The Basics of Patch Antennas

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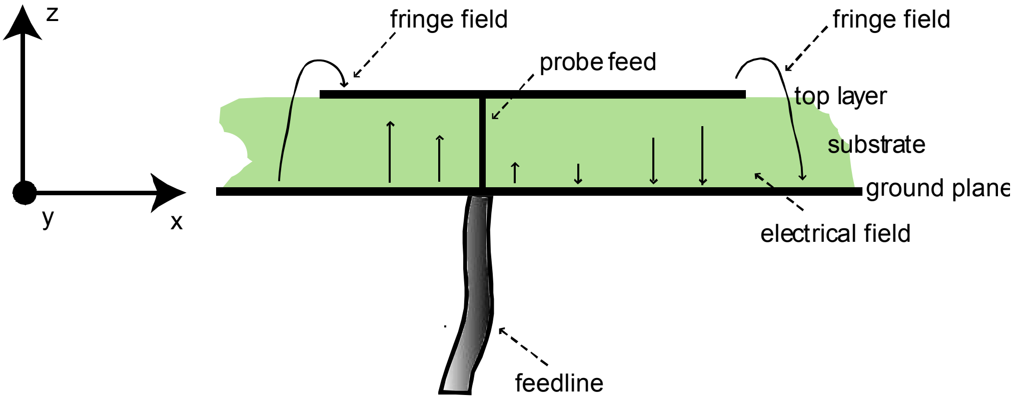
Introduction

This article introduces some of the basic concepts of patch antennas. The main focus will be on explaining the general properties of patch antennas by using the simple rectangular probe-fed patch. It will cover topics including: principles of operation, impedance matching, radiation pattern and related aspects, bandwidth, and efficiency.

Properties of a Basic Microstrip Patch

A microstrip or patch antenna is a low-profile antenna that has a number of advantages over other antennas -- it is lightweight, inexpensive, and easy to integrate with accompanying electronics. While the antenna can be 3-D in structure (wrapped around an object, for example), the elements are usually flat; hence their other name, planar antennas. Note that a planar antenna is not always a patch antenna.

The following drawing shows a patch antenna in its basic form: a flat plate over a ground plane (usually a PC board). The center conductor of a coax serves as the feed probe to couple electromagnetic energy in and/or out of the patch. The electric field distribution of a rectangular patch excited in its fundamental mode is also indicated.



The electric field is zero at the center of the patch, maximum (positive) at one side, and minimum (negative) on the opposite side. It should be mentioned that the minimum and maximum continuously change side according to the instantaneous phase of the applied signal. The electric field does not stop abruptly at the patch's periphery as in a cavity; rather, the fields extend the outer periphery to some degree. These field extensions are known as fringing fields and cause the patch to radiate. Some popular analytic modeling techniques for patch antennas are based on this leaky-cavity concept. Therefore, the fundamental mode of a rectangular patch is often denoted using cavity theory as the TM10 mode.

Since this notation frequently causes confusion, we will briefly explain it. TM stands for transversal magnetic field distribution. This means that only three field components are considered instead of six. The field components of interest are: the electric field in the z direction, and the magnetic field components in x and y direction using a Cartesian coordinate system, where the x and y axes are parallel with the ground-plane and the z-axis is perpendicular. In general, the modes are designated as TMnmz. The z value is mostly omitted since the electric field variation is considered negligible in the z-axis. Hence TMnm remains with n and m the field variations in x and y direction. The field variation in the y direction (impedance width direction) is negligible; thus m is 0. And the field has one minimum-to-maximum variation in the x direction (resonance length direction); thus n is 1 in the case of the fundamental. Hence the notation TM10.

Dimensions

The resonant length determines the resonant frequency and is about $\lambda/2$ for a rectangular patch excited in its fundamental mode. The patch is, in fact, electrically a bit larger than its physical dimensions due to the fringing fields. The deviation between electrical and physical size is mainly dependent on the PC board thickness and dielectric constant.

A better approximation for the resonant length is:

$$L \approx 0.49\ \lambda_d = 0.49\ \frac{\lambda_0}{\sqrt{\varepsilon_r}}.$$

This formula includes a first order correction for the edge extension due to the fringing fields, with:

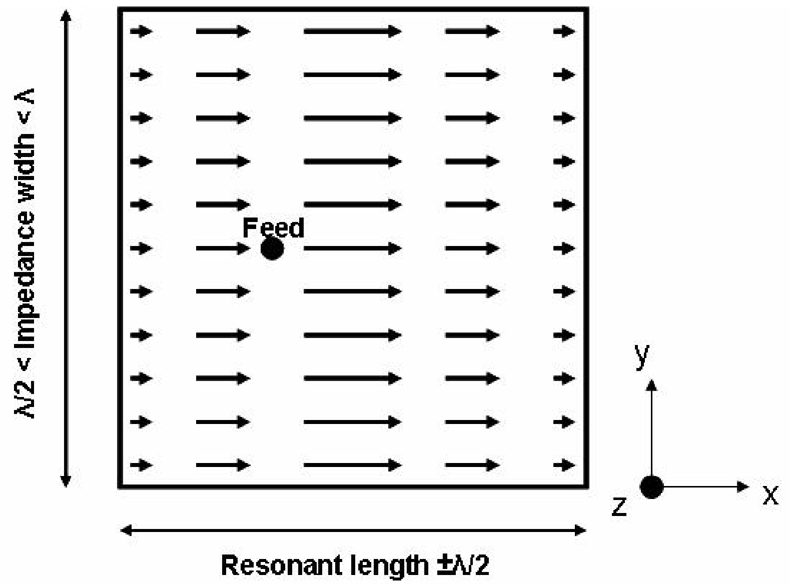
- L = resonant length
- λ_d = wavelength in PC board
- λ_0 = wavelength in free space
- ε_r = dielectric constant of the PC board material

Other parameters that will influence the resonant frequency:

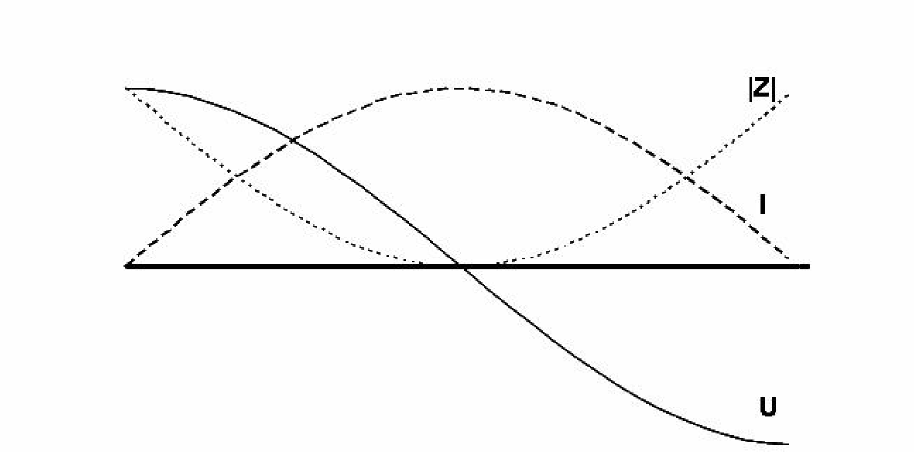
- Ground plane size
- Metal (copper) thickness
- Patch (impedance) width

Impedance Matching

Looking at the current (magnetic field) and voltage (electrical field) variation along the patch, the current is *maximal* at the center and *minimal* near the left and right edges, while the electrical field is *zero* in the center and *maximal* near the left and *minimal* near the right edges. The figures below clarify these quantities.



Current distribution on the patch surface.



Voltage (U), current (I) and impedance (|Z|) distribution along the patch's resonant length

From the magnitude of the current and the voltage, we can conclude the impedance is minimum (theoretically zero Ω) in the middle of the patch and maximum (typically around 200 Ω, but depending on the Q of the leaky cavity) near the edges. Put differently, there is a point where the impedance is 50 Ω somewhere along the "resonant length" (x) axis of the element.

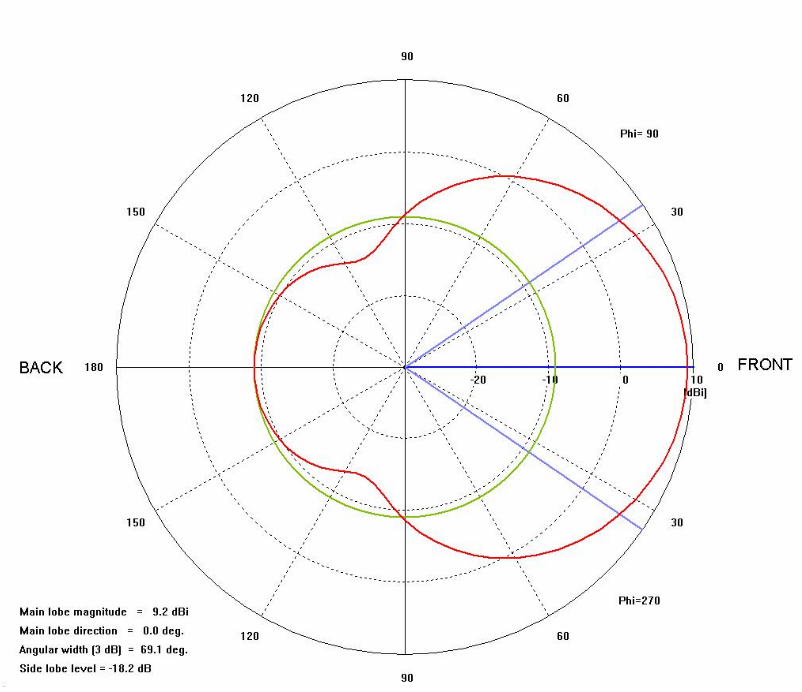
Fundamental Specifications of Patch Antennas

Radiation Pattern

The patch's radiation at the fringing fields results in a certain far-field radiation pattern. This radiation pattern shows that the antenna radiates more power in a certain direction than another direction. The antenna is said to have certain directivity. This is commonly expressed in dB.

An estimation of the expected directivity of a patch can be derived with ease. The fringing fields at the radiating edges can be viewed as two radiating slots placed above a ground-plane. Assuming all radiation occurs in one half of the hemisphere, this results in a 3 dB directivity. This case is often described as a perfect front-to-back ratio; all radiation towards the front and no radiation towards the back. This front-to-back ratio is highly dependent on ground-plane size and shape in practical cases. Another 3 dB can be added since there are 2 slots. The slots are typically taken to have a length equal to the impedance width (length according to the y-axis) of the patch and a width equal to the substrate height. Such a slot typically has a gain of about 2 to 3 dB (cfr. simple dipole). This results in a total gain of 8 to 9 dB.

The rectangular patch excited in its fundamental mode has a maximum directivity in the direction perpendicular to the patch (broadside). The directivity decreases when moving away from broadside towards lower elevations. The 3 dB beamwidth (or angular width) is twice the angle with respect to the angle of the maximum directivity, where this directivity has rolled off 3 dB with respect to the maximum directivity. An example of a radiation pattern can be found below.



Typical radiation pattern of a simple square patch.

So far, the directivity has been defined with respect to an isotropic source and hence has the unit dB*i*. An isotropic source radiates an equal amount of power in every direction. Quite often, the antenna directivity is specified with respect to the directivity of a dipole. The directivity of a dipole is 2.15 dB*i* with respect to an isotropic source. The directivity expressed with respect to the directivity of a dipole has dB*d* as its unit.

Antenna Gain

Antenna gain is defined as antenna directivity times a factor representing the radiation efficiency. This efficiency is defined as the ratio of the radiated power (Pr) to the input power (Pi). The input power is transformed into radiated power and surface wave power while a small portion is dissipated due to conductor and dielectric losses of the materials used. Surface waves are guided waves captured within the substrate and partially radiated and reflected back at the substrate edges. Surface waves are more easily excited when materials with higher dielectric constants and/or thicker materials are used. Surface waves are not excited when air dielectric is used. Several techniques to prevent or eliminate surface waves exist, but this is beyond the scope of this article.

Antenna gain can also be specified using the total efficiency instead of the radiation efficiency only. This total efficiency is a combination of the radiation efficiency and efficiency linked to the impedance matching of the antenna.

Polarization

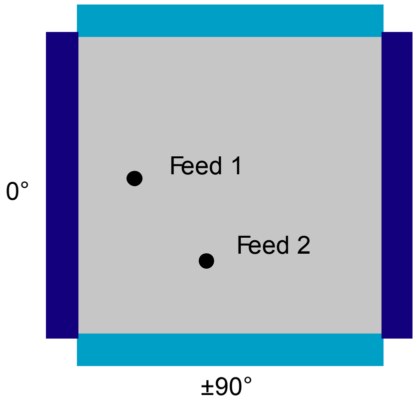
The plane wherein the electric field varies is also known as the polarization plane. The basic patch covered until now is linearly polarized since the electric field only varies in one direction. This polarization can be either vertical or horizontal depending on the orientation of the patch. A transmit antenna needs a receiving antenna with the same polarization for optimum operation. The patch mentioned yields horizontal polarization, as shown. When the antenna is rotated 90°, the current flows in the vertical plane, and is then vertically polarized.

A large number of applications, including satellite communication, have trouble with linear polarization because the orientation of the antennas is variable or unknown. Luckily, there is another kind of polarization -- circular polarization. In a circular polarized antenna, the electric field varies in two orthogonal planes (x and y direction) with the same magnitude and a 90° phase difference. The result is the simultaneous excitation of two modes, i.e. the TM10 mode (mode in the x direction) and the TM01 (mode in the y direction). One of the modes is excited with a 90° phase delay with respect to the other mode. A circular polarized antenna can either be right-hand circular polarized (RHCP) or left-hand circular polarized (LHCP). The antenna is RHCP when the phases are 0° and -90° for the antenna in the figure below when it radiates towards the reader, and it is LHCP when the phases are 0° and 90°.

From this, it is clear what needs to be done in order to get circular polarization, namely:

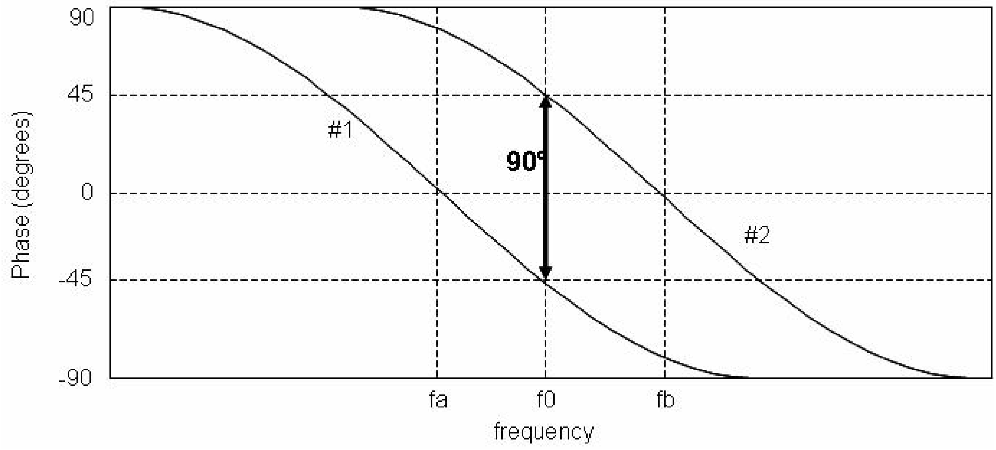
- Split the signal in two equal parts.
- Feed one signal to a horizontal radiator and the other to a vertical radiator (in this case, each radiator is a pair of radiating edges of the patch antenna is indicated in figure below).
- Change the phase of one of the signals by 90°.

Splitting the signal in half can be done with a Wilkinson power divider or similar splitter. If a square patch is fed with two feed points as depicted in the figure below, a vertical and a horizontal radiator are created concurrently. By creating the 90° delay in one of the signal lines and connecting each signal to one feeding pin of the patch, a circularly polarized antenna is created.



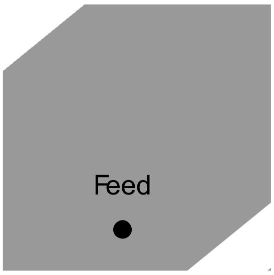
Though this works well, the splitter and delay line take up valuable board space, and they also tend to radiate and degrade radiation pattern.

Another approach is to see the patch as a parallel RLC resonant circuit. This means a phase shift that changes versus frequency is present, as shown in the following plot:



Since there are two resonances, fa and fb (two modes), there are two RLC circuits. When the corresponding resonance frequencies are slightly different, there is a small frequency band where the phase difference of the two RLC circuits is 90°.

Thus circular polarization can be achieved by building a patch with two resonance frequencies in orthogonal directions and using the antenna right in between the two resonances at f0. It is important that the two modes are excited equally strong and with a 90° phase difference. A number of ways exist to implement this, but cutting two corners off the element -- the so-called corners truncated patch -- is a technique widely used in GPS antennas (see figure below). Note, however, that this technique inherently has a lower circular polarization bandwidth than the double fed patch, whose polarization bandwidth is mainly limited by the splitter-phase shifter bandwidth.



The quality of the circular polarization is commonly quantified as the axial ratio (AR), expressed in dB. A 3 dB axial ratio is considered sufficient for most applications. From the outline given previously, it is clear that the axial ratio varies with frequency and has an optimum (0 dB) right in between the resonance frequencies of the two excited modes. However, it is not noticeable in the previous outline that the axial ratio varies with elevation as well. The axial ratio is mostly optimal at broadside (in the direction of z-axis) and degrades towards lower elevations (away from z-axis). The degree of degradation is highly dependent on the antenna geometry. Most antenna vendors only specify one axial ratio value or an axial ratio variation versus frequency, and they don't say anything about axial ratio variation versus elevation.

Another way of expressing the quality of circular polarization is showing the co- and cross-polar radiation patterns. The co-polar radiation pattern is the radiation pattern of the wanted polarization, and the cross-polar radiation pattern is the radiation pattern of the unwanted opposite polarization.

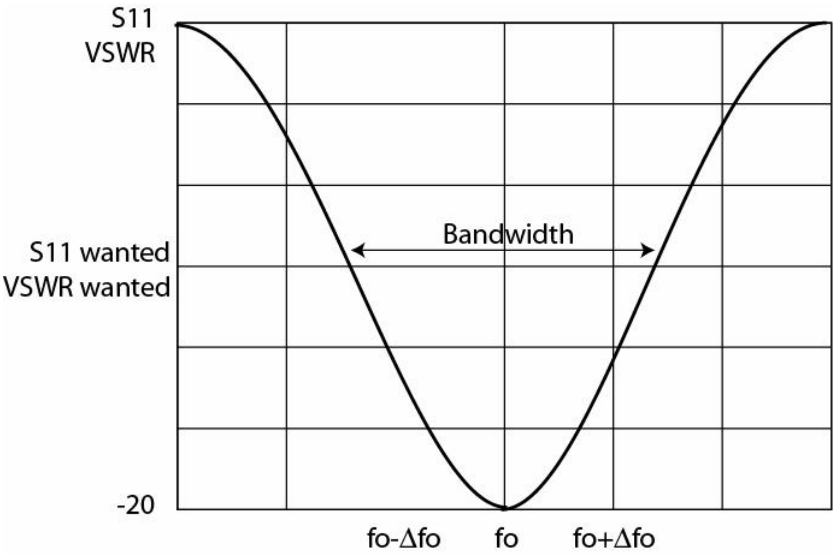
Bandwidth

Another important parameter of any antenna is the bandwidth it covers. Only impedance bandwidth is specified most of the time. However, it is important to realize that several definitions of bandwidth exist -- impedance bandwidth, directivity bandwidth, polarization bandwidth, and efficiency bandwidth. Directivity and efficiency are often combined as gain bandwidth.

Impedance bandwidth/return loss bandwidth

This is the frequency range wherein the structure has a usable bandwidth compared to a certain impedance, usually 50 Ω.

The impedance bandwidth depends on a large number of parameters related to the patch antenna element itself (e.g., quality factor) and the type of feed used. The plot below shows the return loss of a patch antenna and indicates the return loss bandwidth at the desired S11/VSWR (S11 wanted/VSWR wanted). The bandwidth is typically limited to a few percent. This is the major disadvantage of basic patch antennas. Several techniques to improve the bandwidth exist, but these are beyond the scope of this article.



Important note: Several vendors use different definitions of impedance bandwidth, such as: VSWR = 2:1 and other values, S11 values other than –10 dB, the maximum real impedance divided by the square root of two [Z(Re)/√2, bandwidth], etc. This tends to turn selecting the right antenna for a specific application into quite a burden.

Directivity/gain bandwidth
This is the frequency range wherein the antenna meets a certain directivity/gain requirement (e.g., 1 dB gain flatness).

Efficiency bandwidth
This is the frequency range wherein the antenna has reasonable (application dependent) radiation/total efficiency.

Polarization bandwidth
This is the frequency range wherein the antenna maintains its polarization.

Axial ratio bandwidth
This bandwidth is related to the polarization bandwidth and this number expresses the quality of the circular polarization of an antenna.

Conclusions

In this article, the basic properties of linear and circular polarized patch antennas have been covered. We defined a basic set of specifications that allow the user to understand and write a set of requirements for a specific application. Besides the ones covered here, many more design options and different implementations of patch antennas are available. Coverage of these alternatives is beyond the scope of this article, but they should be considered during the specification and development phases of the antenna.