# Design of Rectangular Microstrip Patch Antennas for the 2.4 GHz Band

## This article describes the development of a patch antenna, with particular attention to radiation pattern and polarization purity

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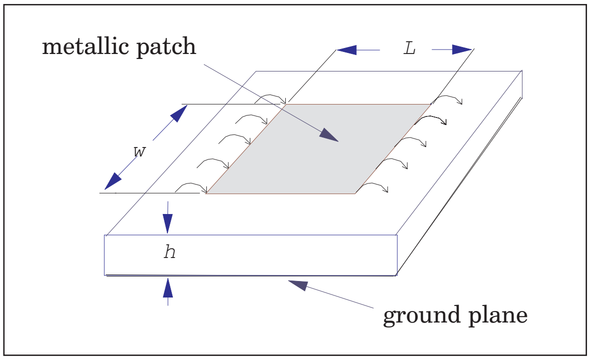
This article describes the design, fabrication and testing of microstrip patch antennas operating at 2.45 GHz. Considerable emphasis is placed on practical design technique, including substrate selection and antenna measurements. Design considerations are given for two microstrip antennas, a single element probe-fed square patch and an electromagnetically-coupled square patch, both operating at a frequency of 2.45 GHz. Measurements of input impedance, return-loss, impedance bandwidth and gain are presented. Particular attention is paid to the radiation properties of the antennas — the radiation pattern and polarization purity.

A microstrip patch antenna consists of a very thin metallic patch placed a small fraction of a wavelength above a conducting ground-plane. The patch and ground-plane are separated by a dielectric. The patch conductor is normally copper and can assume any shape, but simple geometries generally are used, and this simplifies the analysis and performance prediction. The patches are usually photoetched on the dielectric substrate. The substrate is usually non-magnetic. The relative permittivity of the substrate is normally in the region between 1 and 4, which enhances the fringing fields that account for radiation, but higher values may be used in special circumstances.

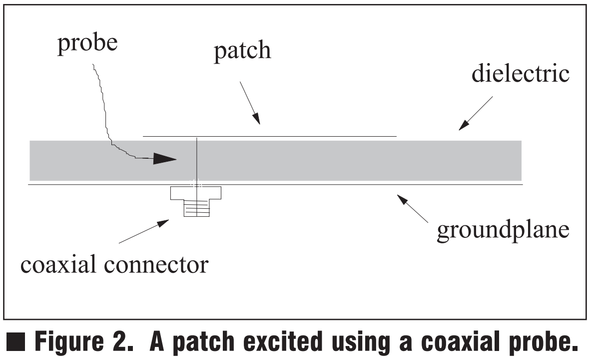
Due to its simple geometry, the halfwave rectangular patch is the most commonly used microstrip antenna. It is characterized by its length $L$, width $w$ and thickness $h$, as shown in Figure 1.



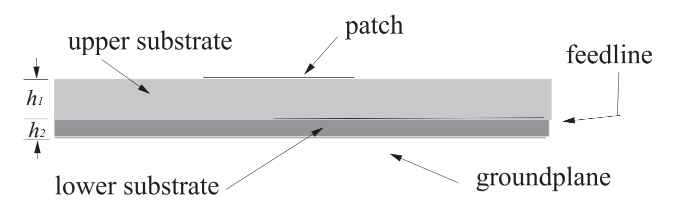

■ **Figure 1. A square microstrip patch antenna showing fringing fields that account for radiation.**

The simplest method of feeding the patch is by a coplanar microstrip line, also photoetched on the substrate. Coaxial feeds are also widely used. The inner conductor of the coaxial-line (sometimes referred to as a *probe*) is connected to the radiating patch, while the outer conductor is connected to the ground-plane, as shown in Figure 2.

Another method is to use aperture coupling. The ground-plane is placed between the patch and the feedline, and coupling between the two is provided by an aperture or slot in the ground-plane. A microstrip patch can be electromagnetically-coupled using a coplanar feedline or a buried feedline. The coplanar feedline tends to radiate more than the buried feedline, because it is printed on the same substrate as the radia-




■ **Figure 2. A patch excited using a coaxial probe.**




■ **Figure 3. An electromagnetically-coupled (EMC) patch has a two-layer dielectric structure.**

tor, which has a high radiation efficiency. The buried feedline technique employs a two-layer substrate as shown in Figure 3, one for the radiator and one for the feedline. The substrate parameters can be chosen separately. The upper substrate on which the antenna is printed requires a relatively thick substrate with a low relative dielectric constant to enhance radiation and increase bandwidth, whereas the lower feedline substrate requires a thin substrate with a higher relative dielectric constant to prevent radiation.

The first antenna described here is a probe-fed square patch designed to operate at a frequency of 2.45 GHz, and subsequently an electromagnetically-coupled (EMC) patch is developed.

## First antenna: A probe-fed square patch antenna

The first design step is to choose a suitable dielectric substrate of appropriate thickness. Many manufacturers offer suitable substrates in various thicknesses and in a variety of claddings. For this antenna, bandwidth and radiation efficiency considerations dictate that the antenna be fabricated on a relatively thick substrate of low relative permittivity. The dielectric loss is proportional to the loss tangent, and values less than about 0.005 are suitable. Conductor losses are not a problem at this frequency, as the skin depth is about 2 µm for copper at 2.45 GHz. The copper thickness is determined by the copper weight. Copper weight refers to the weight of one square foot of copper. Standard copper weights range from 1/8 oz. to 2 oz., which correspond to copper thicknesses of 5 µm to 70 µm, respectively. At lower frequencies, a thicker copper cladding is chosen because it is generally less expensive than a thinner cladding. Thin claddings are required only where dimensional tolerances are critical, for example at high frequencies or where narrow lines are used, because etching accuracy is of the order of the copper thickness [Laverghetta, 1996]. A weight of 1 oz. (35 µm) electrodeposited copper was chosen, since the surface roughness is not an important consideration at this frequency.

RT Duroid 5870 is a high-quality substrate composed of uniformly dispersed glass microfiber in a PTFE matrix. It provides a microscopically-controlled, uniform relative permittivity of 2.33 ±0.02 and a loss tangent of 0.0012. It is manufactured by the Rogers Corporation and is available in various thicknesses and in a variety of claddings. A substrate thickness of 3.18 mm, the largest off-the-shelf thickness available, was chosen to increase the bandwidth and reduce dielectric losses. At a frequency of 2.45 GHz, the ratio of substrate thickness to free-space wavelength $h/\lambda_0$ is 0.025. The cut-off frequency for higher-order surface-wave modes is far above 2.45 GHz; therefore, surface-wave losses should be negligible for this substrate.

## Calculation of patch dimensions

Many available CAD packages are useful for microstrip antenna design. PCAAD 3.1 (Personal Computer Aided Antenna Design), a computer package written by Pozar [1], based on a cavity model, offers a fundamental treatment of the patch antenna.

PATCHD is one of a series of stand-alone executable files, written by Sainati [2], that analyze and solve microstrip problems. It is based on a series of closed form expressions, generated by curve-fitting to numerical solutions obtained by solving the full field equations. PATCH9 is another program by Sainati in the same series, based on the transmission-line model. An accuracy of about 2 percent is claimed, and it is limited in application to thin substrates.

Ensemble 4.0 [3] is a package that may be used for the layout and simulation of microstrip antennas and arrays. It uses the method of moments to solve a mixed-potential integral-equation and includes the effects of surface waves, discontinuities, possible mutual coupling and spurious radiation. However, in the absence of such software a simple transmission-line model may be used, with an accuracy of about 2 percent for thin substrates at a frequency of 2.45 GHz. The following calculations are based on the transmission-line model of Derneryd [4]. The width $w$ of the radiating edge, which is not critical, is chosen first. In this case, a square geometry was chosen because it can be arranged to produce circularly polarized waves. The length $L$ is slightly less than a half wavelength in the dielectric. The calculation of the precise value of the dimension $L$ of the square patch is carried out by an iteration procedure.

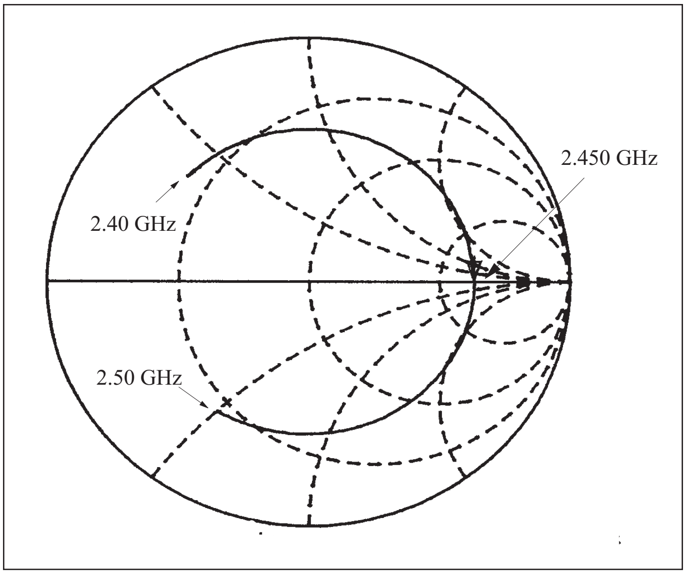
To obtain an initial value of $L$ we use equation (1),

$$L = \frac{c}{2f_0\sqrt{\varepsilon_r}} \tag{1}$$

For $f_0$ = 2.45 GHz and $\varepsilon_r$ = 2.33, this yields the value $L$ = 40.1 mm. We then compute a value for the effective relative permittivity $\varepsilon_{eff}$ for microstrip lines, with $w/h \geq 1$ [5, 6], by means of equation (2) for the square antenna:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + 12h/L}}\right) \tag{2}$$

It is found that $\varepsilon_{eff}$ = 2.141. With this value of $\varepsilon_{eff}$, we may now calculate the fringe factor $\Delta L$ [6], given by equation (3),



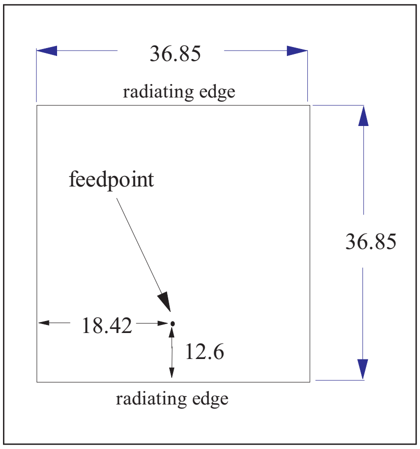

■ **Figure 4. The edge-impedance locus for a square microstrip antenna of dimension 36.85 mm. The impedance was found to be 222.8 + *j*10 Ω at a frequency of 2.450 GHz.**

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.300)}{(\varepsilon_{eff}-0.258)}\frac{(w/h+0.262)}{(w/h+0.813)} \quad (3)$$

The value of $\Delta L$ turns out to be 1.63 mm, and by means of Equation (4),

$$L = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 2\Delta L \quad (4)$$

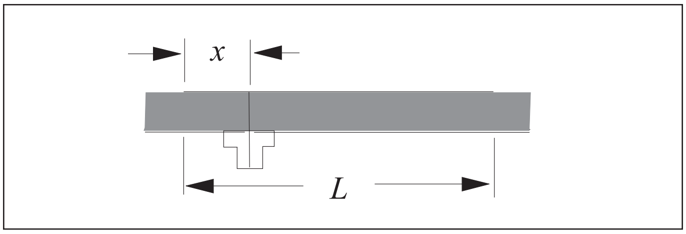
we obtained the improved value of $L$ of 36.84 mm. The foregoing procedure may be repeated with a result that $L$ becomes 36.85 mm, compared with the initial value of 40.1 mm. Further iterations would only produce minor improvements, and the design was based on $L$ = 36.85. The accuracy of this model in predicting resonant frequency is better than 2 percent for thin substrates.




■ **Figure 6. The position of the feedpoint of the square antenna.**

## Excitation

Since linear polarization is required, the patch is excited with a single feed at or near a radiating edge [4]. A coaxial probe feed is used. Initially, it is fed at the edge to determine the edge-impedance. Typically, the input impedance at the edge of a resonant patch can range from about 180 Ω to 300 Ω.




■ **Figure 5. Choice of feed point for a probe-fed patch.**

## Edge impedance

The input impedance at the edge of the patch was found to be 222 + $j$10 Ω at a frequency of 2.450 GHz, using the HP 8753B network analyzer. The locus of the edge impedance from 2.40 GHz to 2.50 GHz is shown on a Smith chart in Figure 4. The impedance locus close to resonance is similar to that of a parallel RLC circuit. The exact value of resonant-frequency is difficult to determine because, due to the unavoidable mismatch between the antenna and network analyzer, the return-loss is small and resonance is not sharp. Also, the coaxial-probe may introduce a small, series, inductive-reactance and cause a slight shift in the impedance [7]. This inductive shift tends to hide the exact point of resonance on the Smith chart.

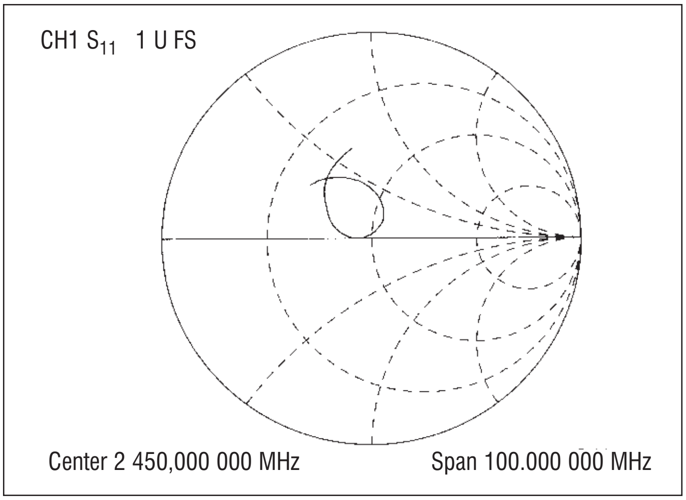
## Matching and return loss

The input impedance can be matched to 50 Ω using several techniques. One method is to use a microstrip quarterwave matching section, printed on the same substrate, which matches the edge impedance to 50 Ω. However, the microstrip matching section is itself a radiating element due to the discontinuity in line width, and the radiation from it may add to that of the antenna in ways that are difficult to determine. For a single antenna element, the simplest feed method is a direct connection to a 50 Ω coaxial feeder. For a feed point at the radiating edge, the input impedance is maximum, and for a feed point at the center of the patch, the input impedance is zero. Thus, the input impedance can be controlled by adjusting the position of the feed point. A match to 50 Ω may be achieved by suitably locating the feed point. The variation of input impedance as a function of feedpoint position is approximated by

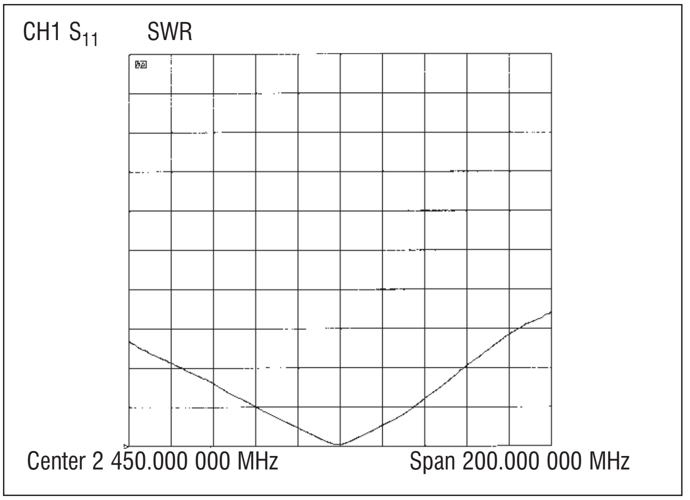
$$R(x) = R_0 \cos^2\left(\frac{\pi x}{L}\right) \quad (5)$$

where $R_0$ is the resistance at the edge of the patch and $x$ is the distance from the edge [8].

From calculation, the feedpoint is located at 12.66 mm from the radiating edge, as shown in Figure 6. Care must be exercised as tolerance in feedpoint-location can be critical. The measured input impedance at this point was 47 – $j$0.1 Ω at 2.448 GHz, and the impedance locus from 2.40 GHz to 2.50 GHz is shown in Figure 7. The swept $S_{11}$ indicates a maximum return loss of 30 dB at a




■ **Figure 7. The feedpoint impedance locus for a square microstrip antenna. At 2.448 GHz, the input impedance was found to be 47 – *j*0.1 Ω.**



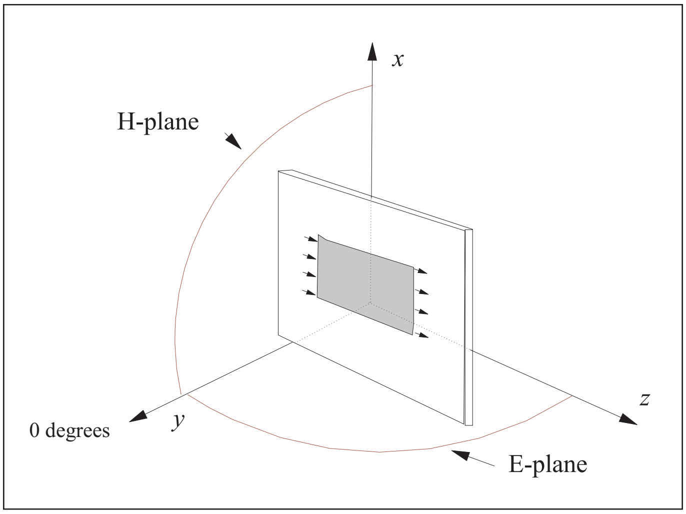

■ **Figure 8. Swept VSWR measurement indicates a minimum VSWR of 1.05 at a frequency of 2.448 GHz, and a 2:1 VSWR bandwidth of 76 MHz.**

frequency of 2.448 GHz, which is the resonant frequency of the antenna.

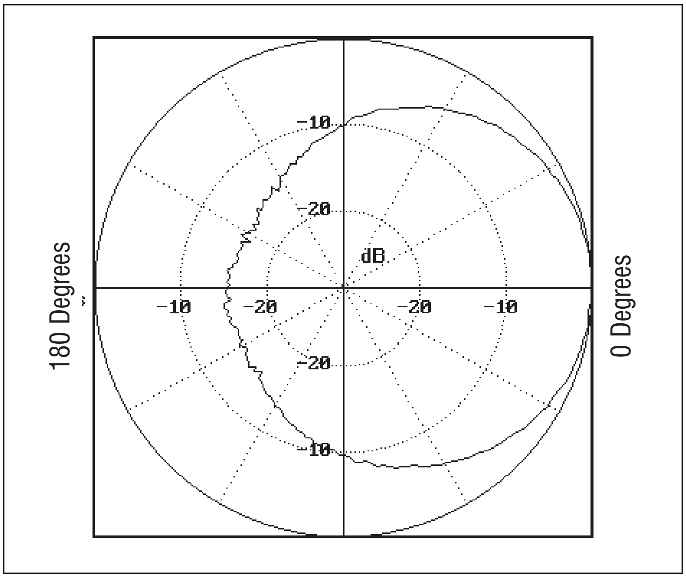
### VSWR and impedance bandwidth

The swept VSWR curve for the range 2.40 to 2.50 GHz is shown in Figure 8 and indicates a bandwidth of 76 MHz, over which the VSWR is less than 2:1, which represents 3.1 percent of the center frequency. The VSWR is 1.06 at the center frequency.

This value of bandwidth needs to be slightly increased for wireless LAN applications. Increasing the substrate thickness to about 4.5 mm may suffice. There are many reasons, however, that dictate this is not the correct approach. This thickness is not readily available. Probe




■ **Figure 9. Orientation of the patch antenna used for the measurement of E- and H-plane patterns.**



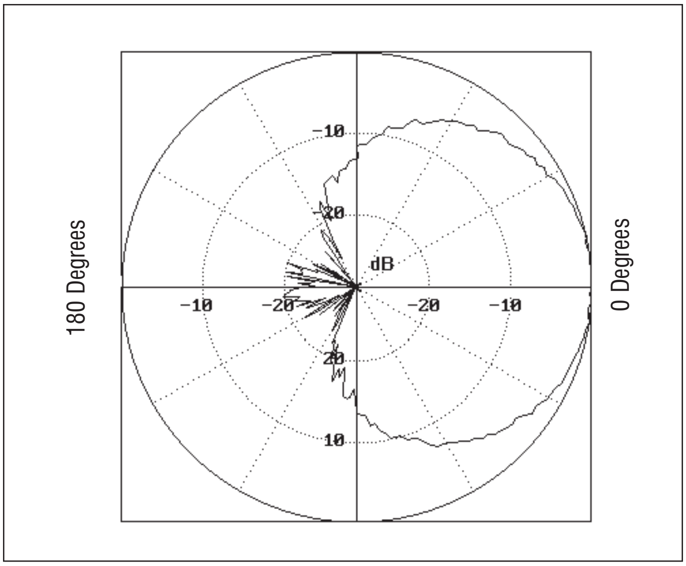

■ **Figure 10. E-plane radiation pattern for a square patch antenna.**

reactance and probe radiation may cause problems, and surface waves can reduce efficiency and distort the radiation pattern.

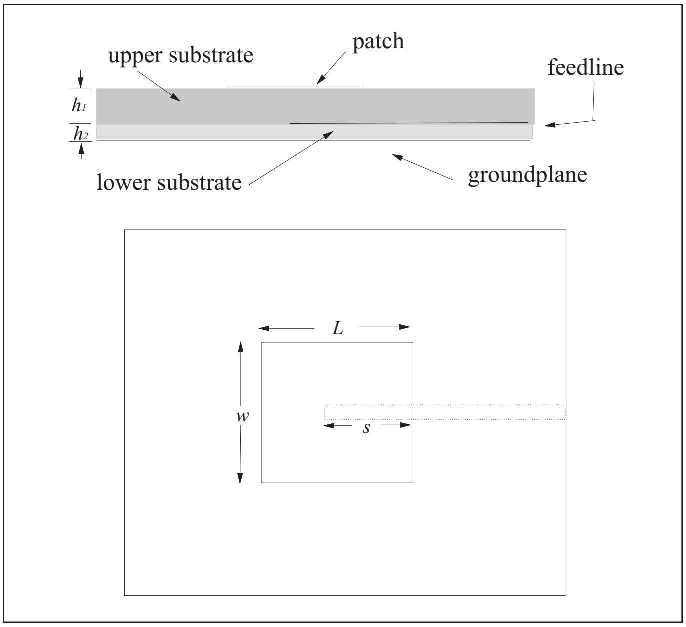
Several other methods are possible. Many different techniques have been developed [9], including the use of parasitic elements [10], stacked elements [11], better impedance matching techniques [12] and electromagnetic-coupling [13].

### Antenna gain and radiation pattern

The antenna gain was found to be 6.4 dBi. The E-plane and H-plane patterns are shown in Figures 10 and



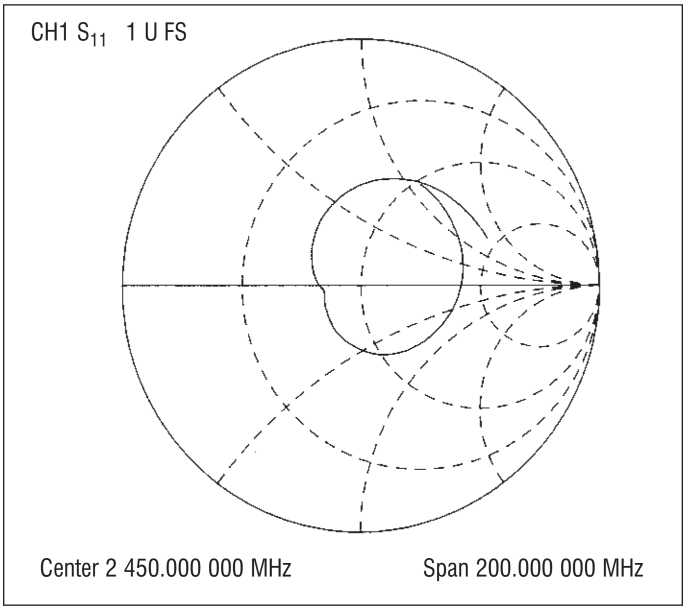

■ **Figure 11. H-plane radiation pattern for a square patch antenna.**




■ **Figure 12. Layout of the EMC patch.**

11, using the orientation given in Figure 9, and indicate an E-plane beamwidth of 98 percent and an H-plane beamwidth of 87 percent. Maximum radiation occurs in a direction normal to the plane of the patch, with very little radiation behind the ground-plane. Rearward radiation is due to the edge-diffraction effects of the finite ground-plane [14].

The ground-plane size used for the measurements was 1.0 λ. The front-to-back ratio for both magnetic and electric-planes is better than 15 dB, while broadside radiation is more than 10 dB below the maximum. The polarization purity was measured and the axial ratio was 21 dB, with cross-polarization levels better than 18 dB over the forward region.




■ **Figure 13. Impedance locus for the EMC patch.**

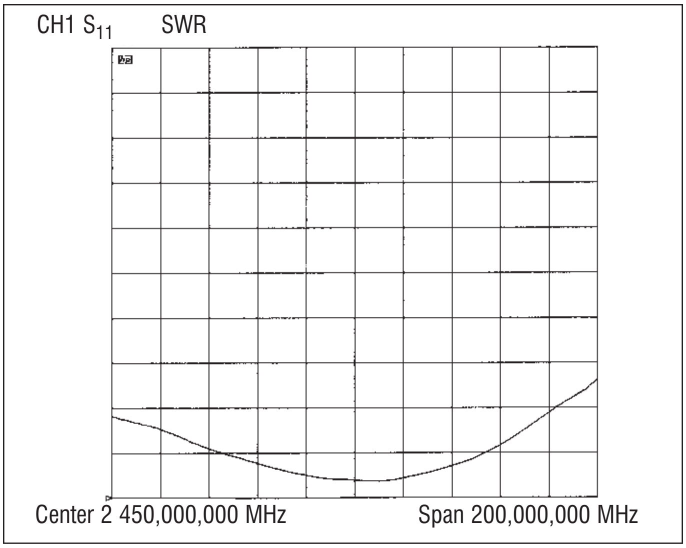
## Second antenna: An electromagnetically-coupled square patch antenna

The first design step is to choose suitable dielectric substrates of appropriate thickness. For the upper substrate on which the radiator is printed, a relatively thick substrate with a low value of relative permittivity is chosen; this increases the radiation efficiency and bandwidth. RT Duroid 5870 is used, which has a relative permittivity of $\varepsilon_r = 2.33$ and a loss tangent of 0.0012. A 35 mm (1 oz./sq.ft.) electrodeposited copper cladding is used, and the substrate thickness is $h_1 = 3.18$ mm. The parameters of the lower substrate are chosen so as to reduce the radiation efficiency of the feedline. This is achieved by employing a thin substrate with a relatively high value of relative permittivity. In this case, $h_2 = 1.54$ mm and $\varepsilon_{r2} = 4.5$ (see Figure 3).

## Patch dimensions and excitation

The patch dimensions can be calculated using the transmission line model, taking into account a two-layer substrate. This is easily achieved using software written by Sainati [2]. The length $L$ was calculated to be 33.7 mm, and a square geometry was chosen. Since linear polarization is required, the 50 Ω feedline is centered with respect to the width $w$ of the patch. The feedline width is 2.9 mm, and the open end of the line overlaps the patch by a distance of $s = 17$ mm, as illustrated in Figure 12.

The patch overlap distance $s$ may be adjusted for best match or optimum impedance bandwidth and has a small effect on resonant frequency [15]. Once optimized, the two layers are bound using a bonding film. The impedance locus from 2.35 GHz to 2.55 GHz is shown in Figure 13.




■ **Figure 14. Swept VSWR curve for the EMC patch.**

### Impedance bandwidth

The swept VSWR curve for the range 2.20 to 2.70 GHz is shown in Figure 14 and indicates a bandwidth of 110 MHz, over which the VSWR is less than 2:1, which represents 4.5 percent of the center frequency. The VSWR is 1.35 at the center frequency of 2.452 GHz.

### Use of a matching stub

If a small matching stub is used, this value of bandwidth can be significantly increased. A small open-circuit stub in the feedline may be used, and a 10 percent impedance bandwidth is achieved easily at this frequency. Pozar and Kaufman [16] have reported an impedance bandwidth of 13 percent for a proximity-coupled rectangular patch with a stub-matched feedline.

### Radiation pattern and gain

The antenna gain was measured for the EMC patch and found to be 6.5 dBi. The E-plane and H-plane patterns are not significantly different from those of the probe-fed patch with the same front-to-back ratio. Polarization measurements indicate an axial ratio of 22 dB with cross-polarization levels better than 18 dB over the forward region. ■

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