2 Microstrip Antenna Theory

This chapter will review the basic theory of microstrip antennas, providing the understanding necessary to design practical microstrip antennas. After introducing basic microstrip characteristics, several types of microstrip antennas that can achieve omnidirectional radiation patterns will be presented. The ideal sounding rocket antenna would be a broadband, dual frequency circularly polarized omnidirectional microstrip antenna having a dielectric overlay for protection. Therefore, this chapter concludes by discussing techniques for designing broadband antennas, overlays for antennas, and dual-frequency elements.

2.1 General Microstrip Properties

To understand the basic properties of any microstrip antenna, it is important to understand the properties of microstrip lines. A microstrip line consists of a thin metallic strip, a dielectric material (substrate), and a ground plane; both the substrate and the ground plane are much wider than the narrow microstrip line. The fundamental mode of propagation is a quasi-TEM mode. While the majority of the fields are confined to the volume between the microstrip line and the ground plane, a small portion extends beyond the width of the microstrip line. The effects of these fringing fields are accounted for by replacing the permittivity of the dielectric with an effective permittivity that has a numerical value between the permittivity of air and the substrate.

Microstrip antennas are similar to microstrip transmission lines. They consist of a metallic ground plane, a dielectric substrate, and a metallic patch. Essentially, they are truncated microstrip lines designed to radiate. Radiation efficiency is greater when the dielectric substrate is thick and has a low permittivity. However, as the substrate thickness is increased, the losses due to surface waves also increase. Since both microstrip transmission lines and antennas are sometimes fabricated on the same substrate, the proper trade-off between guided waves (A) and space waves (B) must be determined, as shown in figure 2.1. As with microstrip lines, there are losses due to the copper and dielectric. Additional losses include energy lost in leaky waves (C), and surface waves (D).

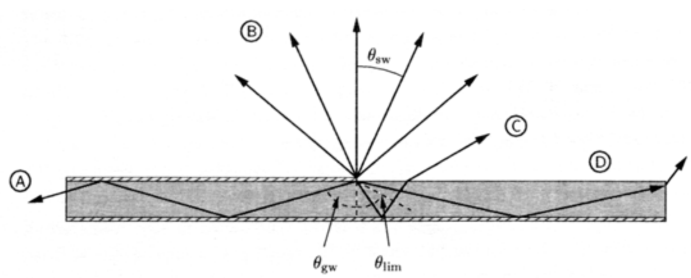
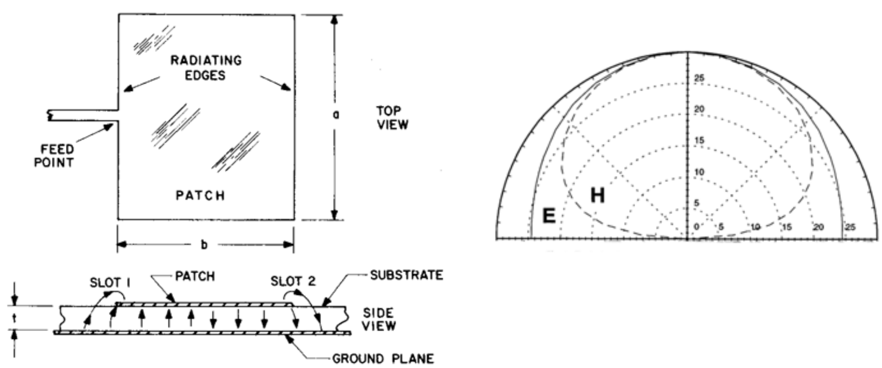


Figure 2.1. Waves present in microstrip structures [5].

2.2 Linearly Polarized Microstrip Antenna

To understand microstrip antenna operation, a description of the simple rectangular microstrip patch serves as the best starting point since its characteristics can be described using simple models. Moreover, understanding its characteristics and properties is beneficial when considering more complicated patch geometries that often are very difficult to analyze and where no simple models or design equations exist.

The rectangular patch and its corresponding radiation pattern are shown in figure 2.2. The substrate is generally very thin compared to the operating wavelength, resulting in the electric fields being perpendicular to both the patch and the ground plane, except for the fringing fields beyond the patch. The fringing fields result from capacitance effects due to the discontinuities of the open ends, or slots. The effect of these fringing fields is an increase in the electric length of the patch. Due to slot discontinuities, modes are developed underneath the patch. A microstrip patch efficiently radiates when it is at resonance. This is achieved when the length, dimension *b*, is slightly less than one half of the guided wavelength. Because two ends of the patch have fields that are 180 degrees out of phase, they radiate and produce the radiated fields shown in figure 2.2b. The fields from the other two sides cancel each other, but not entirely. As a result, some level of cross polarization radiation exists.



a. rectangular patch [6].　　　**b.** radiation pattern [7].

Figure 2.2. Typical rectangular microstrip antenna and its radiation pattern.

The radiated electric field is a result of the fringing fields present at the radiating edges of the patch and is directed along the length of the patch. Due to the ground plane underneath the patch's substrate, the radiation pattern of a microstrip antenna is unidirectional, radiating broadside to the patch and has a 3 dB beamwidth of approximately 80 to 90 degrees. The total losses of the patch antenna consist of a combination of its surface wave, copper, dielectric, and radiation losses, where the radiation losses are the most significant. For thin substrates, the losses due to surface waves are considered negligible. Rectangular patches have typical gains of approximately 4-8 dB.

The RF signal's energy can be fed to the microstrip element by several techniques. These include coax fed, edge fed, inset-edge fed, proximity coupled, and aperture coupled, as shown in figure 2.3. A comparison of the main feed types is listed in table 2.1. Probe and edge feeds are both simple to fabricate. The advantage of the edge fed method is that it can be fabricated at the same time as the patch. Another advantage is that it is amenable to array feed networks. Its two main disadvantages are that its spurious radiation can affect the radiation of the patch, or array of patches, and that there can be significant transmission loss if the feed network is very large. The aperture coupled technique, although difficult to fabricate due to the alignment of its several layers, provides an increase in bandwidth. Additionally, due to the ground plane that separates the patch and the feed, the aperture coupling method exhibits very low levels of spurious radiation from the feed.

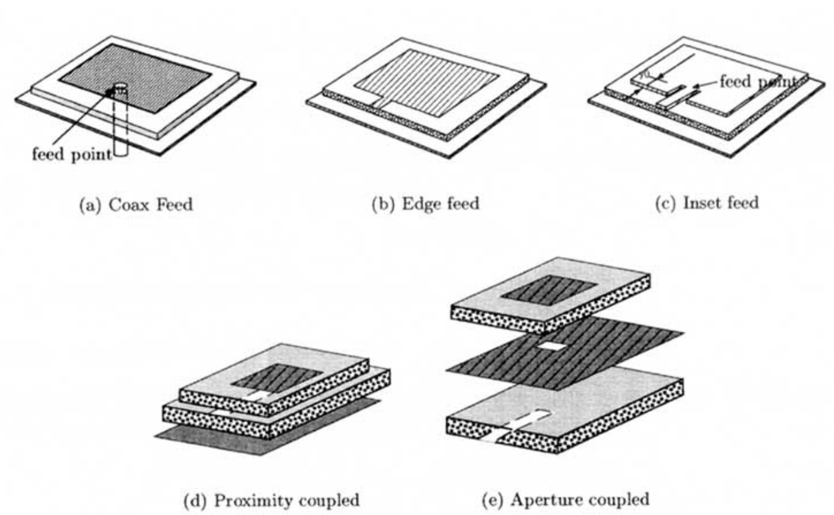


Figure 2.3. Various feeding techniques [8].

Table 2.1. Comparison of feeding techniques.

	Coax Fed	Edge Fed	Aperture Coupled
Fabrication	Relatively simple	Simple	Difficult
Matching	Probe's position	Using inset feed	Aperture dimensions
Bandwidth	2-5 %	2-5 %	Up to 13 %
Spurious Radiation	Low	High due to feed	Minimal

2.3 Circularly Polarized Microstrip Antennas

Circular polarization (CP) is achieved when two orthogonal modes are excited with equal amplitude and quadrature phase, resulting in a rotating radiated field. The sign of the relative phase determines the polarization sense. These conditions are satisfied by

$$\angle E_{\theta} - \angle E_{\phi} = \pm 90^{\circ} \tag{2.1}$$

and

$$\left|E_{\theta}\right| = \left|E_{\phi}\right|. \tag{2.2}$$

Circular polarization can be achieved quite easily using microstrip antennas [9-16]. Moreover, there are many different techniques and geometries that exist. While they each have their own advantages, the particular type used depends on the application and requires tradeoffs between bandwidth, gain, efficiency, and size. The design and tuning of a circularly polarized patch is generally much more difficult than the linearly polarized, rectangular patch. Its performance is generally comparable to that of the linearly polarized patch. Its main limitation, especially with single fed circularly polarized elements, is the narrow axial ratio (AR) bandwidth (frequency range where the circularly polarized antenna can be considered circularly polarized).

2.3.1 Single Element

Circular polarization can be achieved using only a single microstrip element. There are many different types of single element geometries. They vary from the simple single edge fed patch to very complex aperture fed, multiplayer patches. The main advantage of a single circularly polarized element is its small size. The most common, geometries are shown in figure 2.4.

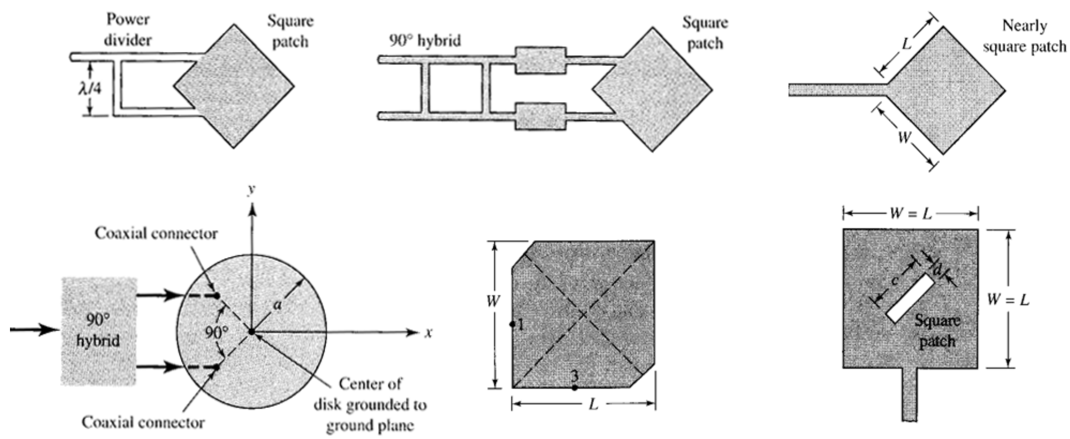


Figure 2.4. Circularly polarized patch antenna geometries [17].

When using edge feeding, either single or dual feeds can be used. The dual feed requires a feeding network for the necessary phase quadrature. This is not required for the single fed elements, because the phase quadrature is accomplished by the element geometry. While this has the advantage of requiring less space, it has the disadvantage of a very narrow axial ratio bandwidth (less than 1%). Because this is less than its impedance bandwidth, the axial ratio bandwidth usually is the most critical performance parameter to consider in the design process.

The more common elements discussed in literature are the nearly square and truncated corner elements. The single fed patch is excited by two separate modes, the

TM_{01} and TM_{10} modes. The asymmetry of the patch excites the orthogonal modes. The result is two degenerate modes, having a resonant frequency in between the TM_{01} and TM_{10} mode resonant frequencies, as shown in figure 2.5. Circular polarization is achieved when the electric fields of the orthogonal modes have equal magnitudes and are in phase quadrature. The asymmetry is accomplished by modifying the patch dimensions until the conditions specified by equations 2.1 and 2.2 are met.

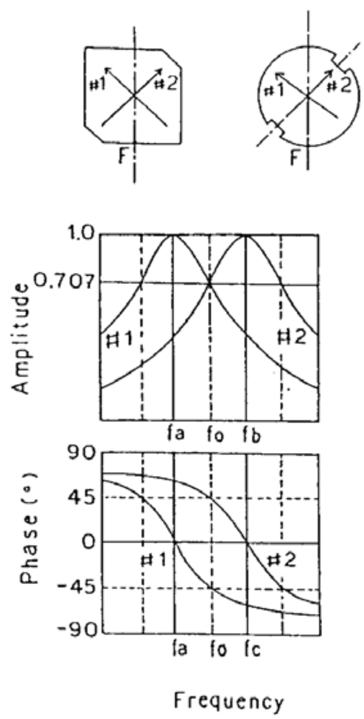
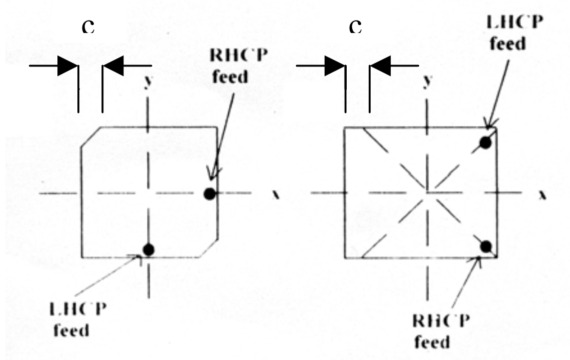


Figure 2.5. The resonant modes of orthogonal TM_{01} and TM_{10} modes [18].

The two most common single fed circularly polarized patches are shown in figure 2.6. In figure 2.6a, the required perturbation is produced by trimming off opposite corners on one diagonal of a square patch. The patch is fed on either side, resulting in either right hand or left hand circular polarization. In figure 2.6b, the perturbation is produced by making one side of the patch slightly longer than the other.



a. truncated **b.** nearly square

Figure 2.6. Truncated and nearly square patch elements [19].

2.3.2 Multiple Elements

There are several techniques for achieving circular polarization by using a combination of patch elements. The simplest combination is to use two linearly polarized elements spatially separated, having different polarizations, and fed in quadrature. The problem with this two-element configuration is that the phase centers of each patch are displaced, resulting in a degradation of the axial ratio [20]. Improved performance is accomplished when four elements are used, as shown in figure 2.7. The possible combinations of patches are not limited to 2 or 4 patches. A more general case is the sequential array shown in figure 2.8. Circular polarization is achieved using M patches having rotations of ϕ_M.

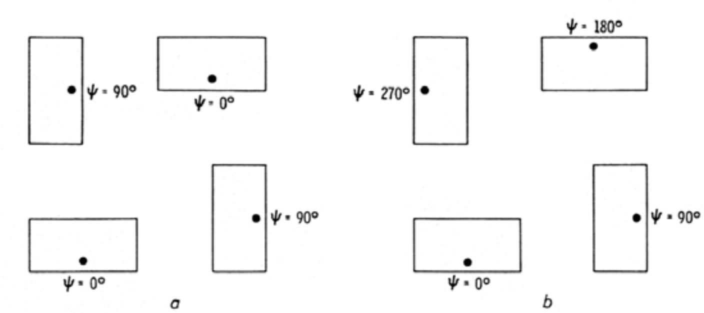


Figure 2.7. Circular polarization using 4 elements [21].

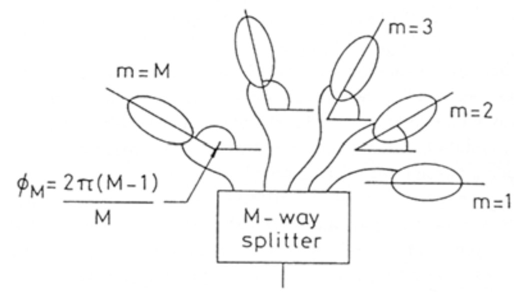


Figure 2.8. Sequential patch array [22]

2.3.3 Microstrip Line Arrays

Circular polarization can be achieved by using microstrip lines called line arrays [23, 24], as shown in figure 2.9. The beam direction and axial ratio of these traveling wave antennas are frequency dependent, resulting in narrow bandwidths. They consist of a microstrip meander line having a series of corner bends with a matched load at the opened end of the line. Radiation occurs from the discontinuities at the corner bends.

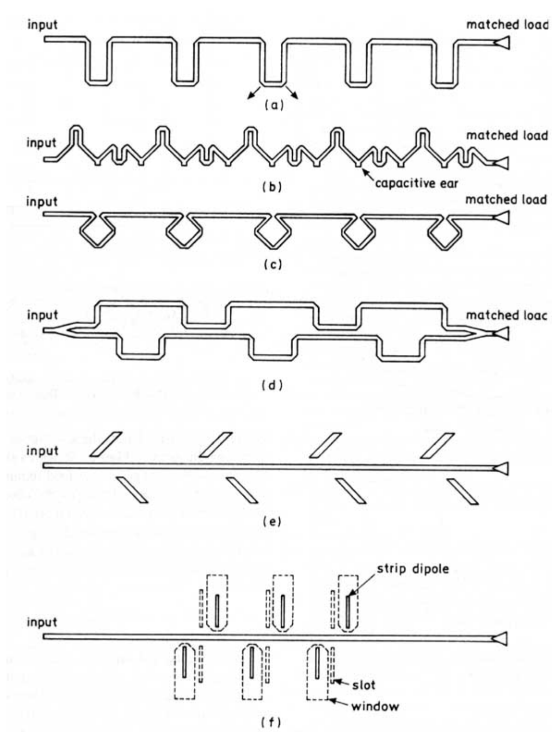


Figure 2.9. Line arrays [25].

2.4 Antennas having an Omnidirectional Pattern

There are two common methods to create an omnidirectional pattern, each taking advantage of a microstrip's unidirectional, broadside radiation pattern. The simplest method is to wrap a single patch around a cylindrical structure. A more complicated but improved method is to replace the single wraparound patch with an array of single elements. In both these cases, a complicated feed network is required.

2.4.1 Corporate Feed Networks

The feed network must provide impedance matching for efficient transfer of signal energy to the elements. Moreover, to obtain an omnidirectional pattern, the signals arriving at each element must be in phase. A common feeding technique that accomplishes these requirements is the corporate feed shown in figure 2.10. It is relatively easy to design and fabricate because the patch and the feed network are fabricated on the same substrate. The antenna elements are fed in parallel, using a microstrip transmission line. The feed line is branched using power dividers until it reaches each of the patch elements. One limitation of the corporate feed is ohmic losses. This can be significant for large arrays. There are also losses due to mismatch, which can be minimized by matching networks. The most common matching networks are quarterwave transformers, for matching to purely real impedances, and L-section matching networks. There are also losses due to the discontinuities of corner bends and power dividers. Bend discontinuity effects can be compensated as shown in figure 2.11. Power divider discontinuities are generally more complicated to compensate for than corner bends. Two compensation designs for T-junctions are shown in figure 2.12.

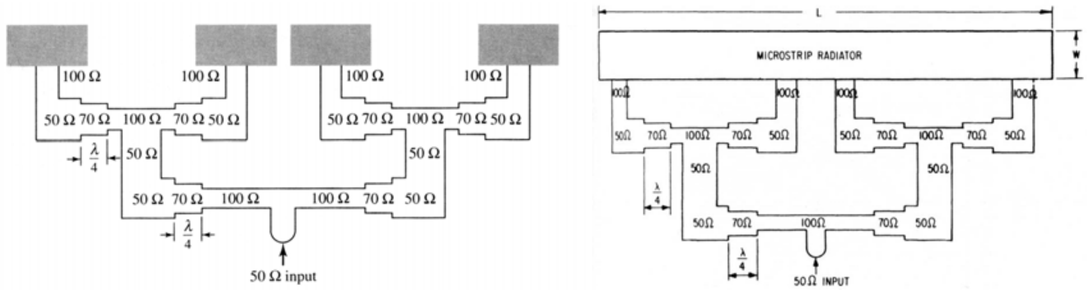
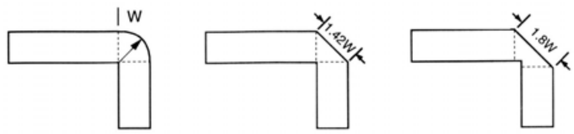
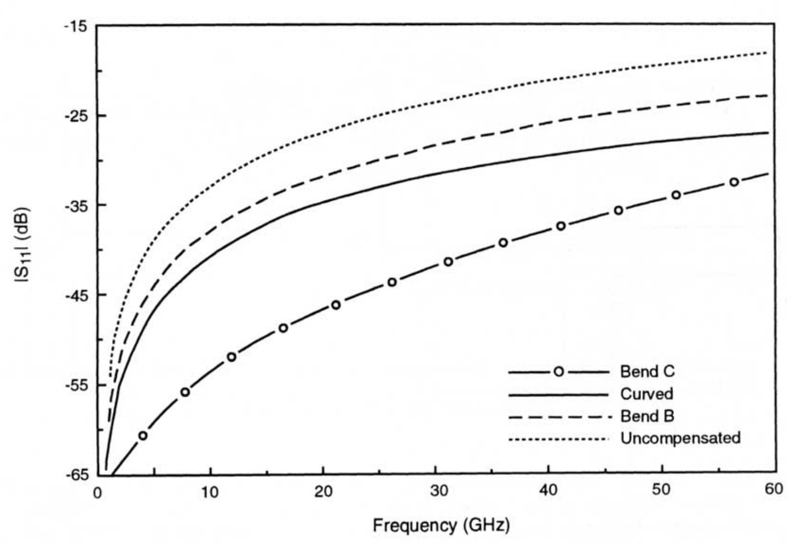


Figure 2.10. Corporate feeding arrangements for microstrip arrays [26, 27].



a. curved **b.** bend B **c.** bend C



d. comparative S_{11} plot

Figure 2.11. Bends and their S_{11} characteristics [28].

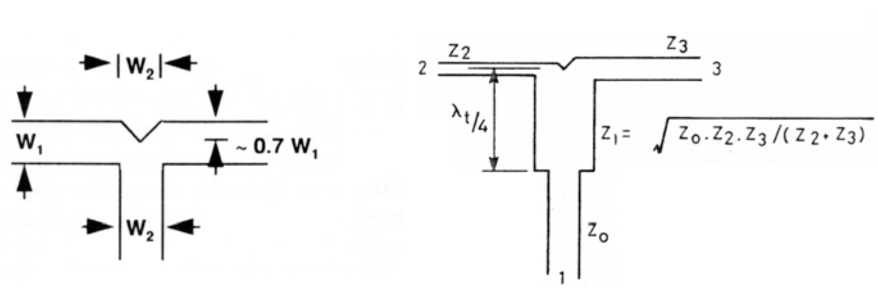


Figure 2.12. T-Junction power dividers [29].

2.4.2 Wraparound Element with Multiple Feed Points

In many applications, including missiles, satellites, and aircraft, conformal microstrip antennas are used. One of the first types of microstrip antennas used for achieving omnidirectional patterns was the single wraparound patch (see figure 2.13). The width of the patch is the circumference of the cylinder (W = pD). The longitudinal length of the band is approximately a quarter wavelength. This microstrip patch is fed at multiple points along the band's circumference and is linearly polarized, with the electric fields are parallel to the longitudinal axis of the cylinder.

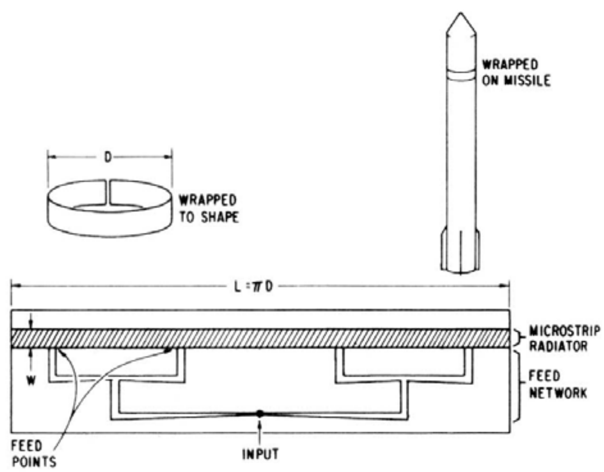


Figure 2.13. Wraparound patch antenna [30].

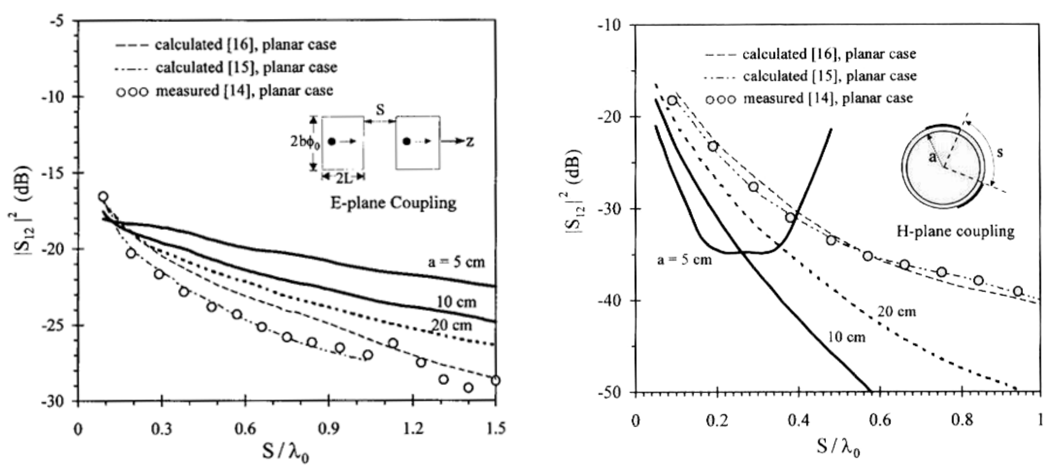
2.4.3 Wraparound Array of Single Elements

To achieve an omnidirectional, circularly polarized pattern, an N x 1 array of circularly polarized elements can be wrapped around the circumference of the rocket [31]. The amount of ripple in the pattern is largely dependent on the element spacing. When designing an array, the sidelobe, cross polarization, and mutual coupling effects must be kept to a minimum by using well designed feeding networks, substrates with appropriate permittivity and thicknesses, and sufficient element spacing.

2.5 Mutual Coupling

Mutual coupling results when surface or space waves from one antenna element or transmission line affect the characteristics of another spatially separated component. The effects of mutual coupling [32-34] cause the input impedance and the radiation pattern to be a function of the complicated excitation of the coupled lines or elements. Mutual coupling can be a serious problem, particularly in scanning and phased arrays. The effects are not significant for fixed, broadside beams. However, this is not the case when arrays have high permittivity substrates or a thick covering layer and for arrays having high gain or operating at high frequencies. Coupling due to space waves can be minimized by proper spacing between elements and minimizing the size of the feeding networks.

The mutual coupling of the E- and H-planes of two patches is shown in Figure 2.14, where the operating frequency is 1.417 GHz and the dielectric constant is 2.5. In



a. E-plane coupling **b.** H-plane coupling

Figure 2.14. Mutual coupling effects for a cylindrical array [35].

this figure, the mutual coupling of planar cases are compared with cylinder cases with different radii. In general, the mutual coupling present in the cylindrical cases is similar to the planar cases. However, for small cylinders, the mutual coupling of the H-plane fields can be significant. In the specific case shown in figure 2.14, the H-plane coupling performance is greatly affected by curvature when a is equal to 5 cm and the guided wavelength is 13.39 cm.

2.6 Curvature Effects versus Radius

The effects of curvature [36-41] become significant when the radius of the rocket is less than one guided wavelength. The diameter where the curvature effects become significant for the telemetry and GPS antennas that use RT-Duroid 5870 substrate are listed in table 2.2. The main effects of curvature are a broadening of the radiation pattern, and changes in the resonant frequency and input impedance.

Table 2.2. Guided wavelengths for telemetry and GPS frequencies.

Telemetry and GPS Frequencies	Guided Wavelength		Curvature Becomes Significant when:	
			Radius <	Diameters <
(GHz)	(cm)	(in)	(in)	(in)
2.21550	8.87	3.49	3.49	6.99
2.23550	8.79	3.46	3.46	6.92
2.24150	8.77	3.45	3.45	6.90
2.24650	8.75	3.44	3.44	6.89
2.25150	8.73	3.44	3.44	6.87
2.25500	8.72	3.43	3.43	6.86
2.25950	8.70	3.42	3.42	6.85
2.26550	8.68	3.42	3.42	6.83
2.26950	8.66	3.41	3.41	6.82
2.27650	8.63	3.40	3.40	6.80
2.27950	8.62	3.39	3.39	6.79
2.29550	8.56	3.37	3.37	6.74
1.57542	12.48	4.91	4.91	9.82

A nearly square, circularly polarized patch antenna was designed for an 8 inch diameter cylinder and matched to a 50 ohm line using an L-section matching network. It was then analyzed on cylinders having various radii, using the CAD software program Clementine[1]. The effect of changing the cylinder's radius is shown in figures 2.15 and 2.16. The minimum axial ratio for each radius is shown in the figures. As seen in figure 2.15, the axial ratio remains relatively constant until the radius approaches 4 inches. This corresponds to the data listed in table 2.2 (radius length approaches the guided wavelength). In figure 2.16, the frequency where the minimum axial ratio occurs begins to change slightly when the radius is twice the guided wavelength and changes significantly when the radius is equal to the guided wavelength.

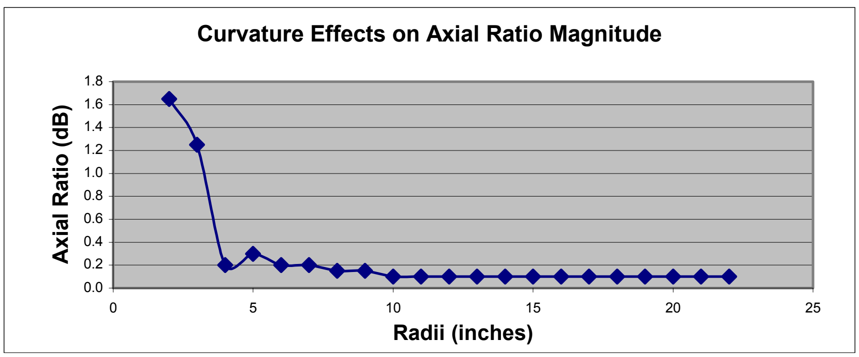


Figure 2.15. Magnitude of minimum axial ratio versus cylinder radii (freq. = 2.2155 GHz).

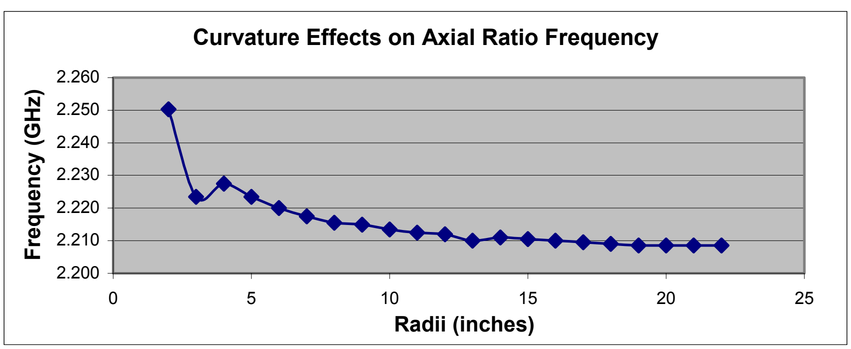


Figure 2.16. Frequency of minimum axial ratio versus cylinder radii (freq. = 2.2155 GHz).

[1] Clementine is available from the Ansoft Corporation, Four Station Square, Suite 660, Pittsburg, PA 15219. Their corporate URL is http://www.ansoft.com.

When the effects of curvature are discussed in the literature, the topic of discussion is typically how to design a microstrip antenna array on a curved surface such that its characteristics are the same as an array on a planar surface. In such cases, the two main design issues to consider are the inter-element spacing of the patches on the cylinder and the length of the transmission lines feeding the patches. The element spacing is usually optimized to minimize the mutual coupling while also achieving the desired radiation pattern. The transmission line lengths are corrected to compensate for any phase changes due to placing the planar array on a curved surface.

However, these considerations are not important when an omnidirectional pattern is desired. It is the mounting structure's curvature that allow for the omnidirectional pattern. An omnidirectional array consists of individual patches spaced at equal and sufficient distances around the circumference of a cylinder to minimize the ripple in the radiation pattern. While, mutual coupling is a concern, an omnidirectional array design is limited to the few choices in element spacing that are permitted by the element size, the circumference of the cylinder, and the desired ripple in the radiation pattern.

2.7 Broadband Techniques

The main limitation with any microstrip antenna is its narrow bandwidth. The two types of bandwidths commonly discussed in microstrip antenna literature are impedance bandwidth and axial ratio bandwidth. Impedance bandwidth describes the frequency range where the antenna's return loss is considered acceptable. Axial ratio bandwidth describes the frequency range where the antenna is considered circularly polarized. The axial ratio bandwidth of a circularly polarized microstrip antenna is usually less than its impedance bandwidth.

The most intuitive way to improve the impedance bandwidth is to use a thick substrate, having a low dielectric constant. The most common broadband design techniques include broadband feed designs, the use of adjacent parasitic patches, and stacked patches, as shown in figure 2.17.

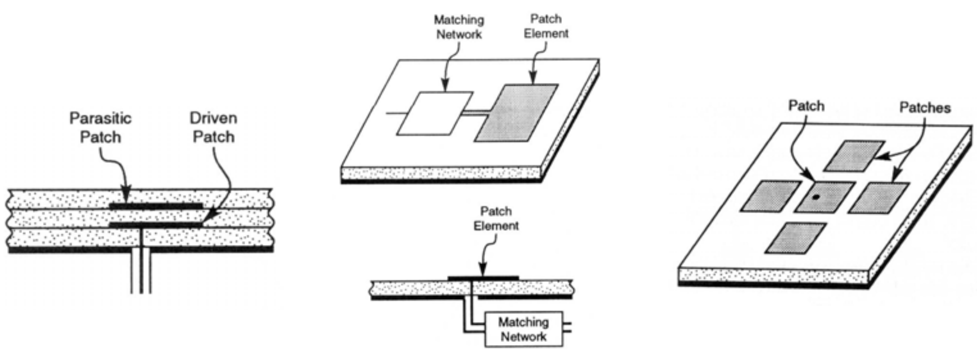


Figure 2.17. Stacked and parasitic patches to increase bandwidth [42].

The simplest way to improve the axial ratio bandwidth of a microstrip antenna is to use a sequential patch array, which was described earlier. However, the cost of achieving this bandwidth improvement is its larger size and more complicated feeding network.

2.8 Superstrate Layer

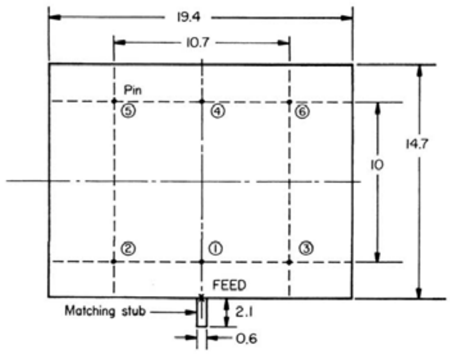
A microstrip antenna can be protected from the environment by placing a dielectric layer over the antenna. This superstrate loading [43-45] can affect resonant frequency, bandwidth, impedance, directivity, efficiency, and the gain of a microstrip antenna. The effects are largely dependant on the permittivity and thickness of the overlay. The resonant frequency tends to decrease as the superstrate permittivity increases.

For an overlay on a circularly polarized patch, the center frequency decreases as superstrate thickness is increased. For higher superstrate permittivity, a large decrease of the center frequency is also observed. The axial ratio bandwidth is almost independent of superstrate permittivity.

2.9 Dual-Frequency Operation

Dual frequency operation is possible with microstrip antennas. If a dual frequency antenna is used on a sounding rocket, then it may be possible that both the telemetry and GPS subsystems could use the same antenna. In general microstrip literature, the antenna geometries considered for dual operation usually apply only to elements that generate linearly polarized waves. The design of a dual frequency circularly polarized patch could be designed based on the design principles of the dual frequency linearly polarized patch. However, achieving dual frequency using the single fed circularly polarized element would be more challenging since the resonant mode is a degenerate mode based on the size of the perturbation segment used. It seems unlikely that this segment would create the necessary degenerate modes at two separate frequencies.

Several dual frequency techniques are stacking patches, using shorting pins, and embedding a smaller patch within a larger patch. Stacked patches resonate at multiple frequencies corresponding to the dimensions of the patches (see figure 2.17). By using shorting pins, different or multiple modes can be excited. An example of using shorting pins is shown in figure 2.18 (the stub shown is for impedance matching and not for dual polarization). Another technique is to etch a microstrip line around a patch



Number of Pins	Pin Positions	f_{01} (MHz)	f_{03} (MHz)	f_{03}/f_{01}
0	-	613	1861	3.04
1	1	664	1874	2.82
2	1,2	706	1865	2.64
3	1,2,3	792	1865	2.36
4	1,2,3,6	813	1865	2.29
5	1,2,3,5,6	846	1865	2.2
6	1,2,3,4,5,6	891	1865	2.09

Figure 2.18. Dual frequency antenna using shorting pins [46].

and connect it to the input port, as shown in figure 2.19. Many of the dual frequency techniques are similar to the broadband techniques mentioned in the last section 2.7.

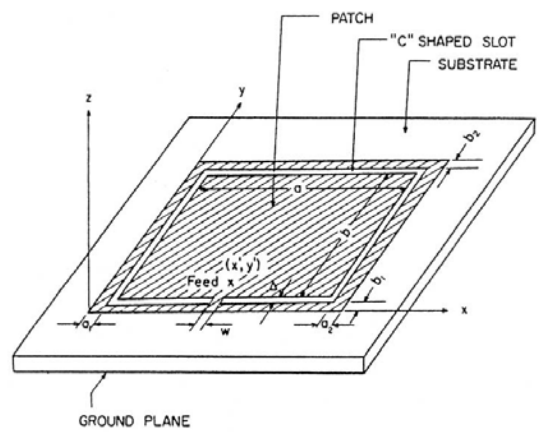


Figure 2.19. Dual frequency antenna using wrapped parasitic line [47].