Application Note 01

V / UHF Antenna Design

Scope

The antenna is usually the last element considered when designing an RF equipment. But remember, a chain is as weak as its weakest element. As part of the transmission chain in a wireless link, the transmit and the receive antenna are directly involved to achieve the desired overall performance.

The purpose of this document is to give some knowledge as well as a guideline to the design of antennas in wireless projects.

Fundamental antenna designers might find the description in this document to simplistic. More accurate and precise descriptions, as well as mathematical developments are described in depth in the documents listed at the last page.

Definition

An antenna is a conductive element which converts electrical energy into an electromagnetic field (transmit), or converts an electromagnetic field into electrical energy (receive).
An important feature is the property of reversibility: the same antenna can be used with the same characteristics as a transmit or as a receive antenna.
An antenna is characterized by its center frequency, bandwidth, polarization, gain, radiation pattern and impedance.

Acronyms and terms

λ Lambda   Wavelength, expressed in meters (m).
The propagation of the electromagnetic field is usually considered in free space, where it travels at the speed of light ($C = 3.10^8$ m/s).

$$\lambda_{(m)} = C / f_{(Hz)}$$

In the VHF / UHF band, the following expression is used:

$$\boxed{\lambda_{(m)} = 300 / f_{(MHz)}}$$

Example   f = 433.92 MHz λ = 300 / 433.92 = 0.691 meters
f = 915 MHz λ = 300 / 915 = 0.327 meters

VSWR   Voltage Standing Wave Ratio

dB   Decibel   For ease of use, values are given in dB
Refer to the chapter *A few figures* for dB conversion

dBm   The dBm is a power value, related to 1 mW

dBi   Value of gain related to the Isotropic reference antenna

Understanding the antenna

The basic phenomenon is easily described, while the in-depth understanding requires strong electromagnetic theory, out of range for this document.

A simple wire in which a current flows generates a magnetic field (H) and an electrical field (E). Both fields are perpendicular between them and also with respect to the wire. The surface generated by the electrical field (E) gives the reference for the polarization's direction.

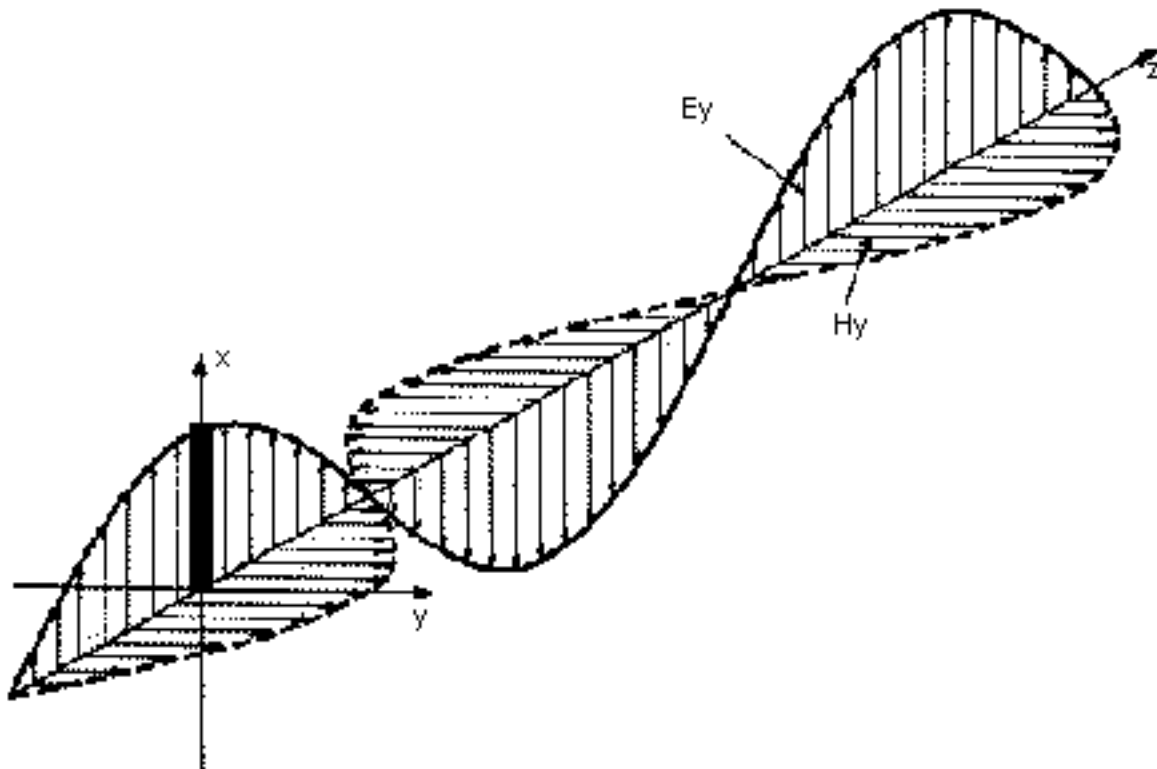The following figure illustrates a vertical polarization.

Fig. 1: Electromagnetic wave

Let us consider an alternative current. The antenna, a single wire only connected on one side, will behave like an impedance. The impedance is a function of various parameters such as wire length, wire shape, and dielectric constant of the environment.

An antenna should be considered as a passive RLC network. Like any RLC network, its characteristic impedance value is directly related to the frequency. Smith's chart is used to visualize the impedance. It is also a very helpful tool to complete the matching.

The maximum performance of the antenna, requires two conditions:

1. <u>Resonance:</u> It will be obtained at the centered frequency, when the characteristic impedance of the antenna is strictly resistive: the minimum reactive part should be observed at the considered frequency.
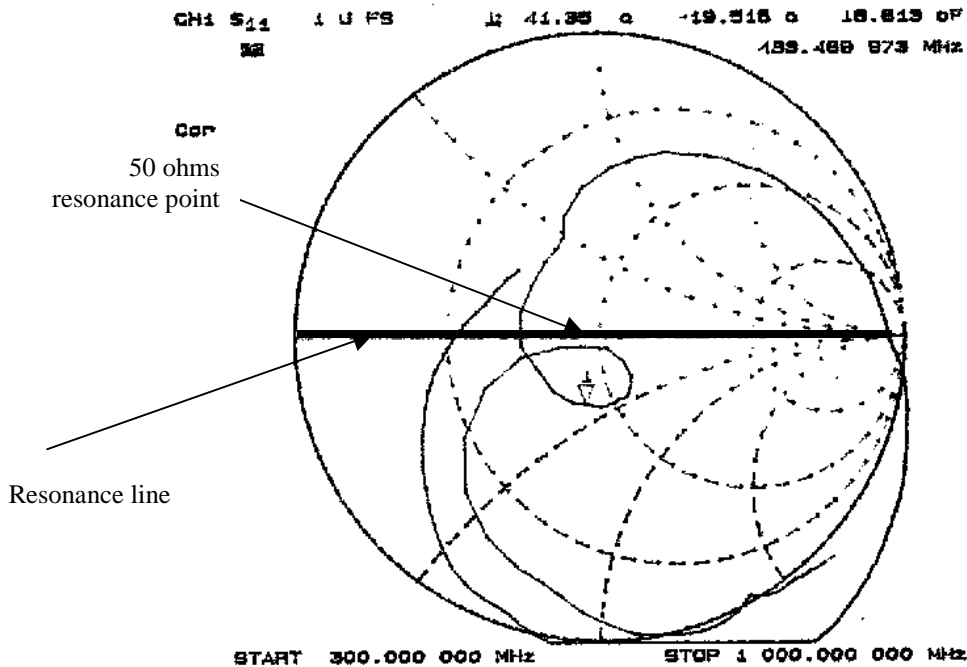

Fig.2 : Smith's Chart

2. <u>Matching:</u> A proper matching of the antenna to the feed point implies that both impedance are identical. This condition ensures that all the energy delivered by the feed point is converted in an electromagnetic field. In case of mismatch, a Standing Wave appears, and part of the energy returns to the transmitter.
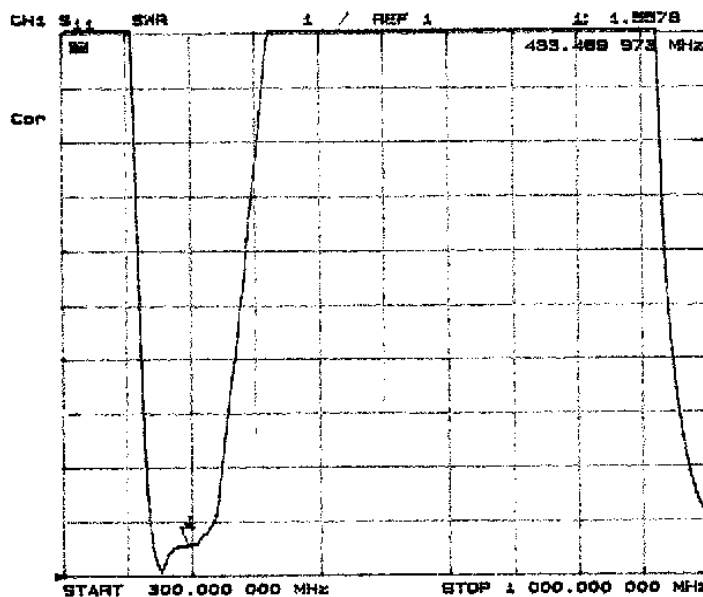

Fig.3: VSWR

The VSWR determines the amount of energy which is not converted by the antenna into an energy. The antenna can either radiate the energy (wanted), or turn it in heat (unwanted).

Measurements against a reference antenna should be made in order to understand if the energy is just burned, or radiated. So the equivalent drawing of an antenna looks like 4 elements connected in series : L, C, $R_{radiated}$, R_{loss} .

All the above explanation have been made for a transmitter feeding an antenna. The reversibility property of the antenna makes it also valid for the case of an antenna feeding a receiver.

The major difficulty with small antennas is the validity of the measurement performed: proximity of the hands, connectors, environment, may completely modify the measurement. It is recommended to perform measurements as close as possible from the final configuration.

Propagation

Usual frame for propagation measurement is the open field. Even though free space's characteristics differ slightly from the open field, it is the commonly used model. Estimation of transmission range in free space is given by

$$P_r = P_t.G_t.G_r.(\lambda / (4.\pi))^2.(1/d^2)$$

Where
P_r is the received power (dBm)
P_t is the transmitted power (dBm)
G_t is the gain of the transmitter's antenna (dB)
G_r is the gain of the receiver's antenna (dB)

This equation in <u>free space</u> is valid in the following conditions:
- Far field, i.e. over $2.D^2 / \lambda$, with D the overall diameter of the antenna. Practically, for the considered range of frequency, far field should start at a minimum of 3 or 4 times this distance.
- Minimum decoupling height between antennas and the ground of at least one λ
- Propagation distance is limited by the optical line of sight, itself limited by the earth's curve.

When the propagation is in urban areas or inside facilities, it may suffer from several damages:

1. Multipath effect, when waves bounce from one wall to another. It may cause some sort of echo on the receiver.

2. Multipath fading. The same effect can generate a very important fading if the bounced waves come back to the main one with a 180° shift.

3. Increase of attenuation: the $(1/d^2)$ model valid in open space can be reduced to $(1/d^3)$ or $(1/d^4)$ for propagation through concrete walls or windows for example.

Once again, a target free space range should be specified. But the real measurement happens on the site with all the difficulties specific to this location.

Antenna Types

Basically, an antenna is made out of 2 conductors. One of them is radiating with respect to the other. Bearing this consideration in mind, different shapes can be used, each of them having their specific properties.

As a general physical rule, an antenna's efficiency is directly proportional to its volume. As we will see in the next examples, the size of the antenna is also related to the wavelength. In other words, a small antenna operating on low frequencies doesn't have a chance to be efficient.

Reference antenna
Radiation pattern is purely isotropic, which means that it radiates equally in every x, y, z axis. As it is considered as the reference for any measurements, the gain is 0 dBi.

This antenna is a purely theoretical model because an isotropic radiation is not compatible with the electromagnetic vibration's nature. However, it is a very useful model because of all the simplifications brought to the calculations.

Dipole antenna
An antenna which length is multiple of $\lambda/2$ is a resonant antenna. The current distribution inside a half-wave dipole is as follows.
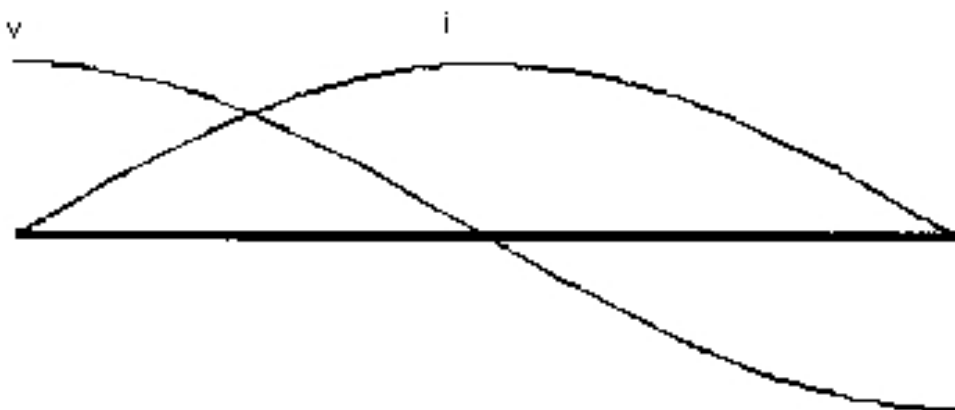
Wire length: $\lambda/2$

Fig.4: Resonant antenna

Let us suppose that the wire is fed by its center point, and we have a resonant dipole antenna.

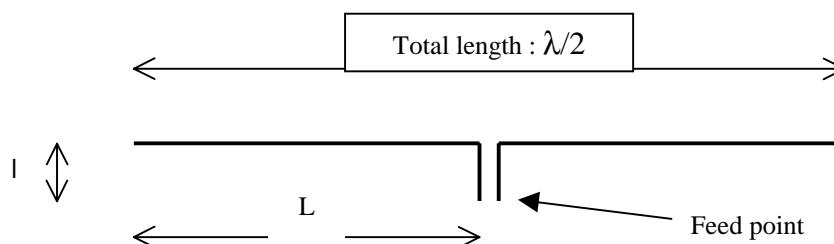The following description is also called the Lenz antenna.

Fig.5: Lenz antenna

For a practical application in 434 MHz, the following values give good results:

      Diameter of the poles: 4 mm

      l : 10 mm

      L: 157.5 mm

      Spacing between both poles: 6 mm (10 mm between pole's center)

The total length of this antenna is 2 x 157.5 + 6 = 321 mm, and $\lambda/2$ is 691/2 = 345 mm

So the real antenna length is 0.93 x $\lambda/2$.

Measured impedance of this antenna is slightly above 50 Ω. Gain expected is close to 2 dBi.

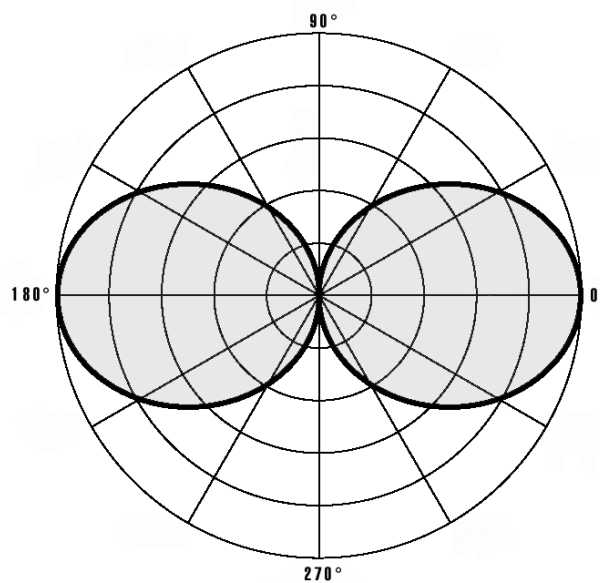The radiation pattern is omnidirectional in the E plan

Fig.6: $\lambda/2$ radiation pattern

The dipole antenna is typically an external antenna used when the horizontal range optimization is required.

Quarter Wave
The quarter wave antenna is the simplest model of antenna: it only requires a rigid wire and a ground plane.
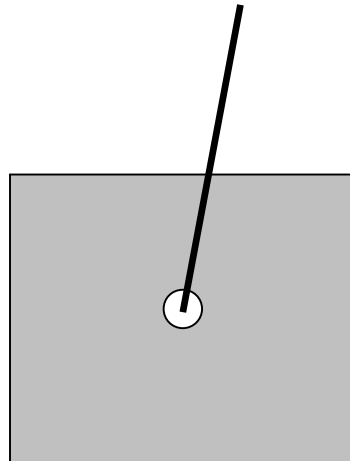

Fig.7: λ/4 antenna

The quarter wave antenna (λ/4 length) must radiate with respect to a ground plane. The ground plane can be either the PC board itself, or the metal case of the outlet. In both cases, make sure the wire is vertical to get the highest impedance. Anyhow, the impedance value will remain under 50 Ω. If the antenna is tilted parallel to the ground, the impedance value will decrease significantly.

The λ/4 length is purely theoretical. Depending on the nature of the wire and the geometry of the ground plane, consider the length as (k . λ/4) with k comprised between 0.93 and 0.98 . Wire size should be at least 0.34 mm^2 (AWG 22).

In case the antenna is to be set outside the case, the radiating length to be considered is only the part outside the case. However, the connection from inside the case to the PC board must be done with an adapted coaxial cable.
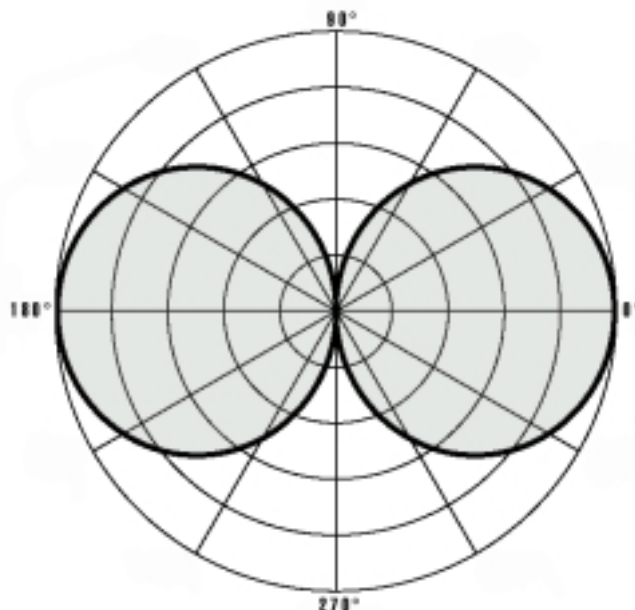

Fig.8: λ/4 radiation pattern

Compared to the λ/2 dipole, the radiation pattern in the E plane looks much rounder: lobes go higher in altitude, but not as far away (negative gain: - 4.5 dBi).In many data-sheets, the quarter wave antenna is the reference antenna, hence with a 0 dBi gain.

Loop
The loop antenna's main advantage is its cost, directly included in the cost of the PC board. Polarization is on the same surface as the PC board, with an omnidirectional radiation pattern. The variable tuning capacitor may be replaced by a fixed capacitor when the value has been determined, depending upon the location of the PC board.

This antenna has a theoretical gain of –5dBi. The realization showed a gain closer to –8dBi, due to the very poor tg σ of the FR4 substrate.

The components must be placed in the center of the PC board, leaving a gap over 3.5 mm to the antenna. When inserting the PC board inside a case, make sure the case is not shielded, that no screws would come closer than 4 mm to antenna. Make sure also that no external wires cross the antenna's layout on its surface.

The design is optimized for an FR4 PC board 0.5 mm thick, 35 um copper and 1 um gold covering. With a series capacitor of 10 pF, the impedance is exactly 75 ohms at 433.92 MHz, giving a VSWR close to 1.5 .
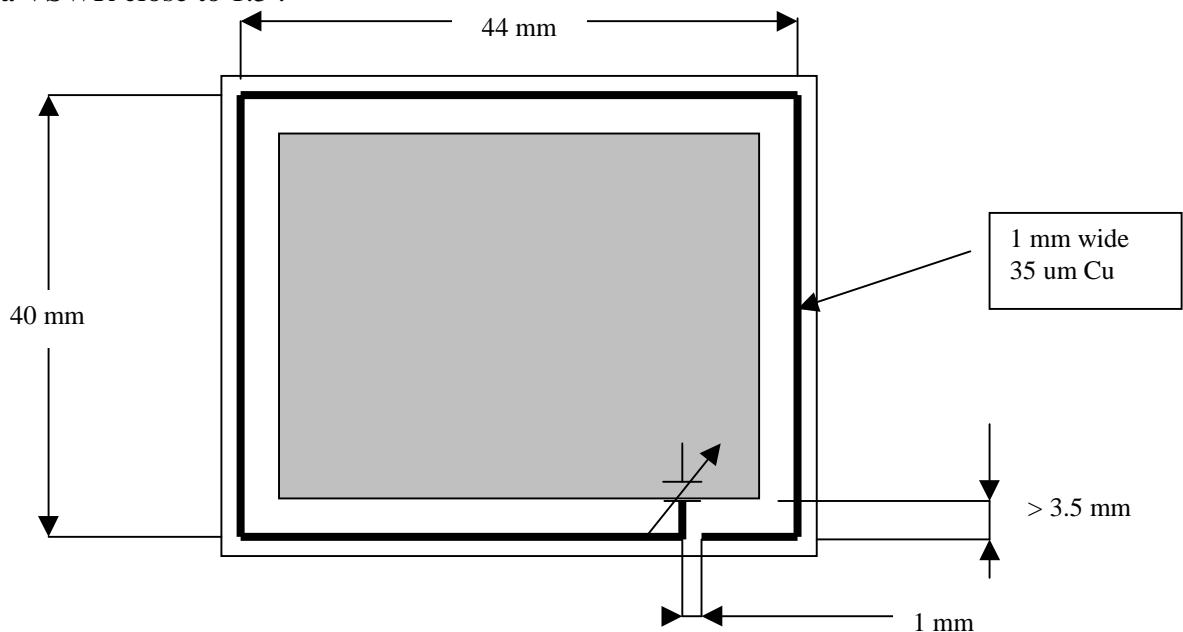

Fig.9: loop antenna

The loop antenna is perfect for portable instruments which are not to demanding in terms of range. Beware of attenuation and directivity caused by body effect in case the antenna is to be placed close to the body.

Helical
The helical antenna is very space effective, and also quite easy to setup. Unfortunately, it is very difficult to define a theoretical model for this kind of antenna. So tuning has very much to do with empirical maneuvers. An important parameter to bear in mind is the difficulty to fix the resonant point of this antenna due to its narrowband characteristic.

Directivity is an important character of the helical antenna. Unlike all of the above described antennas the gain cannot be expressed as an isotropic gain in the E plane. Also, polarization can not be considered as horizontal or vertical. It has more to do with an ellipsoidal polarization.

Parameters are the following for a defined frequency, with a sample of values working correctly for the 434 MHz:

- Material used, and section of the wire   Copper, 0.34 mm^2
- Section of the coil   5.5 mm
- Number of turns   15
- Spacing between each coil   Stretch to tune

When the correct spacing has been found, it is important to keep this value. We recommend to fix the last coil on the PC board with a slight drop of glue. Beware not to fill the whole coil with glue as it might change significantly the dielectric constant in which the field is generated, hence de-tuning the antenna.

An approximation of the inductance value of the coil can be given as

$$L_{(\mu H)} = d^2 n^2 / (18d + 40l)$$

Where L is the inductance in microhenrys,
d is the external diameter of the coil in inches (from wire centers)
n the number of turns
l the coil length in inches

Patch
More often used at higher frequencies, the patch antenna's main advantage is the real omni-directional pattern. The drawback is definitely the very sharp bandwidth available.

Like any other antenna type, the patch antenna is heavily dependant on the dielectric constant of the substrate. Commonly used substrate is the FR4 epoxy board. Unfortunately, this doesn't design very precisely the substrate, which has been measured from 4 to 4.7, depending on the source.

The following results show the difference:
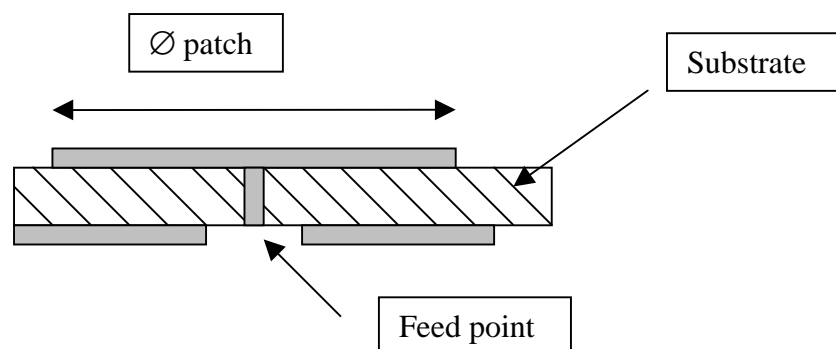The patch is circular, fed in its center.

Fig.10: Patch antenna

Patch diameter: 20.10 cm

	Center frequency	Bandwidth VSWR = 2	Impedance
εr = 4 1.6 mm thick	433.920 MHz	1.7 MHz	163.5 + j4.2
εr = 4.7 1.6 mm thick	400.405 MHz	1.7 MHz	155.3 + j3.9

So the same patch behaves totally differently with 2 different sources of FR4.
The reader may also notice that the impedance is very different from the conventional 50 Ω.
Which means that the patch needs a matching close to its feed point in order to use a coaxial connector.

Rules of thumb

Center frequency
Depends on the size of the wire. For fine tuning, take a wire just a little bit longer than the theoretical value, perform field measurement, and shorten until the correct value is obtained.

Bandwidth
Depends on the width of the wire. The bandwidth will depend on the number of channels required, the data rate, the kind of modulation used. If a large bandwidth is required, use a rather thick wire.

Polarization
Needs to be the same on both sides. Prefer a horizontal polarization which gives better immunity against industrial noise in most cases.

Gain
Might be a wanted or unwanted effect. If the gain is omnidirectional ($\lambda/2$ compared to $\lambda/4$ antenna), it is probably a wanted effect. In the case of an antenna placed close to another object, some reflection might occur, enhancing the electromagnetic field in one direction, but reducing it in the opposite direction. To double the free space range, the gain must be +6 dB above the reference.
The gain can be a positive figure, or a negative in case the output power is lower than the references.

Radiation pattern
Dependant upon the shape of the antenna. Place the receiver's antenna in the horizontal plane perpendicular to the transmitter's antenna. Beware that a high gain antenna may have a flatter radiation pattern of the E field. If the antennas may move otherwise than on a horizontal plane, it might be worth considering a lower gain antenna.
Like for the gain, the proximity of an antenna with other objects might disturb the radiation pattern. The body effect is an example of radiation pattern disturbance.

Impedance
Closely related with the center frequency. The reactive part of the impedance will be mostly reduced when the antenna resonates at the correct frequency. For most applications 50 ohms is the reference impedance. Impedance relies very much on the close environment of the antenna. Make sure the measurements are made as close as possible to the final environment.

Antenna matching

Antenna matching is critical in order to get the lowest VSWR, i.e. the best amount of energy transmitted to the antenna.

Several techniques are available for antenna matching. The easiest, because the most visual, is the Smith's chart. Let us with an example make our antenna a perfectly resonant antenna, as close as possible to 50 Ω.
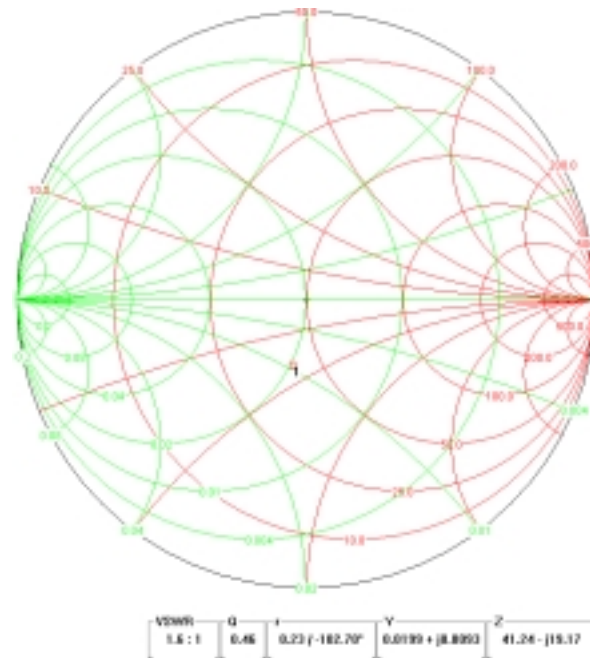

Fig.11: Smith's Chart
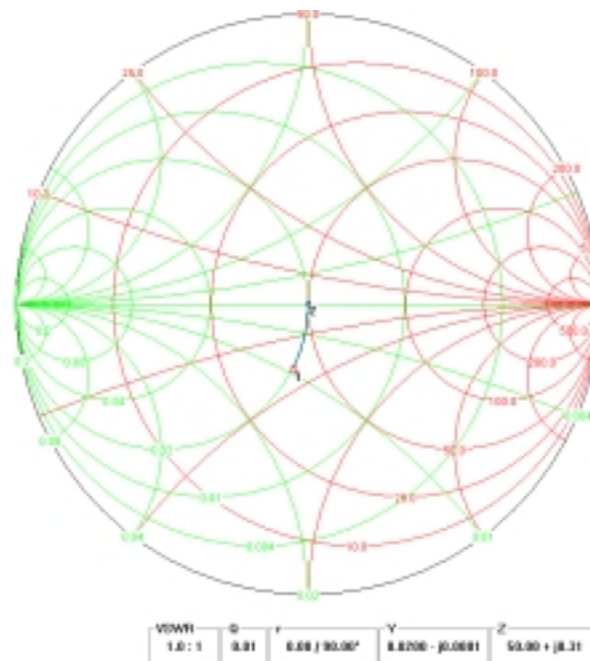
Impedance is 41.24 – j19.17 ohms at 434 MHz

Fig.12: Smith's Chart

Add a 33 nH shunt inductor and you get a perfect 50 ohms resonance point at 434 MHz

The adjunction of shunt or series inductor or capacitor changes the position of the initial point on the chart. For more details we recommend Artech, Advanced Automated Smith Chart.

A few figures

Decibel conversion

Power (mW) in dBm:

$$P_{(dBm)} = 10 \, \text{Log} \, P_{(mW)}$$

Voltage (mV) to dBmV:

$$U_{(dBmV)} = 20 \, \text{Log} \, U_{(mV)}$$

VSWR

$$SWR = (1 + |\rho|) / (1 - |\rho|)$$

With ρ , reflection coefficient magnitude defined as

$$\rho = \sqrt{(\text{Power reflected} / \text{Power forward})}$$

VSWR	Transmitted Power = 1 – Power reflected	Reflection Coefficient
1	100 %	0
1.222	99 %	0.100
1.925	90 %	0.316
2.61	80 %	0.445
3	75 %	0.500
4.4	60 %	0.631
5	55 %	0.666
11.8	30 %	0.844

Microstrip line impedance
Material: FR4, impedance 50 Ω

Board ⇒ Copper	0.5 mm	1.5 mm	1.6 mm
35 μm	0.84 mm	2.66 mm	2.85 mm
70 μm	0.78 mm	2.6 mm	2.78 mm

Fig.13: Microstrip line

Bibliography

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       Kazimierz Siwiak; 1995

3. Artech, Advanced Automated Smith Chart, Version 3.0: Software and User's Manual
       Leonard Schwab; 1998

4. ARRL, ARRL Antenna Book, © 1997 – 18th edition

Drawings