# Small Antennas Designed on Printed Circuit Boards

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**Abstract:** This paper covers the case summary for the steps to scale small antenna design on PCB boards while keeping the same bandwidth, Radiation Resistance, and Efficiency. Empirical design of small PCB antennas can be costly and time consuming when trying to port an existing design to a new layout. In order to keep the design cost low, design time minimum and maintain antenna performance this paper discusses the procedure for creating an antenna design on PCB material and validates through the use of current software tools available to an engineer.

## Introduction

Normal antennas are designed to operate in air and have well known equations for designing the antenna and setting the antennas performance in air. This paper continues the discussion by implementation of the PCB antenna based upon antenna theory, RF micro strip theory and electrical models of the antenna. The rules for reducing a 3-dimesnional antenna to a 2-D dimensional plane are reviewed. But the main topic is discussing the how the structures efficiency is maintained through the process.

## PCB Small Antennas

Placing an antenna on PCB FR4 material reduces the antenna wavelength since the wavelength is a function of media and air. The wavelength slows when waves travel through a media so setting the antenna parameters involves determining the corrections for the new media. Through the use of today's 3-D Magnetic software tools and measurements it's some what simple to show how the PCB antenna can achieve high efficiency even with changes in media thickness.

A radiator in air has a wavelength set by $\lambda = \frac{c}{f}$ (m/sec), where c is the speed of light and f is the resonant frequency. For a dipole antenna placed in free space with two opposing dipoles as shown in Figure 1, it consisting of radiators (red and yellow) as shown in the diagram. If you insert FR4 material and copper metal you affectively control the 2nd dipole through the size of the ground plane. This type of antenna is normally termed a monopole antenna.

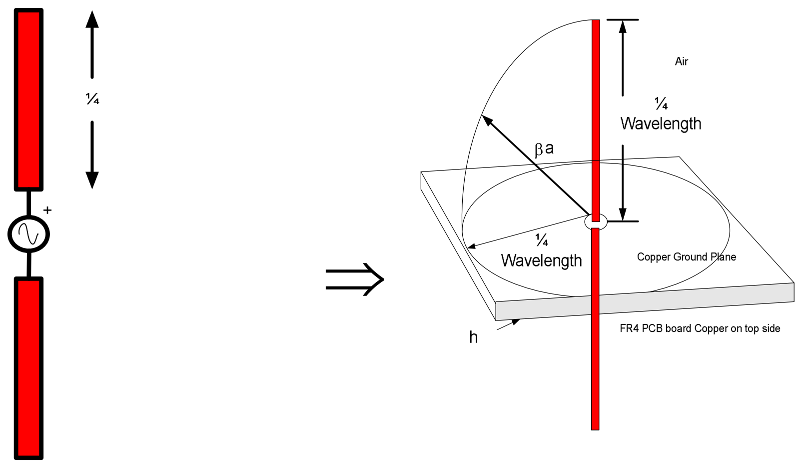


**Figure 1, Dipole in Air & with Dielectric**

If the ground is set to a ratio of the radiator's wavelength in this case ¼ wavelengths it allows for use of one antenna radiator while the other is now ground. The ground in is orthogonal to the primary radiator, but one can imagine an imaginary radiator still exist. Reducing the antenna from 3-D to 2-D is done in steps by applying imagining and reciprocity theorems that results in folding of planes at multiples the wavelength. After several folds the antenna a 2-Dimension antenna results over FR4 and a PCB antenna while virtual images still are present for the second radiator.

Early studies by "Wheeler and Chu" defined the antennas pattern in terms of ground and its electrical properties, Q and Bandwidth (BW)[12].

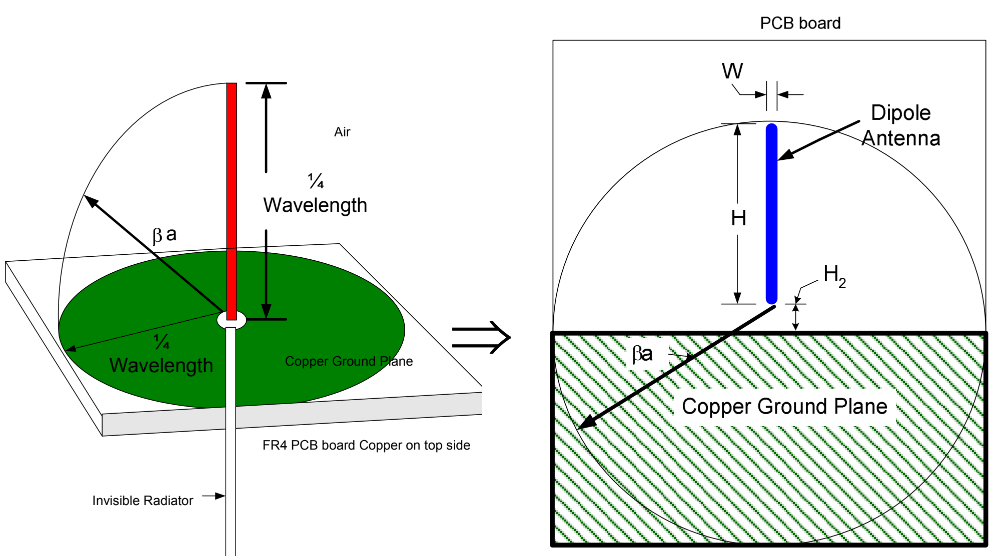

**Figure 2, 3-D to 2-D Antenna**

Since the ground plane now sets the directivity and gain we have all the adjustments to properly set the antenna performance. The antenna can be rotated so it's on the same plane as the ground where the radiator is now touching laminated FR4 material just above the ground plane. Since the wave must travel half in air and half in the media, we can define a velocity factor to correct for the wave speed. The follow equation is used to derive the correction for effective velocity due to permittivity of two media, $\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \cdot \frac{1}{\sqrt{1 + \frac{12 \cdot h}{w}}}$ where $\varepsilon_r$ is the permittivity of the FR4 laminate, "h" is the thickness of the laminate and "w" is the radiator width.

Using "Wheeler or Chu" equations to define the grounds ratio for Omni-Directional pattern defines the "a" term in the ratio "βa". Where β is the $\frac{2\pi}{\lambda}$ or radians/length.

Using "Wheeler's or Chu's equations $Q = \frac{1}{(\beta a)^3} + \frac{1}{\beta a}$, and select a Q that allows for the correct bandwidth where the antenna's bandwidth is derive from the equation of $BW = \frac{VSWR - 1}{Q \cdot \sqrt{VSWR}}$. From this equation it is apparent you cannot design the antenna for a VSWR of 1. At the same time the upper limit is set by ratio of a to ground planes directivity. For Omni-directional pattern the value of "a" is 1. A typical industry standard for VSWR is 1.2. Plotting the two components as seen in Figure 3, the antenna has a finite range for Q and bandwidth for a desired antenna pattern of Omni-directional. Selecting a typical value for antenna's VSWR of 1.2 the Q then decreases as bandwidth increases. Consequently as Q increases the bandwidth decreases for the antenna.

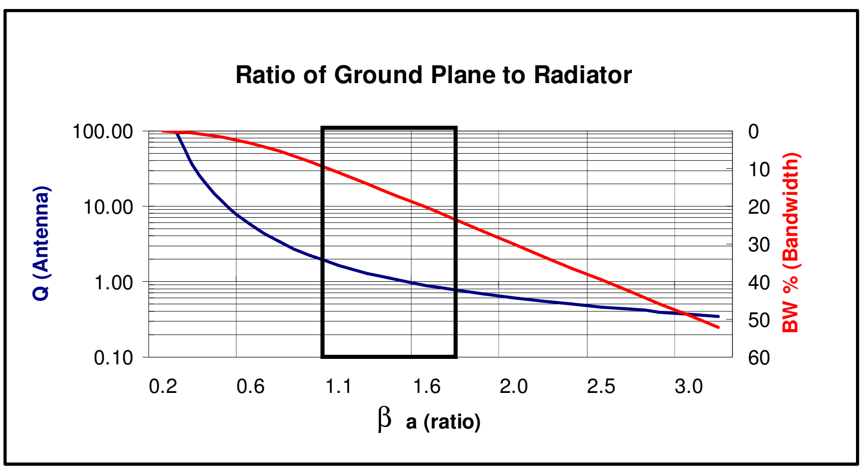


**Figure 3, Plot of Q and BW**

An open radiator can be modeled as a series RLC components as seen in Figure 4 and associate the component values for Q to achieve the bandwidth. In addition the antenna radiator must output the correct power to meet high efficiency. This occurs when the fields of E x H are maximum at the desired wavelength.

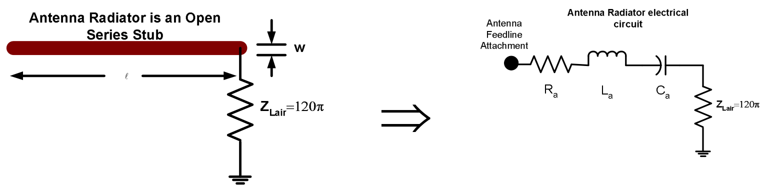


**Figure 4, Electrical Model**

The impedance for the dipole antenna is $Z_a(\omega) = R_a + X_a$, where $R_a = r_{ohmic} + R_r$. $R_r$ is the resistance due to the radiated field. $X_a = X_{La} - X_{ca}$ is the imaginary impedance of the radiator.

To achieve high efficiency the current through the radiator is maximum or stated more simply when the impedance allows maximum power to occur at the input. For quarter wave antenna this is when $R_a = 36$ ohms.

The Q for the antenna is $Q = \frac{X_a}{R_a}$, so when Q equal to 1 then $X_a$ is also equal to 1 at the resonant frequency.

A dipole radiator model equates to the trace similar to micro strip line but for our case the ground is not underneath the radiator but on the same side and below the radiator. This is shown in Figure 5, Vertical Dipole on PCB materialbelow. The distance "d" is much greater than micro strip constraint where radiator width is larger than the dielectric thickness spaced between ground plane and radiator. Instead the radiators capacitance is very small compared to the radiator's inductance.

Efficiency is measurement of Power into the radiator to Power outputted by the radiator.

$$Antenna\_efficiency = \frac{P_o}{P_{in}} \cdot 100\%$$

To reduce the antenna folding the radiator to a vertical position like Figure x reduces PCB board's size. At the same time it increases the capacitance to inductance ratio to allow proper tuning of the antenna's resonance and setting its input impedance for a high efficiency number.

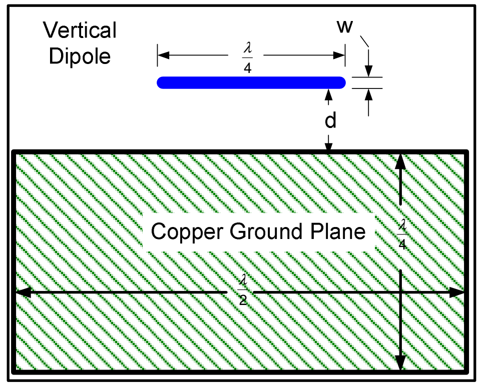


**Figure 5, Vertical Dipole on PCB material**

Power to the antenna is simply a function of the input impedance set to the optimum value so most of the current flows into the radiator.

The radiator's width sets the value of input impedance and its length sets the resonance frequency. The length of the antenna is the resonance frequency reduces its effective length by the velocity factor which is $V_f = \frac{1}{\sqrt{\varepsilon_{eff}}}$ or $\ell = V_f \cdot \lambda_{air}$.

The width of the antenna trace is approximated by the following equation, $L_a = \frac{\mu_r \mu_o}{\pi} \cosh^{-1} \frac{d}{w}$ by equating the $X_{La} = 2\pi f_r L_a = 36$ and solving as a function of the distance "d". The antenna resonant frequency is equal to $f_r = \frac{1}{2\pi(L_a \cdot C_a)}$, but the capacitance is a function of the spacing between the radiator and ground and can be derived by the following equation. $C_a = \varepsilon_{eff} \cdot \varepsilon_o \frac{A}{d}$. The "A" is the copper thickness times the radiator length, $\varepsilon_o = 8.854e^{-12}(\frac{F}{m})$. Since the ground is larger it allows for tuning the capacitance at the value of "d" defined for the width of the radiator.

Now the antenna resonant frequency is set and the input impedance is set. The input impedance corrected for PCB thickness will measure approximate impedance of 36+j220. Using micro strip open and short stubs the antenna impedance is altered to match a typical transmission input of 50+j0. Adding shorting stub to the input of the antenna moves to an input impedance of 36+j22.5 then impedance line to change the input impedance to 50+j0.

This creates the commonly know antenna of inverted F. The antennas efficiency is also spec in terms of the antennas directivity and gain numbers. For an Omni-directional antenna the directivity is 1.59 or 2.21dBi and the gain must be set to 1.59 or 2.21dBi.

Then efficiency is defined as $\varepsilon_a = \frac{G}{D}$. The system efficiency is $\varepsilon_{system} = \varepsilon_{a\cdot} \cdot \varepsilon_{match}\varepsilon_r$, where $\varepsilon_{maatch}$ is the reflection mismatch, and $\varepsilon_r$ is the ohmic loss of the radiator.

The directivity for a small PCB antenna is $D = \left(\frac{2\pi a}{\lambda}\right) + 0.0926$ or in $D_{(db)} = 10 \cdot \log\left[\left(\frac{2\pi a}{\lambda}\right) + 0.0926\right]$, where "a" is the ratio as defined earlier. For a design the directivity is set by the ground plane, Figure 6, width a value "a" and is equal to $\ell$ or 2.2dBi. This also means the gain of the radiator must be set to 2.21dBi. This is done by setting the radiator ground plane length to "a". The maximum possible value of directivity for the inverted F antenna is $D_{\max} = \left(\frac{2\pi a}{\lambda}\right)^2 + 3$. [3]

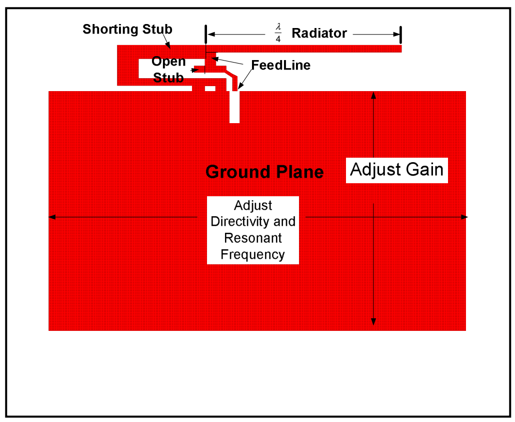


**Figure 6, Typical Inverted F & Antenna Adjustments**

For antenna with directivity set for $2 \cdot \frac{\lambda}{4}$ and gain set for $\frac{\lambda}{4}$, simulations shown for an Omni-directional antenna Figure 7 with values of 2.84dBi with Gain of 2.74dBi. The efficiency is 97% for the Inverted_F antenna. Here the antennas increased numbers where for a larger bandwidth.

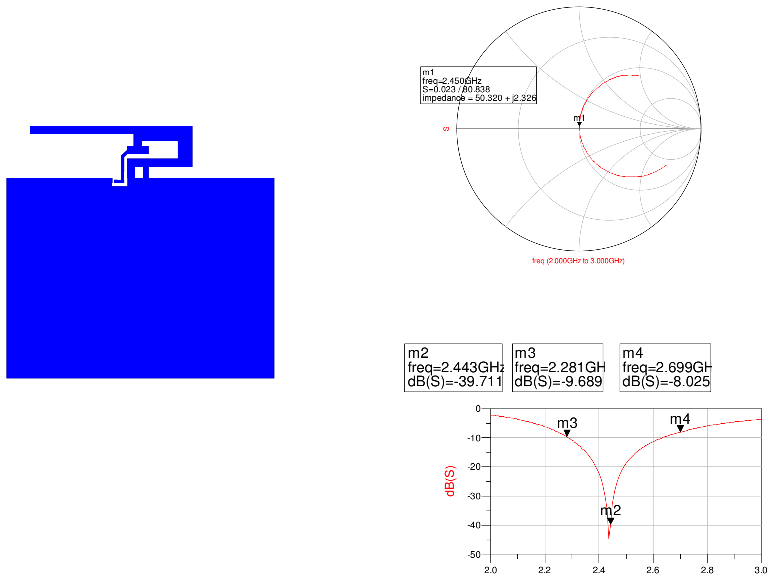


**Figure 7, Simulation of Impedance**

As can be seen by the radiation field generated in Agilent FEM -3-D simulator the radiation field in the XY is approximately symmetrical as shown in Figure 8.

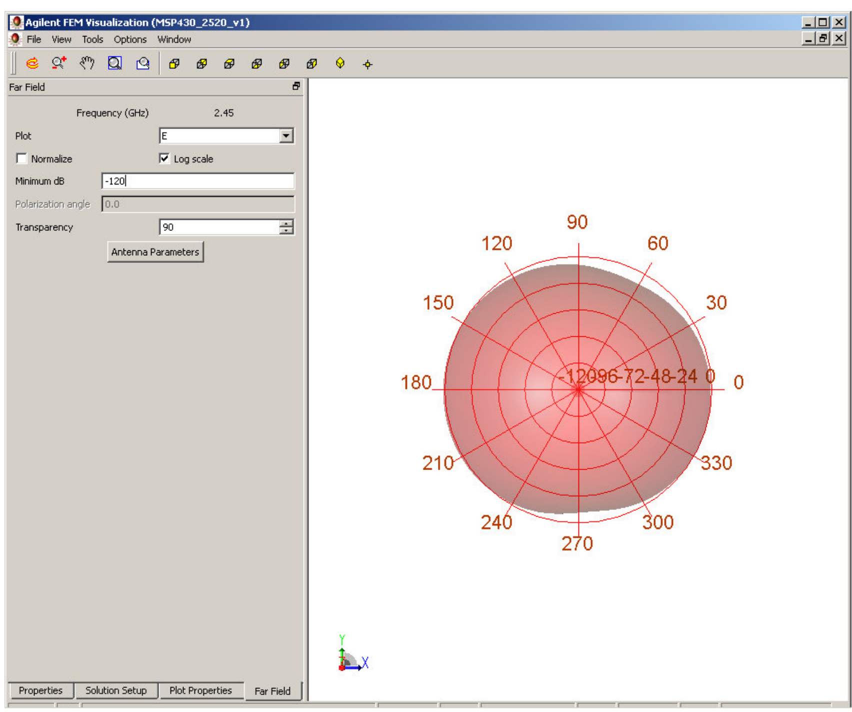


**Figure 8, ADS Simulation using FEM**

The radiation field resembles a spherical radiation field with coverage in all directions as seen in Figure 9.

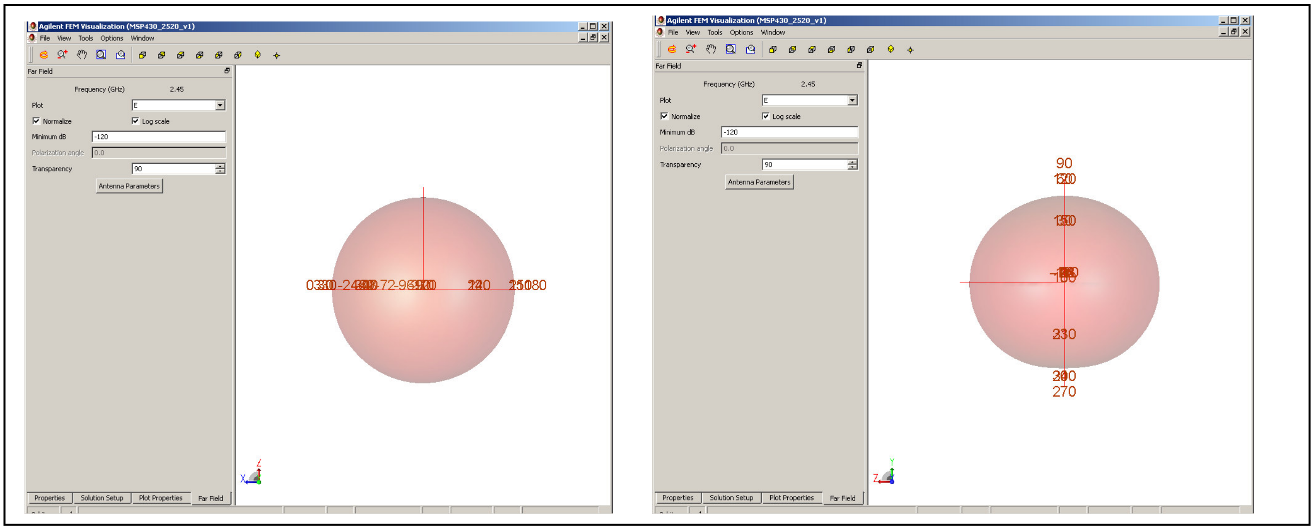


**Figure 9, XZ and YZ Antenna Patterns**

In summary the Small PCB antennas impedance values scale with PCB board thickness. This is done through changes in Velocity Factor to scale the antenna length. Maintaining high efficiency for a printed circuit board antenna must be done at the radiator input not the input feed line. The maximum resistance of the radiator sets the efficiency. The value is for radiator input impedance $Z_a$ is 36Ω. The radiation pattern is set by adjusting the Directivity through the ground plane and as a function of the wavelength of the corrected antenna velocity factor of the PCB board material. Adjusting the ground plane width and length sets the antennas resonant frequency, directivity and gain. Not shown is how polarization changes with position over the ground plane therefore allowing it to be physically rotate the torrid from 0 degrees to 90 degrees.

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[1] H. A. Wheeler, "The wide-band matching area for a small antenna," *IEEE Trans. Antennas Propagat.*, vol. AP-31, pp. 364–367, Mar. 1983.

[2] Gary A. Thiele*, Fellow, IEEE*, Phil L. Detweiler*, Member, IEEE*, and Robert P. Penno*, Senior Member, IEEE, "*On the Lower Bound of the Radiation Q for Electrically Small Antennas", IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 51, NO. 6, JUNE 2003

[3] Per-Simon Kildal, Steven R. Best, "Further Investigations of Fundamental Directivity Limitations of Small Antennas With and Without Ground Planes", Chalmers University of Technology, Gothenburg, Sweden and MITRE, Bedford, MA USA