CHAPTER ONE

Introduction and Overview

1.1 INTRODUCTION

Conventional microstrip antennas in general have a conducting patch printed on a grounded microwave substrate, and have the attractive features of low profile, light weight, easy fabrication, and conformability to mounting hosts [1]. However, microstrip antennas inherently have a narrow bandwidth, and bandwidth enhancement is usually demanded for practical applications. In addition, applications in present-day mobile communication systems usually require smaller antenna size in order to meet the miniaturization requirements of mobile units. Thus, size reduction and bandwidth enhancement are becoming major design considerations for practical applications of microstrip antennas. For this reason, studies to achieve compact and broadband operations of microstrip antennas have greatly increased. Much significant progress in the design of compact microstrip antennas with broadband, dual-frequency, dual-polarized, circularly polarized, and gain-enhanced operations have been reported over the past several years. In addition, various novel broadband microstrip antenna designs with dual-frequency, dual-polarized, and circularly polarized operations have been published in the open literature. This book organizes and presents these recently reported novel designs for compact and broadband microstrip antennas.

1.2 COMPACT MICROSTRIP ANTENNAS

Many techniques have been reported to reduce the size of microstrip antennas at a fixed operating frequency. In general, microstrip antennas are half-wavelength structures and are operated at the fundamental resonant mode TM_{01} or TM_{10}, with a resonant frequency given by (valid for a rectangular microstrip antenna with a thin microwave substrate)

$$f \cong \frac{c}{2L\sqrt{\varepsilon_\mathrm{r}}}, \tag{1.1}$$

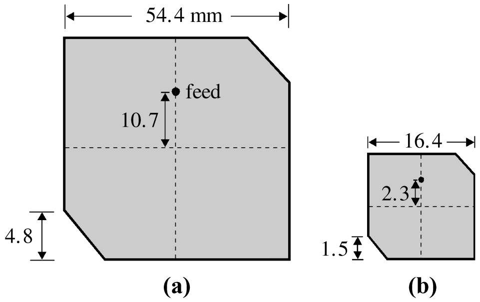


FIGURE 1.1 Circularly polarized corner-truncated square microstrip antennas for GPS application at 1575 MHz. (a) Design with a microwave substrate ($\varepsilon_r = 3.0$, $h = 1.524$ mm); (b) design with a ceramic substrate ($\varepsilon_r = 28.2$, $h = 4.75$ mm). Dimensions are in millimeters and not to scale.

where c is the speed of light, L is the patch length of the rectangular microstrip antenna, and ε_r is the relative permittivity of the grounded microwave substrate. From (1.1), it is found that the radiating patch of the microstrip antenna has a resonant length approximately proportional to $1/\sqrt{\varepsilon_r}$, and the use of a microwave substrate with a larger permittivity thus can result in a smaller physical antenna length at a fixed operating frequency. Figure 1.1 shows a comparison of the required dimensions for two circularly polarized corner-truncated square microstrip antennas with different substrates for global positioning system (GPS) application. The first design uses a microwave substrate with relative permittivity $\varepsilon_r = 3.0$ and thickness $h = 1.524$ mm; the second design uses a high-permittivity or ceramic substrate with $\varepsilon_r = 28.2$ and $h = 4.75$ mm. The relatively larger substrate thickness for the second design is needed to obtain the required circular polarization (CP) bandwidth for GPS application. From the patch areas of the two designs, it can be seen that the second design has a patch size about 10% of that of the first design. This reduction in antenna size can be expected from (1.1), from which the antenna's fundamental resonant frequency of the design with $\varepsilon_r = 28.2$ is expected to be only about 0.326 times that of the design with $\varepsilon_r = 3.0$ for a fixed patch size. This result suggests that an antenna size reduction as large as about 90% can be obtained if the design with $\varepsilon_r = 28.2$ is used instead of the case with $\varepsilon_r = 3.0$ for a fixed operating frequency.

The use of an edge-shorted patch for size reduction is also well known [see the geometry in Figure 1.2(a)], and makes a microstrip antenna act as a quarter-wavelength structure and thus can reduce the antenna's physical length by half at a fixed operating frequency. When a shorting plate (also called a partial shorting wall) [see Figure 1.2(b)] or a shorting pin [Figure 1.2(c)] is used instead of a shorting wall, the antenna's fundamental resonant frequency can be further lowered and further size reduction can be obtained. In this case, the diameter of a shorting-pin-loaded circular microstrip patch [2] or the linear dimension of a shorting-pin-loaded rectangular microstrip patch [3] can be as small as one-third of that of the corresponding microstrip patch without a shorting pin at the same operating frequency. This suggests that an antenna size reduction of about 89% can be obtained. Moreover, by applying the

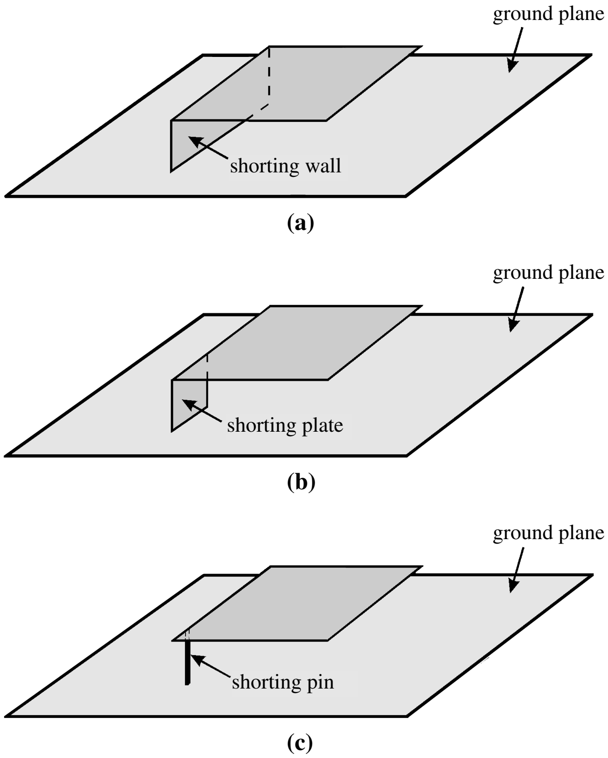


FIGURE 1.2 Geometries of a rectangular patch antenna with (a) a shorting wall, (b) a shorting plate or partial shorting wall, and (c) a shorting pin. The feeds are not shown.

shorting-pin loading technique to an equilateral-triangular microstrip antenna, the size reduction can be made even greater, reaching as large as 94% [4]. This is largely because an equilateral-triangular microstrip antenna operates at its fundamental resonant mode, whose null-voltage point is at two-thirds of the distance from the triangle tip to the bottom side of the triangle; when a shorting pin is loaded at the triangle tip, a larger shifting of the null-voltage point compared to the cases of shorted rectangular and circular microstrip antennas occurs, leading to a greatly lowered antenna fundamental resonant frequency.

Meandering the excited patch surface current paths in the antenna's radiating patch is also an effective method for achieving a lowered fundamental resonant frequency for the microstrip antenna [3, 5–8]. For the case of a rectangular radiating patch, the meandering can be achieved by inserting several narrow slits at the patch's nonradiating edges. It can be seen in Figure 1.3(a) that the excited patch's surface currents are effectively meandered, leading to a greatly lengthened current path for a fixed patch linear dimension. This behavior results in a greatly lowered antenna fundamental resonant frequency, and thus a large antenna size reduction at a fixed operating frequency can be obtained. Figure 1.3(b) shows similar design, cutting a pair of triangular

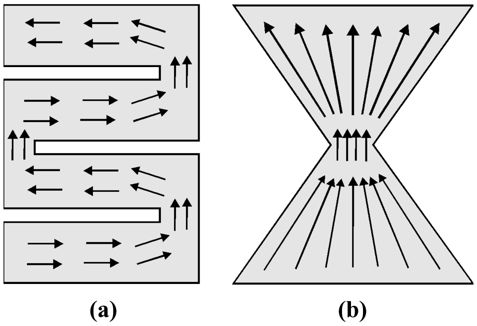


FIGURE 1.3 Surface current distributions for meandered rectangular microstrip patches with (a) meandering slits and (b) a pair of triangular notches cut at the patch's nonradiating edges.

notches at the patch's nonradiating edges to lengthen the excited patch surface current path [8]. The resulting geometry is referred to as a bow-tie patch. Compared to a rectangular patch with the same linear dimension, a bow-tie patch will have a lower resonant frequency, and thus a size reduction can be obtained for bow-tie microstrip antennas at a given operating frequency.

The technique for lengthening the excited patch surface current path mentioned above is based on a coplanar or single-layer microstrip structure. Surface current lengthening for a fixed patch projection area can also be obtained by using an inverted U-shaped patch [Figure 1.4(a)], a folded patch [Figure 1.4(b)], or a double-folded patch [Figure 1.4(c)]. With these microstrip patches, the resonant frequency can be greatly lowered [9, 10] compared to a regular single-layer microstrip antenna with the same projection area. Note that the resonant frequency is greatly lowered due to the bending of the patch surface current paths along the antenna's resonant or excitation direction, and that no lateral current components are generated, in contrast to the case of the meandering technique shown in Figure 1.3. Probably for this reason, it has been observed that compact microstrip antennas using the bending technique described here have good cross-polarization levels for frequencies within the operating bandwidth.

By embedding suitable slots in the radiating patch, compact operation of microstrip antennas can be obtained. Figure 1.5 shows some slotted patches suitable for the design of compact microstrip antennas. In Figure 1.5(a), the embedded slot is a cross slot, whose two orthogonal arms can be of unequal [11] or equal [12–14] lengths. This kind of slotted patch causes meandering of the patch surface current path in two orthogonal directions and is suitable for achieving compact circularly polarized radiation [11, 12] or compact dual-frequency operation with orthogonal polarizations [13, 14]. Similarly, designs with a pair of bent slots [15] [Figure 1.5(b)], a group of four bent slots [16, 17] [Figure 1.5(c)], four 90°-spaced inserted slits [18] [Figure 1.5(d)], a perforated square patch or a square-ring patch with a cross strip [19] [Figure 1.5(e)], a circular slot [20] [Figure 1.5(f)], a square slot [21] [Figure 1.5(g)], an offset circular slot [22] [Figure 1.5(h)], and a perforated tip-truncated triangular patch [23] [Figure 1.5(i)] have been successfully applied to achieve compact circularly polarized or compact dual-frequency microstrip antennas.

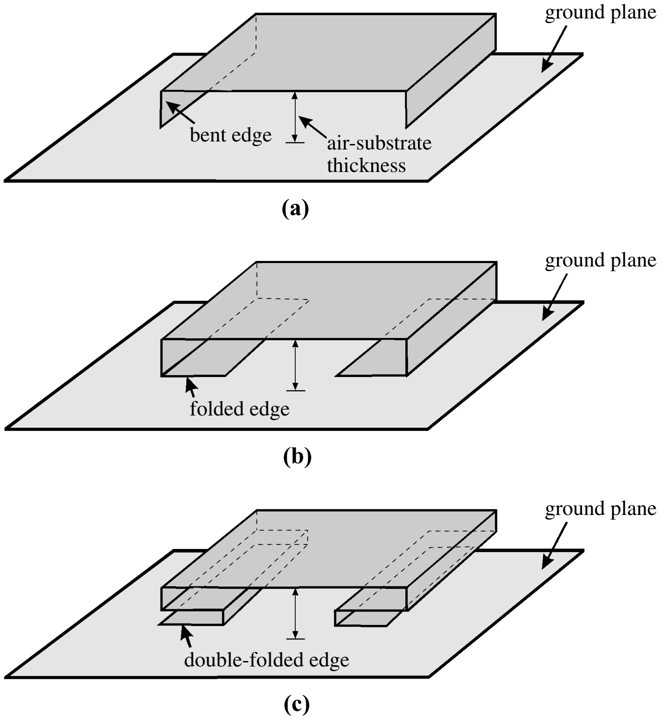


FIGURE 1.4 Compact microstrip antennas with (a) an inverted U-shaped patch, (b) a folded patch, and (c) a double-folded patch for achieving lengthening of the excited patch surface current path at a fixed patch projection area. The feeds are not shown.

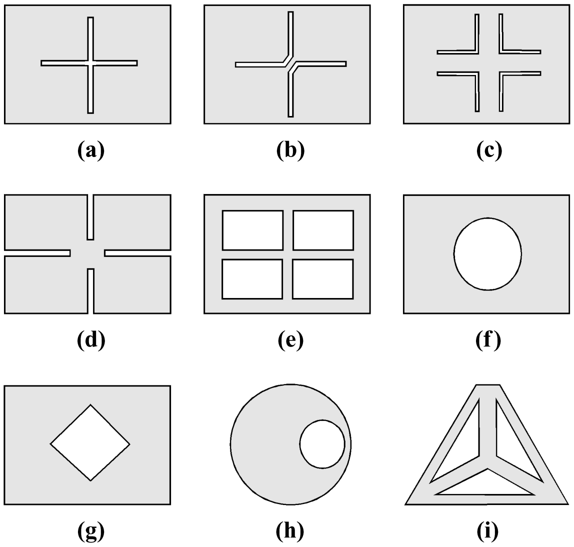


FIGURE 1.5 Some reported slotted patches suitable for the design of compact microstrip antennas.

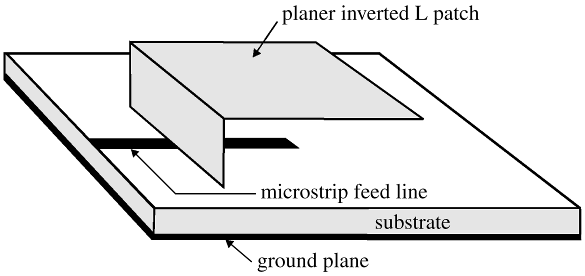


FIGURE 1.6 Geometry of a microstrip-line-fed planar inverted-L patch antenna for compact operation.

The microstrip-line-fed planar inverted-L (PIL) patch antenna is a good candidate for compact operation. The antenna geometry is shown in Figure 1.6. When the antenna height is less than $0.1\lambda_0$ (λ_0 is the free-space wavelength of the center operating frequency), a PIL patch antenna can be used for broadside radiation with a resonant length of about $0.25\lambda_0$ [24]; that is, the PIL patch antenna is a quarter-wavelength structure, and has the same broadside radiation characteristics as conventional half-wavelength microstrip antennas. This suggests that at a fixed operating frequency, the PIL patch antenna can have much reduced physical dimensions (by about 50%) compared to the conventional microstrip antenna.

Figure 1.7 shows another interesting compact design for a microstrip antenna. The antenna's ground plane is meandered by inserting several meandering slits at its edges. It has been experimentally observed [25] that similar meandering effects to those with the design with a meandering patch shown in Figure 1.3(a) can be obtained. Moreover, probably because the meandering slits in the antenna's ground plane can effectively reduce the quality factor of the microstrip structure, the obtained impedance bandwidth for a compact design with a meandered ground plane can be greater than that of the corresponding conventional microstrip antenna.

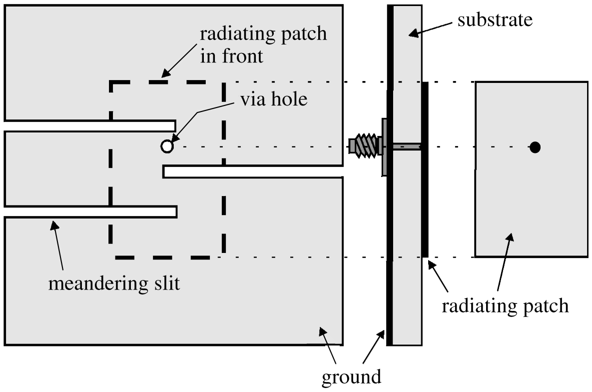


FIGURE 1.7 Geometry of a probe-fed compact microstrip antenna with a meandered ground plane. (From Ref. 25, © 2001 John Wiley & Sons, Inc.)

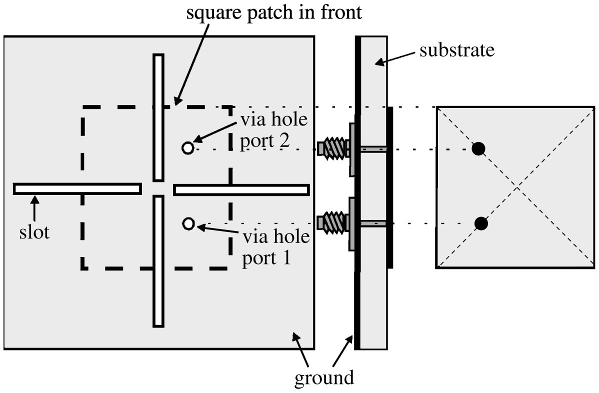


FIGURE 1.8 Geometry of a probe-fed compact microstrip antenna with a slotted ground plane suitable for dual-polarized radiation.

1.3 COMPACT BROADBAND MICROSTRIP ANTENNAS

With a size reduction at a fixed operating frequency, the impedance bandwidth of a microstrip antenna is usually decreased. To obtain an enhanced impedance bandwidth, one can simply increase the antenna's substrate thickness to compensate for the decreased electrical thickness of the substrate due to the lowered operating frequency, or one can use a meandering ground plane (Figure 1.7) or a slotted ground plane (Figure 1.8). These design methods lower the quality factor of compact microstrip antennas and result in an enhanced impedance bandwidth.

By embedding suitable slots in a radiating patch, compact operation with an enhanced impedance bandwidth can be obtained. A typical design is shown in Figure 1.9. However, the obtained impedance bandwidth for such a design is usually about equal to or less than 2.0 times that of the corresponding conventional microstrip antenna. To achieve a much greater impedance bandwidth with a reduction in antenna size, one

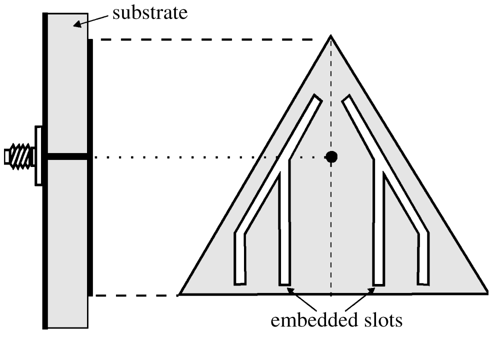


FIGURE 1.9 Geometry of a probe-fed slotted triangular microstrip antenna for compact broadband operation.

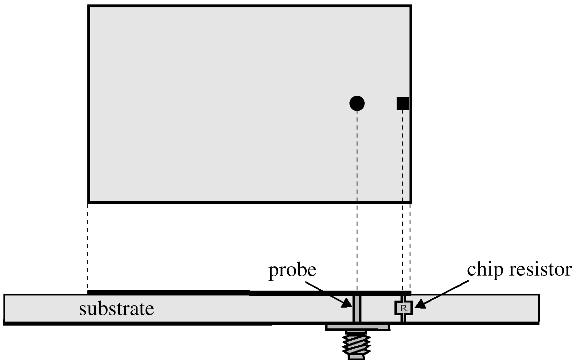


FIGURE 1.10 Geometry of a compact broadband microstrip antenna with chip-resistor loading.

can use compact designs with chip-resistor loading [26, 27] (Figure 1.10) or stacked shorted patches [28–31] (Figure 1.11). The former design is achieved by replacing the shorting pin in a shorted patch antenna with a chip resistor of low resistance (generally 1 Ω). In this case, with the same antenna parameters, the obtained antenna size reduction can be greater than for the design using chip-resistor loading. Moreover, the obtained impedance bandwidth can be increased by a factor of six compared to a design using shorting-pin loading. For an FR4 substrate of thickness 1.6 mm and relative permittivity 4.4, the impedance bandwidth can reach 10% in L-band operation [26]. However, due to the introduced ohmic loss of the chip-resistor loading, the antenna gain is decreased, and is estimated to be about 2 dBi, compared to a shorted patch antenna with a shorting pin. For the latter design with stacked shorted patches, an impedance bandwidth of greater than 10% can be obtained. For this design, of course, the total antenna volume or height is increased.

1.4 COMPACT DUAL-FREQUENCY MICROSTRIP ANTENNAS

Compact microstrip antennas with dual-frequency operation [32] have attracted much attention. The two operating frequencies can have the same polarization planes [7] or orthogonal polarization planes [33]. One of the reported compact dual-frequency designs with the same polarization planes uses the first two operating frequencies of shorted microstrip antennas with a shorting pin [34–36], and the obtained frequency ratios between the two operating frequencies have been reported to be about 2.0–3.2

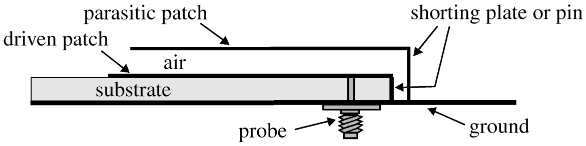


FIGURE 1.11 Geometry of a stacked shorted patch antenna for compact broadband operation.

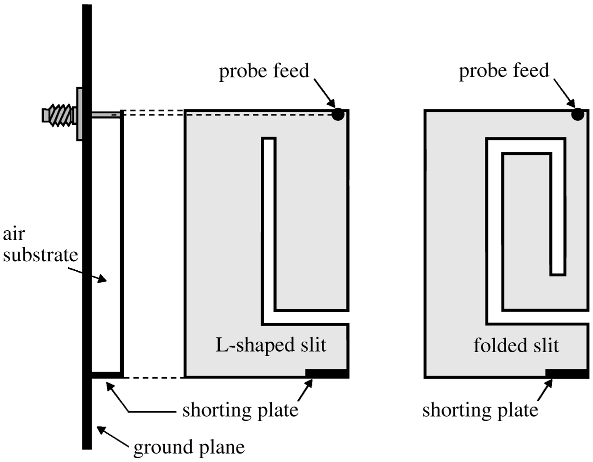


FIGURE 1.12 Geometries of a shorted rectangular patch antenna with an L-shaped or a folded slit for dual-frequency operation.

[34], 2.55–3.83 [35], and 2.5–4.9 [36] for shorted rectangular, circular, and triangular patches, respectively.

Dual-frequency operation can be obtained using the compact design of a shorted rectangular patch antenna with an L-shaped or a folded slit (see Figure 1.12) [37, 38]. This antenna can be considered to consist of two connected resonators of different sizes. The smaller resonator is encircled by the slit and resonates at a higher resonant frequency; the larger resonator encircles the smaller one and resonates at a lower resonant frequency. This kind of compact dual-frequency design is very suitable for applications in handset antennas of mobile communication units. By loading a pair of narrow slots parallel and close to the radiating edges of a meandered rectangular or bow-tie patch (see Figure 1.13), dual-frequency operation with tunable

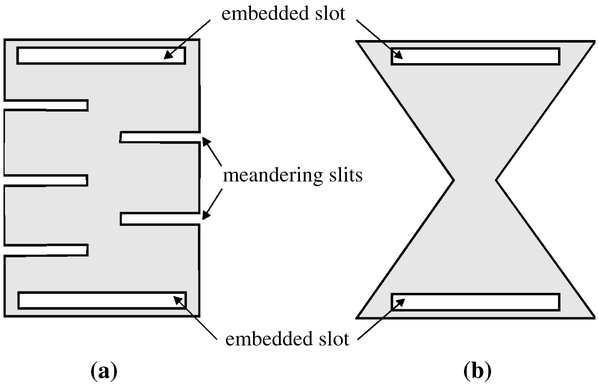


FIGURE 1.13 Geometries of slot-loaded meandered (a) rectangular and (b) bow-tie microstrip patches for compact dual-frequency operation.

frequency-ratio ranges of about 1.8–2.4 [7] and 2.0–3.0 [39], respectively, have been reported. Many designs have been reported for compact dual-frequency operation with orthogonal polarization [13–15, 20–22]. These design methods mainly use the loading of suitable slots, such as a cross slot, a pair of bent slots, four inserted slits, a circular slot, a square slot, an offset circular slot, and so on in a rectangular or circular patch [see Figures 1.5(a), (b), (d), (f)–(g)].

1.5 COMPACT DUAL-POLARIZED MICROSTRIP ANTENNAS

Dual-polarized operation has been an important subject in microstrip antenna design and finds application in wireless communication systems that require frequency reuse or polarization diversity. Microstrip antennas capable of performing dual-polarized operation can combat multipath effects in wireless communications and enhance system performance. Designs of compact microstrip antennas for dual-polarized operation have been reported. Figure 1.14 shows a typical compact dual-polarized microstrip antenna fed by two probe feeds [17]. Antenna size reduction is achieved by having four bent slots embedded in a square patch. Results [17] show that, with the use of an FR4 substrate (thickness 1.6 mm and relative permittivity 4.4), good port decoupling (S_{21} less than -35 dB) is obtained for the compact dual-polarized microstrip antenna shown in Figure 1.14 which is better than that of the corresponding conventional square microstrip antenna without embedded slots.

1.6 COMPACT CIRCULARLY POLARIZED MICROSTRIP ANTENNAS

Various novel designs have been reported recently to achieve compact circularly polarized radiation with microstrip antennas. In addition to the well-known technique of

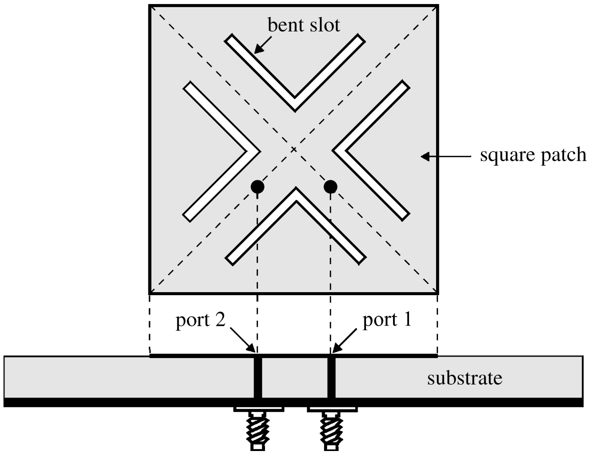
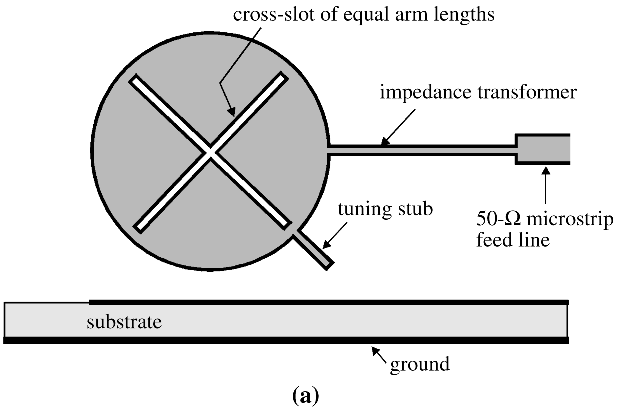


FIGURE 1.14 Geometry of a probe-fed compact microstrip antenna with four bent slots for generating ±45° slanted dual linear polarizations.

using a high-permittivity substrate as described in Figure 1.1, compact CP designs can be achieved by embedding suitable slots or slits in the radiating patch [11, 12, 16, 18, 40–47] or the antenna's ground plane. These designs mainly use a single probe feed or an edge-fed microstrip-line feed. By using a single inset microstrip-line feed, it is possible for microstrip antennas with a slotted patch to achieve compact CP radiation [48].

For a compact CP design using a tuning stub [12, 47] (Figure 1.15), the required length of the tuning stub increases as the CP center operating frequency is lowered. The increase in allowable tuning-stub length accompanying the reduction in antenna size for such compact CP designs allows a greatly relaxed manufacturing tolerance compared to the corresponding conventional circularly polarized microstrip antenna at the same operating frequency. This is a great advantage for practical applications,



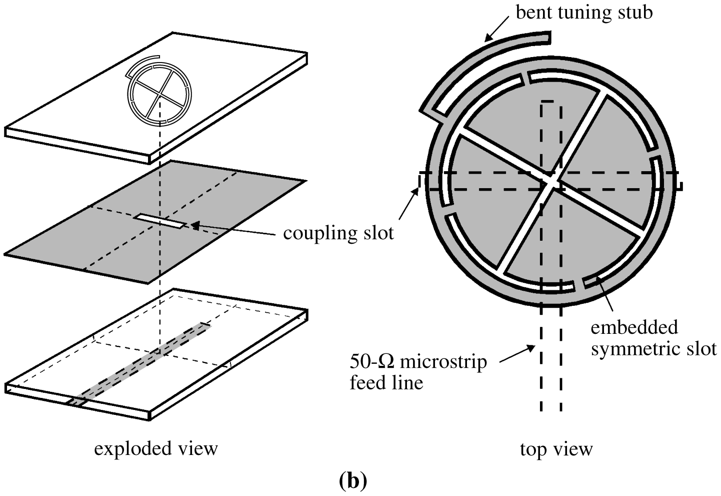


FIGURE 1.15 Geometries of (a) a microstrip-line-fed compact circularly polarized microstrip antenna with a tuning stub and (b) an aperture-coupled compact circularly polarized microstrip antenna with a bent tuning stub.

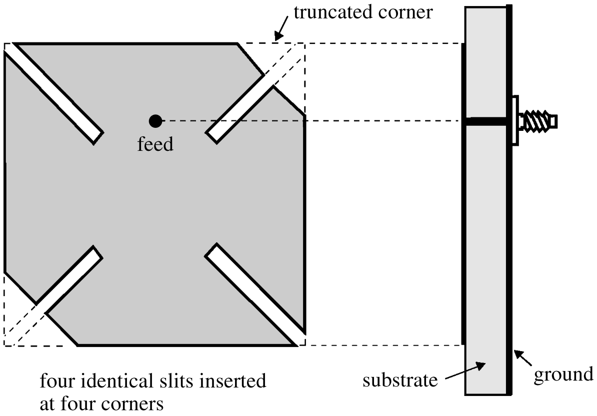


FIGURE 1.16 Geometry of a probe-fed corner-truncated square microstrip antenna with four inserted slits for compact CP radiation.

especially when a large reduction in antenna size is required for circularly polarized microstrip antennas. The design for a probe-fed corner-truncated square microstrip antenna with four inserted slits for compact CP radiation (see Figure 1.16) shows similar behavior [43]. When the length of the inserted slits increases, leading to a lowering in the antenna's fundamental resonant frequency and thus a reduction in the antenna size at a fixed operating frequency, the required size of the truncated corners increases. Thus, there is a greatly relaxed manufacturing tolerance for a large antenna size reduction for this kind of circularly polarized microstrip antenna.

1.7 COMPACT MICROSTRIP ANTENNAS WITH ENHANCED GAIN

It is generally observed that when the antenna size is reduced at a fixed operating frequency, the antenna gain is also decreased. To obtain an enhanced antenna gain, methods involving the loading a high-permittivity dielectric superstrate [40, 49] or an amplifier-type active circuitry [50, 51] to a compact microstrip antenna have been demonstrated. For the former case, with the antenna's projection area unchanged or even smaller, the antenna gain can be enhanced by about 10 dBi [49]. For the latter case, the radiating patch is modified to incorporate active circuitry to provide an enhanced antenna gain, and an extra antenna gain of 8 dBi in L-band operation has been reported [50].

1.8 BROADBAND MICROSTRIP ANTENNAS

A narrow bandwidth is a major disadvantage of microstrip antennas in practical applications. For present-day wireless communication systems, the required operating bandwidths for antennas are about 7.6% for a global system for mobile communication

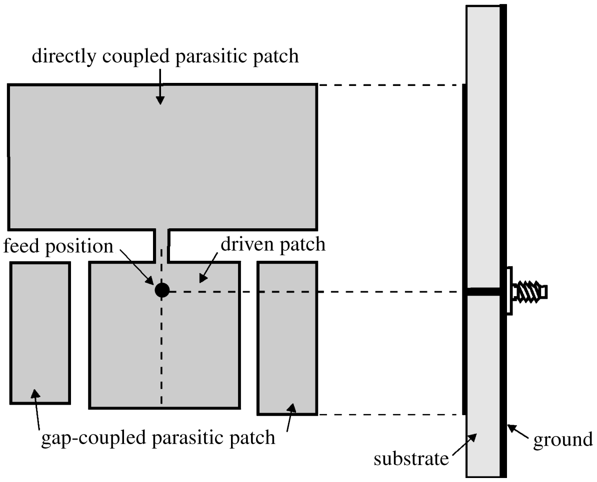


FIGURE 1.17 Geometry of a broadband microstrip antenna with a directly coupled patch and two gap-coupled patches.

(GSM; 890–960 MHz), 9.5% for a digital communication system (DCS; 1710–1880 MHz), 7.5% for a personal communication system (PCS; 1850–1990 MHz), and 12.2% for a universal mobile telecommunication system (UMTS; 1920–2170 MHz). To meet these bandwidth requirements, many bandwidth-enhancement or broadband techniques for microstrip antennas have been reported recently. One bandwidth-enhancement technique uses coplanar directly coupled and gap-coupled parasitic patches [52]. A typical design is shown in Figure 1.17, which shows a rectangular microstrip antenna with a directly coupled patch and two gap-coupled patches. This antenna has a compact configuration such that the required realty space for implementing the antenna is minimized. Experimental results show that, with the use of an inexpensive FR4 substrate of thickness 1.6 mm and relative permittivity 4.4, such an antenna can have an impedance bandwidth of about 12.7% [52], which is about 6.35 times that of the antenna with a driven patch only (about 2%). The parasitic patches can be stacked on top of the microstrip antenna [53, 54] and significant bandwidth enhancement can be achieved.

Decreasing the quality factor of the microstrip antenna is also an effective way of increasing the antenna's impedance bandwidth. This kind of bandwidth-enhancement technique includes the use of a thick air or foam substrate [55–65] and the loading of a chip resistor on a microstrip antenna with a thin dielectric substrate [26, 66]. In the former case, for feeding using a probe feed, a large reactance owing to the long probe pin in the thick substrate layer is usually a problem in achieving good impedance matching over a wide frequency range. To overcome this problem associated with probe-fed microstrip antennas, designs have been reported that embed a U-shaped slot in the patch (U-slotted patch) [55, 56], use a three-dimensional (3D) microstrip transition feed [57], cut a pair of wide slits at one of the patch's radiating edges

(E-patch) [58], bend the patch into a 3D V-shaped patch [59] or the ground plane into an inverted V-shaped ground [60], and use modified probe configurations such as an L-strip feed [61], an L-probe feed [62], a gap-coupled probe feed [63], or a capacitively coupled feed [64, 65], among others. With the above-mentioned designs, the impedance bandwidth of a probe-fed microstrip antenna with a thick air substrate can easily be enhanced to greater than 25%. It has also been demonstrated that the use of a larger coupling slot for the case with an aperture-coupled feed can effectively lower the quality factor of a microstrip antenna, and impedance matching can be enhanced [67].

Another effective bandwidth-enhancement technique is to excite two or more resonant modes of similar radiating characteristics at adjacent frequencies to form a wide operating bandwidth. Such bandwidth-enhancement techniques include the loading of suitable slots in a radiating patch [68–75] or the integration of cascaded microstrip-line sections (microstrip reactive loading) into a radiating patch [76–80]. For both slot loading and integrated microstrip reactive loading, the low-profile advantage of the microstrip antenna is retained, and the impedance bandwidth can be about 2.0–3.5 times that of the corresponding conventional microstrip antenna. Through the design of an external optimal matching network for a microstrip antenna, bandwidth enhancement can also be obtained [81, 82]. This design technique increases the realty space of the microstrip antenna due to the external matching network, and it has been reported that the impedance matching can be increased by a factor of three if an optimal matching network is achieved [81].

Some novel designs for broadband microstrip antennas with reduced cross-polarization radiation have also been demonstrated. An effective method is to add an additional feed of equal amplitude and a 180° phase shift to the microstrip antenna; significant cross-polarization reduction of about 5–10 and 12–15 dB in the E-plane and H-plane patterns, respectively, has been achieved [83]. Details of the related antenna designs and experimental results are given in Chapter 7.

1.9 BROADBAND DUAL-FREQUENCY AND DUAL-POLARIZED MICROSTRIP ANTENNAS

Designs of dual-frequency microstrip antennas with impedance bandwidths of both their two operating frequencies greater than 10% have been reported [59, 84]. By using an L-probe feed for a two-element patch antenna [84], dual-frequency operation for a GSM/PCS dual-band base-station antenna has been demonstrated. It has also been shown that broadband dual-frequency operation can be obtained by using a three-dimensional V-shaped patch [59]. This design can be fed by an aperture-coupled feed or a probe feed (see Figure 1.18). For the case with an aperture-coupled feed, two separate operating bands with a 10-dB return-loss bandwidth greater than 10% can be obtained, and the frequency ratios between the two operating frequencies are about 1.28–1.31 [59].

Various broadband dual-polarized microstrip antennas have been reported recently [85–90]. High isolation between two feeding ports and low cross-polarization for two linear polarizations over a wide impedance bandwidth are the major design

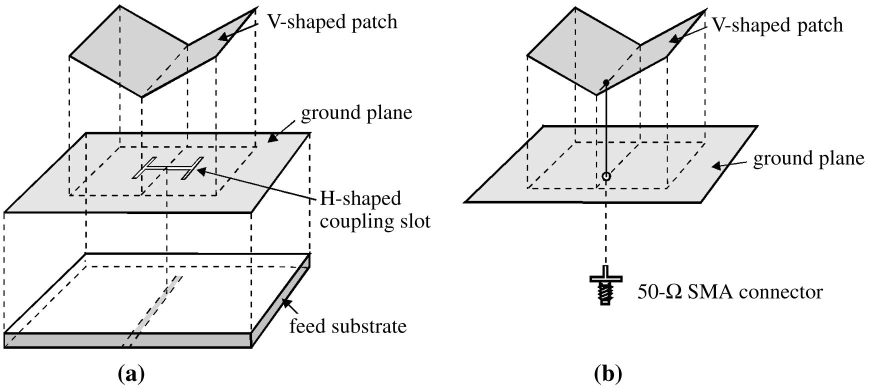


FIGURE 1.18 Exploded views of a three-dimensional V-shaped patch with (a) an aperture-coupled feed and (b) a probe feed.

considerations. Very good port decoupling ($S_{21} < -40$ dB) between two feeding ports for an aperture-coupled microstrip antenna across a wide impedance bandwidth has been obtained by carefully aligning the two coupling slots in the antenna's ground plane [86]. The use of hybrid feeds of a gap-coupled probe feed and an H-slot coupled feed has also been found to be a promising dual-polarized design for achieving high port decoupling [85]. Details of typical design examples are included in Chapter 8.

1.10 BROADBAND AND DUAL-BAND CIRCULARLY POLARIZED MICROSTRIP ANTENNAS

To achieve broadband, single-feed, circularly polarized microstrip antennas, a design with chip-resistor loading has been shown to be promising [91, 92]; the CP bandwidth can be enhanced by a factor of two. By using an aperture-coupled feed with a Y–Y-shaped coupling slot for a rectangular microstrip antenna [67], the CP bandwidth can also be enhanced to about 2.1 times that obtained using a simple inclined slot for CP operation. The obtained CP bandwidths for these broadband single-feed microstrip antennas with a thin dielectric substrate are generally less than 3%. As for the case of a single-feed microstrip antenna with a thick air substrate, it is not an easy task to achieve a CP bandwidth larger than 6%.

To achieve a much larger CP bandwidth, one should use a two-feed design incorporating a thick air substrate and an external phase shifter or power divider. It has been reported that, by using two gap-coupled or capacitively coupled feeds with a Wilkinson power divider to provide good equal-power splitting for the two feeds, the obtained 3-dB axial-ratio bandwidths can be as large as about 46% [93] and 34% [94], respectively. One can also use a branch-line coupler as the external phase shifter, and the obtained 3-dB axial-ratio bandwidth can reach 60% referenced to a center frequency at 2.2 GHz. A four-feed design with 0°–90°–180°–270° phase shifts for a

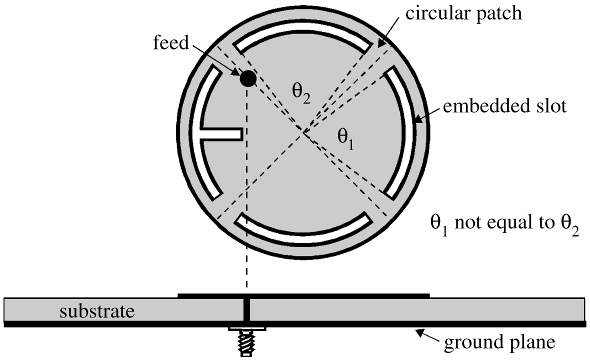


FIGURE 1.19 Geometry of a dual-band circularly polarized microstrip antenna.

single-patch microstrip antenna has also been implemented, and very good CP quality has been obtained. The 2-dB axial-ratio bandwidth is 38%, and the 3-dB axial-ratio beamwidth for frequencies within the obtained CP bandwidth can be greater than 100°. Relatively very slow degradation of the axial ratio from the antenna's broadside direction to large angles can be obtained compared to a corresponding broadband circularly polarized microstrip antenna with two-feed design.

Several dual-band CP designs have been reported [95–98]. A typical design is shown in Figure 1.19. Dual-band CP operation is obtained by embedding two pairs of arc-shaped slots of proper lengths close to the boundary of a circular patch and protruding one of the arc-shaped slots with a narrow slot. The two separate CP bands are centered at 1561 and 2335 MHz, with CP bandwidths of about 1.3% and 1.1%, respectively [95]. Other methods include the use of a probe-fed square microstrip antenna with a center slot and inserted slits [96], a probe-fed stacked elliptic microstrip antenna [97], and an aperture-coupled stacked microstrip antenna [98]. Typical constructed prototypes are described in detail in Chapter 9.

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