we refine the model to include more advanced concepts. We keep refining until we have accounted for all significant variables that provides useful information.

A wire antenna consists of some length of wire at some height over the earth. Such a structure will have some capacitance to the earth, some inductance, and some resistance. The resistance term is more complicated than just the simple ohmic resistance of the wire as it includes a series term known as radiation resistance. In very simple terms radiation resistance accounts for a flow of energy between the antenna and free space involving time-dependent electromagnetic fields not considered in a simple RLC circuit. Our initial model is based on frequencies much less than that where the antenna is one-quarter wavelength resonant. For typical crystal radio applications this is not a bad model as it is rare to have the luxury of enough space to construct an antenna approaching one-quarter wavelength in the AM broadcast band.

Capacitance

The diode can be modeled as ideal (i.e. zero voltage drop and resistance) in series with a resistance that is a function of the applied signal. The net demodulated signal is the result of voltage division between this resistance and the load resistance. This series resistance becomes high at low signal levels resulting in poor rectification efficiency.

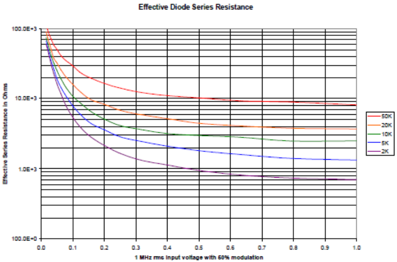


Figure 8: Effective diode series resistance versus applied signal

The effective input resistance to the rectifier circuit is the sum of the load resistance and the diode series resistance. (check factor of 2 for half-wave)

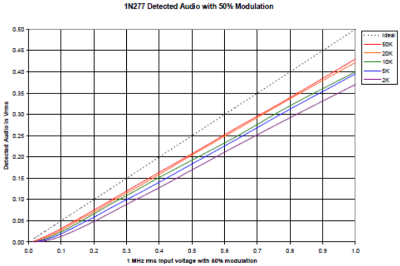


Figure 6: Demodulated audio signal amplitude versus applied voltage

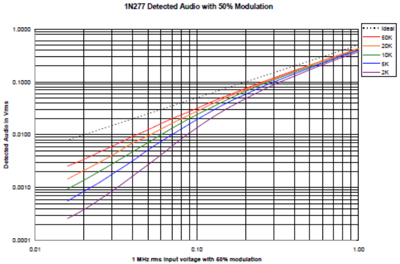


Figure 7: Demodulated audio signal amplitude versus applied voltage

We start with the capacitance of the antenna to the earth. From the basic laws of physics, a capacitance will exist between any two conductors separated by insulation. Here, we are making the rather crude assumption that the earth is a good conductor. That turns out not to be bad as we will see that the reactance of this capacitance at frequencies in the AM broadcast band is large compared to the actual resistance of the earth. A brief but excellent derivation of the capacitance between a cylinder (i.e. the antenna wire) and a plane is provided in Reference 1. The summary result is:

$$\text{Capacitance per meter} = \frac{2 * \pi * \varepsilon 0}{\ln(2 * \text{height} / \text{diameter})} \quad \text{Eq. 1}$$

where height and wire diameter are in meters and ε0 is the permittivity of free space, 8.85 pF/meter. Note that this equation assumes that propagation time over the wire length is negligibly small. This equation also assumes that the earth is a perfect conductor.

Although there is an error when considering the composite antenna, there is no error for an incremental portion that satisfies the assumptions.

A quick example indicates that a 20 meter antenna of #14 wire (1.63 mm dia.) at a height of 3 meters would have a total capacitance of 135 pF at frequencies low enough so that the propagation time over the length is negligibly small. That is not true for broadcast band frequencies and the capacitance will be smaller as will be seen in the plots at the end.

Inductance

On page 141 of Reference 1 the inductance of a wire over a plane is given as

$$\text{inductance per meter} = \frac{\mu 0}{2 * \pi} * \ln(2*\text{height} / \text{diameter}) \quad \text{Eq. 2}$$

where height and wire diameter are in meters and μ0 is the permeability of free space, 4*π*1E-07 henries/meter. Equation 2 simplifies to

inductance per meter = (0.2 uH) * ln(2*height / diameter) Eq. 3

A quick example indicates that a 20 meter antenna of #14 wire (1.63 mm dia.) at a height of 3 meters would have a total inductance of 33 uH if propagation time is negligibly small. Note that Equation 2 assumes that the current is uniform over the length of the wire and that propagation time is negligibly small. The first part of the assumption can not be true for our antenna as the far end is an open circuit. The equation also assumes that the earth is a perfect conductor. The typical error for our use in antennas for crystal radios falls into the category of not bad. We are not going to worry about it as this is just a starting point and we are going to make refinements. Although there is an error when considering the composite antenna, there is no error for an incremental portion that satisfies the assumptions.

Resistance

The resistance of a wire antenna is the sum of the ohmic resistance including skin effect and the radiation resistance. The resistance of #14 wire including skin effect at a frequency

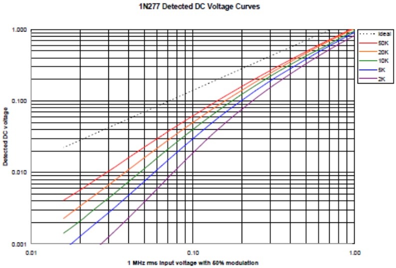


Figure 5: Family of curves showing detected DC voltage

Figure 6 shows a family of curves of the demodulated signal versus the applied voltage for the resistance loads given. The detection of a theoretically ideal diode is shown for reference. Figure 7 shows the same data plotted on logarithmic scales.

Figure 4 shows the detected DC voltage versus the applied signal for the load resistances shown. The transfer curve of a theoretical ideal diode is shown for reference. Note that the higher load resistances result in a higher detected voltage. This is especially true at very low applied voltages. Figure 5 is the same data plotted using logarithmic scales which expands the view at very low signal voltages.

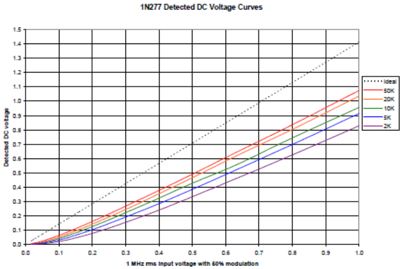


Figure 4: Family of curves showing detected DC voltage

of 1 MHz is around 0.05 ohms per meter. Thus a 20 meter antenna would have a total resistance of 1 ohm. This assumes that the current is uniform over the length which can not really be true since the far end is an open circuit. However, this is not going to be an issue for us as the resistance of the ground will be significantly larger.

The ohmic resistance represents a power loss. Radiation resistance becomes a factor when we consider the coupling of energy between the antenna and electromagnetic fields of free space. The concept is easy to understand in the case of a transmitter which delivers power to the antenna (perhaps significant power in the case of a 50 kW transmitter!) but with efficient design the heating of the antenna is very small –i.e. the power is radiated as an electromagnetic wave instead of being converted to heat –i.e. power is coupled to free space. The transmitter delivers the power to the antenna as some voltage and some in-phase current. Thus, the antenna appears to have a resistance. That resistance is known as the radiation resistance. Unlike ohmic resistance, it does not represent a power loss –it represents a power coupling to free space instead. There is no magic or optimum value for antenna impedance. However, values between single digit ohms and several hundred ohms are the easiest to interface to and so are preferred.

It is not as easy to visualize radiation resistance when the antenna is used for reception. However, the concept of reciprocity applies. Thus, however an antenna appears in the transmitting case, it appears identically in the receiving case. The calculation of radiation resistance is very complicated at the easiest. At this point in our model development we have no way to determine what the radiation resistance of our antenna might be. However, the incremental capacitance and inductance are essential for the next level model.

A finite propagation time model

This model is based on well-developed transmission line theory and treats the wire antenna as a lossy unterminated transmission line where the loss is electromagnetic radiation instead of heat. This model builds on the previous equations for capacitance and inductance and gives us a realistic picture of what goes on. In general, because there are a lot of variables that we are unable to quantify the accuracy of this model is not great. However, the model can be tweaked to provide a good fit to a specific scenario. That is what makes the model useful. It is great at providing us general information for understanding. Understanding what is going on can be more valuable than knowing specific data accurately.

The impedance looking into a transmission line is

$$Z = Z0 * \frac{(ZT/Z0) + \tanh(\alpha + j\theta)}{1 + (ZT/Z0) * \tanh(\alpha + j\theta)} \qquad \text{Eq. 4}$$

where:
Z is in ohms and is in general complex
Z0 is the characteristic impedance of the line –often taken as real but could be complex
ZT is the termination impedance at the end of the line and could be complex
α is the loss over the length of the line
$\theta$is the phase angle on the line and is equal to $2*\pi*$length/wavelength
j is the square root of -1

Plot of input impedance to diode as function of signal amplitude and load resistance. The typical signal applied to the diode in a crystal radio ranges from less than one millivolt for a very weak signal to perhaps several hundred millivolts for a very strong signal. In special cases with a nearby (less than about 10 km) station the signal might be over one volt. Our primary interest is the diode response to small signals in the ten to one hundred millivolt range.

A test circuit was constructed as shown in Figure 3 to measure the characteristics of a 1N277 diode at very low signal voltages. The RF signal generator makes a 1 MHz signal with 50 percent amplitude modulation of a 1 kHz sine wave. The RF signal generator has a 50 ohm output impedance and a terminated 50 ohm attenuator was used to make the small signals. This results in a 25 ohm source impedance to the diode which is negligibly small. Load resistances of 2K, 5K, 10K, 20K, and 50K were used and the filter capacitor was 10, 3.9, 2.2, 1.0, and 0.47 nF respectively to provide a low-impedance path for RF without excessive filtering of the demodulated audio. The nominal time constant of the filter is 20 microseconds which results in an audio cutoff frequency of 8 kHz. The 100K resistors in series with the DC voltmeter and AC voltmeter served the purpose of reducing any signal pickup from the connecting cables in an effort to reduce errors.

Figure 3: Test setup

For each load resistance, the attenuator was switched in 2 dB steps from 0 down to -36 dB and the DC voltage and AC signal voltage was measured. This data was used to make the following plots.

There are myths that full-wave rectification is superior to half-wave and delivers twice the audio signal. In practice that is hard to achieve because diode losses become more significant. Full-wave rectification roughly halves the load impedance seen by the resonant circuit. That in turn lowers the operating Q by roughly half which means that roughly half the voltage is developed. The process just described tends to negate any apparent advantage of full-wave rectification. The scenario for full-wave detectors to work their best is for the load impedance to be very high such that the net load on the resonant circuit is optimum for maximum power transfer. However, the losses using two diodes will always be higher than for one. My advice is to stick with half-wave and try a variety of diodes in a search for one that delivers the most audio signal.

*** Note: the following is very rough –more to come soon –a lot of material is missing at the moment ***

A simple capacitor filter is used on the

It is important that the DC load on the diode be as nearly identical to the AC load as possible. Any difference in loading can cause signal loss and distortion. Show diode plots. show conductance plots. show efficiency calculations. Use actual diodes.

We can model the diode detector as an ideal diode (i.e. zero series resistance and no voltage drop when forward biased) in series with a resistance as shown in Figure _. The diode does not have a “threshold” voltage –it is just that at low signal amplitudes the effective series resistance is very high which causes a high voltage division factor. The following figures illustrate several common diode detectors.

The form of the equation I have chosen to use includes length in the α and θ terms as a matter of convenience. Other forms of the equation have the length as a multiplier on the inside of the tanh term.

If the terminating impedance is an open circuit as it will be for our wire antenna then we can write Equation 4 simply as

$$Z = Z0 / [\tanh(\alpha + j\theta)] \qquad \text{Eq. 5}$$

For reference:

$$\tanh(x) = \frac{e^{x} - e^{-x}}{e^{x} + e^{-x}} \qquad \text{Eq. 6}$$

The Euler relations are:

$$e^{j\theta} = \cos(\theta) + j*\sin(\theta) \qquad \text{Eq. 7}$$

$$e^{-j\theta} = \cos(\theta) - j*\sin(\theta) \qquad \text{Eq. 8}$$

These relations let us write Equation 5 as

$$Z = Z0 * \frac{e^{\alpha+j\theta} + e^{-\alpha-j\theta}}{e^{\alpha+j\theta} - e^{-\alpha-j\theta}}$$

$$= Z0 * \frac{e^{\alpha} * [\cos(\theta) + j*\sin(\theta)] + e^{-\alpha} * [\cos(\theta) - j*\sin(\theta)]}{e^{\alpha} * [\cos(\theta) + j*\sin(\theta)] - e^{-\alpha} * [\cos(\theta) - j*\sin(\theta)]}$$

$$= Z0 * \frac{(e\alpha + e\text{-}\alpha)*\cos(\theta) + j*(e\alpha - e\text{-}\alpha)*\sin(\theta)}{(e\alpha - e\text{-}\alpha)*\cos(\theta) - j*(e\alpha + e\text{-}\alpha)*\sin(\theta)} \qquad \text{Eq. 9}$$

Although Equation 9 looks complicated it really consists of just three components and it is simple to substitute values and reduce it to a simple real plus imaginary result.

For reference: Eq. 10

$$\frac{A + jB}{C + jD} = \frac{A + jB}{C + jD} * \frac{C - jD}{C - jD} = \frac{AC + BD}{C2 + D2} + j\frac{BC - AD}{C2 + D2}$$

Equation 10 gives us a basic method to evaluate the division of complex numbers.

When the series and shunt losses are low the characteristic impedance of a transmission line is

Z0 = sqrt(inductance per unit length / capacitance per unit length)   Eq. 11

We substitute Equations 1 and 2 into Equation 11 to obtain

$$Z0 = \text{sqrt}\left[\frac{\dfrac{\mu 0}{2 * \pi} * \ln(2*\text{height} / \text{diameter})}{\dfrac{2*\pi*\varepsilon 0}{\ln(2*\text{height} / \text{diameter})}}\right] \qquad \text{Eq. 12}$$

which simplifies to

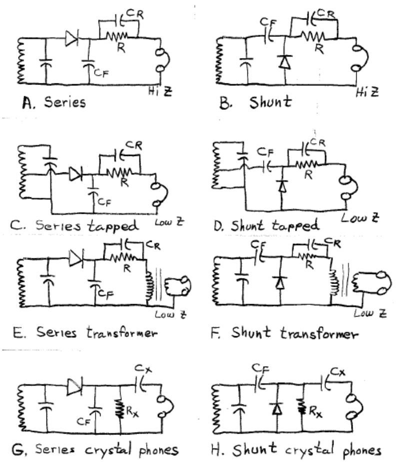


Figure 2: Various diode detectors

The detector places a load resistance on the resonant circuit it is connected to. For very large signals the load resistance is roughly twice the impedance of the headphones as conduction only occurs for one half cycle. The load impedance for very small signals is higher because of diode losses.

the coil. The purpose of capacitor, CR, is to form an AC bypass around R so that there is no signal attenuation. CR is of such value to form a time constant of about 1 to 3 milliseconds with R.

The purpose of capacitor, CF, is to filter the RF signal without affecting the audio. CF is of such value to form a time constant of about 10 to 30 microseconds with the load impedance – either the magnetic headphones or the transformer primary. When low-impedance headphones are used then the resonator coil must be tapped appropriately so that there is a proper match of impedance.

When crystal headphones are used there needs to be some large resistance, RX, (typically in the fifty to several hundred thousand ohms) across the detector output for a DC load and a coupling capacitor, CX, to block any DC voltage from being across the crystal headphones. The value of CX should be large enough to pass low audio frequencies. The value needed will depend on the headphone characteristics but values in the 10 to 100 nF range are typical.

$Z0 = 60.0 * \ln(2*height / diameter)$ Eq. 13

Thus, we make use of our previous work on the simple model.

The free-space wavelength in meters for a given frequency in MHz is

$\lambda = 300 / FMHz$ Eq. 14

The propagation velocity on wire antennas is about 95 percent of free space so we use

$\lambda = 285 / FMHz$ Eq. 15

$\theta = 2*\pi*FMHz*length / 285$ Eq. 16

So far this has not been too complicated. Now, we delve into the challenge of determining the remaining constant, α. This factor, which is a function of frequency, will determine the antenna impedance characteristics. There is no way to calculate this factor. Instead, we will use available information to fit an approximate equation to it. We begin by noting that the free space impedance of a half-wave dipole antenna is 73 ohms. Our wire antenna is only half of a dipole so the free space impedance will be nominally 37 ohms (rounded half of 73) at a frequency where the wire length is an electrical one-quarter wavelength.

However, our antenna is very close to the ground so the result must be modified. Reference 2 shows a theoretical plot of the impedance of a half-wave dipole over a perfectly conducting plane as a function of height. This plot is reproduced below.

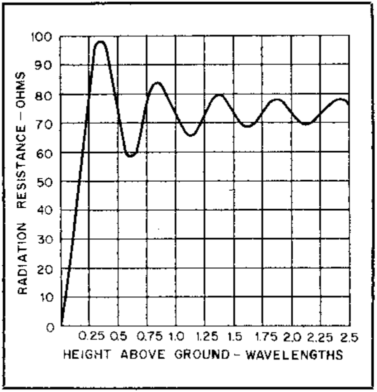


Figure 1: Theoretical impedance of half-wave dipole over perfect ground plane

Reference 2 describes that the impedance of a half-wave dipole over a realistic ground is very little affected by height over about one-half wavelength and the impedance soon attains the 73 ohm free space value.

We will use a simplified exponential to provide us with an approximate impedance of our antenna at the one-quarter wave resonant frequency. We first need a relation that converts the physical height of our antenna to height in wavelengths at the

There are two fundamental types of rectifier circuits, series and shunt. Series is probably the most common but shunt can work well too. I recommend that you try both. Whether series or shunt, the most common circuit is half-wave using only a single diode. Neither of these two types of rectifier circuits is superior to the other. But there are various esoteric viewpoints that drive different people to one or the other configurations. My advice is to use the one you like.

It is desirable to perform the rectification process at the highest voltage possible in the radio. This voltage is the entire voltage across the resonant circuit. One problem with this is that the headphone impedance may be low which will result in the tuned circuit being overloaded –thus low signal and poor selectivity. There are two solutions. One is to connect the diode to an appropriate lower impedance tap on the inductor. The other is to use a transformer to magnify the headphone impedance. Each method can work but the second method is the better option if the right transformer is available. Otherwise the first option is better. Small signal audio transformers tend to be very lossy. It is not uncommon to lose 30 to 50 percent of the audio power. If you use a transformer, consider a larger one physically so that losses will be in the 10 percent range.

Figure 2 shows various diode detectors. Many of the circuits show a series resistor, R, with a shunt capacitor labeled CR. The purpose of this network is to make the AC and DC loads as similar as practical. Differences in these loads cause distortion and even weak detection in some cases. This network is often omitted and the results may be satisfactory but the best results will be obtained with the network. See Reference 1 for a detailed discussion. The resistor, R, is roughly equal to the midband impedance of the magnetic headphones or transformer primary minus the DC resistance of it is possible to see the reverse resistance of that diode which is about 100 k. The reverse current for the other diodes does not show up on the scale. Note that the forward current of the silicon diode barely shows up on the scale. The silicon 1N4148 diode barely shows any forward conductivity at these low forward voltages. This graph clearly shows why silicon diodes do not work well in crystal radios. The transfer curve of a popular microwave diode is also shown. The diode has significantly better forward conduction than silicon but is not as good as germanium.

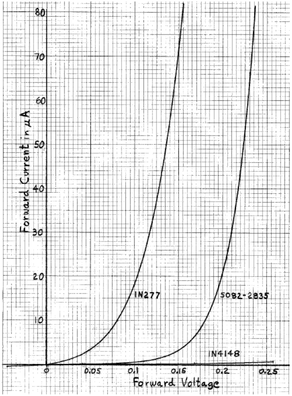


Figure 1: Diode Curves

quarter-wave resonant frequency. This is provided by the following relation.

h/λ= height / wavelength = height * FMHz / 300   Eq. 17

$R = 37 * (1 - e^{-k1*h/\lambda})$ Eq. 18

The k1 value is chosen to be 7 because that provides the best least squares fit over the first 0.2 wavelengths of height. We can write this as

$R = 37 * (1 - e^{-0.02333*height*FMHz})$ Eq. 19

Equation 19 provides us with a target to set the appropriate value for α. At the frequency where the line length is one-quarter wave resonant, the cosine term in Equation 9 goes to zero and the sine term goes to one. This produces a real result with the imaginary part zero. It should be noted for this case that:

$A = 0$

$B = e^{\alpha} - e^{-\alpha}$

$C = 0$

$D = 2$

Using Equation 10 the above results in a resistance of

$R = Z0 * (e^{\alpha} - e^{-\alpha}) / 2 = Z0 * \sinh(\alpha)$ Eq. 20

We invert Equation 20 to obtain the required value for a for a given value of R as follows

$\alpha = \sinh^{-1}(R/Z_0) = \ln[(R/Z_0) + \mathrm{sqrt}[(R/Z_0)^2 + 1)]]$ Eq. 21

Before continuing, let us review where we are at. We know Z0 from the height and diameter of the antenna wire. We know a target resistance, R, for the antenna impedance at the one-quarter wave resonant frequency based on the height. Equation 21 lets us calculate αfor that frequency. We need to expand this so that we can calculate the appropriate αfor any frequency.

We make use of the following general knowledge about wire antennas to complete our model. At frequencies well below the one-quarter wave resonance the resistive component of the antenna impedance is practically zero. At frequencies where the antenna is many quarter wavelengths long the resistive component of the antenna impedance converges to Z0. This suggests that we have a basic scale factor on αand a multiplier based on the number of quarter wavelengths are on the line. This leads us to Eq. 22

$\alpha = k_0 * Z_0 * 37 * (1 - e^{-0.02333*height*FMHz}) * (F / Fq)$
where:

k0 is a constant to achieve the target quarter-wave resonant impedance
Z0 is the characteristic impedance of the antenna
height is in meters
F is the frequency in MHz

Fq = (71.25 / length) and is the frequency in MHz where the antenna is one-quarter wave resonant

happier and satisfied with the performance. After you have a working crystal radio you can experiment with ancient methods –always begin with a working circuit before trying something different or challenging.

Commercial diodes that can be used for crystal radios include the germanium diodes 1N34 and 1N277 (note: the 1N277 has in most cases replaced the old 1N34), silicon diodes such as the 1N914 and 1N4148, and a variety of microwave diodes with the Avago (formerly Agilent and formerly HP) 5082-2835 being a popular choice. Until the advent of microwave diodes the germanium diodes were and still are very popular because they work so well for crystal radios. Microwave diodes were never intended for use in crystal radios but they have significantly better conduction that silicon although they are not as good as germanium. However, germanium diodes are sometimes hard to find and microwave diodes are relatively easy to find. Some microwave diodes have a noticeable reverse conductivity which detracts from their performance but overall many microwave diodes can do an excellent job. I would definitely try several of them. Silicon diodes are a poor choice for crystal radios because they have very low conductivity at very low currents –i.e. they are very lossy. But, if you are in a strong signal area and do not have better diodes, then silicon is much better than nothing and you can make a working crystal radio. But, you will want to upgrade to a diode better for the purpose as soon as you can. If you are driving very high impedance headphones such as the crystal type then you may find that silicon is not too bad. Figure 1 shows the current versus voltage curves for several common diodes. These plots were made using an XY recorder.

Note that the germanium diode shows significantly better forward conductance than the other diodes. On the scale shown

DIODE DETECTORS

A diode is a non-linear device that conducts electrical current significantly better in what is referred to as the forward direction than in the reverse direction. This process can convert an AC signal to a DC signal through a process known as rectification. If the amplitude of a high-frequency AC signal is varying in response to a low-frequency amplitude modulation (such as audio) then rectification will result in a varying DC signal with the modulation superimposed. The original audio signal is recovered by discarding the DC term.

Although the term, threshold, is often used in discussions about diodes in regards to some minimum signal no actual threshold exists. The forward resistance of the diode generally has a reciprocal relation to the forward current –i.e. the diode conducts better as the forward current increases. The poor conductivity of diodes at very low currents gives rise to the "threshold" discussion. A diode ideally has no conductivity in the reverse direction although all diodes will exhibit some reverse conductivity and a number of excellent microwave diodes have significant reverse conductivity as a consequence of their internal structure. Reverse conductivity works against us but what is more generally important is the ratio of forward to reverse conductivity –the higher the better.

Diodes in the early days of radio were homemade and typically consisted of the junction of some metal such as a stiff wire against a non-metallic conductor. Considerable effort was required to locate a "sweet spot" that had good diode qualities. Some purists still insist on this method today and that is fine but I highly recommend that you purchase a manufactured diode (such as a 1N277) made for the intended purpose. You will be much

The only unknown in Equation 22 is k0. We calculate k0 when F is equal to Fq. The procedure is as follows:

First we set FMHz = Fq from the above relation

R = 37 * (1 –e-0.02333*height*FMHz) (Eq. 19)

Z0 = 60.0 * ln(2*height / diameter) (Eq. 13)

α= sinh-1(R/Z0) = ln[(R/Z0) + sqrt[(R/Z0)2 + 1)]] (Eq. 21)

k0 = α/ (Z0 * R) Eq. 23

Studies done with this equation indicated very good results as long as the frequency was greater than the quarter-wave resonance. For lower frequencies this model gave very poor results –indicating significantly higher impedance than reality and even a negative slope in some cases. A modifier to the model was needed to highly attenuate αfor low frequencies only. The factor, (1 –1/(1 + 0.14*(F/Fq)2+ 1.0*(F/Fq)3 + 0.79*(F/Fq)4 + 50*(F/Fq)24)), was determined to significantly improve results. The factors were derived from a least squares fit to an alternative equation for short dipoles provided by reference 3 –shown below modified for only half a dipole.

R = 40*π2*(L/λ)2 Eq. 24

where L is the antenna length and λ is the wavelength, both in meters. This equation is reported to give good results up to about 0.2 wavelengths. A plot showing the fitted model to Equation 24 is shown below. Note that the model has an excellent fit to the theoretical "correct" model for wavelengths shorter than 0.2. The "correct" model under predicts the resistance for longer wavelengths and the effect of the 24th power term comes into play to bring the resistance close to the theoretical 37 ohms at 0.25 wavelengths. This is not exactly what goes on but is a simple to work with fit.

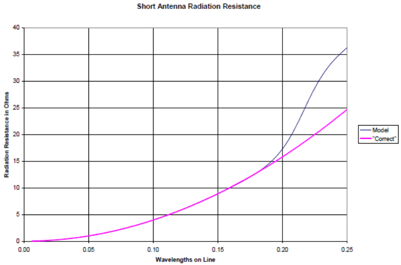


Figure 2: Model fit to short antenna radiation resistance

The complete equation for α is (using n = F/Fq) is shown below. Eq. 25

$$\alpha = k0*Z0*37*(1 - e-0.02333*height*F)*n*\left(1 - \frac{1}{1 + 0.14*n2 + 1.0*n3 + 0.79*n4 + 50*n24}\right)$$

To calculate the approximate impedance of the antenna for any frequency we first compute the αfactor for the frequency using Equation 25. Then we compute the positive and negative exponentials using α. Next, we compute theta using Equation

TAPPING INDUCTORS

This note is very short for now –more of a placeholder. There are two taps needed for the coil that makes up the resonant circuit. One tap is to provide a low impedance connection to the antenna/ground circuit and the other tap is for impedance matching to the diode detector. Both taps need to be variable as impedance characteristics vary across the AM broadcast band. A good method of tapping is to use a rotary switch to select the appropriate tap. A six position switch –one for the antenna circuit and another for the detector can provide adjustable optimums for a variety of situations. Calculations are not generally possible for determining where to place the taps so measurements with laboratory equipment are the only practical method. When this article continues, the author will present data on a typical coil for a crystal radio …

loose end length inside the tube so it is out of the way while winding.

It is best to wind the coil by hand as the set up for using a lathe is not worth the trouble for a single coil. There are a number of “poor man’s” lathes such as a power drill that have been used but I do not recommend that as you are more likely to make a mess or cause injury than you are to wind a coil. It only takes a couple of minutes to wind a coil by hand so take the time to think what you are doing. It is important to keep the winding tight at all times. The wire will spring off if it ever gets loose. You will very likely have some fractional turn as a result of your calculations. I recommend that you round that to the nearest integer as it is not worth the trouble of making measurements to stop at a specific fractional turn.

References:

1. Electronic and Radio Engineering, fourth edition, Frederick Emmons Terman,
McGraw-Hill Book Company, 1955, pages 30 – 33.

2. The Radio Amateur’s Handbook, 44th edition, 1967, The American Radio
Relay League, Newington, Conn., page 26

16 and then the cosine and sine terms. We substitute these values into Equation 9 and use Equation 10 to solve. This is best done in a spread sheet for a range of frequencies and the results plotted. A wide range plot showing multiple quarter-wave resonances for a wire antenna is shown in Figure 3.

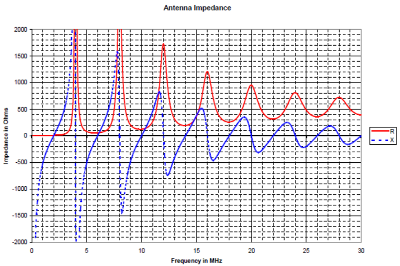


Figure 3: 2 MHz resonate antenna 5 meters off ground

The computed impedance at 2 MHz of this antenna is 7.5 ohms. The impedance at the third harmonic (6 MHz) is 55 ohms –for both resonant frequencies the reactive part is zero. It should be observed that the impedance is at a minimum and purely resistive at odd harmonics of the quarter-wave resonance. The impedance is very high at even harmonics. This figure should be viewed as illustrative rather than accurate. Although the pattern of impedance variations is true, the magnitude could vary considerably depending on actual ground conditions and the proximity of other structures. It is true that the impedance variations become smoother as the number of quarter-waves increases. Only a minimal attempt has been made to correctly model that for this model

as the primary interest is in the sub quarter-wave region. More work will be done on the high frequency region at a later date. It is expected that the required effect can be obtained by the appropriate exponent on the n term that immediately follows the exponential in Eq. 25 –but some kind of short power series might be required instead. Example Antennas

The following plots show the typical impedance for several wire antennas. In each case #14 AWG wire was used and the solid line is the radiation resistance and the dotted line is the reactance. In all cases the radiation resistance is very low. The key feature is the
capacitive reactance of the antenna.

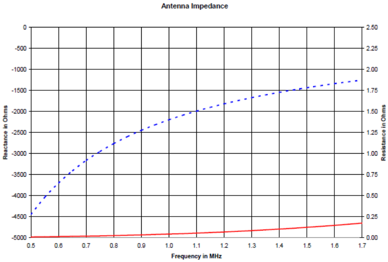


Figure 4: Antenna length = 10 m, height = 3 m

is another material you might consider. None of these materials are made with any consideration about high frequency dielectric losses but because only a small amount of material is used the losses are probably minimal.

Wood is a convenient coil form and has low losses if very dry. Common sizes that have been used are 2x2, 4x4, or a pair of 2x4 combined to make 4x4. Round dowel rods may also be used but their diameters are often much less than optimum. When using a square coil form there is a logical question about how that affects the inductance calculations. A simplistic (but good) answer is to use an effective circle diameter that has the same area as the square form since area is a strong factor in inductance. Losses with a square form will be somewhat higher than for a circular form. Rectangular forms (such as a single 2x4) have even higher losses in comparison –it takes more wire to encompass a given area.

Winding the coil
Counting turns is a tedious and error prone task. It is much simpler to cut the length of wire needed and then wind that until finished. The resulting turns count will be very close if not exact. Wire is springy and will jump off the form in a tangled mess if not restrained. Start by securing the wire at one end of the form and have a means for easily (preferably with one hand) securing the opposite end when you finish. It is tempting to use some kind of adhesive tape and that will work if you are careful and understand what you are doing. The forces will build and the tape may give way which will result in a frustrating mess of tangled wire. Make sure the tape can not slip. A good way to secure the ends is to first drill a hole in the tube at the starting and end points. Then feed the starting end through the starting hole and bend the wire such that it naturally resists tension and secure the wire with tape. Stuff the

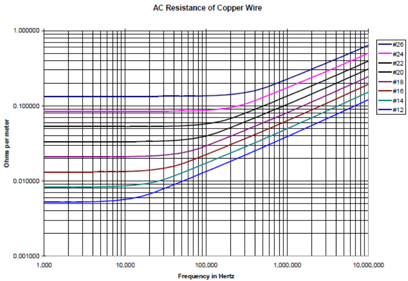


Figure 3: AC Resistance of Copper Wire

Coil Forms

From a loss standpoint air is the best coil form material there is. The obvious problem is that air has no structural strength. However, there are methods used by commercial inductor companies that employ a minimal structure so that the coil form is around 99 percent air. Manually, you can achieve the effect by first winding the coil using large diameter solid copper wire (i.e. #18, #16, #14, etc.) on a rigid coil form and then carefully sliding the winding off of the form. The stiff wire will retain the shape and you can easily space the turns to the optimal discussed previously. You will need a few supports to keep the whole thing from being too loose.

A popular coil form is some kind of cardboard tube that you have salvaged from a variety of sources such as used for paper towels or shipping tubes. These are great if you are using small diameter wire as small wire will not self support. Plastic pipe

This is about as short as an antenna can be and still be practical. This antenna appears as 73 pF.

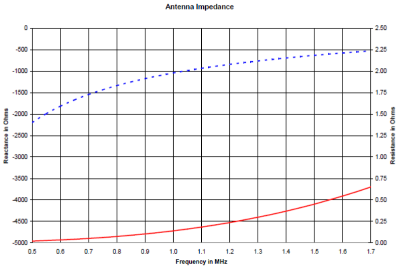


Figure 5: Antenna length = 20 m, height = 3 m

This antenna appears as 145 pF at low frequencies and 184 pF at high frequencies. The change in capacitance with frequency is because the reactance of the series inductance cancels part of the capacitive reactance.

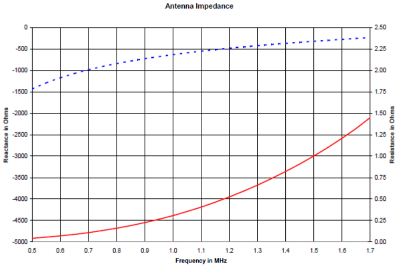
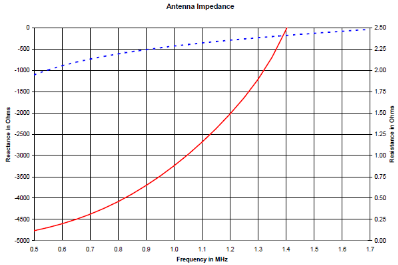


Figure 6: Antenna length = 30 m, height = 3 m

This antenna appears as 220 pF at low frequencies and 375 pF at high frequencies.



or the other may have physical advantages for your particular construction method. Avoid wires that are plated as those will have higher losses since skin-effect will cause most of the conduction to be in the plating which has higher resistance than copper. Avoid wires with rubber or cheap plastic insulations as dielectric losses will be higher. An exception is silver plated Teflon wire as that has the best conductivity and the lowest dielectric losses –but it is expensive.

For use in low to medium frequency inductors there is a special wire called Litzengrad or just Litz for short. It is designed to minimize skin-effect losses and is made by assembling many strands of enamel insulated magnet wire together to form a wire that has a large surface area. Litz wire is not easy to find and tends to be expensive. If you are going to use Litz wire then make sure that other losses as previously discussed are minimized. Otherwise Litz wire will make little if any difference and will be wasted effort and expense. Avoid belief in a variety of myths about skin-effect. Although it is true that skin-effect is more severe on large diameter conductors, a larger diameter still conducts better than a smaller diameter at any frequency. This can be seen in Figure 3 which shows the frequency dependence of the resistance per meter factor of some common wire sizes.

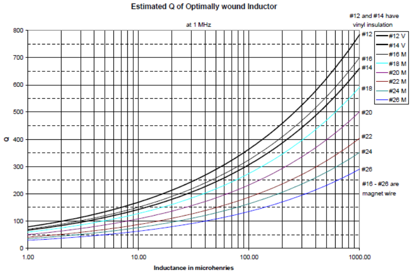


Figure 2: Estimated Q of Inductor

The Q we obtain from Equation 11 is for the unloaded coil (i.e. antenna and crystal detector not connected). The net loaded Q will typically be significantly smaller but ideally (as discussed in another chapter) would be in the general range of one hundred. Thus, we would like to start with an unloaded Q of several hundred. As can be seen in Figure 2 the Q of the inductor can be made higher by using larger diameter wire. From Figure 1 this also means using a large diameter coil form. This is a very important conclusion –high Q coils need to be physically large.

Type of wire

The only material to consider for the wire is copper. A variety of styles of copper wire is readily available. The most basic choice is between solid or stranded. Although a variety of arguments can be made for and against each, in practical terms you will not notice any difference in performance although one

Figure 7: Antenna length = 40 m, height = 5 m

This antenna appears as 290 pF at low frequencies and is almost resonant at 1.7 MHz. This is about as long as an antenna needs to be for excellent reception. Note also that the antenna is higher. The increase in radiation resistance at higher frequencies is an indication that quarter wave resonance is being approached.

References:

1. Theory and Problems in Electromagnetics, Schaum's Outline Series, Joseph A.
Edminister, McGraw-Hill Book Company, 1979, pages 92-93, 141.

2. The ARRL Antenna Book, edited by Gerald L. Hall, The American Radio Relay
League, Inc. Newington, CT, 1984, Fourteenth edition, page 2-20.

3. Antennas and Transmission Lines, John A. Kuecken, MFJ Enterprises, Inc., 1996,
First edition, page 64.

RESONANT CIRCUIT

The resonant circuit plays a very important role in a radio receiver. Its primary purpose is to be a tunable narrow band-pass filter for selecting a desired station while rejecting undesired stations. An important secondary purpose is to be a means for transforming the low impedance antenna up to the high impedance detector.

A resonant circuit is comprised of an inductor and a capacitor, one or both of which may be variable. Energy flows back and forth between the inductor and capacitor at the resonant frequency. Energy in the inductor is stored in a magnetic field and energy in the capacitor is stored in an electric field. If there were no losses, this cyclic process could continue forever. In reality there is some loss each time the energy moves. This loss is expressed as a resistance. A common term used to account for this loss is Q which is the inverse of the loss. Thus, a high-Q resonance has very low loss and the cyclic process can continue for many cycles. A common example is a bell which continues to ring long after being hit.

Figure 1 shows the frequency response of a resonant circuit at 1 MHz for a range of Q.

XL is the inductive reactance in ohms at the frequency of interest
Rs is the equivalent series resistance in ohms at the frequency of interest

Note that inductive reactance, XL, is calculated as

$$XL = 2*\pi*F*L$$

where
F is the frequency in Hz
L is the inductance in henries

The equivalent series resistance is the net of ohmic losses including skin effect, dielectric losses in distributed capacitance and coil structure, absorption losses by nearby conducting media, magnetic losses in nearby magnetic media, etc. With care these losses can be kept small but it takes very little loss to reduce the Q of an inductor from 400 to 200. The magnitude of Rs can be measured on sophisticated impedance equipment but it is hard to calculate the effect of all factors. Figure 2 shows an estimated value of Q at 1 MHz considering typical losses assuming the coil is wound optimally and is not disturbed by nearby lossy materials. Use the figure only as a guideline as your specific results may be better or worse. The expected Q at 540 kHz will be between about 50 to 70 percent of what is shown and the expected Q at 1.6 MHz will be around 1.2 to 1.5 times that shown.

Gauge	diameter
#12	7.75”
#14	6.75”
#16	3.75”
#18	3.15”
#20	2.65”

A piece of 4.5” OD PVC pipe is available and #14 electrical wire is available. From Table 1, #14 insulated wire will make about 7.7 turns per inch. Thus, the effective diameter is 4.5 plus 1/7.7 = 4.63 inches. Using Equation 11 the number of turns required is 86. Using Equation 8 the length of the winding is 11.2 inches. The length/diameter ratio is 2.4 which is a bit longer than the optimum of 0.96. The length of wire required is given by Equation 12 and is 1,251 inches. The length would have been 1,058 inches if the optimal diameter could have been used. This extra length will cause somewhat higher losses –it might still meet the desired spec though. This is about as far as I would go in rounding to an available coil form diameter.

Estimation of Inductor Q

All inductors have an equivalent series resistance loss as discussed earlier and is comprised of a number of components. We measure the quality factor or Q of the inductor by computing the ratio of inductive reactance at the frequency of interest to the series loss resistance as follows:

$$Q = \frac{XL}{Rs} \qquad \text{Eq. 13}$$

where

Q is the dimensionless “quality” factor of the inductor

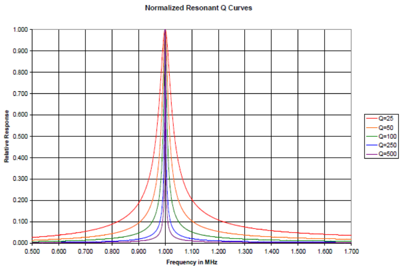


Figure 1: Normalized resonance curves at 1 MHz

Figure 2 shows a zoomed in version of Figure 1.

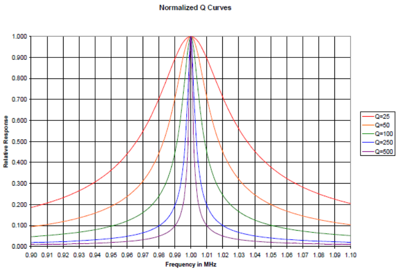


Figure 2: Normalized resonance curves at 1 MHz

Note that the Q=100 curve has a band-pass of 10 kHz which is about the minimum that can be used to recover the entire double-sideband signal.

Tuning capacitor

Generally, when the capacitor is variable, the inductor is fixed and visa-versa. Mechanical variable capacitors (often 10 –365 pF or similar) were very popular in older times but are more difficult to find in modern times. A modern substitute can be made using one or more rotary switches as will be illustrated later.

The well know equation for the resonant frequency of an inductor and capacitor is

$$F = \frac{1}{2 * \pi * \text{sqrt}(L * C)} \qquad \text{Eq. 1}$$

where
F = resonant frequency in Hz
L = inductance in henries
C = capacitance in farads

For a given inductance the required value of capacitance can be determined from

$$C = \frac{1}{(2 * \pi * F)2 * L} \qquad \text{Eq. 2}$$

$$l = n/t \qquad \text{Eq. 8}$$

We now substitute Equation 8 into Equation 2 and solve for n

$$d2*n2 - 18*d*L - 40*(n/t)*L = 0 \qquad \text{Eq. 9}$$

$$t*d2*n2 - 40*L*n - 18*d*t*L = 0 \qquad \text{Eq. 10}$$

Solving for n gives:

$$n = \frac{20*L + \text{sqrt}(400*L2 + 18*t2*d3*L)}{t*d2} \qquad \text{Eq. 11}$$

Although a precise value (in inches) for the length of wire required can be calculated using trigonometry for a spiral, a very close value can be calculated as

$$w = pi*d*n \qquad \text{Eq. 12}$$

Remember that d is the sum of the coil form diameter and the diameter of the wire. This approximation assumes that the diameter of the wire is very small in comparison to that of the coil form. Also remember to allow an extra couple of inches for connecting leads at each end of the coil.

Example: A 300 uH coil is needed. The expected Q should be over 350. What coil diameters and wire sizes could possibly meet this?
Solution: Using Figure 2 it can be seen that wire sizes #12, #14, #16, #18, and #20 could achieve the required Q. Using Figure 1 the required coil form diameters are:

Optimum

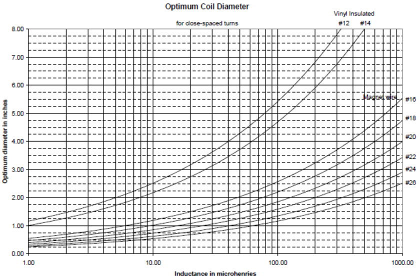


Figure 1: Optimum coil diameter

The following table provides typical values for t (turns per inch) for some common wire sizes:

Table 1: Wire data

Gauge	t	Comments
12	6.2	Vinyl insulated house wire
14	7.7	Vinyl insulated house wire
16	19	Enamel insulated magnet wire
18	24	ditto
20	31	ditto
22	39	ditto
24	50	ditto
26	62	ditto

The length of the winding will be the number of turns divided by the turns per inch of the wire. That is:

The required tuning range, Cmax / Cmin, of a variable capacitor can be determined using Equation 2 as follows

$$\frac{Cmax}{Cmin} = \frac{\dfrac{1}{(2 * \pi * Fmin)2 * L}}{\dfrac{1}{(2 * \pi * Fmax)2 * L}} = \frac{Fmax2}{Fmin2} \qquad \text{Eq. 3}$$

For the AM broadcast band Fmax is generally 1.7 MHz and Fmin is 0.54 MHz. Thus, the ratio of Cmax to Cmin should be around 10.

Tuning inductor

The classic ancient method of making a variable inductor was to provide a movable wiper to connect to individual turns of the winding. Modern methods use a movable ferrite rod to vary the inductance. Similarly to the development of Equation 3, the ratio of Lmax to Lmin is the square of the desired frequency ratio and works out to be around 10 for the AM broadcast band.

Discussion of Q

Q can be defined in several ways and each way is compatible with the others as shown below.

Q = resonant frequency / bandwidth3 db   Eq. 4

Q = Rshunt / reactance   Eq. 5

Q = reactance / Rseries Eq. 6

Inductors and capacitors have internal losses which appear as a resistance load either in series or shunt with the component. Losses in picofarrad capacitors used at broadcast frequencies tend to be very small and thus these capacitors have a high Q (typically many hundreds) or as it is more commonly referred to in capacitors, low dissipation (the reciprocal of Q). Inductors have the dominant loss. This loss is commonly the series resistance of the wire (including skin-effect) but can also include losses in any magnetic medium used in the inductor. For good crystal radios we need inductors to have a Q in the hundreds.

Resonant circuits are not used in isolation. The antenna is coupled to the resonator as well as the diode detector. Both of these represent a resistive load which lowers the Q of resonance. This is referred to as the loaded Q. That may sound bad but it is actually fine. The loads represent power that we are interested in. We prefer that the resonator have low losses or high-Q. That permits the maximum transfer of power from the antenna to the detector.

Since any resistive load such as the antenna radiation resistance or the detector resistance lowers the net Q (i.e. Qloaded) of resonance, it is important to start with a high unloaded Q known as Qu. The Qu of an LC resonant circuit is primarily determined by the Q of the inductor as its losses tend to dominate. Typical values for the inductor Q range from around 50 to over 500. If the tuning capacitor is of very good quality (i.e. air or silver mica insulation, etc.) then its Q will typically be in the 500 to over 2000 range. Although we like for the unloaded Q of the resonator to be as high as practical for low losses, it is desirable for the loaded Q to be no more

k2*t2*d3
L = -------------- Eq. 6
18 + 40*k

We will use 0.96 for k and t will be that of the particular wire we have available. Solving Equation 6 for the optimum diameter gives:

d_optimum = 4*(L/t2)1/3 Eq. 7

Figure 1 shows a plot of this Equation 7 for common wire sizes. In all cases the turns are close-spaced. The lower curves are for common enamel insulated magnet wire. The two upper curves are for vinyl insulated house wire which can be considered if a large diameter coil form is available. To use the curves, select the desired inductance and the wire size that will be used. Look up the optimum coil form diameter and then use the closest practical form you have to that size. The optimum is broad so do not worry about being exactly on it. Note that the true diameter is the sum of the diameter of the coil form and the diameter of the wire since by definition the coil diameter is measured between opposite centers of the wire.

between about 1.3 to 2.0 times the diameter of the conductor. Coils for crystal radios are commonly wound using what is known as magnet wire (thin enamel insulation) and the turns are tightly wound next to each other corresponding to a spacing factor slightly greater than 1.0 (the thin insulation is of finite thickness). Although it is less than the optimum discussed it works well.

Without some special technique (such as a lathe) it can be very difficult to manually wind a coil with controlled spacing between the turns. One easy method for achieving a spacing factor of 2.0 is to wind two wires tightly side by side at the same time and then remove one of the windings when finished. Smaller spacing factors can be achieved using a smaller diameter wire for the spacer but the difficulty of controlling two wires will increase. It might occur to someone to use a wire with a thicker insulation so that a spacing is naturally formed with a tight winding. The problem with this method is that the insulation may increase dielectric losses and become self defeating –although this may be a small issue –be sure to try it before tossing the concept. This method can work great if Teflon wire is used as that is a very low-loss material and the internal wire strands are silver plated.

Equation 4 can be used to determine the optimum coil diameter for a given inductance and wire size. We note that the coil length is the number of turns divided by t (turns per inch of the wire). We also note that the coil length has previously been related to the coil diameter by the constant, k. Thus:

$$n = k*d*t \qquad \text{Eq. 5}$$

Substituting Equation 5 into Equation 4 gives:

than about 50 so that the bandwidth is not too narrow. An excessively narrow bandwidth makes tuning very sharp and also distorts the audio. The bandwidth needs to be at least 10 kHz with 20 to 50 kHz being common. The following table illustrates the maximum, typical, and minimum loaded Q values to use across the AM broadcast band. Keep in mind that the unloaded Q of resonance should be significantly higher – preferably in the hundreds. The maximum Q value is for the minimum bandwidth of 10 kHz. The typical Q is a good value to try to achieve although realistically it is likely to be lower. The minimum Q has a fairly wide bandwidth and will not be able to separate stations well.

Frequency	QLmax	QLtyp	QLmin
0.5 MHz	50	25	10
1.0 MHz	100	50	20
1.7 MHz	170	85	34

Table 1: Practical ranges for Q of resonance in the AM broadcast band

The resonator has an effective resistance across it that represents coil losses. This resistance will be referred to as RQ. Ideally, RQ is infinity (i.e. no losses) but realistic values are typically in the many tens to hundreds of thousands of ohms. There are two loads on the resonator –one is effective source resistance, RS, of the matching network to the antenna and the other is the effective load resistance, RL, of the diode detector and audio transducer. For maximum power transfer from the antenna to the audio transducer the source and load resistances should be equal.

How to determine the required inductance

Although there are an infinite number of combinations of inductance and capacitance that will resonate at a desired frequency there is only a limited range of practical values that can be used. An excellent question to ask is if there is an optimum inductance. If there is then that is what we will use. There is not a specific answer to that question other than there is an identifiable range of inductance that provides the best overall results. We will determine the extremes starting with the minimum practical value that will result in the highest allowable loaded Q followed by calculating the maximum practical value that will result in the lowest acceptable loaded Q. Any practical value of inductance between these two extremes can be used.

Determination of minimum practical inductance: As discussed previously, the highest loaded Q of resonance that is practical to use is such that the 3 dB bandwidth is about 10 kHz. This permits the full double sideband width to be detected. In extreme cases where we are willing to forfeit some audio fidelity to achieve better selectivity the bandwidth can be reduced to about 6 kHz –but we are not going to consider that case here. At 1 MHz (the rough center of the AM broadcast band), a 10 kHz bandwidth occurs with a loaded Q of 100. The antenna and detector circuits may be operating from taps on the inductor for the purpose of impedance matching (the method to design the taps is discussed in another chapter). The impedance at each tap can be transformed to an equivalent impedance across the entire coil. We will assume that the antenna circuit and detector circuit are impedance matched via this tapping process (this provides the much needed maximum power transfer from the antenna to the detector). Thus, for the impedance matched condition the antenna and detector impedance will transform to the identical impedance across the inductor. We will refer to the net parallel impedance of these

relations to known constants. We first replace the coil length by a factor that relates it to the diameter.

$$l = k*d \qquad \text{Eq. 3}$$

where
l = coil length in inches
k = a dimensionless constant
d = coil diameter in inches as before
Substituting Equation 3 into Equation 2 gives:

$$L = \frac{d2*n2}{18*d + 40*k*d}$$

which reduces to:

$$L = \frac{d*n2}{18 + 40*k} \qquad \text{Eq. 4}$$

It can be shown that the value of k that minimizes the length of wire to wind the coil is 0.450. However, other research indicates (see Reference 1) that the value of k that minimizes coil losses is approximately 0.96 even though that value uses about twenty percent more wire. Factors contributing to coil losses include:

- Ohmic losses in the wire including skin-effect
- Dielectric losses in the coil form and nearby materials
- Dielectric losses in the insulation around the wire
- Induction losses in nearby materials

There are also losses caused by adjacent turns being too close together. It has been found (see Reference 1) that the optimum spacing (wire center to wire center) of adjacent turns is

$$L = \frac{r2*n2}{9*r + 10*l} \qquad \text{Eq. 1}$$

where:
L = inductance in microhenries
r = coil radius in inches (center of coil to center of conductor)
n = number of turns
l = coil length in inches (center of starting turn to center of ending turn)

This equation is generally accurate to around one percent for inductors of common dimensions. It is more convenient to work with coil diameter and Equation 1 can be written as:

$$L = \frac{d2*n2}{18*d + 40*l} \qquad \text{Eq. 2}$$

where d is the coil diameter in inches (center of conductor to center of conductor)

Example: What is the inductance of a coil has a diameter of 2.5 inches, a length of 2.33 inches, and has 72 turns?

$$L = \frac{2.5*2.5*72*72}{18*2.5 + 40*2.33} = 234 \text{ uH}$$

Development of design equations

Equations 1 and 2 are fine for determining the inductance of an existing coil but are very awkward to apply to the design of a desired coil as there are many variables. Any time there are a multitude of variables then the possibility of optimum combinations or relations should be explored. In the following development the number of variables is reduced by finding

two across the coil as Rsignal. It was discussed previously that losses in the inductor can be represented by an effective resistance across the entire coil. We will refer to this loss resistance across the coil as Rloss. The parallel combination of Rsignal and Rloss is the net resistance across a lossless inductor. We will refer to this net resistance as Rshunt. From Equation 5 we can write

$$XL = \text{Rshunt} / \text{loaded Q} \qquad \text{Eq. 6}$$

Thus, using a frequency of 1 MHz

$$\text{Lmin} = XL / (2 * \pi * 1 \text{ MHz}) = \text{Rshunt} / (2 * \pi * 1 \text{ MHz} * \text{loaded Q}) \qquad \text{Eq. 7}$$

The detector impedance is typically in the 2,000 to 50,000 ohm range. With antenna matching the net resistance, Rsignal, will be half this range as discussed above. Table 2 shows a summary calculation for the minimum value of inductance to use to achieve a loaded Q of 100 for various loads either directly or transformed across the coil. The Q of 1,000,000 row represents essentially infinite Q and the Q of 1,000 is not normally attainable and are shown for reference only.

1,000,000	Hz, resonant frequency					
10,000	Hz, BW		100.0 Qloaded			
	Rdetector transformed across entire inductance					
Qunloaded	**2K**	**5K**	**10K**	**20K**	**50K**	**100K**
1,000,000	1.6E-6	4.0E-6	8.0E-6	15.9E-6	39.8E-6	79.6E-6
1,000	1.4E-6	3.6E-6	7.2E-6	14.3E-6	35.8E-6	71.6E-6
500	1.3E-6	3.2E-6	6.4E-6	12.7E-6	31.8E-6	63.7E-6
250	954.9E-9	2.4E-6	4.8E-6	9.5E-6	23.9E-6	47.7E-6
125	318.3E-9	795.8E-9	1.6E-6	3.2E-6	8.0E-6	15.9E-6

Table 2: Minimum Inductance in Henries

All of the inductances in Table 2 are small –some very small. But our target was the absolute minimum inductance that could be used. The details would be a chapter in of itself but I can tell you that the practical absolute minimum inductance that is useful for a resonator in the AM broadcast band is around 40 microhenries as it is a challenge to obtain a high Qu for inductances less than this in that frequency range. Thus, only the last column of Table 2 is useful.

Determination of maximum practical inductance: This calculation is done the same way as before except that the lowest value of loaded Q is used. That results in a higher inductance. Table 3 is a summary calculation. Again, the top two rows are for reference only.

1,000,000	Hz, resonant frequency					
50,000	Hz, BW		20.0 Qloaded			
	Rdetector transformed across entire inductance					
Qunloaded	2K	5K	10K	20K	50K	100K
1,000,000	8.0E-6	19.9E-6	39.8E-6	79.6E-6	198.9E-6	397.9E-6
1,000	7.8E-6	19.5E-6	39.0E-6	78.0E-6	195.0E-6	389.9E-6
500	7.6E-6	19.1E-6	38.2E-6	76.4E-6	191.0E-6	382.0E-6
250	7.3E-6	18.3E-6	36.6E-6	73.2E-6	183.0E-6	366.1E-6
125	6.7E-6	16.7E-6	33.4E-6	66.8E-6	167.1E-6	334.2E-6

Table 2: Maximum inductance in Henries

Conclusions:

The conclusions from studying Tables 2 and 3 are that low values of inductance are needed for low impedance circuits and that high values of inductance are needed for high impedance circuits. Typical values of inductance used for the resonant circuit in crystal radios ranges from around 100 microhenries up to around 700 microhenries with more common values in the 200 to 400 microhenry range.

We can work Equation 7 backwards to determine a good value for the net shunt resistance across the coil at 1 MHz as follows.

DESIGNING AN AIR-CORE INDUCTOR

Introduction

This chapter describes the mathematical process for designing an air-core inductor comprised of a single layer solenoid winding over a rigid coil form. Although the development of the mathematics is a bit complicated the final result is simple to apply. For practical reasons, this chapter will make use of English rather than metric units. A well designed and constructed air-core coil has better performance than those with ferrite cores. Ferrite acts as a flux multiplier and has the advantage that the physical size of the inductor can be reduced. That is very important for small radios and the chief reason ferrite is used. The price paid for small size is loss of performance but that loss is generally negligible in active radios. The loss is not bad for crystal radio performance and many good crystal radios have been built using ferrite core inductors. But ferrite is not required. Purists correctly argue that the coil should be air core as that is how early radios were built. A mediocre ferrite core inductor will work considerably better than a poorly designed air-core one and that has probably led to the popularity of ferrite as the process for designing good air-core inductors is not widely known. This chapter reveals those secrets.

Analytic equation

The classic equation (which you can find in any book or article about winding inductors) for calculating the inductance of a given single layer coil is (Reference 2):

proper impedance match although it is not very critical. The issue is how to determine the proper point. A second issue is that the required impedance level varies across the AM broadcast band. Thus, the tap should be variable.

If the coil is wound on a ferrite toroid core which enables a high degree of flux coupling from turn to turn then it is fairly easy to calculate at what turn a tap should be for the desired impedance transformation. However, our coil is typically an air-core solenoid which has a complicated flux relationship. Calculation is difficult and very error prone. The best way is to make a variety of taps and measure the impedance using laboratory methods and note the results. I will present the data of just such an experiment on a typical coil for crystal radios when this article continues …

Rshunt = 2 * π * 1 MHz * loaded Q * L   Eq. 8

As an example, if we have a 240 uH coil and we want the loaded Q to be 20 at 1 MHz then the total shunt load should be 30,000 ohms. Assuming coil losses are small this means that the detector impedance should be 60,000 ohms and that the antenna impedance should be transformed (via a tap near the ground end of the coil) up to 60,000 ohms. This particular scenario is a practical one that can be built.

Concluding remarks

Although it is discussed in other chapters it should be mentioned here that we generally want to make the detector impedance as high as possible in order that we can use the highest inductance practical. This results in the maximum signal voltage applied to the detector thus lowering the losses in the detector circuit.

A significant factor to be aware of is stray capacitance across the inductor. This capacitance results from the natural physics of the winding (conductors separated by insulation). This stray capacitance is typically in the 10 to 50 pF range depending on how the inductor is wound and is in shunt with the tuning capacitance. The effect is to limit the upper frequency that the inductor can be tuned too. The effect is worse in large value inductors and that typically limits the maximum practical inductance to something less than 1 millihenry. There are some advanced winding methods that minimize stray capacitance but those are beyond the scope of this chapter.

ANTENNA MATCHING

As discussed in an earlier chapter the ten to thirty meter antenna used for crystal radios has a very low resistance and a high capacitive reactance. The ground resistance discussed previously is typically in the several tens of ohms and is effectively in series with the antenna. As an example, an antenna/ground system may have an impedance of 20 –j1000 ohms at 1 MHz. For maximum power transfer from the antenna to the resonant circuit the input impedance of the set should be a conjugate match –that is have similar resistance but the reactance will be equal in magnitude but opposite in sign. For the example this means that the crystal set should have an input resistance of about 20 ohms and a reactance of about +j1000 ohms (160 uH) at 1 MHz. The positive reactance is obtained by an inductance in series with the antenna circuit. This inductance should be variable to tune out the capacitive reactance of the antenna across the AM broadcast band. Tuning is not sharp as the Q of resonance is low. Table 1 shows some typical values. Note that the inductance tuning range becomes wider for longer antennas since the capacitive reactance drops rapidly as the length approaches one-quarter wavelength at the upper end of the AM band. It is important that this series inductance have very low losses or the advantage of using it will vanish –a lossy inductor could be worse than nothing.

Antenna Length	**Typical Antenna XC @ 550 kHz**	**Typical Antenna XC @ 1.7 MHz**	**Antenna series Inductor tuning range**
10 m -	j4040 ohms -	j1250 ohms	1200 –120 uH
15 -	j2680 -	j780	780 – 70
20 -	j1990 -	j530	580 – 50
25 -	j1580 -	j360	460 – 30
30 -	j1290 -	j240	370 – 20

Table 1: Antenna series inductance tuning range

One effect of not tuning out the reactance of the antenna is that the resonant frequency of the tuned circuit will shift because the antenna becomes a reactive load. One way to know if the series inductance has been tuned to the right value is that the station is received at the calibration point –assuming the radio tuning was calibrated.

The next issue is creating a low input impedance of several tens of ohms. There are two ways to do this and they are essentially the same. One method is wind a turn or so of wire near the ground end of the coil of resonant circuit –one end of the wire goes to the series inductor to the antenna and the other end connects to ground. This small winding transforms the low antenna/ground impedance to a high impedance across the coil. The other method is to make a tap a turn or so above the ground end of the coil of the resonant circuit to accomplish the same effect. If the winding or tap is too few turns then there is an impedance mismatch and a weak signal will result although selectivity will be relatively sharp. If the winding or tap has too many turns then the coil is overloaded by the antenna/ground impedance which also results in weak signals and the selectivity will be broad. The optimum is the point of