



ANTENNAS FOR LOW POWER APPLICATIONS

By Kent Smith

Introduction:

There seems to be little information on compact antenna design for the low power wireless field. Good antenna design is required to realize good range performance. A good antenna requires it to be the right type for the application. It also must be matched and tuned to the transmitter and receiver. To get the best results, a designer should have an idea about how the antenna works, and what the important design considerations are. This paper should help to achieve effective antenna design.

Terminology:

Wavelength - Important for determination of antenna length, this is the distance that the radio wave travels during one complete cycle of the wave. This length is inversely proportional to the frequency and may be calculated by: $\text{wavelength in cm} = 30,000 / \text{frequency in MHz}$.

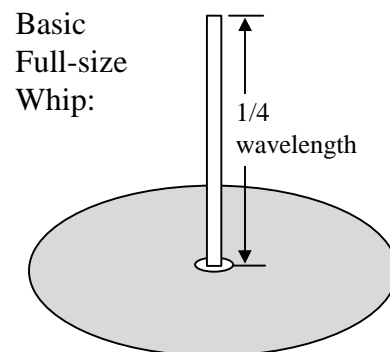
Groundplane - A solid conductive area that is an important part of RF design techniques. These are usually used in transmitter and receiver circuits. An example is where most of the traces will be routed on the topside of the board, and the bottom will be a mostly solid copper area. The groundplane helps to reduce stray reactances and radiation. Of course, the antenna line needs to run away from the groundplane.

dB (decibel) - A logarithmic scale used to show power gain or loss in an RF circuit. +3 dB is twice the power, while -3 dB is one half. It takes 6 dB to double or halve the radiating distance, due to the inverse square law.

The Basic Antenna and how it Works.

An antenna can be defined as any wire, or conductor, that carries a pulsing or alternating current. Such a current will generate an electromagnetic field around the wire and that field will pulse and vary as the electric current does. If another wire is placed nearby, the electromagnetic field lines that cross this wire will induce an electric current that is a copy of the original current, only weaker. If the wire is relatively long, in terms of wavelength, it will radiate much of that field over long distances.

The simplest antenna is the “whip”. This is a quarter wavelength wire that stands above a groundplane. The most common examples are found on automobiles and are used for broadcast radio, CB and amateur radio, and even for cellular phones. This design goes back to the 1890's when Marconi set out to prove that radio signals could travel long distances. To be successful, he had to stretch a long wire above the ground. Due to the low frequencies, thus a long wavelength, the wire had to be long. He also found that the wire worked better when it was high above ground.



All antennas, like any electronic component, have at least two connection points. In the case of the whip, there must be a connection to a ground, even if the groundplane area is nothing more than circuit traces and a battery. The whip and groundplane combine to form a complete circuit. The electromagnetic field is set up between the whip and the ground plane, with current flowing through the field, thus completing the circuit. Ideally, a groundplane should spread out at least a quarter wavelength, or more, around the base of the whip. The groundplane can be made smaller, but it will affect the performance of the whip antenna. The groundplane area must be considered when designing an antenna.

A quarter-wave whip is not a compact antenna. At 1 MHz, in the AM Broadcast band, one quarter of the wavelength is about 246 feet, or 75 meters. At 100 MHz, in the FM Broadcast Band, it is nearly 30 inches (75 cm). This dimension continues to shrink at higher frequencies, being nearly 3 inches (7.5 cm) at 1000 MHz. A simple formula for the quarter-wave (in cm) is: 7500 divided by the freq. (in MHz), or for inches: 2952 / freq. (in MHz). This formula is only a starting point since the length may actually be shorter if: the whip is overly thick or wide, has any kind of coating, or is not fed close to ground. It may need to be longer if the ground plane is too small.

The length of the antenna should be measured from the point where it leaves close proximity to ground, or from the transmitter output. If a whip is mounted on a box, and connected to the transmitter with plain wire, that wire becomes part of the antenna! To avoid mistuning the antenna, coaxial cable should be used to connect to an external antenna. On a circuit board, the equivalent to coax is a trace that runs over a groundplane (groundplane on the backside). The above are examples of transmission lines, whose purpose is to efficiently transfer power from one place to another with minimum loss. Do not try to run an antenna line too close to ground, it becomes more of a transmission line than an antenna. Fortunately for those who need a small remote device, a transmission line left open-ended will radiate some energy.

Antenna Characteristics:

Gain:

An antenna that radiates poorly has low "gain". Antenna gain is a measure of how strongly the antenna radiates compared to a reference antenna, such as a dipole. A dipole is similar to a whip, but the groundplane is replaced with another quarter-wave wire. Overall performance is about the same. An antenna that is 6 dB less than a dipole is -6 dBd. This antenna would offer one half the range, or distance, of the dipole. Compact antennas are often less efficient than a dipole, and therefore, tend to have negative gain.

Radiation Pattern:

Radiation is maximum when broadside, or perpendicular to a wire, so a vertical whip is ideal for communication in any direction except straight up. The radiation "pattern", perpendicular to the whip, can be described as omnidirectional. There is a "null", or signal minimum, at the end of the whip. With a less than ideal antenna, such as a bent or tilted whip, this null may move and partly disappear. It is important to know the radiation pattern of the antenna, in order to insure that a null is not present in the desired direction of communication.

Polarization:

It is important that other antennas in the same communication system be oriented in the same way, that is, have the same polarization. A horizontally polarized antenna will not usually communicate very effectively with a vertical whip. In the real environment, metal objects and the ground will cause reflections, and may cause both horizontal and vertical polarized signals to be present.

Impedance:

Another important consideration is how well a transmitter can transfer power into an antenna. If the antenna tuning circuit on a transmitter (or receiver) is designed for a 50 ohm load, the antenna should, of course, have an impedance near 50 ohms for best results. A whip over a flat groundplane has an impedance near 35 ohms, which is close enough. The impedance changes if the whip is mistuned or bent down, or if a hand or other object is placed close to it. The impedance becomes lower as the antenna is bent closer to ground. When the whip is tilted 45 degrees, the impedance is less than 20 ohms. When the whip is bent horizontal to

one-tenth of a wavelength above ground, the impedance approaches 10 ohms. The resulting impedance mismatch, a 5:1 ratio (VSWR) will contribute an additional loss of 2.6 dB.

Printed Circuit Whip, or “Stub”

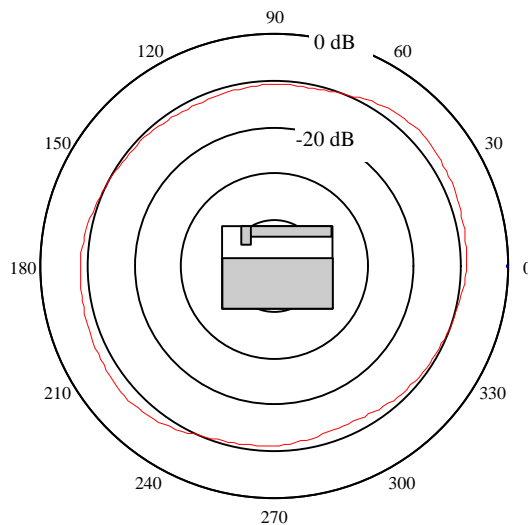
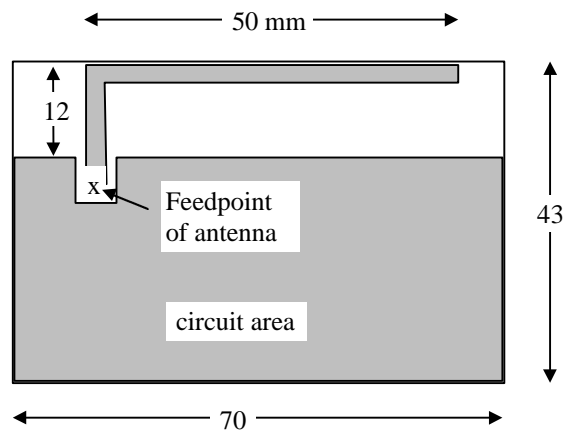
The whip can be made as a trace on a printed circuit board (PCB). This is very practical at frequencies over 800 MHz. At lower frequencies, a full size whip may be too long, even when wrapped around a few corners. The length of the whip should be 10 to 20% shorter than the calculation, depending on the dielectric and the thickness of the board. In most cases, 15% shorter is close enough. If the unit is to be hand held, the antenna can be made a little shorter, to compensate for the effect of the hand.

At 916 MHz, a trace that is 2.25 inches (57 mm) long will provide a reasonable impedance when hand effects are included. Keep the antenna trace away from other circuitry and ground, a quarter of an inch (6 mm), or more. Non-ground circuit traces may be seen by the antenna as part of the ground system, and RF voltages can be induced on nearby traces.

Our sample PCB Stub is shown in the drawing at right. The overall size of the board and ground is not critical. The radiation pattern is omnidirectional, with a gain of -8 to -12 dBd, when the board is horizontal. Polarization is horizontal. If the whip did not run parallel to ground, the gain would be higher, however, two sharp nulls would be present. If the board were oriented vertically, with the antenna above the groundplane, the polarization would be vertical. The antenna would have an omnidirectional pattern with -8 dBd of gain.

Printed Open Stub:

916.5 MHz



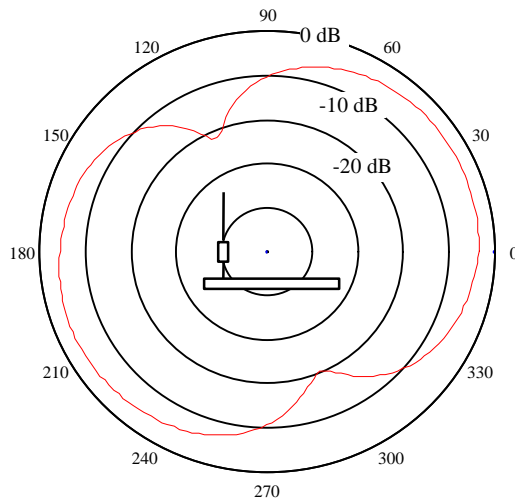
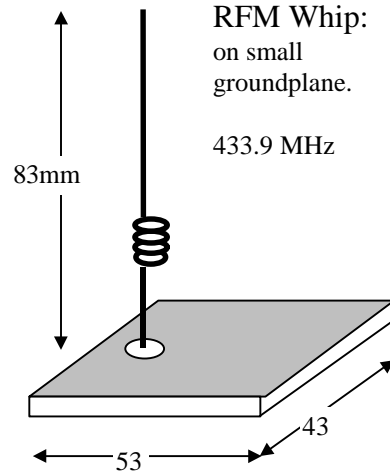
Radiation Pattern of Open Stub Antenna
(916.5 MHz)

Compact Antennas:

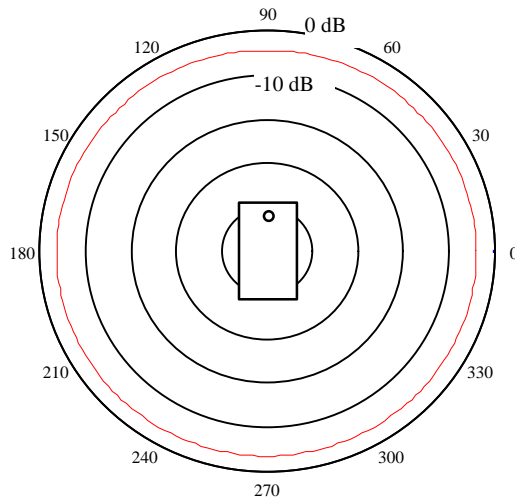
The Short Whip

A simple alternative to the whip is to make it shorter than a quarter wavelength and add an inductor near the base of the whip to compensate for the resulting capacitive reactance. The inductor can be made by coiling up part of the whip itself. This type of antenna can have performance nearly equal to that of a full size whip.

RFM uses such a design for the wire antennas that are supplied with our demonstration boards. Details of the design can be found in the HX/RX portion of the Product Data Book. The RFM short whip is optimized for under-sized groundplanes. When tested on the edge of a small board, gain was only 3 to 4 dB less than a full sized whip and groundplane.



Loaded Whip Antenna (434 MHz)



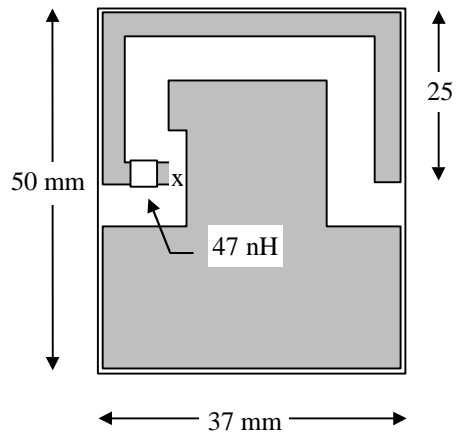
The Short PCB Stub

One big advantage for the short whip is that it can be a trace on a PCB, with a chip inductor used to tune out the capacitive reactance of the antenna. If the trace runs parallel to ground, the real part of the antenna impedance will be approximately 10 ohms. In a hand-held unit, the impedance will be raised substantially through hand effects. For a tenth wavelength strip on a board with hand effects included, the antenna has a capacitive reactance of about 150 ohms. At 433.9 MHz, this would require a 56 nH inductor to cancel the capacitive reactance of the 2.7 inch (70 mm) long line.

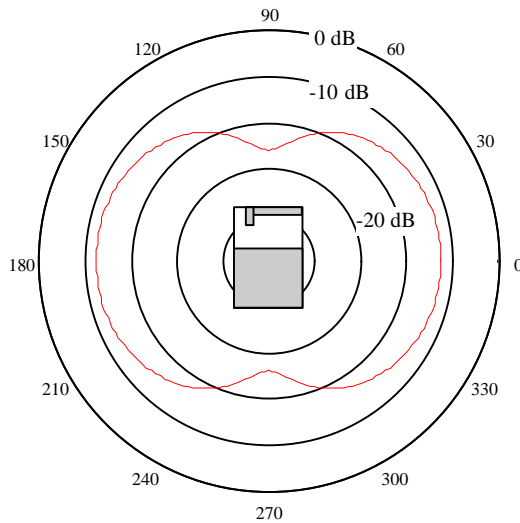
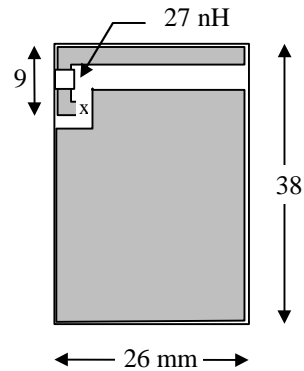
The radiation pattern will be fairly omnidirectional, with a shallow null along one axis. The polarization is roughly parallel with the edge of the board. Tuning is not extremely critical, small variations in inductor value or antenna length will not have a great effect on performance. Our sample designs, at 433.9 and 916 MHz, resulted in maximum gains of between -12.5 to -14 dBd off the side of the board. The null dipped down to about -26 dBd. This is more omnidirectional than some other designs, and hand effects will help to reduce the null depth.

The key to this design is to keep resistive losses low, use wide traces (if a PCB trace), and good quality inductors. Adjust the inductor value for maximum output in the environment that it will be used. Gain can be improved by making the whip longer and thus reducing inductance. But, in some cases, it may be better to shorten the trace and add inductance rather than to run the antenna close to other circuit board traces.

Short Stub: 433.9 MHz



Short Stub: 916.5 MHz



Short Stub (916 MHz)

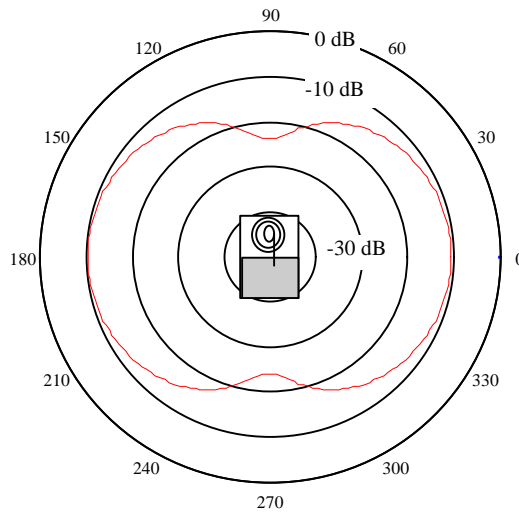
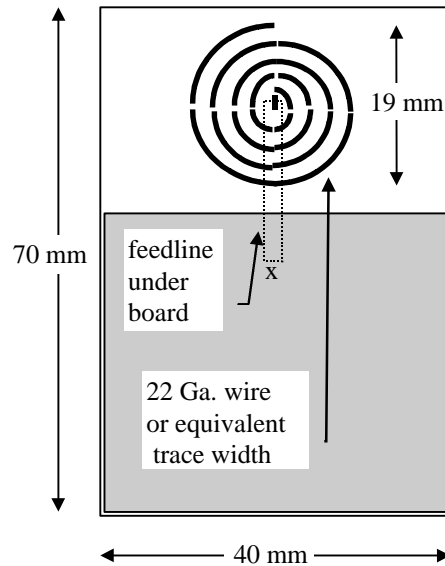
The Spiral

Another way to shorten a whip is to coil it up to form a flattened coil of wire. It can be a trace printed onto a circuit board. On a board, the length of the trace is a little shorter than a quarter wavelength. The antenna must not have a groundplane directly under it, and should occupy a clear end of the board. For example, start with a six inch long thin trace wrapped in a 0.75 inch (19 mm) square area, then trim a little of the length until it resonates at 433.9 MHz.

Antenna gain and impedance will vary with the size of the groundplane. Our 433.9 MHz version had a fairly small groundplane area of 17 sq. cm, while the 916 MHz version had a quarter-wave long ground. The 433.9 MHz antenna had a maximum gain of -10.5 dBd, with a small null of -24 dBd. The 916 MHz antenna had a gain of -5 dBd max. Comparable gain is also seen when looking at the board face-on.

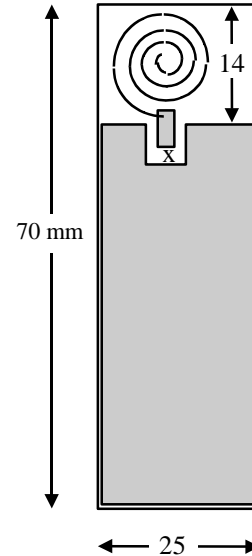
This antenna does not give circular polarization; the polarization is parallel to the long edge of the board. As with a stub, when the board is oriented vertically, it is vertically polarized and omnidirectional. This antenna is more easily detuned by a hand, which makes it less suitable for hand-held remotes.

Spiral: 433.9 MHz



Spiral Antenna (434 MHz)

Spiral: 916.5 MHz

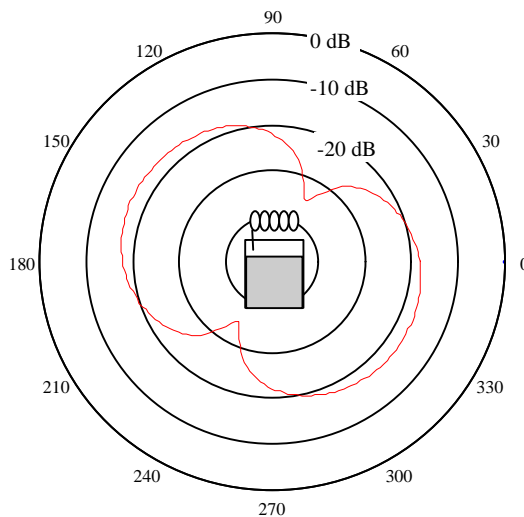
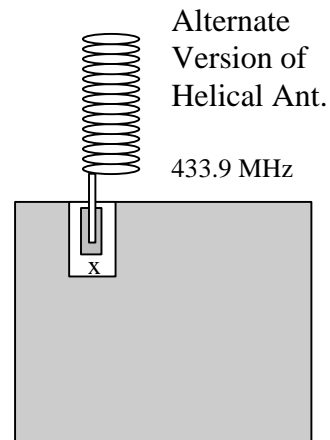
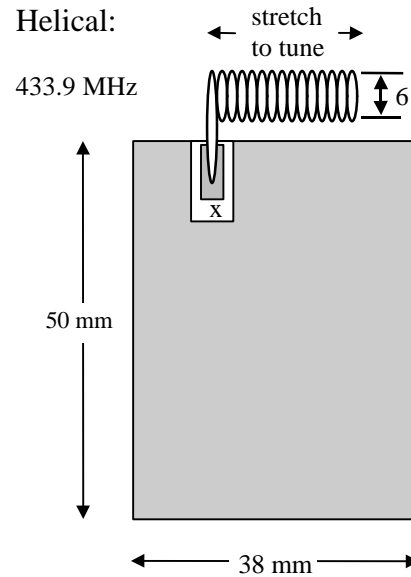


The Helical (Coil)

This is similar to a spiral that is not flattened. Start with a piece of wire that is 2 or 3 times longer than a whip and wind it into a coil. The number of turns on the coil will depend on wire size, coil diameter, and turn spacing. The coil will need to be cut to resonate, and can be fine tuned by spreading or compressing the length of the coil. If the coil is wound tightly enough, it may be shorter than one-tenth of a wavelength. This antenna tunes sharply, requiring care in tuning. The real part of the antenna impedance is less than 20 ohms, and depends on the size of the coil and its orientation to ground.

For 433.9 MHz, we wound 14 turns of 22 gauge wire around a 0.25 inch (6 mm) form. When tuned, it's length was just under one inch. The proximity of this coil to ground makes a big difference in performance. When the coil runs near and parallel to ground, maximum gain is only -18 dBd. When the loose end of the coil was pulled away from ground, as shown in the alternate version drawing, gain increased to -5.5 dBd, and the null became deeper.

The big problem with this antenna is the mechanical construction and it's bulky size. It can be easily de-tuned by nearby objects, including a hand, so it may not be good for hand-held use.



Helical Antenna (434 MHz)

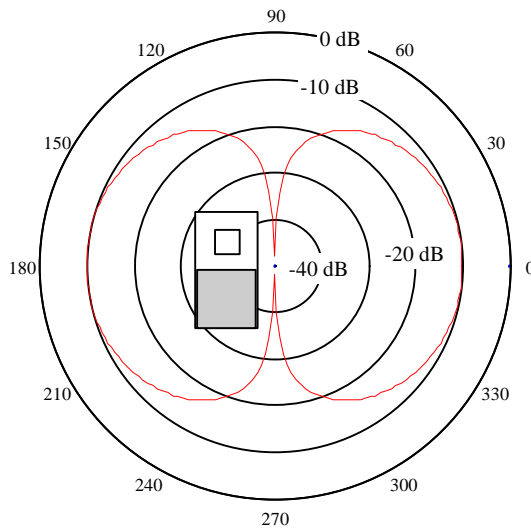
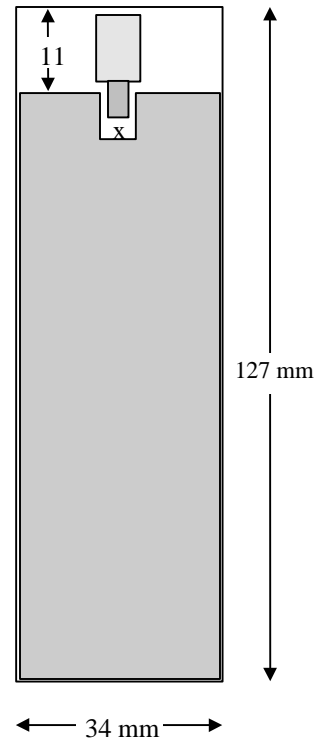
“Chip” Antenna

The latest entry into the antenna field is the tiny “chip” antenna. They are surface mount devices that are typically 8 by 5 by 2.5 mm, making them the smallest design available. They may be found for frequencies less than 300 MHz and up to 2500 MHz. These antennas are similar to whips in behavior, only much smaller. If an antenna can be reduced in size, while maintaining efficiency, bandwidth will be reduced. So these devices have a very narrow bandwidth and must be made to the exact frequency.

These devices are very groundplane dependant. As a result, they are easily detuned by hand effects, the wrong size groundplane, or even the wrong thickness and dielectric of the board. The chip antenna must be used according to the manufacturer’s recommendations.

For 433.9 MHz, we mounted a chip on a 5 inch long board and obtained a maximum gain of -10 dBd. Not bad when you consider that the spiral has equal gain, but consumes five times as much area on the board. The 916 MHz version did better with a 2.6 inch long groundplane for a maximum gain of -3.2 dBd. The polarization is parallel to the long axis of the chip, so maximum radiation is perpendicular to the long axis. There is a deep null (nearly 40 dB!) looking at each end of the chip. This would be a big problem if an omnidirectional pattern is required from a horizontal circuit board. When the board is vertical, the pattern is omnidirectional.

“Chip” Ant.: 433.9 MHz



Chip Antenna (434 MHz)

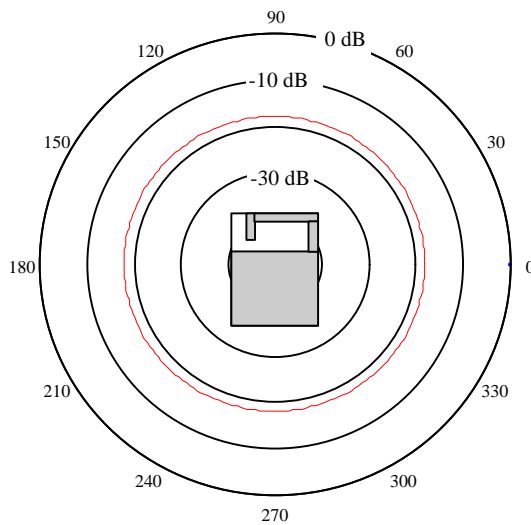
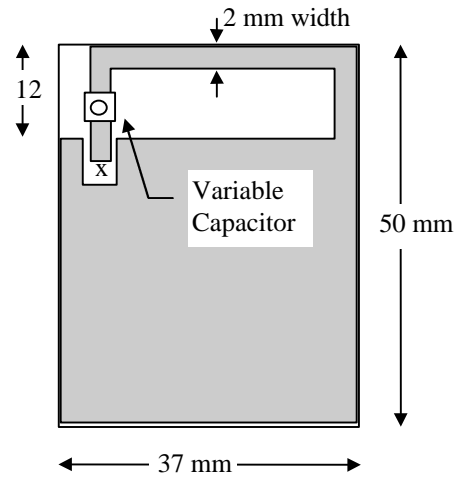
The Loop

The loop is entirely different from a whip, in that both ends of the antenna are terminated. In this case, the end that is opposite the transmitter (or receiver) is grounded. A capacitor is used to tune the antenna to a real impedance, instead of a coil. An advantage of a loop is that it is not easily detuned by hand effects, although the impedance may still vary. The loop can be made small, does not require a groundplane, and takes no more space than a short whip. For these reasons, loops are very common in hand-held devices.

There are some disadvantages. Small loop antennas have a reputation for poor gain. A small loop will have a very narrow bandwidth. This makes tuning extremely critical. Tuning is often done with a variable capacitor, which adds to the cost, both parts and labor. If the loop is large enough, it may be practical to use a non-variable capacitor. This requires careful adjustment in engineering stages, to ensure that it is properly tuned with a standard value capacitor.

Our example loop antenna covers a 12 by 35 mm area on the end of a board. It is tuned to 433.9 MHz with a variable capacitor. This antenna is very omnidirectional, but had a gain of only -18 dBd. A larger loop should have improved gain.

Loop: 433.9 MHz



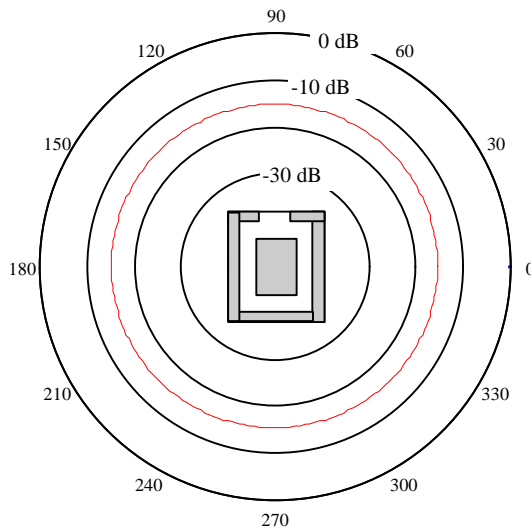
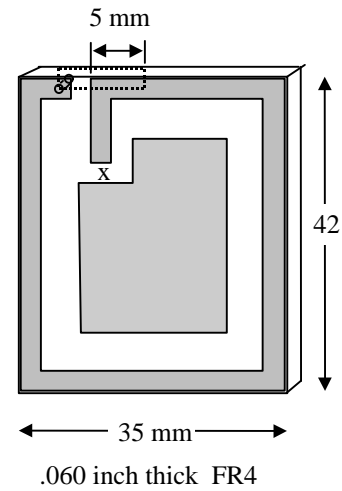
Loop Antenna (434 MHz)

Semi-Loop

This is an unusual design that looks like a loop, but requires no direct grounding. It is comparable to a loop in performance, and can be adjusted to present a non-reactive load. This antenna uses a trace that runs all the way around the edge of a small PCB. The far (open) end is capacitively coupled, through the board, back to the transmitter end of the antenna. The antenna is resonated by varying the length of the short overlapping line. Tuning is not very critical. Hand effects will improve the impedance, with little effect on tuning. Polarization is parallel to the PCB, and the pattern is omnidirectional. Our design had a gain of -15 dBd at 433.9 MHz. This design works very well for hand-held devices.

As with any other designs, this antenna should not run too close to ground. For this design, the transmitter and other circuitry, including battery, should be grouped around the center of the board, leaving the antenna in the clear. The circumference of the board needs to be well under one-quarter wavelength. We have had good results with a circumference of about 0.15 wavelength, and a line width of 1 to 1.5 mm, when used in the 400 MHz region. If the design is used on a thinner board, the 5 mm overlap will need to be shortened.

Semi-Loop: 433.9 MHz



Semi-Loop Antenna
434 MHz

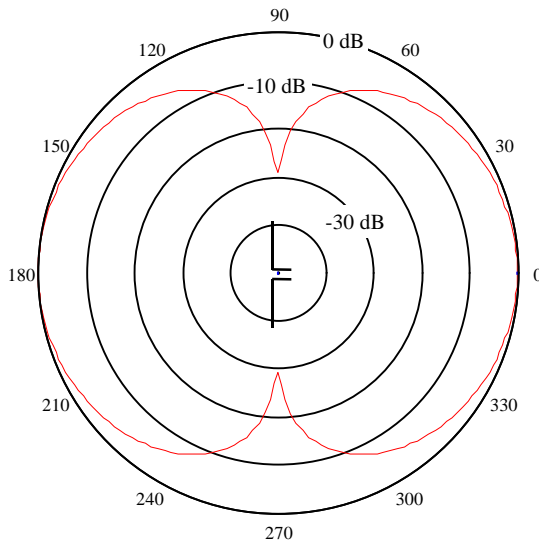
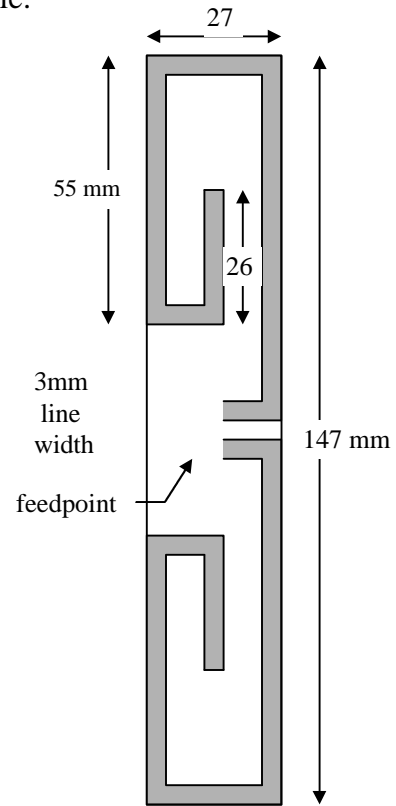
Modified Dipole Antenna

A dipole can be shortened somewhat by bending the wire or line back on itself, but not too close to itself. We built a version on a PCB, shown at right. This antenna has almost the same performance as a full size dipole, but is more compact. The thickness and dielectric constant of the board will affect the tuning, so the length may need to be adjusted.

This type of antenna is an attractive solution where space allows. However, a dipole should not be located close to a large metal area or groundplane. The groundplane will become part of the antenna, and performance will suffer.

Like the normal dipole, the radiation pattern shows deep nulls and good gain. The impedance is a little lower, but still near 50 ohms. Like many of the previous antennas, radiation from the face of the board is just as strong as from the long edge.

Folded Dipole:

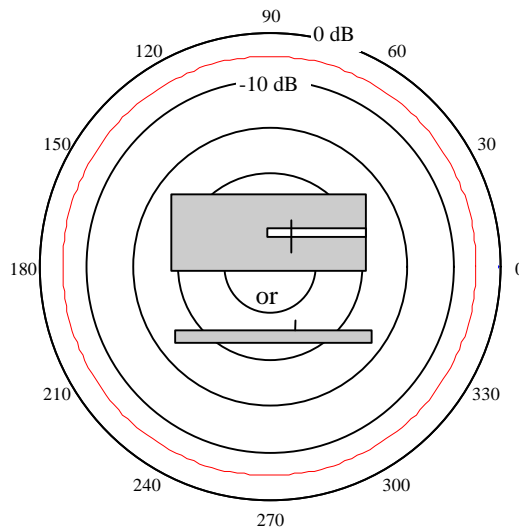
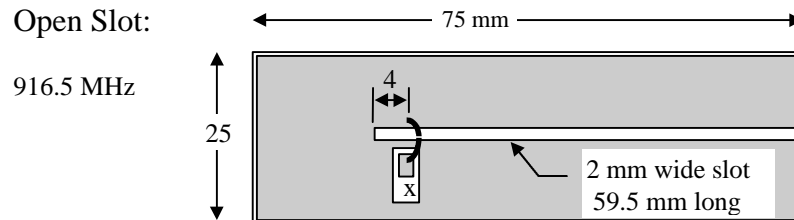


Folded Dipole Antenna (434 MHz)

The Slot

Common in radar systems and/or on aircraft, a variation of the slot antenna may have potential above 800 MHz. A quarter-wave slot is cut into a metal sheet or unetched PCB, and if enough area is available, will provide omnidirectional coverage. Our sample antenna at 916 MHz required a 75 mm long PCB. The length of the slot was 59.5 mm for 0.060 inch (1.5 mm) thick FR4. A different thickness or dielectric will require changing the length of the slot. One end of the slot must be left open. The slot was fed near the closed end, in this case 4 mm from the end. The feedpoint impedance can be adjusted by moving the feed toward or away from the closed end. Tuning is somewhat critical.

When the board is horizontal, the pattern is omnidirectional around the edge of the board, thus horizontally polarized. We also see omnidirectional coverage when the board is vertical (with the slot horizontal). In this case, polarization is vertical! It may not make sense, but a horizontal slot is equivalent to a vertical whip in this case. Gain is -4.5 to -6 dBd. The feed can be a trace on the backside of the board, with a via used to make connection with the top of the board near the slot.



Half Open Slot Antenna
(916.5 MHz)

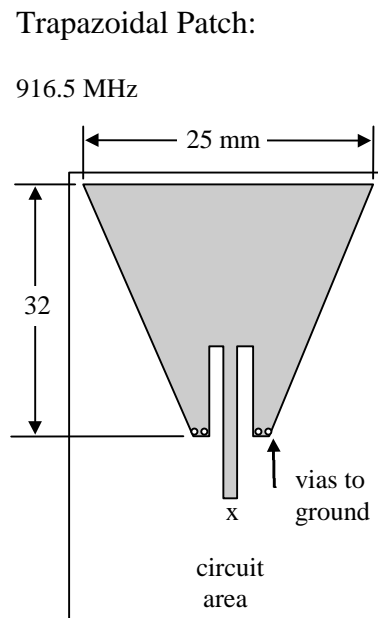
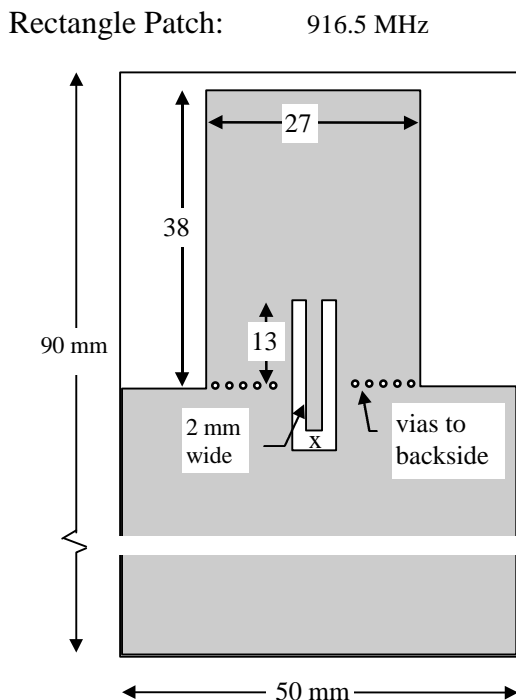
The Patch

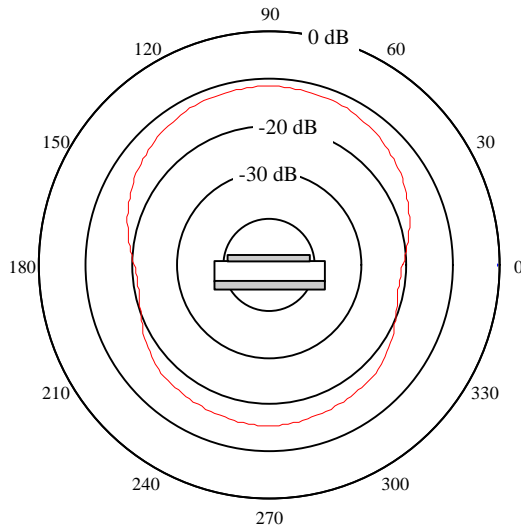
The Patch antenna is a very low profile design, which consists of a round or rectangular patch of metal very close to a groundplane. The patch is usually printed on a circuit board and can be made as part of the enclosure. Antenna coverage is in any direction above the groundplane, or a hemispherical area. The patch antenna does require a substantial amount of area on a PCB, which makes it more practical above 800 MHz. It has a narrow bandwidth so care must be taken to tune the size of the patch carefully. It is sensitive to the thickness and dielectric constant of the PCB and small variations will mistune the patch completely. It is also sensitive to coatings, but not extremely sensitive to hand effects.

A practical example for 916 MHz can fit into an area only 30 by 40 mm. The patch size is 27 mm wide by 38 mm long for a board thickness of 0.060 inch. A thinner board or higher dielectric can require cutting the antenna a little shorter. About one-tenth of an inch of board space should be left around any ungrounded edge of the patch. One edge of the patch should be grounded with multiple PCB vias. The antenna is fed with a line crossing through the grounded edge to the 50 ohm point on the patch, or by a transmission line coming up through the bottom of the PCB. The 50 ohm point is about 13 mm away from ground on our example patch. The 50 ohm point for any design can be found by moving the vias toward or away from the grounded edge. The farther the feed is away from the ground vias, the higher the impedance will be.

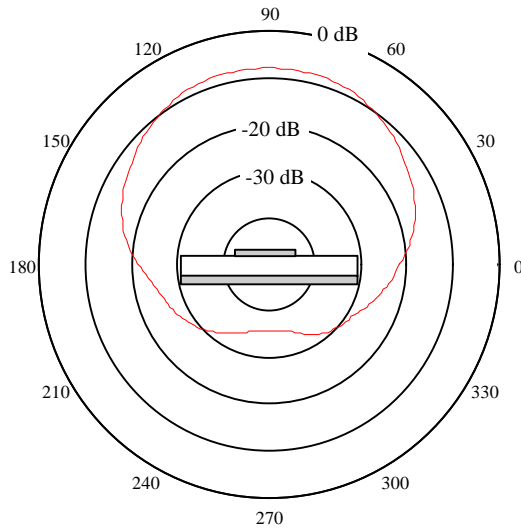
This type of patch is not a full-size, half-wavelength patch, so performance is not as good as a larger size patch. A full-size patch has no grounded edge, so vias are not required. Our example rectangular patch has a gain of -8 dBd. Placing the board against a larger sheet of metal will improve the gain by another 4 dB. If the antenna is made wider than one inch, up to about 3 inches wide, a few more dB can be gained. Polarization is perpendicular to the grounded edge. Gain is good in almost any direction where the patch can be seen, but drops rapidly when looking at the edge of the board.

The trapezoidal version allows for less length so that it can fit into smaller spaces. Patterns and behavior are the same, but the gain is a little lower. We measured about -12 dBd maximum, on a 40 by 90 mm board.





**Trapezoidal Patch over a
Small Ground Plane
(916.5 MHz)**



**Trapezoidal Patch over a
Large Ground Plane
(916.5 MHz)**

Enclosures

An antenna should not be located inside a conductive, or metal enclosure. Care should be taken to keep the antenna away from metal surfaces. If a conductive area is large in terms of wavelength (one half wave or more), it can act as a reflector and cause the antenna to not radiate in some directions. If a metal box is used for an enclosure, an external antenna is required.

Testing and Tuning

Antennas may seem to be a mystical art. Unlike many electronic devices, any change in nearby materials or dimensions can affect antenna performance. Trying to build a published design does not guarantee results. Testing an antenna design is necessary, tuning is usually required, and there are pitfalls along the way.

A network analyzer is normally used to test the impedance or VSWR of the antenna. Some antennas that have an impedance near 50 ohms can be tuned by looking at return loss or a VSWR display. Low impedance antennas may require the use of a Smith Chart display to get good results. In this case, the antenna should be tuned to a point near the pure resistance line.

There are other options, such as a spectrum analyzer with a tracking generator, that can be used with a directional coupler. The coupler will feed power to the antenna while feeding the reflected power from the antenna back to the analyzer. The coupler must have an isolation between the Generator and RF Input Port of 20 dB or more. Calibration is done by noting the power readings with a 50 ohm load connected and then unconnected. Using this technique, "return loss" can be measured. If the antenna is near 50 ohms, the return loss back to the RF input port will be high, due to the antenna absorbing most of the power. A good antenna will show as a dip on the screen at the correct frequency. A dip of only 3 or 4 dB (about a 5:1 VSWR) is normal for a low impedance antenna measured on a 50 ohm analyzer. A dip of 9 dB (about 2:1) or more indicates a well-matched antenna in a 50 ohm system. If the dip is not centered at the right frequency, the antenna length or tuning needs to be adjusted.

Antenna measurements of any kind are tricky since the antenna is affected by nearby objects, including the size and shape of the circuit board, and even by the cable connections to the network analyzer. Pass your hand close to the antenna and the dip should move around a little. If it does not, the antenna may not be connected properly. Antennas that are ground plane sensitive may see all additional wires as an extension of that ground. Try wrapping your hand around the cable that goes to the analyzer. If the measurement changes much, you may need to try a different tactic. One possibility to minimize RF currents on the cable is to put a few good high frequency ferrite toroids or some absorptive material over the cable.

The best way to fine tune a remote transmitter antenna is by using the transmitter itself. Put an antenna on a spectrum analyzer and try to keep other large metal objects out of the way. Find a place to locate the transmitter that is away from metal and a few feet away from the analyzer. Always locate the transmitter in the exact same spot when testing. If you have a desk that is wood, mark it's position with a pencil or tape. If hand held, hold it in your hand just above the marking on the desk. Be sure to position your hand, and the rest of your body, the same way during each test. Take a reading of the power level, and tune the antenna to achieve maximum radiated power. The same thing can be done for a receiver. Transmit a signal to it, and adjust the antenna to receive the lowest signal level from the generator.

Common problems with antennas usually involve insufficient free space around the antenna. The antenna cannot run close to ground or any other trace without effecting the antenna performance. This includes traces on the other side of the board, batteries, or any other metal object.

Receiver performance can be degraded by digital circuits. Digital switching is very fast and creates high frequency noise that can cause interference. Keep receiving antennas away from digital circuit traces. Try to keep digital traces short, and run them over a groundplane to help confine the electromagnetic field that is generated by the digital pulses. If an external antenna is used, then use a coaxial cable.

A transmission line for G-10 material that is .06 inch thick requires a trace width of a tenth of an inch , half of that for a .03 inch thick board. This results in a 50 ohm transmission line that will carry RF with minimum loss and interference.

High static voltages may damage sensitive semiconductors or SAWs. We recommend placing an inductor between the antenna and ground to short out any static voltages. For the 400 MHz region, a value near 200 nH is a good choice. At 916 MHz, a more appropriate value may be 100 nH.

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