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Microstrip Patch Antennas

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6.1 Introduction

Microstrip patch antennas were first proposed in the early 1970s and since then a plethora of activity in this area of antenna engineering has occurred, probably more than in any other field of antenna research and development. Microstrip patch antennas have several well-known advantages over other antenna structures, including their low profile and hence conformal nature, light weight, low cost of production, robust nature, and compatibility with microwave monolithic integrated circuits (MMICs) and optoelectronic integrated circuits (OEICs) technologies. Because of these merits, forms of the microstrip patch antenna have been utilized in many applications such as in mobile communication base stations, spaceborne satellite communication systems, and even mobile communication handset terminals.

Unfortunately, the expression, "there is no such thing as a free lunch," also applies to microstrip patch technology. Despite the previously mentioned features, microstrip patch antennas suffer from several inherent disadvantages of this technology in its pure form, namely, they have small bandwidth and relatively poor radiation efficiency resulting from surface wave excitation and conductor and dielectric losses. Also, to accurately predict the performance of this form of radiator, in particular, its input impedance nature, typically a full-wave computationally intensive numerical analysis is required.

Probably the saving grace of the microstrip patch antenna that prevented this technology from becoming one of the numerous white elephant technologies was its ease of fabrication or development. Because of this characteristic, universities and other research institutions (with somewhat limited budgets) throughout the world could make serious impacts on the shortcomings of microstrip patch technology without incurring huge expenses. Fortunately, because of the efforts of many research and development teams throughout the world, most of these issues have been addressed and solved so that the area of microstrip patch antennas is a thriving technology and will continue to be for many years to come.

The outline of this chapter is as follows: Section 6.2 gives a brief review of the general characteristics of a single-layer microstrip patch antenna, including performance trends as a function of the dielectric material used to form the radiating element. From this some of the shortcomings of this technology are evident. Also in this section, the different conductor shapes used for metallic patch conductor are examined, highlighting the pros and cons of each shape. Section 6.3 presents the different excitation methods for a microstrip patch antenna, including edge fed, probe fed, proximity coupled, and aperture coupled. Advantages and disadvantages of each technique are presented. In Section 6.4, methods to enhance the bandwidth of a microstrip patch antenna are summarized, including using parasitic elements, such as a stacked-patch configuration. In this section a brief comparison to other broadband printed antenna technologies are given, highlighting the advantages of disadvantages of each. Section 6.5 gives a brief summary on techniques for generating circular and dual polarization using microstrip patch technology. Section 6.6 looks into means of reducing the conductor size of the microstrip patch antenna and also the issues related to doing this, including the effect on bandwidth and gain. Section 6.7 summarizes some of the problems associated with integrating printed antennas with active circuits and how high-performance, fully monolithic solutions can be obtained. Finally, examples of integrated active patches are presented.

6.2 General Characteristics

Figure 6.1 shows a schematic diagram of a microstrip patch antenna. Here an arbitrarily shaped metallic conductor is etched on a grounded dielectric laminates. A microstrip patch antenna is a resonant-style radiator so one of its dimensions must be approximately $\lambda_g/2$, where λ_g is a guided wavelength taking into consideration the surrounding environment of the printed antenna. It is apparent that the properties of the substrate, namely, its dielectric constant, ε_r and its height play a fundamental role in the performance of the printed antenna. For a detailed explanation of how a microstrip patch antenna conceptually operates in terms of equivalent slots, etc., please consult one of the many articles on this subject.[1]

Figure 6.2 shows some very important performance trends of a single-layer microstrip patch antenna performance as a function of the laminate properties used to fabricate the antenna. These performance trends represent the properties of microstrip patch antennas in their pure form with a simple, ideal excitation method. Although the trends are for rectangular patches, other conductor shapes have similar responses. In Fig. 6.2a, the impedance bandwidth (defined as 10-dB return loss) is given for various

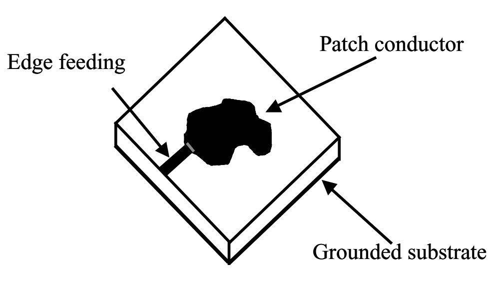


FIGURE 6.1 Schematic diagram of arbitrarily shaped microstrip patch antenna.

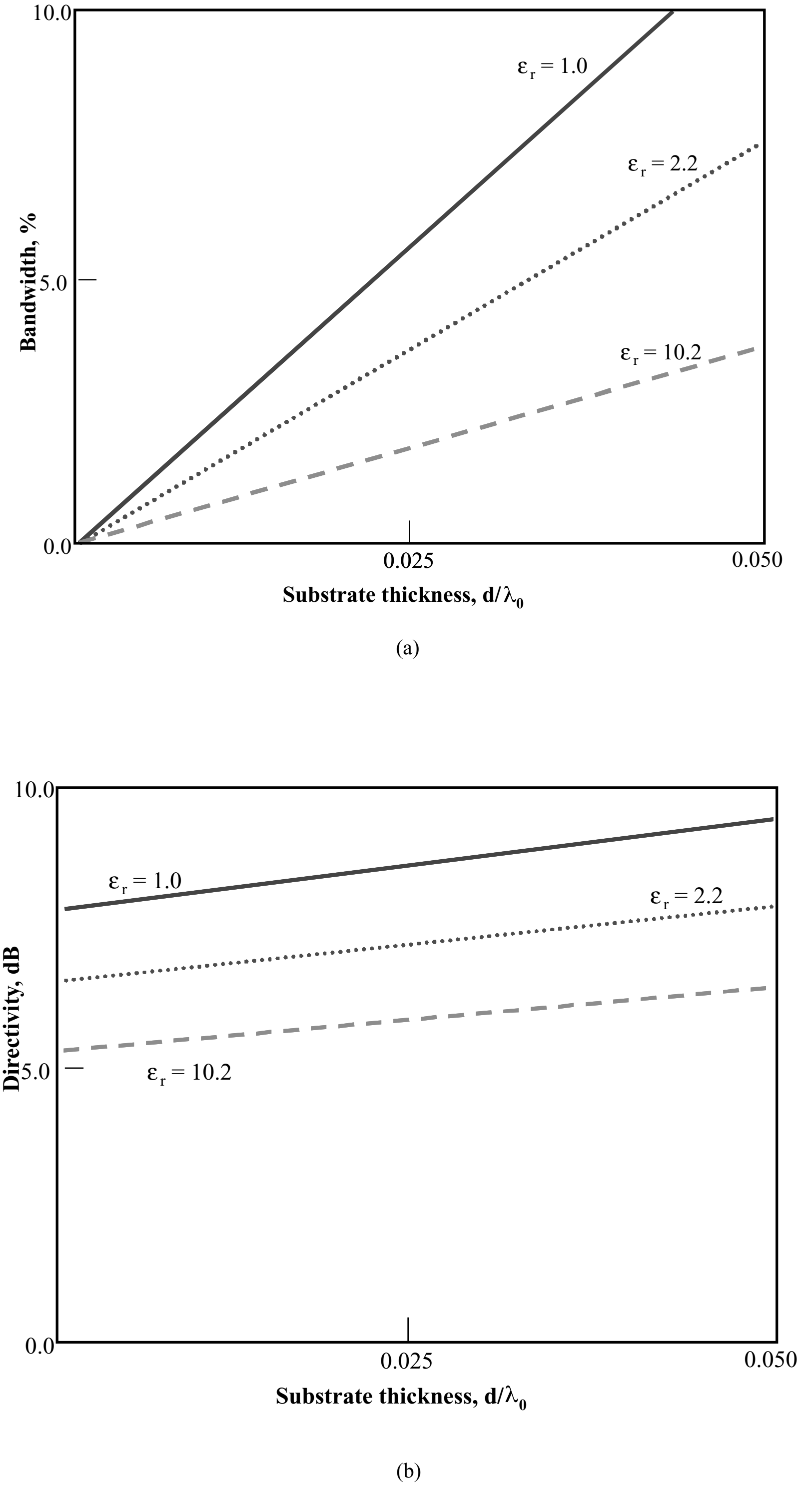
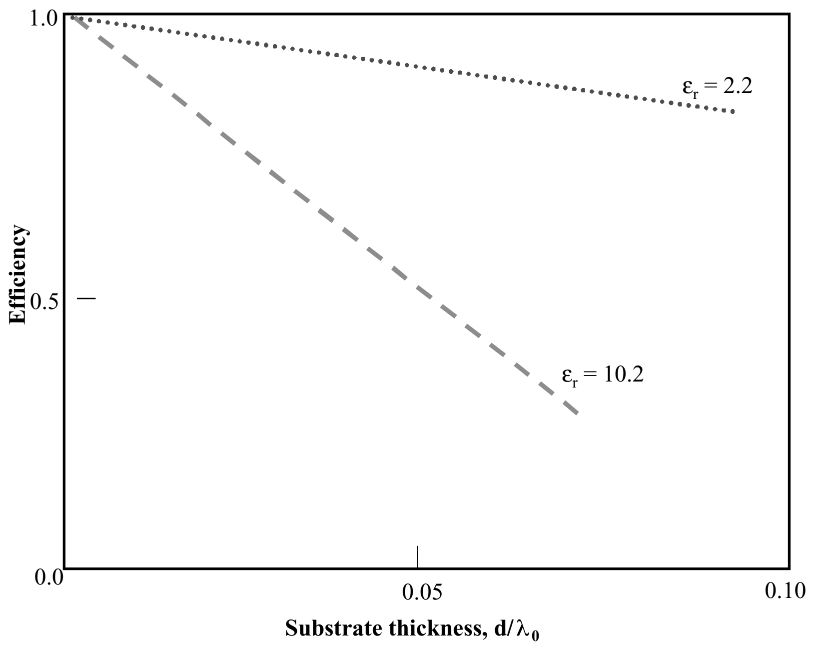


FIGURE 6.2 Performance trends of single-layered microstrip patch antenna: (a) impedance bandwidth; (b) directivity; (c) surface wave efficiency.



(c)

FIGURE 6.2 (continued).

dielectric constant values as a function of the electrical thickness of the laminate. As can be seen from this plot, the thicker the material is, the greater the bandwidth. Please note that these values are somewhat lower than what is generally required for present-day communication systems. Methods to significantly enhance these are given in Section 6.4. The other important observation is that the lower the dielectric constant, the greater the bandwidth that can be obtained.

Figure 6.2b shows the directivity of a patch antenna once again for different dielectric constants as a function of the electrical thickness. Simplistically, what is observed here is that because the microstrip patch antenna mounted on the low dielectric constant material is physically bigger than the antenna on the high dielectric constant laminate, it has a larger collecting area and therefore greater directivity. The directivity slightly increases as the thickness increases because of the increasing volume of the antenna. Please note that efficiency is not included in this plot.

Figure 6.2c shows the surface wave efficiency of a microstrip patch antenna for several dielectric constants as a function of thickness of the substrate. As can be seen from this figure, the higher the dielectric constant, the more power is lost to the surface wave and therefore the antenna is less efficient. Please note there are no surface waves excited for the case when $\varepsilon_r = 1.0$.

From Fig. 6.2 there appears to be a fundamental problem concerning the integration of microstrip patch antennas with MMIC and OEIC technology. MMICs and OEICs are typically developed on high dielectric constant, thin material (note that the dielectric constant for GaAs and AlGasInP, common materials for MMICs and OEICs, is approximately 13). Trying to develop a microstrip patch antenna in this environment would result in an antenna with poor bandwidth and radiation performance. Even trying to directly integrate microstrip patch technology with passive microwave circuits such as filters and couplers presents a problem, because to make these circuits compact, once again high dielectric constant and thin laminates are typically utilized, such as alumina materials ($\varepsilon_r = 10.2$). Fortunately, the ways in which to overcome this problem are addressed later in Section 6.7.2.

Over the years there have been many conductor shapes proposed and investigated for a microstrip patch antenna. Schematic diagrams of these are shown in Fig. 6.3, and a brief summary of the advantages and disadvantages follow:

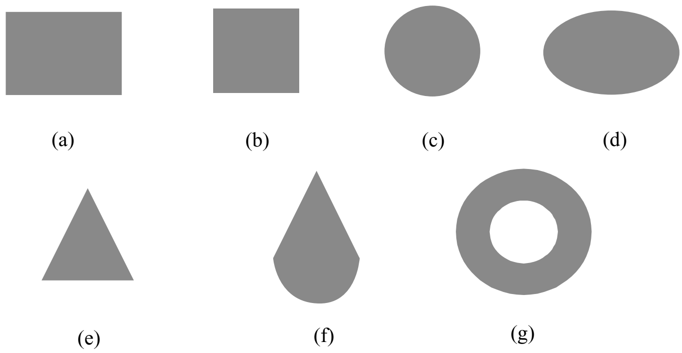


FIGURE 6.3 Common patch conductor shapes.

1. Rectangular and square patches (Figs. 6.3a and b) are the first and probably the most utilized patch conductor geometries. Rectangular patches tend to have the largest impedance bandwidth, simply because they are larger than the other shapes. Square patches can be used to generate circular polarization.
2. Circular and elliptical patches (Figs. 6.3c and d) are probably the second most common shape. These patches are slightly smaller than their rectangular counterpart and as a result have slightly lower gain and bandwidth. One of the primary reasons the circular geometry was quite expensively investigated in the past was because of its inherent symmetry. This allowed full-wave analysis tools utilizing a spectral domain technique to be written that were computationally more efficient than their rectangular counterpart. This was important in the early stages of patch design and development; however, with the advent of several rigorous, computationally fast full-wave design tools, such as Ensemble© and IE3D© systems, incorporating circular patch antennas are becoming increasingly rare.
3. Triangular and disk sector patch (Figs. 6.3e and f) geometries are smaller than their rectangular and circular counterparts, although at the expense of further reduction in bandwidth and gain. Triangular patches also tend to generate higher cross-polarization levels, because of their lack of symmetry in the configuration. Dual-polarized patches can be developed using these conductor shapes; however, the bandwidth is typically very narrow.
4. Annular ring (Fig. 6.3g) geometries are the smallest conductor shape, once again at the expense of bandwidth and gain. One problem associated with an annular ring is that it is not a simple process to excite the lowest order mode and obtain a good impedance match at resonance. Noncontact forms of excitation are typically required. The symmetry issues mentioned for the circular patch cases also apply here.

6.3 Feeding Techniques

Four fundamental techniques to feed or excite a microstrip patch antenna include edge fed, probe fed, aperture coupled, and proximity coupled. These can be further simplified into direct (edge and probe) and noncontact (aperture and proximity-coupled) methods. Some new excitation techniques are being developed, such as the L-shape probe;[2] however, this is really a hybrid representation of the probe and proximity-coupled versions. The properties of each feeding method are summarized below.

6.3.1 Edge-Fed Patches

One of the original excitation methods for a microstrip patch antenna is the edge-fed, or microstrip-line fed technique.[3] A schematic diagram representing this method is shown in Fig. 6.4. Here a microstrip feed line of width w_f is in direct contact with a rectangular patch conductor of length L and width W.

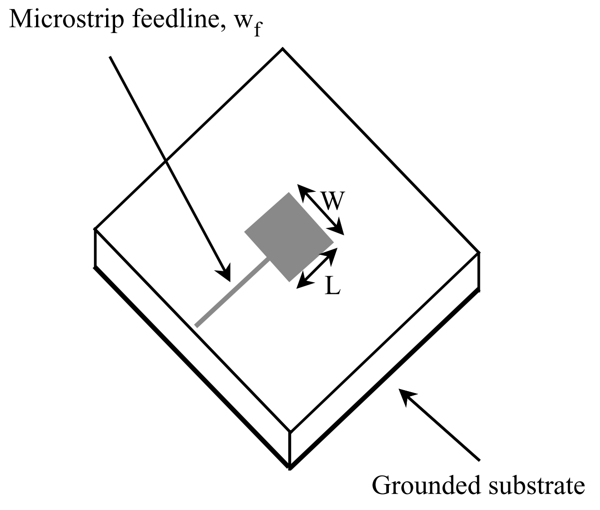


FIGURE 6.4 Schematic diagram of edge-fed microstrip patch antenna.

Typically the microstrip feed line comes in contact with one of the radiating edges of the patch, as shown in Fig. 6.4, although cases where the contact is located along the width of the patch have also been examined.

Edge-fed patches have several advantages over other feeding techniques. One of the key features of this technology is its ease of fabrication, because the feed layout and patches can be etched on one board. For this reason many large planar arrays have been developed using edge-fed patches. It is also very easy to control the level of the input impedance of an edge-fed patch. Simply by inserting the feed into the patch conductor the impedance at resonance can be adjusted from very high 150 to 250 Ω when the contact point of the feed line and the patch at the radiating edge of the patch, down to a couple of ohms if the contact point is near the center of the patch.

Edge-fed patches in their simplest form are relatively easy to model, if electrically thin material is used. Simple transmission line models can be utilized to give estimations of the input impedance performance of the antenna. For cases when thicker materials are used, the modeling of the performance is not too straightforward. This is because of the current distribution of the discontinuities associated with the contact point between the microstrip line and the patch antenna.

Edge-fed microstrip patches have bandwidth and gain characteristics consistent with Fig. 6.2, that is, these patches are relatively narrow bandwidth antennas. As is evident from Fig. 6.2, if high dielectric constant material is used as the substrate, the surface wave efficiency is poor. Also this form of feeding technique suffers from relatively high spurious feed radiation. This is simply because the feed network is not separated from the antenna and thus material suitable for efficient radiation for the antenna also causes the feed network to radiate, too.

6.3.2 Probe-Fed Patches

Probe feeding a microstrip patch antenna is another form of the original excitation methods proposed in the mid-1970s.[3] A schematic diagram representing this configuration is shown in Fig. 6.5, in which a probe of radius r_0 extends through the ground plane and is connected to the patch conductor, typically soldered to it. The probe or feeding pin is usually the inner conductor of a coaxial line; hence, probe feeding is often referred to as a coaxial feed. The probe position provides the impedance control in a similar manner to inserting the feed for an edge-fed patch. Because of the direct contact between the feed transmission line and the patch antenna, probe feeding is referred to as a direct contact excitation mechanism.

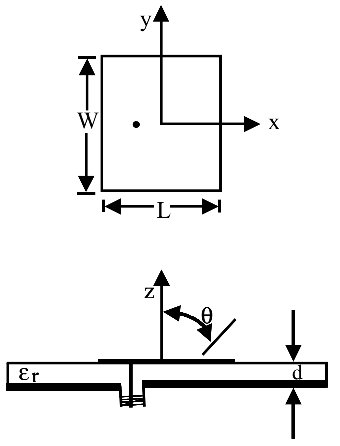


FIGURE 6.5 Schematic diagram of probe-fed microstrip patch antenna.

The probe-fed patch has several key advantages. First, the feed network, where phase shifters and filters may be located, is isolated from the radiating elements via a ground plane. This feature allows independent optimization of each layer. Second, of all the excitation methods, probe feeding is probably the most efficient because the feed mechanism is in direct contact with the antenna and most of the feed network is isolated from the patch, minimizing spurious radiation. The high efficiency of this printed antenna has seen a renaissance of the probe-fed-styled patch, despite the added complexity of developing a connection.

Probe-fed microstrip patches have similar issues to edge-fed patches; namely, their bandwidth is somewhat small and these printed antennas are somewhat difficult to accurately analyze. The probe used to couple power to the patch can generate somewhat high cross-polarized fields if electrically thick substrates are used. Also because this antenna is no longer a single-layer geometry, as a result of the location of the feed network, it is more complicated to manufacture.

6.3.3 Aperture-Coupled Patches

Because of the shortcomings of the direct contract feeding techniques, namely, the small inherent bandwidth and the detrimental effect of surface waves, noncontact excitation mechanisms were introduced. The first of these is the aperture-coupled patch.[4] A schematic diagram of this printed antenna, as given in Fig. 6.6, shows how separate laminates are used for the feed network and the patch antenna.

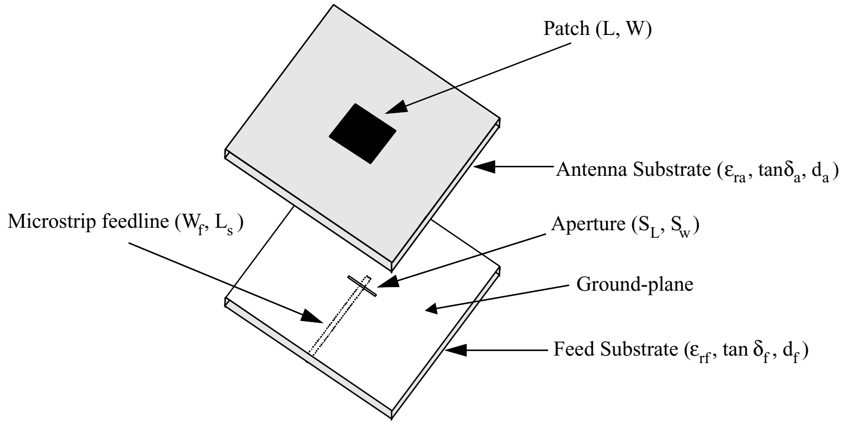


FIGURE 6.6 Schematic diagram of aperture-coupled microstrip patch antenna.

The laminates are separated by a ground plane and coupling between the feed, in this case a microstrip line, and the patch antenna is achieved via a small slot in the ground plane.

The configuration shown in Fig. 6.6 has advantages over its direct contact counterparts. Unlike the edge-fed patch antenna, independent optimization of the feed and antenna substrates can be achieved. Unlike the probe-fed configuration, no vertical interconnects are required, simplifying the fabrication processes and also adhering to the conformal nature of printed circuit technology. However, alignment issues can be important and also multilevel fabrication processes are typically required. A multilayered antenna can create other problems. The presence of small gaps between the layers of dielectric can significantly alter the input impedance nature of the antenna, especially at high frequencies, where these gaps appear larger electrically. Also, the material required to bond the layers could play a significant role in the performance of the antenna. If the bonding material is lossy and is located near, for example, the slot, the efficiency of the antenna is reduced.

The aperture-coupled patch has more design parameters than the direct contact fed patches and therefore has more flexibility or degrees of freedom for the antenna designer. Despite its somewhat complex appearance, the aperture-coupled microstrip patch antenna is relatively easy to accurately model, even when using full-wave analyses. The reason for this is that unlike for the direct contact fed patches, there are no abrupt current discontinuities. Thus, relatively simple, accurate, computationally fast, full-wave analyses are easy to develop.

In its original form the aperture-coupled patch has similar bandwidth and gain responses as the direct fed patches; however, it is very easy to significantly enhance the impedance bandwidth of this antenna. This is discussed in the next section. Aperture-coupled microstrip patch antennas are probably the most utilized microstrip patches in today's global market.

6.3.4 Proximity-Coupled Patches

The second form of noncontact fed patches created to overcome the shortcomings of the direct contact fed patches is the proximity-coupled patch.[5] A schematic diagram of this printed antenna is shown in Fig. 6.7. The microstrip antenna consists of a grounded substrate where a microstrip feed line is located. Above this material is another dielectric laminate with a microstrip patch etched on its top surface. Please note there is no ground plane separating the two dielectric layers. The power from the feed network is coupled to the patch electromagnetically, as opposed to a direct contact. This is why this form of microstrip patch is sometimes referred to as an electromagnetically coupled patch antenna.

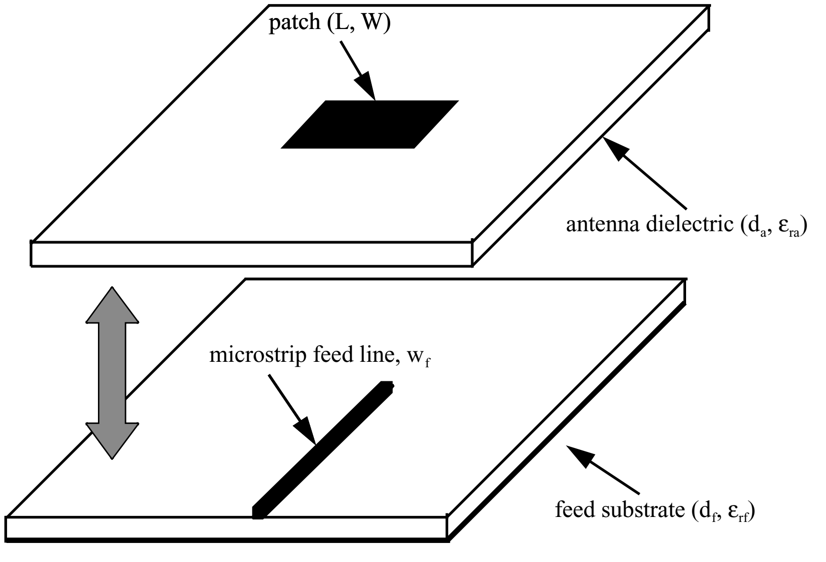


FIGURE 6.7 Schematic diagram of proximity-coupled microstrip patch antenna.

A key attribute of the proximity-coupled patch is that its coupling mechanism is capacitative in nature. This is in contrast to the direct contact methods, which are predominantly inductive. The difference in coupling significantly affects the obtainable impedance bandwidth, because the inductive coupling of the edge- and probe-fed geometries limits the thickness of the material useable. Thus, bandwidth of a proximity-coupled patch is inherently greater than the direct contact feed patches.

As with the aperture-coupled patch, full-wave analyses are not too difficult to develop for the proximity-coupled patch because of the lack of a current discontinuity between the feed network and the radiating element. The proximity-coupled microstrip patch has some shortcomings. The feed and antenna layers are not fully independent, because power must be coupled efficiently to the antenna. Therefore, these printed antennas can have relatively high spurious feed radiation, although not as high as for an edge-fed case. The antenna is a multilevel structure and thus alignment procedures are important. Small air gaps between the feed substrate and the laminate for the antenna can affect the coupling to the patch and, therefore, care must be taken when fabricating these antennas.

6.4 Enhancing Bandwidth

As mentioned previously, the microstrip patch in its pure form cannot satisfy the bandwidth requirements for most wireless communication systems. Typically, a modification to the structure of the printed antenna must be undertaken to meet the impedance bandwidth specifications. Over the years there have been numerous bandwidth enhancements investigated, all with varying degrees of success and complexity. The general philosophy of most of these techniques is to add one or more resonant antennas to the microstrip patch configuration. These additional elements may be in the form of slots or other patches. Once the additional radiator or radiators have been chosen, the objective of the antenna designer is to ensure there is the right degree of interaction between these elements so that the performance of the printed antenna is enhanced. In this section a summary of some of the more recognized methods are presented.

6.4.1 Parasitically Coupled (or Gap-Coupled) Patches

In the early to mid-1980s, parasitically coupling patches in a horizontal manner to the driven patch were proposed and investigated.[6] The philosophy behind this technique is that if the resonant frequency of the coupled element or elements is slightly different to that of the driven patch, then the bandwidth of the entire antenna may be increased. Figure 6.8 shows an example of a driven probe-fed rectangular patch with two parasitic patches positioned on either side of the excited patch in the *y*-axis direction. The critical parameters are the lengths and widths of each patch for the control of resonant frequency and bandwidth, as well as the gap between the elements. The gaps tend to control the coupling between the patches and therefore the tightness of the *resonant loop* (or loops) in the impedance locus of the antenna.

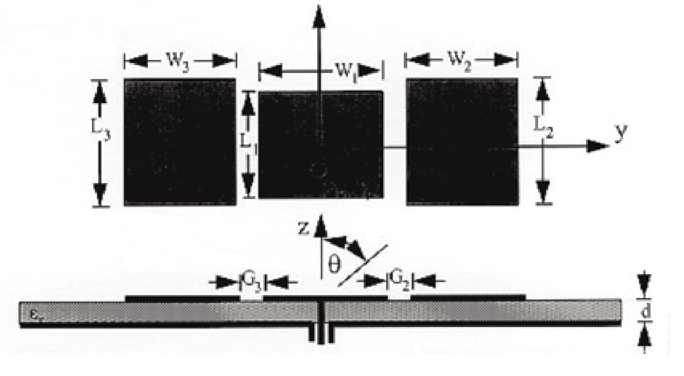


FIGURE 6.8 Schematic diagram of parasitically coupled (horizontal direction) microstrip patch antennas.

Bandwidths on the order of 20% have been achieved using this enhancement technique,[6,7] although there are several shortcomings of using parasitically coupled patches. First, to achieve these reasonable bandwidths, wide parasitic elements are required to make the overall size of the printed antenna configuration electrically large and, therefore, it is difficult to develop an array without incurring grating lobe problems.[7] Second, the radiation patterns of parasitically coupled patches tend to be somewhat distorted across the useful impedance bandwidth, because of the lack of symmetry of the generated currents with respect to the center of the printed antenna.

6.4.2 Stacked Microstrip Patches

Stacking patches on top of each other is probably the most common procedure utilized to enhance the bandwidth of a microstrip antenna. Figure 6.9 shows a schematic diagram of an edge-fed stacked patch configuration, where an arbitrarily shaped patch is etched on a grounded substrate and is fed by a microstrip transmission line. Another patch antenna is mounted on a second laminate (with no ground plane) and is placed directly above the driven patch.

Interestingly, when stacking was first proposed in the late 1970s to increase the bandwidth of direct contact fed patches, only moderate improvements were achieved.[8] One possible reason as to why such minor improvements were observed can be attributed to the relative complexity nature of these printed antennas. By looking at Fig. 6.9, there are many variables in this configuration and thus a rigorous full-wave analysis to accurately model the performance of the antenna is required. Importantly, the analysis needs to be not only accurate but also computationally fast so that trends in the impedance nature can be accurately and rapidly observed and then later optimized. Such accurate, fast codes are available nowadays, thanks mainly to the order of magnitude increases in the computational speeds of computers. A thorough investigation into how to design broadband direct contact stacked patches was undertaken, in particular, focusing on what optimum parameters are needed to achieve good bandwidth characteristics.[9] From this study, direct contact feed-stacked patches with bandwidths approaching 30% have been achieved. This order of bandwidth can also be achieved using noncontact, feed-stacked patches, such as aperture-coupled stacked patches,[10] of which a schematic diagram is shown in Fig. 6.10. Advantages of utilizing direct contact feed-stacked patches over aperture-coupled stacked patches include ease of fabrication and a minimal backward-directed radiation. As mentioned previously, aperture-coupled patches do have more degrees of freedom than direct contact fed patches and therefore an aperture-coupled stacked patch is somewhat easier to design.

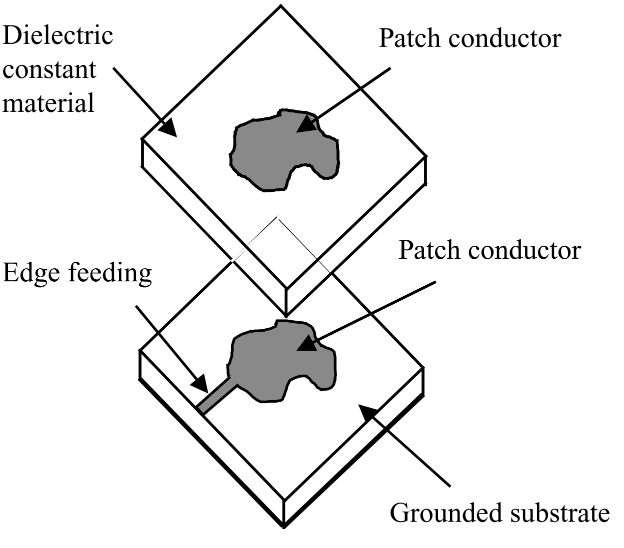


FIGURE 6.9 Schematic diagram of edge-fed arbitrarily shaped stacked microstrip patches.

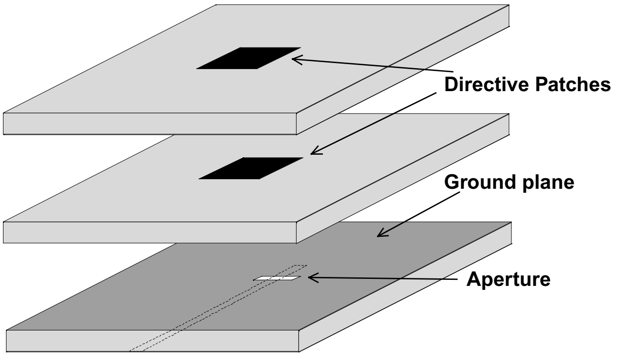


FIGURE 6.10 Schematic diagram of aperture-coupled rectangular stacked microstrp patches.

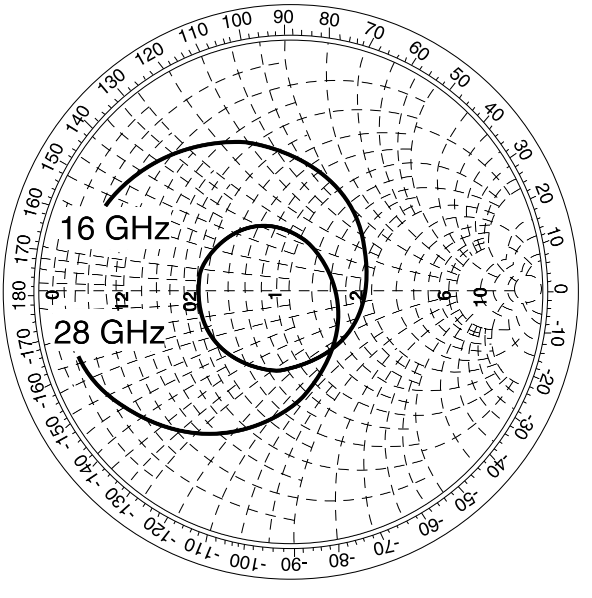


FIGURE 6.11 Typical input impedance locus of stacked microstrip patches.

Figure 6.11 shows a typical impedance locus of a stacked patch antenna configuration. The important characteristic to observe is the *resonant loop* created by the interaction between the two patches. This interaction governs the achievable bandwidth. In any stacked patch configuration there are many degrees of freedom and to say that one parameter controls the resonant loop over the other parameters is not necessarily true. However, the gap between the two patches (d_2) does primarily control the tightness of the resonant loop. The closer the patches are, the bigger the loop. It can be postulated simplistically that the closer the patches are together, the more coupling or interaction. In the extreme, with the second patch located directly on top of the driven patch, the loop becomes very large because only one patch can be seen. As the patches are moved farther apart, the coupling becomes less and the loop contracts. Eventually the loop closes entirely until the locus looks identical to a single-element configuration, because the driven patch no longer sees the parasitic antenna. Readers interested in the design procedures of stacked microstrip patches may refer to the articles within the literature[9,10] for details.

A stacked patch geometry over other bandwidth enhancement techniques has several advantages: they are relatively easy to design — once the design trends have been established; their radiation pattern remains reasonably constant over the 10-dB return loss bandwidth; and they can be easily accommodated into an array environment.

It is possible to stack more patches on top of the driven element, such as a triple-stacked patch. The success of such a configuration is very susceptible to the dielectric layers used and in fact has been shown to give minimum improvement over a conventional stacked patch when low dielectric constant laminates are utilized.[11] Triple-stacked patches are discussed further in Section 6.7.3.

6.4.3 Large Slot Aperture-Coupled Patches

A simple way of enhancing the bandwidth of an aperture-coupled patch without increasing the complexity of the antenna by means of stacking is to increase the size of the slot.[12] By having the slot close to resonance allows an impedance response similar to that presented in Fig. 6.11, because there are now two strongly coupled radiating structures, namely, the slot and the patch. In fact, having a relatively large slot is a natural progression to achieve large bandwidth. As shown in Fig. 6.2, to increase the bandwidth of a microstrip patch antenna, thick dielectric material is required. In an aperture-coupled patch environment, to ensure power is coupled to the patch located on a thick dielectric layer, the size of the slot must be increased. Bandwidths in excess of 40% have been achieved using this relatively simple technique. There are two problems with using a large slot aperture-coupled patch:

1. The front to back ratio can become poor. Because a slot in a ground plane radiates equally in both the upper and lower half spaces (ignoring the effect of the dielectric materials surrounding the ground plane), the level of backward radiation can become somewhat high. This leads to less power available in the power budget of a link and more importantly for sectored wireless communication systems, it can lead to increased levels of interference. This latter factor is very important for mobile communications systems. Typical base stations/radio hubs provide a sectoral coverage area to increase the system capacity; for example, for local multipoint distribution services (LMDS) the 360° azimuth plane is usually split into four 90° sectors, whereas for a mobile base station it is usually three 120° sectors. Imperative for these sectoral systems is to minimize the back radiation from each antenna to ensure interference from adjoining subcells that are also minimized. Several ways to overcome the inherent back radiation problem of a large slot aperture-coupled patch antenna are available, although these are usually accompanied by added structural complexity. These include using a cavity-backed configuration[13] or a reflector element[14] to minimize the backward directed radiation.
2. Scalping of the radiation pattern, particularly in the E-plane, can occur. This results from using a large slot in conjunction with a small ground plane. Because a reasonable portion of the power radiated from a slot is directed toward endfire, this power can be easily diffracted off a truncated ground plane, resulting in a deformation of the radiation pattern. Figure 6.12 shows an example of this phenomenon associated with the large slot of an aperture-coupled patch antenna. Possible ways to alleviate this problem are to ensure the ground plane extends a relatively large distance with respect to the center of the patch and slot, on the order of a couple of wavelengths. Also, absorbing material can be used to coat the edges of the ground plane.

Despite these problems, large slot aperture-coupled patches, or modifications of this microstrip patch antenna, are currently utilized as the antenna for several mobile communications base stations throughout the world.

6.4.4 Aperture-Stacked Patches

From the previous two bandwidth enhancement cases, a natural progression would be to use a large slot aperture-coupled stacked patch configuration to further improve the bandwidth. This printed antenna, referred to as an aperture-stacked patch (ASP) has been proposed, designed, and developed.[15,16] A schematic diagram of the antenna is shown in Fig. 6.13 and a photograph of the original ASP[15] is shown

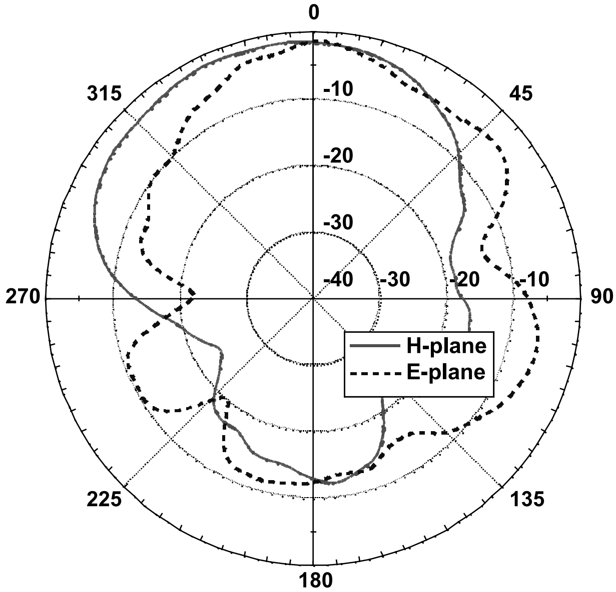


FIGURE 6.12 Example of radiation pattern scalping for large slot aperture-coupled microstrip patch antenna.

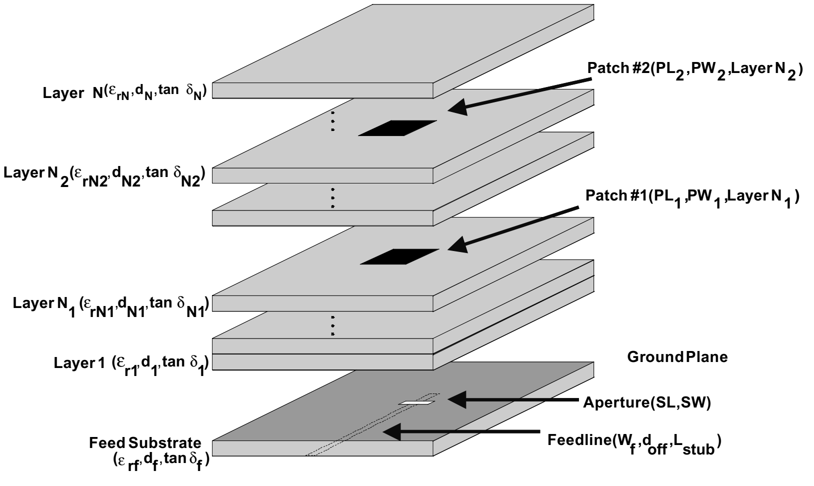


FIGURE 6.13 Schematic diagram of aperture-stacked patch (ASP) antenna.

in Fig. 6.14. The printed antenna consists of a large slot and two directive patches. Impedance bandwidths in excess of an octave have been achieved using this printed antenna configuration. A typical impedance locus of an ASP is shown in Fig. 6.15. As can be seen in this plot, there are two *resonant loops* resulting from the mutual resonances set up between with the three radiators, namely, the slot and the two directive patches. The gain of the ASP is also relatively constant over the octave bandwidth. The front to back ratio is not as poor as for that of a large slot aperture-coupled patch because of the additional directive patch, typically with values no less than 12 dB across the entire octave impedance bandwidth. This has been improved by utilizing cavity-backed solutions[17] as well as reflector patch solutions to values greater than 30 dB.[18] The design procedure for these wideband printed antennas is relatively straightforward.[16]

Presently, ASPs are probably the ultimate wideband printed antennas based on microstrip patch technology. These antennas have all the characteristics deemed important for wideband operation,

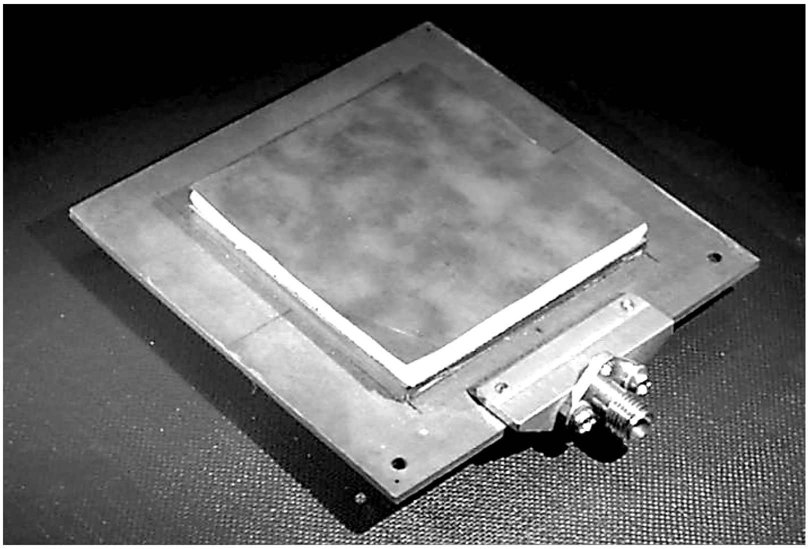


FIGURE 6.14 Photograph of ASP.

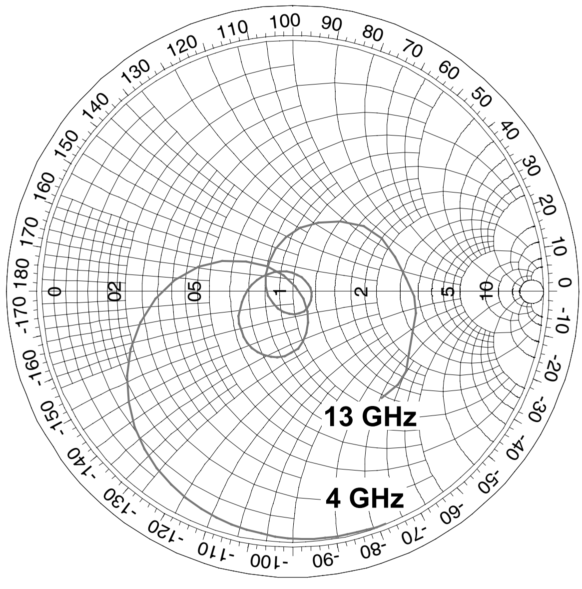


FIGURE 6.15 Typical input impedance locus of ASP.

namely, good impedance and gain bandwidth, good polarization control, compactness, and relatively simple development. In essence, the ASP can be thought of as a vertical log-periodic printed antenna; however, importantly it does not suffer from surface wave problems despite its electrical thickness. This is because the surface wave power is coupled to the adjoining patches and radiated into free space. ASP antennas, when designed appropriately have surface wave efficiencies greater than 85% even though the material used is greater than 0.1 λ_0, where λ_0 is the free-space wavelength at the center of the operation band. The large bandwidth encountered using ASPs potentially solves one of the problems that have dogged the universal deployment of microstrip patch technology into communication systems. The development of a printed antenna that is fundamentally broadband should enable various radio service applications to share some equipment hardware, thereby reducing the number of hub sites required to deliver these services and the overall cost of the radio network. Having a wideband printed antenna also potentially reduces the design stages required for the antenna development, because it tends to be more tolerant of fabrication discrepancies.

6.4.5 Alternative Printed Antenna Solutions

Of course, other printed antenna solutions can provide very wide bandwidths: printed spirals,[19] tapered slots,[20] and printed bow-tie antennas.[21] However, unless the bandwidth required is well in excess of an octave, these solutions are not as simple or as elegant as the ASP configuration. Tapered slots as well as printed spirals can yield multioctave bandwidth performance; however, the structural complexity and overall size of these antennas is a deterrent, especially if such bandwidths are not required.

Other printed antennas that have recently shown reasonable promise at providing broad bandwidth responses (10-dB return loss bandwidths between 30 and 45%). These include the L-shaped excited stacked patch,[2] incorporating slots into the patch conductors,[22] and also the printed quasi yagi antenna.[23]

6.5 Circular Polarization Techniques

One of the stated advantages of microstrip patch technology is the relative ease to generate dual and hence circular polarization (CP). This feature is one reason why microstrip patch antennas have been utilized for space-borne communication antennas on satellites. Three methods are used for generating CP: using a single feed and perturbation approach, a dual-feed excitation technique, or a synchronous subarray approach. Each method has its merits and disadvantages, which are summarized in this section.

6.5.1 Single-Feed Circular Polarization Patch Antenna

This approach requires no external circuitry for the microstrip patch antenna to generate CP. The principle relies on the fact that CP is obtained when two orthogonal but otherwise identical modes are excited with a 90° phase difference between them. To do so on a single patch with only one feed is not too difficult to implement. Figure 6.16 shows a schematic diagram of how this can be done. The patch is fed on one of its diagonal planes; therefore, it excites two orthogonal modes, one resonant in the x direction and the other in the y direction, satisfying one of the requirements for CP. To achieve 90° phase shift between the two modes, one mode (or field) is slightly perturbed with respect to the other. This can be done by making one resonant dimension slightly longer than the other, truncating a set of the corners of the patch or even putting a slot within the patch. The philosophy here is that by slightly

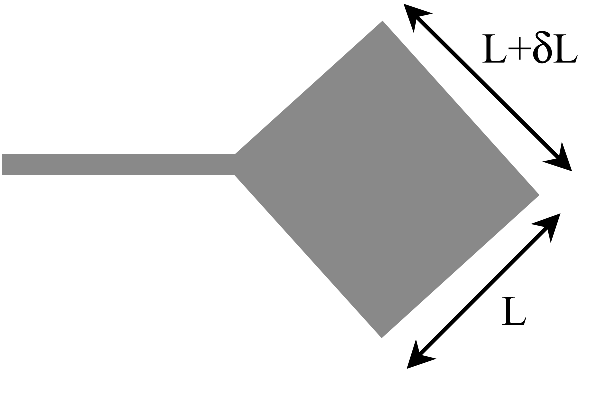


FIGURE 6.16 Schematic diagram of single-feed CP edge-fed microstrip patch antenna.

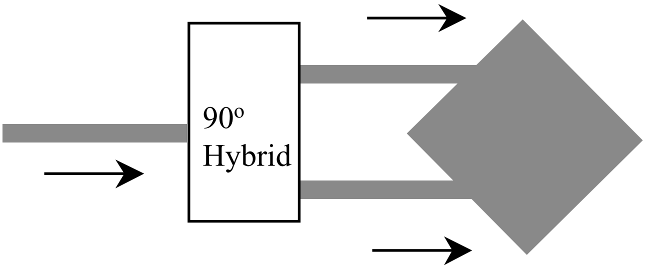


FIGURE 6.17 Schematic diagram of dual-feed CP edge-fed microstrip patch antenna.

adjusting the resonant frequency of one mode with respect to the other, if properly designed, then the overall phase difference between the self-impedances of the modes and therefore the fields will be 90°, satisfying the second requirement for CP generation.

Although relatively simple to implement, there is a critical flaw in this design procedure: the CP bandwidth (axial ratio less than 3 dB) is extremely narrow, typically a fraction of the impedance (10-dB return loss) bandwidth. Effectively the problem here is to ensure the phase relationship (90° phase difference) holds across a range of frequencies. This is quite difficult to do, especially when considering the rapid impedance variation of a typical microstrip patch antenna near resonance. A case has been presented where the CP bandwidth was greater than 10%, but still a fraction of the impedance bandwidth of the antenna.[24] The key to successfully broadening the CP bandwidth of this antenna is reducing the impedance variation of each mode as a function of frequency.

6.5.2 Dual-Feed Circular Polarization Patch Antenna

Probably the simplest and most common means of producing CP on a microstrip patch antenna is to excite two orthogonal modes using separate feeds and ensuring there is 90° phase difference between the modes by incorporating a 90° phase shift within one of the feed lines, as shown in Fig. 6.17. CP bandwidths comparable to the impedance bandwidth of the patch antenna are usually observed for this configuration. It can be somewhat difficult to obtain true CP (0-dB axial ratio) for a direct contact dual-feed CP patch antenna because of the inherent asymmetry of the configuration as well as the asymmetrical cross-polarization levels generated by the patch (note that the H-plane levels are higher than the E-plane levels off broadside, $\theta = 0°$).

6.5.3 Synchronous Subarrays

By far the best CP bandwidths and lowest axial ratios can be achieved using a synchronous subarray.[25] A four-element synchronous subarray in Fig. 6.18 shows each patch spatially rotated 90° with respect to the previous patch. In addition to the spatial rotation, the feeds are also phase rotated sequentially by 90°. Thus, port 2 leads port 1 by 90°, port 3 leads port 1 by 180°, and port 4 leads port 1 by 270°. Having such a feed arrangement cancels the generated cross-polarization fields of the individual patches. It has been shown in the past that very good axial ratio bandwidths can be achieved using a synchronous subarray of elements that individually do not radiate CP.[26] Also the impedance bandwidth of this CP antenna is typically larger than that of the single element because of the feed network. Synchronous subarrays do not necessarily consist of four elements; cases of three (0°, 120°, and 240°) and higher order cases have been investigated. As long as there is a spatial symmetry with respect to the center of the configuration as well as the appropriate phase rotation, this approach should provide good axial ratio performance. A typical axial ratio plot of a four-element synchronous subarray is shown in Fig. 6.19.

One significant disadvantage of the synchronous subarray is its electrical size. Because of this a synchronous subarray can have severe grating lobe problems when implemented in an array. It is potentially possible to utilize the synchronous subarray concept on a single patch; however, the limited

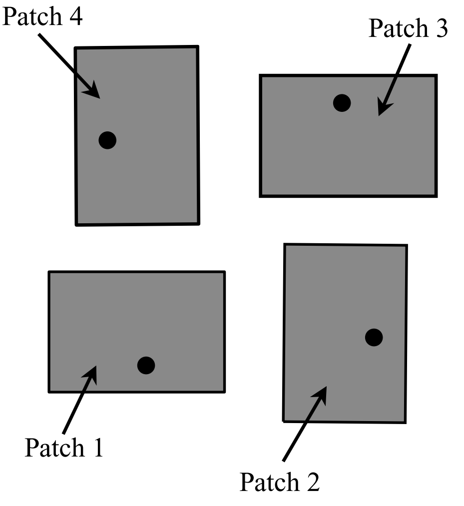


FIGURE 6.18 Schematic diagram of synchronous subarray of four probe-fed microstrip patch antennas.

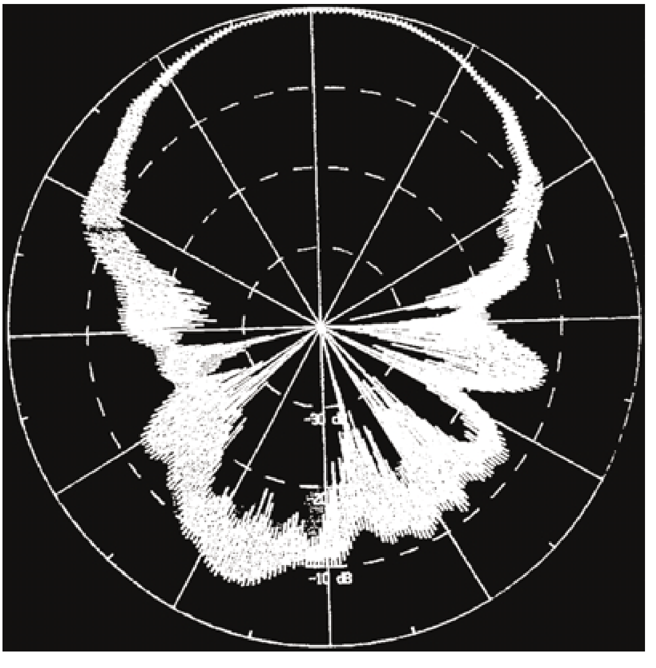


FIGURE 6.19 Typical axial ratio plot of synchronous subarray of microstrip patch antennas.

patch real estate as well as the effect of the coupling of each feed on the input impedance of the printed antenna could make this difficult to implement.

6.6 Reducing Conductor Size

With the advent and popularity of many wireless services, a quandary has arisen in the antenna community about how to develop small antennas that can satisfy the performance requirements for these systems as well as be aesthetically pleasing to the user. It is interesting to note that the latter point is not insignificant. As with the computer industry, mobile communications is very much a customer-driven market and thus the user requests, although technically with little merit, must be addressed. Ideally, an antenna that is unobtrusive and low cost, and can be located within the casing of the handset would ensure the compactness of the handset terminal and therefore please the users.

Microstrip antennas would appear to be possible candidates because of several attractive features outlined in Section 6.1, including their low profile, light weight, and ease of fabrication. Unfortunately, most present-day mobile communication systems are in the lower microwave region of the spectrum (less than 3 GHz) where these antennas in their conventional form are too large for wireless communication handsets. Several approaches have been reported in the literature to effectively reduce the size of the printed conductor of a microstrip patch antenna and are summarized as follows:

1. The quarter-wave patch antenna[27] is probably the first technique used to reduce the size of a patch antenna. Here one of the radiating edges is terminated in a short-circuit plane connecting the patch antenna to the ground plane. By doing so, the short-circuit plane acts as a mirror and the size of the patch conductor can be effectively halved, similar to the relation between a wire dipole and a wire monopole. Several cases of successfully developed quarter-wave patch antennas have been reported in the literature. Unfortunately, two drawbacks associated with this size reduction technique make it unsuitable for present-day mobile communication handset terminals. First, the size reduction is not great enough. Second, impedance bandwidth is reduced. Another issue related to this technology, although not that critical for mobile communication handset terminals, is the increased level of cross-polarized radiation.
2. The patch antenna on high dielectric constant material[28] is probably the most obvious means of reducing the patch conductor size. The main issues are the associated reduction in bandwidth and efficiency when using such a technique (refer to Fig. 6.2 for details). Having such narrowband radiators makes the performance of these antennas very susceptible to manufacturing tolerance errors. Also the cost associated with high dielectric constant material can be somewhat prohibitive, although the recent availability of some low-cost, high dielectric constant ceramic materials may alleviate the cost issue to an extent. Care, however, must be taken when using these materials because the high loss tangents can considerably degrade the radiation performance of the printed antenna.
3. Shorted patch antennas[29] have shown that a significant reduction in physical size of the patch conductor can be achieved if a single shorting post is used, instead of the conventional short-circuit plane of a quarter-wave patch. A schematic diagram of a probe-fed shorted patch is shown in Fig. 6.20. A rectangular patch is loaded with a shorting pin located in close proximity to the probe feed. Reductions in size of greater than a further halving have been achieved using this procedure and the bandwidth and efficiency issues appear not to be as severe as for the case of using very high dielectric constant substrates. However, the fundamental problem associated with this form of printed antenna is that it is still difficult to achieve the necessary bandwidth, and also the close proximity between the feed and the shorting post, especially when high dielectric constant or thick materials are used, makes the antenna difficult to fabricate. A summary of the design procedure and performance of shorted patch antennas is available in the literature.[30] Since then, there have been several variations of shorted patch that have alleviated some of the encountered problems to an extent, although typically at the expense of increased volume (e.g., a stacked shorted patch[31]), or increased overall complexity and component count. These factors are very important when considering high-volume manufacturing runs. It should be noted that with respect to size reduction, in the limit, shorted patches are very similar to planar inverted-F antennas (PIFAs).[32] The difference really is associated with how the problem is formulated. Shorted patches were derived from the patch antenna concept and therefore are electrically thin, whereas PIFAs originated from folded wire antennas and thus the thickness between the radiating conductor and the ground plane is somewhat large. One means of increasing the bandwidth of a shorted patch is to

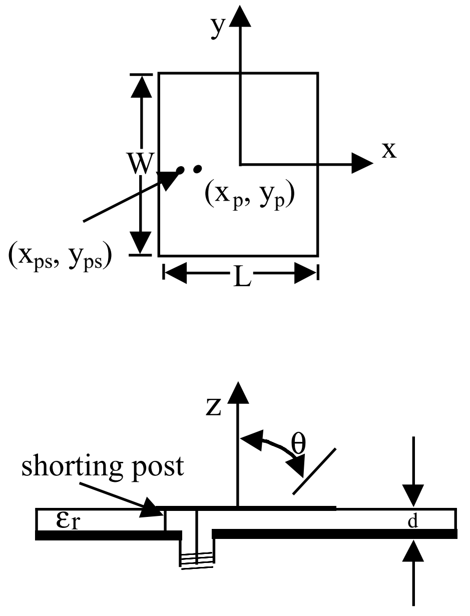


FIGURE 6.20 Schematic diagram of probe-fed shorted microstrip patch antenna.

increase the thickness of the substrate. As this is done, the characteristics, both electrical and mechanical, of the shorted patch antenna become more and more similar to that of a PIFA.

4. Resistive loading patch antennas[33] using resistive terminations as opposed to a shorting pin have been proposed to give size reduction of the conductor of a microstrip patch without reducing the associated impedance bandwidth. A very important disadvantage of using resistive terminations to reduce the size of an antenna is the associated reduction in radiation efficiency. Thus although an antenna using a resistor as a load can yield small size and reasonable bandwidth, the associated decrease in efficiency has a more dramatic effect on the system performance. This can be simply proved by applying the Friis transmission equation[1] to a link utilizing the antenna.

6.7 Integration with Active Devices and Examples of Active Patches

As is evident in Fig. 6.2 and was previously discussed, the microstrip patch antenna in its pure form despite the initial enthusiasm is not suited to monolithic integration with active devices, because of the low achievable bandwidths and poor radiation efficiency. Over the years there have been several techniques developed to allow such integration and these are summarized next.

6.7.1 Noncontact Feed Mechanisms

As shown in Section 6.3, noncontact feed mechanisms can alleviate these problems to an extent. Proximity coupled patches, although allowing some degree of independent optimization of the feed substrate and antenna laminate, are not well suited to integration with MMIC and OEIC technology because of the relatively poor surface wave efficiencies and also the difficulty in coupling power to the patch antenna. The first problem results from the patch antenna still seeing some of the high dielectric constant material used for the active devices and therefore affecting the efficiency. The latter problem can be simply explained by the fact that the microstrip line on the high dielectric constant material has most of its field contained between the conductor and the ground plane, therefore making it difficult to couple power to

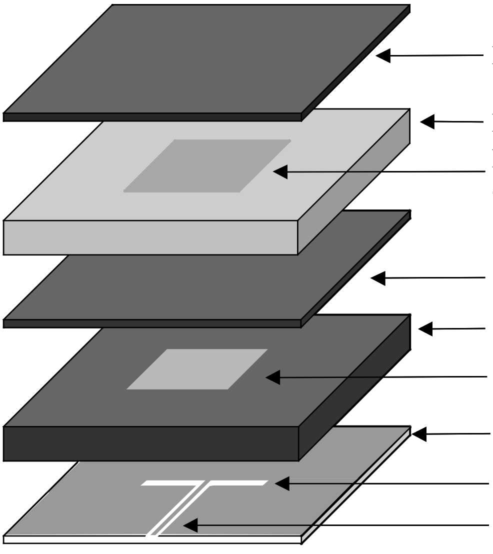


FIGURE 6.21 Schematic diagram of CPW-fed ASP.

the antenna. To do so, the high dielectric constant substrate must be increased in thickness, or the antenna laminate must be reduced in thickness. Both of these measures result in poor bandwidth and surface wave efficiency.

Aperture-coupled solutions are better suited to integration with active devices, although care must be taken to ensure surface wave efficiencies remain high. When the aperture or slot is small and a high dielectric constant substrate is used for the feed, the surface wave losses associated with the feed can be high, significantly reducing the radiation efficiency of the antenna.[34] However, as the aperture size is increased, the reduction in surface wave efficiency because of the high dielectric constant feed material seems to diminish. Simply, the slot tends to draw power from the surface wave thereby increasing the efficiency of the antenna. Versions of co-planar waveguide (CPW)-fed ASP antennas (refer to Section 6.4 for a description of the ASP antenna), using high dielectric constant substrates for the feed, have been designed and developed with impedance bandwidths greater than 40% and surface wave efficiencies greater than 85% across this band.[35] A schematic diagram of this antenna is shown in Fig. 6.21. CPW feed configurations were considered because of the popularity of this transmission line for integration with active devices. Similar results for microstrip line fed ASP antennas using a high dielectric constant feed substrate can also be achieved. As pointed out in Section 6.4, for large aperture or slot-coupled printed antennas care must be taken with backward radiation. Although the ASP can be easily integrated with millimeter-wave and photonic devices in its present form, one potential difficulty is that these active devices need some form of heat sinking and support structure. To implement this for the ASP is not typically straightforward because the performance of the antenna may be compromised if a metal plate for mechanical support is located in close proximity to the electrically large slot or if the ground plane in which the slot resides is electrically thick.[36] One possible solution to the design problem is to incorporate a cavity-backed structure as outlined in Section 6.4, where a cavity is located under the slot of the antenna. This not only provides a good support structure for the antenna and the active devices but also improves the front to back ratio of the antenna itself.

6.7.2 Antennas with Reduced Surface Wave Excitation

Another technique to overcome the problem of inefficient patch antennas resulting from surface wave excitation has been proposed.[37] In this case, it was shown that if the size of the antenna were beyond a critical dimension related to the propagation constant of the TM_0 surface wave, the TM_0 surface wave

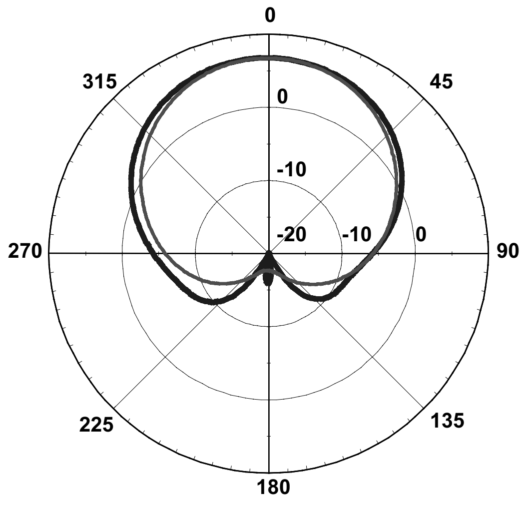


FIGURE 6.22 Measured radiation pattern of circular microstrip patch with concentric annular ring.

mode would not propagate. Several printed antennas were demonstrated, although these microstrip patch antennas are relatively difficult to construct and are extremely narrowband. Simpler microstrip patch antennas, consisting of a circular patch and a concentric annular coupled ring have been developed using the same principal and showing similar improved efficiency and also slightly enhanced bandwidths.[38] The measured co-polar radiation patterns of a circular patch and a concentric annular coupled ring[38] mounted on an electrically thick, high dielectric constant material is shown in Fig. 6.22 at the resonant frequency of the antenna. Note that despite a small ground plane used, there is no detectable ripple in either the E-plane or H-plane patterns. This can be attributed to the minimum surface wave excitation and hence the minimum diffraction off the ground plane of the patch. There are two relatively fundamental drawbacks of the oversized patch technique: only moderate bandwidths can be achieved; and also the large size of the patch conductor is required. This latter problem is indeed an issue when only limited space on a wafer is available.

6.7.3 Stacked Patch Structures

It is interesting to note that throughout the history of the development of stacked patch technology, a thorough investigation into the most appropriate materials/laminates to achieve the optimum performance had not been undertaken. This can be explained by the results presented in Fig. 6.2, namely, that single-layer patch antennas do not perform well when high dielectric constant materials are used as a substrate; thus, it was thought that similar results would result when a stacked configuration was utilized. However, this has been shown to be incorrect. It has been reported that a combination of high dielectric constant and low dielectric constant laminates, referred to as hi–lo configurations,[24] can yield similar impedance bandwidths and radiation performance to that of a conventional stacked patch.[9] Unlike cases where a single-layer case using a high dielectric constant substrate where the surface wave efficiency is poor, the hi–lo stacked patch has very high surface wave efficiency across the impedance bandwidth. This somewhat startling revelation opens up a new avenue in the area of integration research. Hi–lo stacked patches have several salient features that are useful for integration with MMICs and OEICs: (1) good bandwidth can be achieved; (2) minimum back radiation is present because of the ground plane; (3) they are relatively simple to design;[24] (4) low cross-polarization levels are radiated, indicating that good quality CP can easily be generated.[24]

Maximum bandwidths of approximately 30% have been achieved with a hi–lo stacked patch configuration. This has been further extended utilizing a third patch, or a triple-stacked patch configuration.[11] A schematic diagram of the triple patch is shown in Fig. 6.23. A triple-stacked patch arrangement only

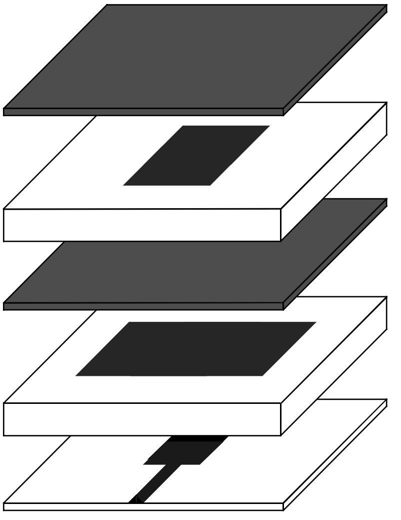


FIGURE 6.23 Schematic diagram of edge-fed, triple-stacked patch antenna.

shows improved characteristics, beyond that achievable for a conventional stacked patch antenna, when the lowest layer material has a relatively high dielectric constant. Bandwidth performance approaching that of a large slot aperture-coupled patch has been achieved without the problems of backward-directed radiation. A comparison of the radiation patterns of a hi–lo patch structure and a CPW-fed ASP antenna is shown in Fig. 6.24.[39] As can be seen from these plots, the hi–lo patch configuration has a significantly better front to back ratio compared with the CPW-fed ASP. The ultimate bandwidth that can be achieved as well as the best combination of materials is ongoing research and hopefully these questions will be answered soon.

6.7.4 Patch Antennas on Photonic Bandgap Structures

Considerable attention has been directed toward the development of metallic electromagnetic structures that are characterized by having high-surface impedances. These structures, unlike conventional surfaces, do not support propagating surface waves. Several versions of these frequency-dependent impedance surfaces have been reported, commonly referred to photonic bandgap (PBG) structures or substrates.[40,41] The material is periodically loaded to create an "electromagnetic crystal" whose surface-wave dispersion diagram presents a forbidden range of frequencies hopefully near the operation frequency of the antenna. Because surface waves cannot propagate along the substrate, an increased amount of radiated power couples to space waves, enhancing the radiation efficiency. Some promising results have been achieved for microstrip antenna structures mounted on PBG materials. However, there are still several questions that need to be resolved before this technology is universally accepted, namely: (1) how large does the periodic structure need to be before it works effectively; and (2) how broadband can the structure be?

6.7.5 Examples of Integrated Antennas

Although from the previous subsections it is evident that there are several techniques to overcome the problem of direct integration of MMICs and OEICs with patch technology, very few successful cases are reported in the literature on direct integration. This is simply because this technology is quite immature at present. On the other hand, the area of hybrid integration, commonly referred to as active integrated antennas, is somewhat more established and there are many cases of such printed antennas. An excellent review article can be found in the literature.[42]

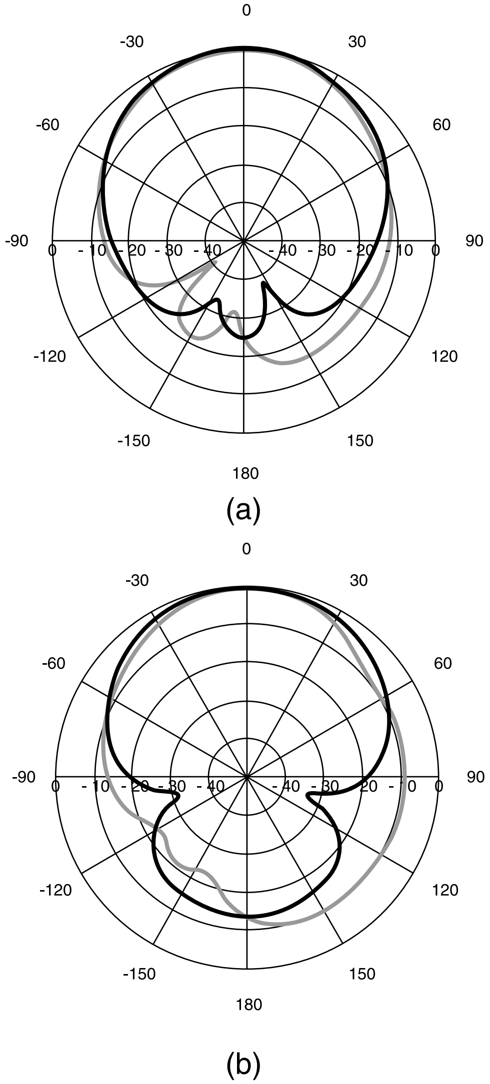


FIGURE 6.24 Comparison of radiation patterns of hi–lo stacked patch antenna and CPW-fed ASP antenna.

The purpose of an active integrated antenna is to have the active circuitry within the antenna structure itself, thereby removing the lossy and sometimes bulky interconnects between the devices and antenna. This concept, if successfully mastered, can yield systems that are compact, low cost, and low profile, with minimum power consumption and a high degree of flexibility. The degree of flexibility is apparent because the designer is no longer restricted to a 50-Ω system and thus the impedance response of the antenna can be tailored to that which gives, for example, the minimum noise response for the amplifier. Over the years there have been several reported cases of printed active integrated antennas including high efficiency power amplifiers,[43,44] quasi-optical power combiners,[45,46] beam-steering arrays,[47,48] optically assisted active integrated antennas,[49,50] retrodirective arrays,[51,52] and transceivers and transponders.[53,54]

It should be noted at this stage that active integrated antennas cannot provide full duplex operation (transmit and receive at the same time) for present-day styled mobile communications systems. This can be attributed to one fundamental reason. Typically, some form of frequency diversity is required, namely, there is an upper band and lower band for transmitting and receiving. The natural filtering response of a patch antenna, whether it be frequency or polarization based, is not pure enough to satisfy both the

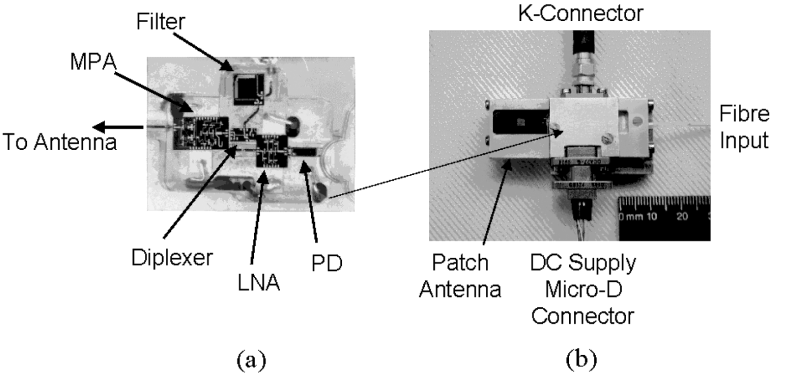


FIGURE 6.25 Photograph of integrated photonic/antenna module.

bandwidth requirements for transmitting and receiving only and to give the isolation required for the small guard band typically used in today's mobile communication systems.

Cases of hybrid integrated antenna photonic modules have also been reported.[55-57] The objectives here are to have modules that can be readily connected to fiber-backbone networks for such applications as picocellular mobile communications. Using fiber technology for these wireless access networks allows most of the expensive switching and signal processing functions to be located at a central office, thereby reducing the overall cost of the system. Imperative for these systems are small, efficient base station units, or photonic/antenna modules. Figure 6.25 shows a photograph of a hybrid integrated antenna photonic module for operation between 28 and 43 GHz.[57] Once again, probably because of the immaturity of the field, successful directly integrated cases have yet to be developed at this stage.

6.8 Conclusions

In this chapter, several concepts related to microstrip patch antenna technology have been summarized. The fundamental characteristics of microstrip patch antennas have been presented; methods to couple power to and from the printed antenna have been summarized; techniques to enhance the bandwidth and efficiency have been reported; and how to reduce the conductor size of a patch antenna and methods to generate circular polarization have been discussed. It is hoped that this chapter has provided the reader with the essentials required to understand microstrip patch technology and how to optimize the performance of this form of antenna for the application at hand. For further information on the topics presented the reader should consult the given reference material.

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