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Antenna Theory and Design

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Chapter 5 Part II

Microstrip antenna



Chapter 5 Part II Microstrip antenna

- Compact Broadband MSA
- Dual-frequency and dual-polarized MSA
- **Compact circularly polarized MSA**
- Broadband planar monopole antennas

1 Introduction

- The major advantage of single-feed, circularly polarized microstrip antennas is their simple structure, which does not require an external polarizer. They can, therefore, be realized more compactly by using less board space than do dual-feed, circularly polarized microstrip antennas.
- Many designs of single-feed, circularly polarized microstrip antennas with square or circular patches are known. Recently, various CP designs with a compact patch size at a fixed operating frequency have been reported.
- In these designs, the compact CP techniques used include embedding a cross-slot of unequal arm lengths, embedding a Y-shaped slot of unequal arm lengths, inserting slits or spur lines at the patch boundary, truncating patch corners or tips, introducing small peripheral cuts at the boundary of a circular patch, adding a tuning stub or a bent tuning stub, among others.
- For feeding these compact CP designs, a probe feed or an edge-fed microstrip-line feed can be used. In this case, the main problem to be solved arises from the perturbation effects caused by the inset microstrip line on the excited patch surface currents, which makes it difficult for the excitation of two orthogonal near-degenerate resonant modes for CP radiation.
- Several possible designs for solving this problem have been reported, and details of the designs applied to a corner-truncated square microstrip antenna are presented.

2 Designs With a Y-Shaped Slot of Unequal Arm Lengths

- A new design for compact triangular microstrip antennas with a Y-shaped slot for CP radiation has been reported. The Y-shaped slot is centered in the triangular patch, with its upper two arms facing either the triangle tip or the bottom of the triangular patch [see Figures (Aa) and (Ab)]. It is expected that, due to the presence of the Y-shaped slot in the patch, the excited patch surface current path is lengthened and thus the resonant frequency of the microstrip patch is reduced. Furthermore, it is found that, by selecting a proper size of the Y-shaped slot, two near-degenerate orthogonal modes with equal amplitudes and a 90° phase difference for CP operation can be excited using a single probe feed; that is, compact CP operation of triangular microstrip antennas can be obtained.

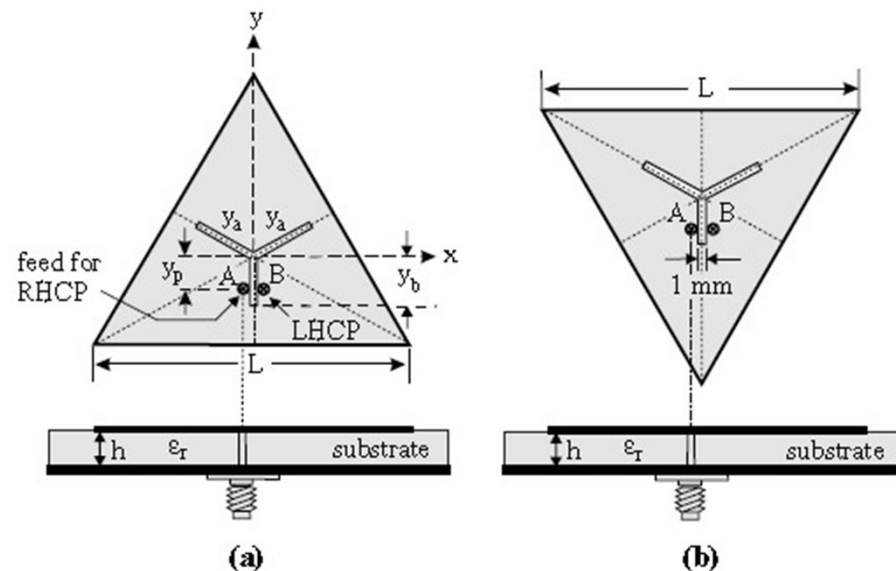


Figure (A) Geometries of compact circularly polarized equilateral-triangular microstrip antennas. (a) The Y-shaped slot facing the triangle tip (antenna 1), (b) the Y-shaped slot facing the bottom side of the triangular patch (antenna 2).

2 Designs With A Y-Shaped Slot Of Unequal Arm Lengths

- As shown in Figure (A), the upper two arms of the Y-shaped slot are of equal length y_a and its lower arm has a smaller length y_b ($y_a > y_b$). By choosing proper arm lengths (y_a , y_b) of the Y-shaped slot and placing a single probe feed at the edge of its lower arm, compact CP operation of the triangular microstrip antenna can be obtained. The feed positions at points A and B in the figure, both a distance y_p from the patch center, are for right-hand and left-hand CP operations, respectively. The case with right-hand CP operation is studied here; that is, the probe feed is placed at point A. Figures (Ba) and (Bb) show, respectively, the measured input impedance for the designs of Figure (Aa) (antenna 1) and Figure (Ab) (antenna 2).

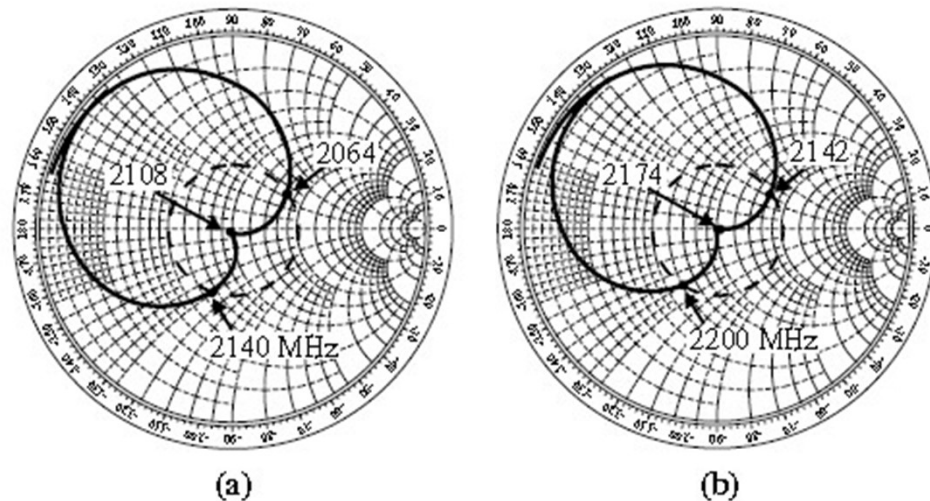


Figure (B) Measured input impedance for the antennas shown in Figure (A); $\epsilon_r = 4.4$, $h = 1.6$ mm, $L = 40$ mm, and feed at point A. (a) Antenna 1: $y_a = 8.4$ mm, $y_b = 7.6$ mm, $y_p = 4.3$ mm; (b) antenna 2: $y_a = 9.4$ mm, $y_b = 7.6$ mm, $y_p = 4.0$ mm.

2 Designs With A Y-Shaped Slot Of Unequal Arm Lengths

- The measured axial ratio is presented in Figures (Ca) and (Cb). The corresponding results are listed in Table (a). For the design of antenna 1 with $y_a = 8.4$ mm and $y_b = 7.6$ mm, a single probe feed with $y_p = 4.3$ mm along the edge of the lower arm of the Y-shaped slot splits the fundamental resonant mode of the slotted triangular patch into two near-degenerate orthogonal modes for CP operation at a center frequency f_c of 2108 MHz, which is about 10% lower than that (2347 MHz) of the design using a regular-size circularly polarized triangular microstrip antenna. This suggests that the present design can have an antenna size reduction of about 19% compared to that of the regular-size CP design at a fixed operating frequency. The 3-dB axial-ratio CP bandwidth is also seen to decrease from 1.1% to 0.9% due to the antenna size reduction.

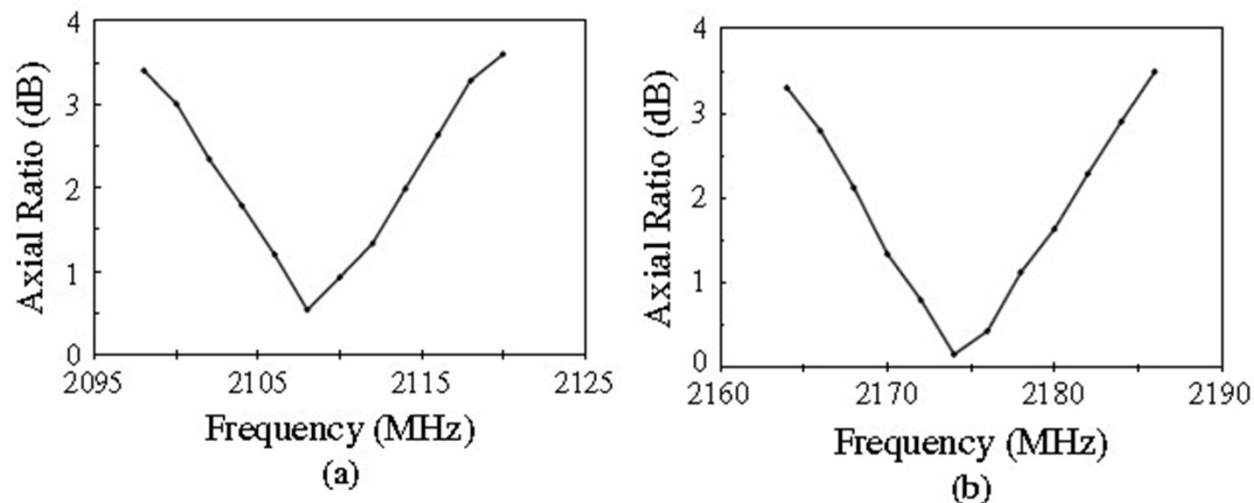
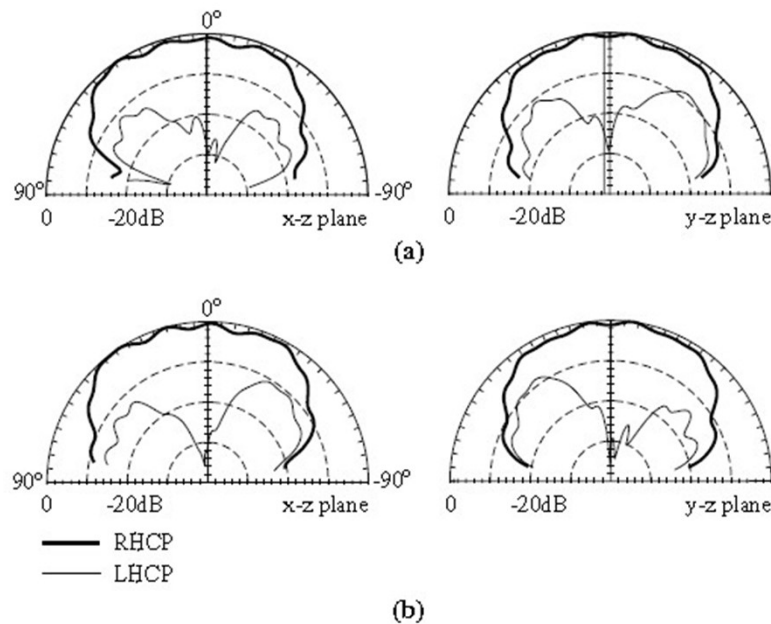


Figure (C) Measured axial ratio in the broadside direction for the antennas studied in Figure (B). (a) Antenna 1, (b) antenna 2.

2 Designs With A Y-Shaped Slot Of Unequal Arm Lengths

- For the design of antenna 2, the center frequency is lowered to 2174 MHz (about 92.7% times that of the regular-size CP design). In this case, an antenna size reduction of about 14% for the present design at a fixed operating frequency is obtained. The CP bandwidth is also smaller (0.8% vs. 1.1%) due to the antenna size reduction. Typical measured radiation patterns in two orthogonal planes for antennas 1 and 2 are plotted in Figures (Da) and (Db), respectively. It can be seen that good right-hand CP radiation is obtained.



	Slot Size y_a, y_b (mm)	y_p (mm)	f_c (MHz)	3-dB Axial-Ratio CP Bandwidth (%)
Antenna 1	8.4, 7.6	4.3	2108	0.9
Antenna 2	9.4, 7.6	4.0	2174	0.8
Reference	—	—	2347	1.1

Table (a) CP Performance of the Antennas in Figures (Aa) and (Ab)

Figure (D) Measured radiation patterns for the antennas studied in Figure (B). (a) Antenna 1 at 2108 MHz, (b) antenna 2 at 2174 MHz.

3 Designs With Slits

- By inserting a single slit to the boundary of a microstrip patch and placing a single feed along an axis 45° to the one containing the slit, CP radiation of microstrip antennas can be achieved. Applications of this CP design technique to square and circular microstrip antennas are discussed in Section 3.1. This CP design technique has also been successfully applied to a triangular microstrip antenna, and details of the results are also described here. Related CP design techniques using a pair of slits or four inserted slits for compact CP radiation are discussed in Sections 3.2 and 3.3, respectively.
- For the case of a pair of slits, CP radiation of an annular-ring microstrip antenna operated at the TM_{11} mode has been achieved. Good CP performance is obtained and the required antenna size at a fixed operating frequency is much less than that of a regular circularly polarized circular microstrip antenna operated in the TM_{11} mode. In the case of four inserted slits, design examples of microstrip antennas with a square patch, a circular patch, a corner-truncated square patch, and a chip-resistor-loaded square patch have been demonstrated.

3.1 With a Slit

3.1.1 With a Square or Circular Patch

- Figure (A) shows the geometries of square and circular microstrip antennas with a slit for CP radiation. A narrow slit of length l and width 1 mm is inserted at the boundary of the microstrip patch. The square patch has a side length L and the diameter of the circular patch is d . For both the square and circular patches, the feed at point C along the diagonal/diameter AB is for right-hand CP operation, while point D is for left-hand CP operation. Due to the slit perturbation, the excited $\hat{x}$ -directed (orthogonal to the slit orientation) patch surface current path is lengthened, with the one in the y direction (parallel to the slit orientation) slightly affected, which splits the dominant resonant mode of the microstrip patch into two orthogonal near-degenerate modes. Then, given a proper slit length (about 0.15 times the side length L of the square patch or about 0.18 times the diameter d of the circular patch for the experiments conducted here), these two orthogonal modes can have a 90° phase difference, resulting in CP radiation.

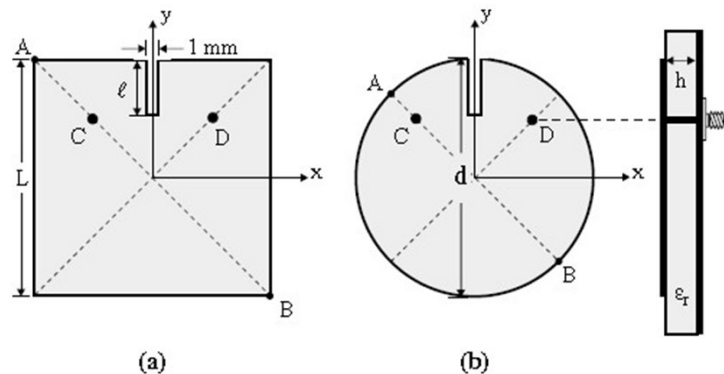


Figure (A) Geometries of microstrip antennas with a slit for CP radiation; the feed at point C is for right-hand CP and the feed at point D is for left-hand CP. (a) Square patch case, (b) circular patch case.

3.1.1 With a Square or Circular Patch

- Several prototypes have been constructed. Figure (B) shows the measured input impedance for a square microstrip antenna with a slit. The case with right-hand CP operation (i.e., the feed at point *C*) is shown. To achieve CP radiation, the slit length is adjusted to be 6 mm (about $0.15L$) and the feed (point *C*) is at a position about $0.3AB$ from the patch corner.

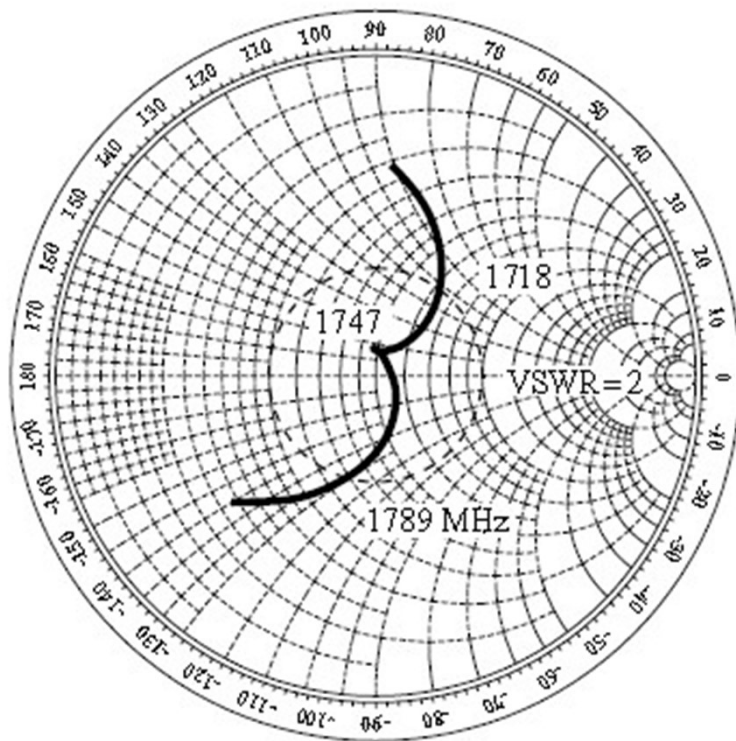


Figure (B) CP operation (i.e., the feed at point *C*) is shown. To achieve CP radiation, the slit length is adjusted to be 6 mm (about $0.15L$) and the feed (point *C*) is at a position about $0.3AB$ from the patch corner.

3.1.1 With a Square or Circular Patch

- The measured axial ratio is presented in Figure (C). The results give the CP bandwidth, determined from the 3-dB axial ratio, as 25 MHz (or about 1.4% with respect to the center frequency, the frequency with a minimum axial ratio). The measured radiation patterns in the x - z and y - z planes at the center frequency (1747 MHz) are plotted in Figure (D).

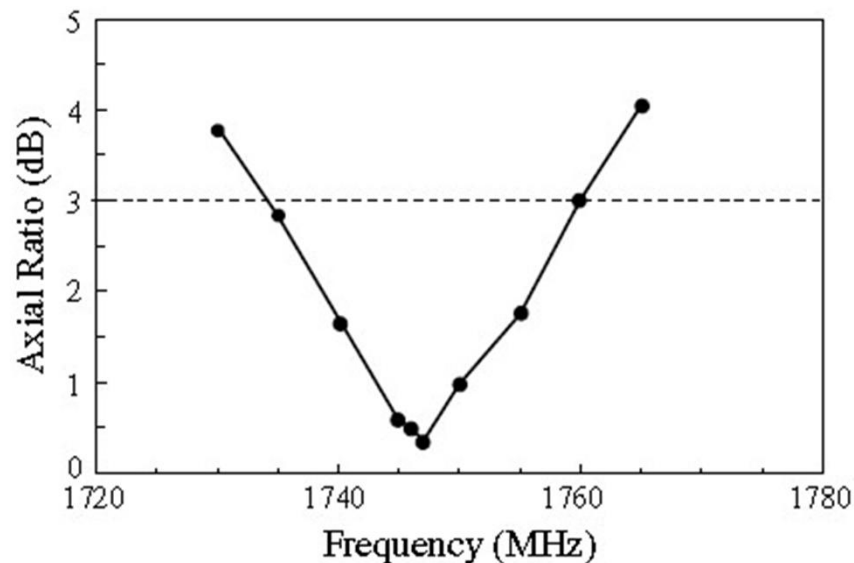


Figure (C) Measured axial ratio for the square microstrip antenna studied in Figure (B)

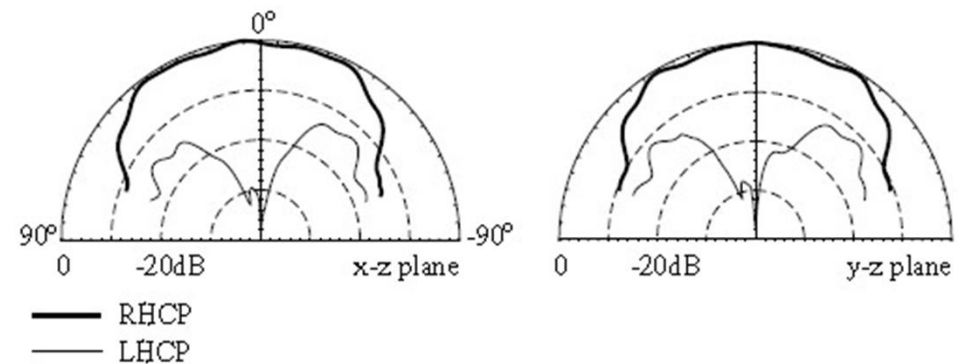


Figure (D) Measured radiation patterns for the antenna studied in Figure (B) at 1747 MHz.

3.1.1 With a Square or Circular Patch

- Good right-hand CP radiation is observed. The results for a circular microstrip antenna with a slit are shown in Figures (E) and (F). For right-hand CP radiation, by adjusting the slit length to be 7.7 mm (about $0.18d$) and the feed at about $0.25AB$ from the boundary of the circular patch, CP radiation with good impedance matching is obtained. From the measured axial ratio shown in Figure (E), a 32 MHz (about 1.7%) CP bandwidth is obtained. The measured radiation patterns in two orthogonal planes plotted in Figure (F) at the center frequency (1875 MHz) show good right-hand CP radiation.

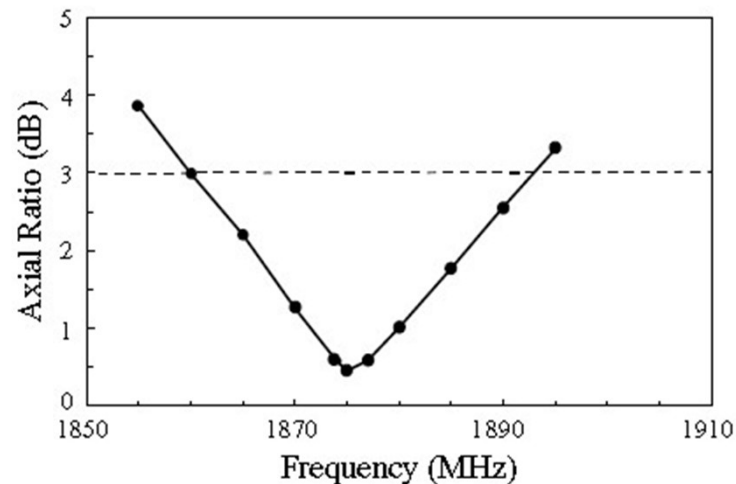


Figure (E) Measured axial ratio for a circular microstrip antenna with a slit [Figure (Ab)] for right-hand CP operation; $r = 4.4$, $h = 1.6$ mm, $d = 43$ mm, $l = 7.75$ mm, and $AC = 10.64$ mm ($\cong 0.25AB$)

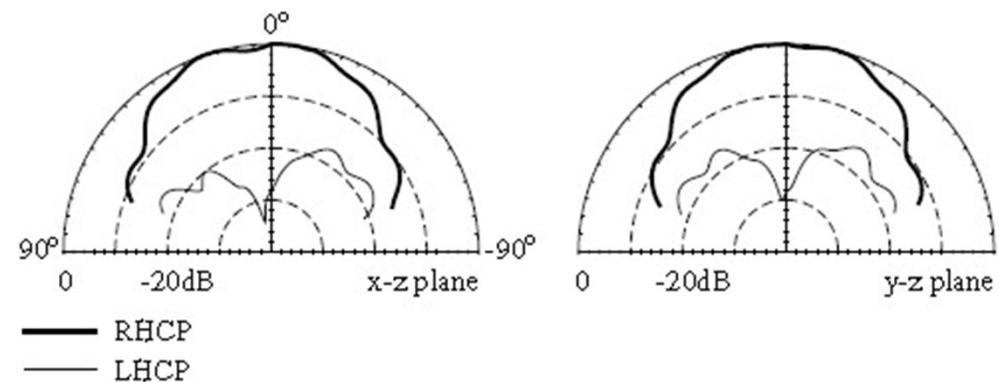


Figure (F) Measured radiation patterns for the antenna studied in Figure (E) at 1875 MHz.

3.1.2 With a Triangular Patch

- The present CP design has been applied to a triangular microstrip antenna. The antenna geometry is shown in Figure (A). In the figure, L_1 and L_2 represent, respectively, the 50- Ω feed-location loci of the two orthogonal modes, which are determined experimentally in the study. For the probe feed at point A, which is the intersection of loci L_1 and L_2 and is usually located in the upper half of the triangular patch, right-hand CP radiation with a good matching condition can be obtained. Conversely, left-hand CP radiation can be obtained by feeding the patch at point B (the mirror image of point A with respect to the inserted slit).

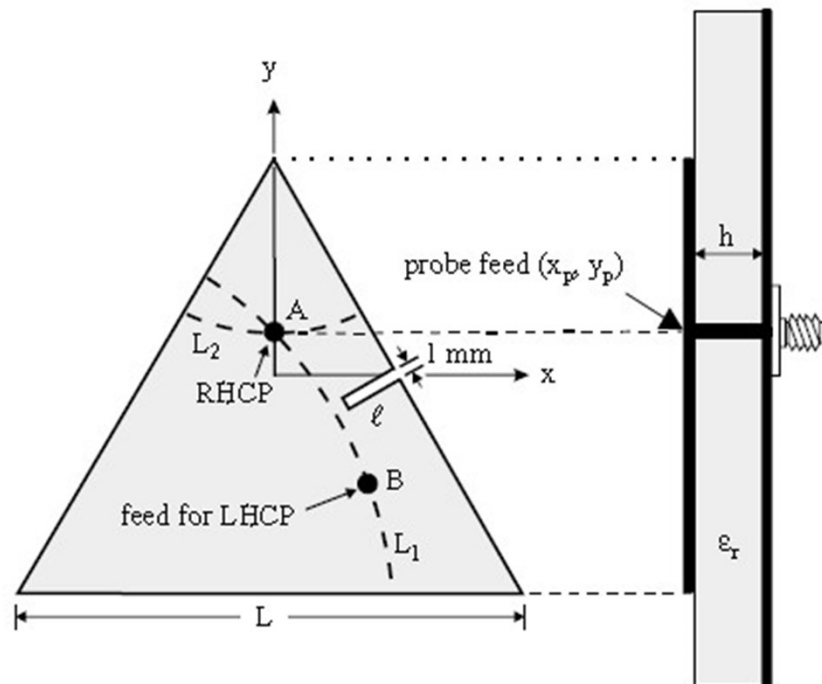


Figure (A) Geometry of a single-feed triangular microstrip antenna with a single slit for CP radiation.

3.1.2 With a Triangular Patch

- Figure (B) shows the measured input impedance of constructed prototypes. Two designs of different triangular patch sizes operated at 1931 and 2423 MHz have been studied, and the case for right-hand CP radiation is shown. The measured axial ratio is presented in Figure (C).

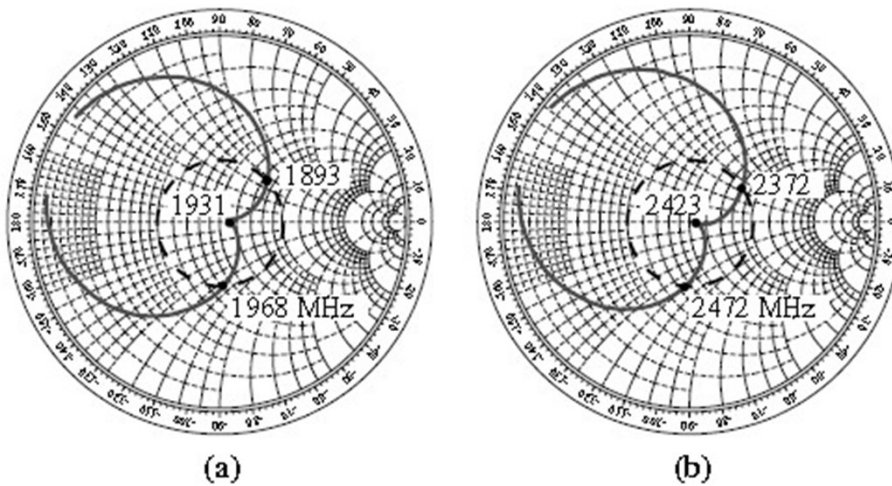


Figure (B) Measured input impedance for the antenna shown in Figure (A); $\epsilon_r = 4.4$, $h = 1.6$ mm, and feed at point C. (a) Antenna 1: $L = 48.2$ mm, $l = 4.5$ mm; (b) antenna 2: $L = 38.5$ mm, $l = 3.8$ mm.

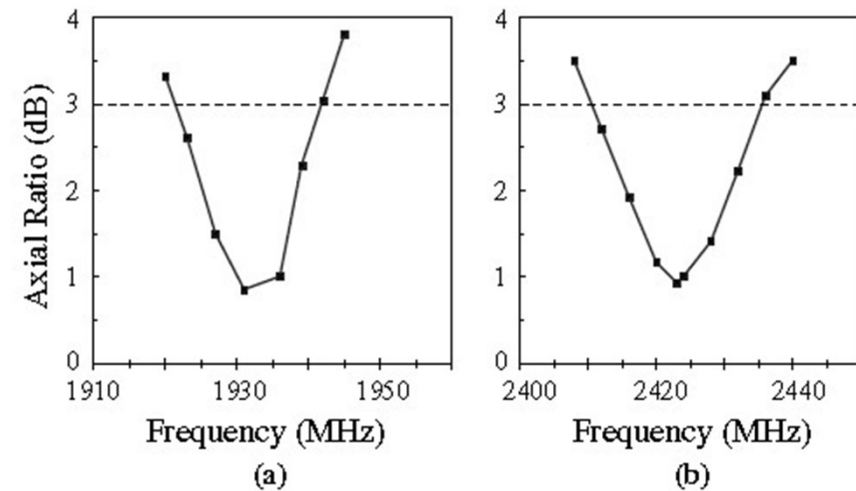


Figure (C) Measured axial ratio for (a) antenna 1 and (b) antenna 2 studied in Figure (B).

3.1.2 With a Triangular Patch

- The corresponding CP performance is given in Table (a). It is found that, by increasing the slit length, the effective excited patch surface current path in the y direction is slightly lengthened with respect to that in the x direction, which means that the $\hat{y}$ -directed resonant mode has a resonant frequency slightly lower than that of the $\hat{x}$ -directed resonant mode. When the slit length is adjusted to be about 0.1 times the side length of the triangular patch (4.5 mm for antenna 1 and 3.8mm for antenna 2), these two resonant modes can be excited with equal amplitudes and a 90° phase difference, resulting in CP radiation. The measured radiation patterns at the center frequency of antennas 1 and 2 were measured, and good right-hand CP operation was observed.

	Side Length L (mm)	Slit Length ℓ (mm)	f_c (MHz)	3-dB Axial-Ratio CP Bandwidth (MHz, %)
Antenna 1	48.2	4.5	1931	19, 1.0
Antenna 2	38.5	3.8	2423	25, 1.0

Table (a) CP Performance of the Antennas in Figure (A)

3.2 With a Pair of Slits

- CP operation of an annular-ring microstrip antenna with a pair of inserted slits at its fundamental TM_{11} mode has been studied. Two examples of the antenna fed using a microstrip line at the inner and outer patch boundaries were studied with the geometries shown in Figures (A) and (B). Results show that such an antenna can have good CP performance, and, moreover, the required antenna size at fixed CP operation can be much less than that of a regular circularly polarized circular microstrip antenna operated in the TM_{11} mode. For the two designs shown, a pair of narrow slits of length s and width 1mm is inserted at the annular ring's inner boundary in the x direction.

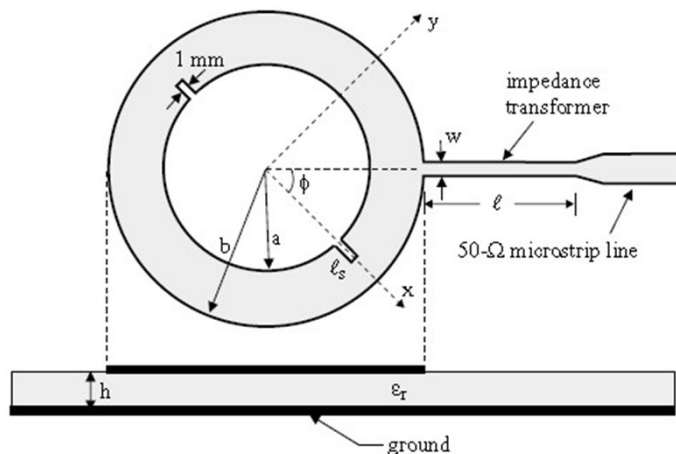


Figure (A) Geometry of a circularly polarized annular-ring microstrip antenna with a pair of inserted slits (design A). The microstrip feed line is at the outer boundary of the patch.

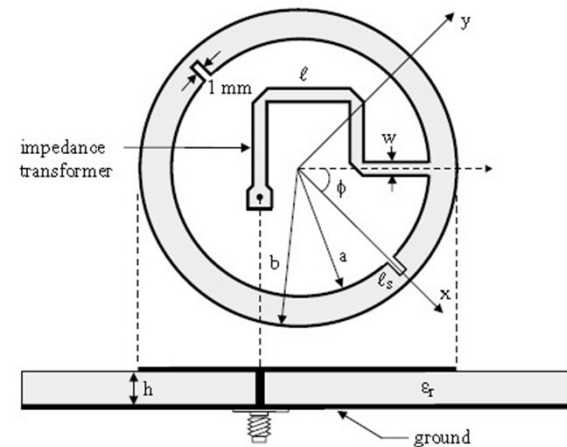


Figure (B) Geometry of a circularly polarized annular-ring microstrip antenna with a pair of inserted slits (design B). The microstrip feed line is at the inner boundary of the patch.

3.2 With a Pair of Slits

- In such an arrangement, the fundamental TM_{11} mode can be split into two near-degenerate resonant modes, and the resonant mode in the x direction can have a slightly larger resonant frequency than the resonant mode in the y direction. Also, upon increasing the inner radius, the two orthogonal modes will both have larger excited patch surface current paths, which causes the resulting CP operation to occur at a lower frequency. This corresponds to a smaller antenna size when the present antenna is used in place of the regular-size circular microstrip antenna.
- For both feed arrangements in Figures (A) and (B), right-hand CP operation can be obtained when the microstrip feed line is placed in the $\phi = 45^\circ$ plane. When the microstrip line is placed in the $\phi = 135^\circ$ plane, left-hand CP operation can be achieved. The transmission-line section of length Ω and width w between the 50- Ω microstrip feed line and the outer/inner patch boundary for impedance transformation is determined by

$$50 = Z_T[(Z_A + jZ_L \tan \beta\ell)/(Z_T + jZ_A \tan \beta\ell)] \quad (\Omega),$$

- where Z_A is the impedance at the outer or inner patch boundary and Z_T and β are, respectively, the characteristic impedance and wave number of the transmission line section. By directly solving the equation, we can select a proper transmission-line section to transform Z_A , usually a complex impedance, to 50 Ω . The determination of the impedance transformer based on the equation, instead of using a quarter-wavelength impedance transformer, gives the present design a much better impedance matching.

3.2 With a Pair of Slits

- In the design shown in Figure (B) for the inner-boundary-fed case, the impedance transformer is connected through a via hole to a 50- Ω probe feed. This design is especially suited for a compact active microstrip antenna in which the associated active circuitry can be integrated inside the annular-ring patch and placed between the impedance transformer and the via hole. Consider the geometry shown in Figure (A) the case with right-hand CP operation is studied. The annular-ring patch is selected to have an outer radius of 20 mm and an inner radius of 10 mm. By adjusting the inserted slit length to be 2.34 mm, CP operation can be obtained. For good impedance matching, the impedance transformer is selected to have a width of 0.8 mm and a length of 32 mm. Figure (C) shows the measured input impedance on a Smith chart. It is clearly seen that two near-degenerate resonant modes are excited with good impedance matching.

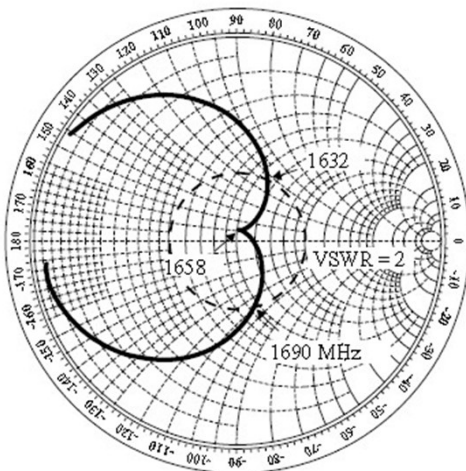
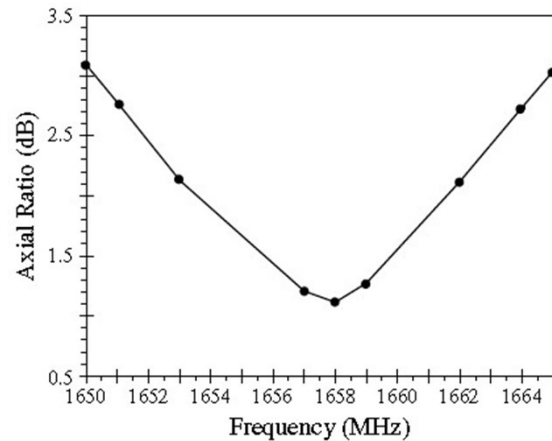


Figure (C) Measured input impedance of the antenna shown in Figure (A); $\epsilon_r = 4.4$, $h = 1.6$ mm, $a = 10$ mm, $b = 20$ mm, $l_s = 2.34$ mm, $\phi = 45^\circ$, $l = 32$ mm, and $w = 0.8$ mm.

3.2 With a Pair of Slits

- The measured axial ratio versus frequency in the broadside direction is presented in Figure (D). The center frequency, defined as the frequency with a minimum axial ratio, is 1658 MHz, and the CP bandwidth is about 14 MHz or 0.8%. For comparison, the results are listed in Table (a) along with those for a reference antenna having the same size as the proposed antenna (design A) and constructed using a regular-size circular microstrip antenna with a tuning stub. We can see that the center frequency (1658 MHz) of design A is about 0.83 times that (2008 MHz) of the reference antenna. This indicates that design A can have a 32% antenna size reduction compared to the reference antenna at a fixed CP operation. The radiation patterns in two orthogonal planes were also measured.



	f_c (MHz)	Impedance Bandwidth (MHz, %)	3-dB Axial-Ratio CP Bandwidth (MHz, %)	Maximum Received Power (dBm)
Design A	1658	58, 3.5	14, 0.8	-49.0
Design B	1526	49, 3.2	12, 0.8	-49.2
Reference	2008	98, 4.9	24, 1.2	-48.8

Figure (D) Measured axial ratio in the broadside direction of the antenna studied in Figure (C).

Table (a) CP Performance of the Antennas in Figures (A) and Figure (B) and a Reference Antenna

3.2 With a Pair of Slits

- Figure (E) plots the radiation patterns of design A at 1658 MHz; good right-hand CP operation is observed. In the CP design shown in Figure (B) (denoted design B), the outer radius of the circular patch and the substrate parameters are the same as for design A shown in Figure (C), but the inner radius is chosen to be 13mm, larger than that of design A. The impedance transformer has a length of 31mm and a width of 0.68 mm, and the inserted slit has a length of 2.0 mm and a width of 1.0 mm. Right-hand CP operation has been demonstrated; that is, the transmission-line section for the impedance transformer is placed in the $\varphi = 45^\circ$ plane.

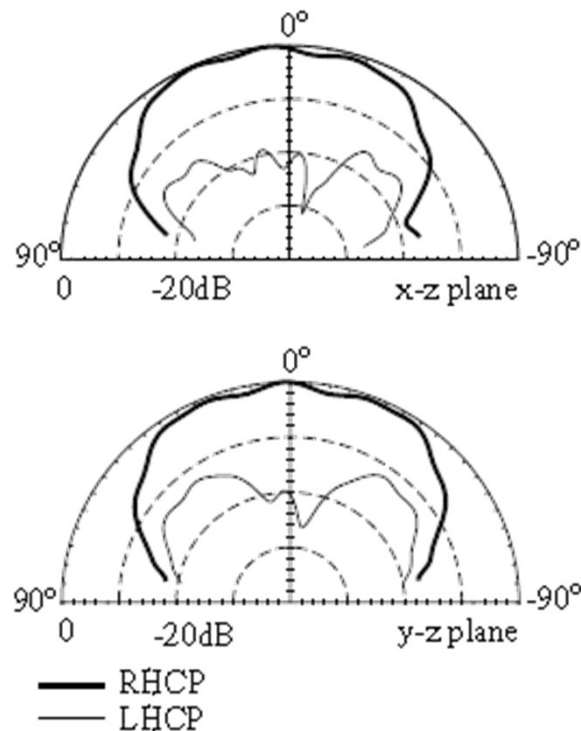


Figure (E) Measured radiation patterns of the antenna studied in Figure (C); $f=1658$ MHz.

3.2 With a Pair of Slits

- The measured input impedance of design B is shown in Figure (F), and the measured axial ratio in the broadside direction is presented in Figure (G). The results show that the center operating frequency is significantly lowered from 2008 MHz (the reference antenna) to 1526 MHz, a 24% reduction in the center frequency, corresponding to a 42% antenna size reduction compared to the design of a regular-size circular patch antenna. The results are listed in Table (a). The CP bandwidth is 12 MHz, or about 0.8%, about the same as that of design A, and is smaller than that of the reference antenna due to the antenna size reduction. Finally, the measured radiation patterns in two orthogonal planes of design B at the center frequency are plotted in Figure (H). Good right-hand CP radiation is observed.

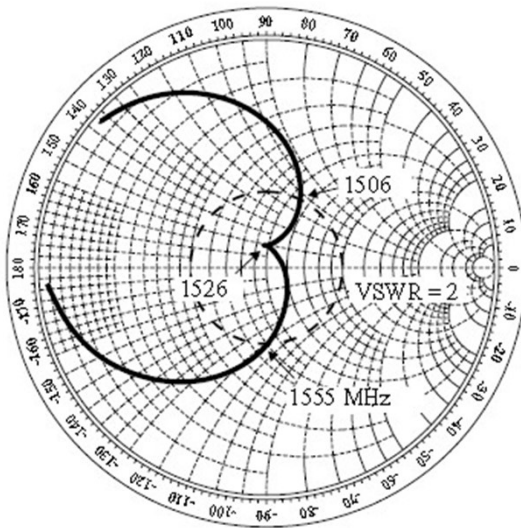


Figure (F) Measured input impedance of the antenna shown in Figure (A); $\epsilon_r = 4.4$, $h = 1.6$ mm, $a = 13$ mm, $b = 20$ mm, $l_s = 2.0$ mm, $\phi = 45^\circ$, $l = 31$ mm, and $w = 0.68$ mm.

3.2 With a Pair of Slits

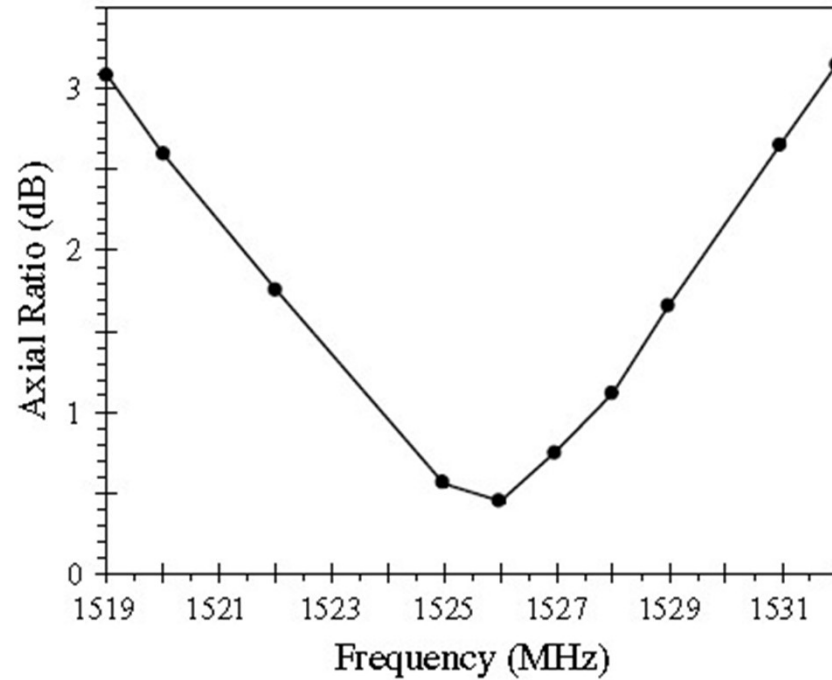


Figure (G) Measured axial ratio in the broadside direction of the antenna studied in Figure (F).

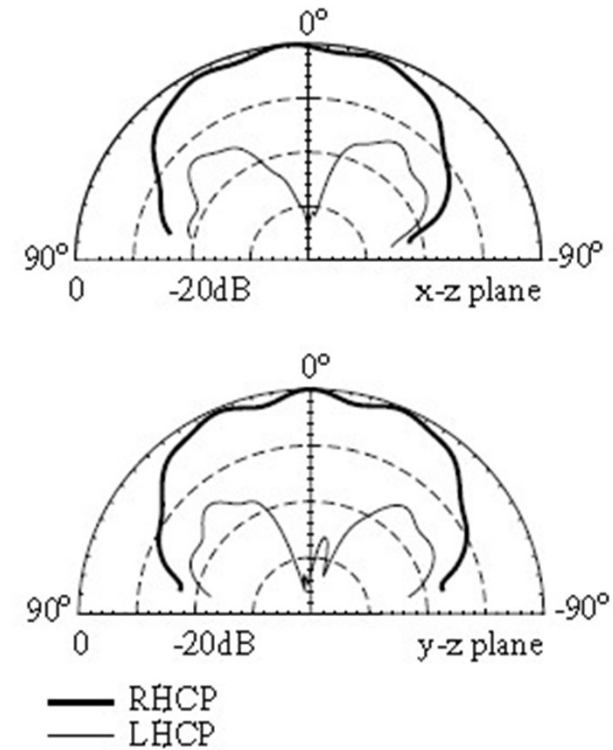


Figure (H) Measured radiation patterns of the antenna studied in (F); $f = 1526$ MHz.

3.3 With Four Inserted Slits

3.3.1 With Four Inserted Slits

- Figure (A) shows a square microstrip antenna with four inserted slits for compact CP operation. Two pairs of slits are cut in the x and y directions in the square patch. Each pair of slits has equal lengths, but the total lengths of the two pairs of slits l_x and l_y are unequal, which splits the resonant mode of interest into two orthogonal near-degenerate modes for CP radiation. When $l_x > l_y$, the feed position at point C along the diagonal AB excites right-hand CP radiation, whereas point D is for left-hand CP operation. Results for right-hand CP operation are presented here.

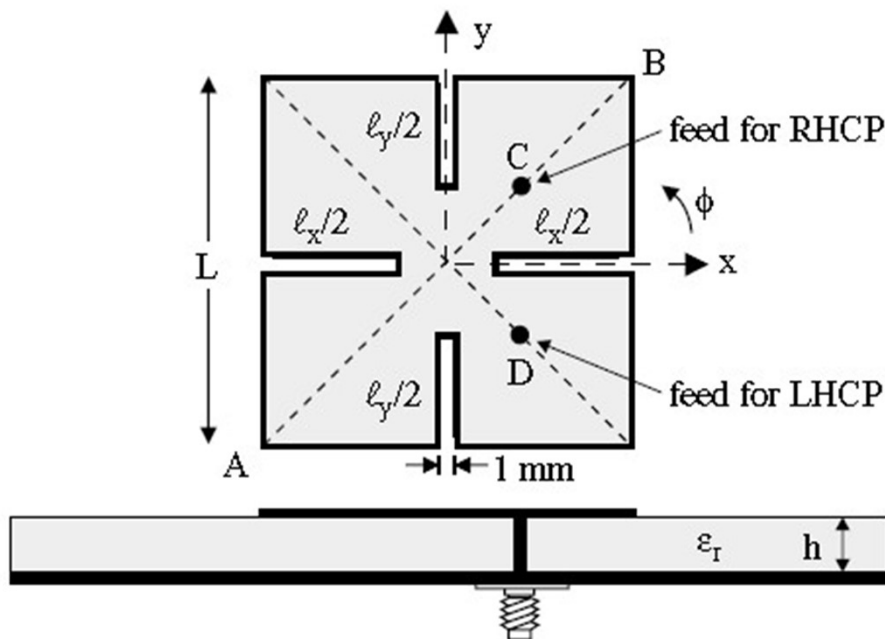


Figure (A) Geometry of a compact square microstrip antenna with four inserted slits for CP radiation.

3.3.1 With Four Inserted Slits

- Figure (B) shows the measured input impedance for several constructed prototypes. The square patch has a side length $L = 30$ mm and is printed on a substrate of thickness $h = 1.6$ mm and relative permittivity $\epsilon_r = 4.4$. When there are no slits, the square patch has a fundamental resonant frequency at 2318 MHz. It can be seen that, with four narrow slits cut in the patch, the fundamental resonant frequency is split into two near-degenerate resonant frequencies, which decrease with increasing slit length.

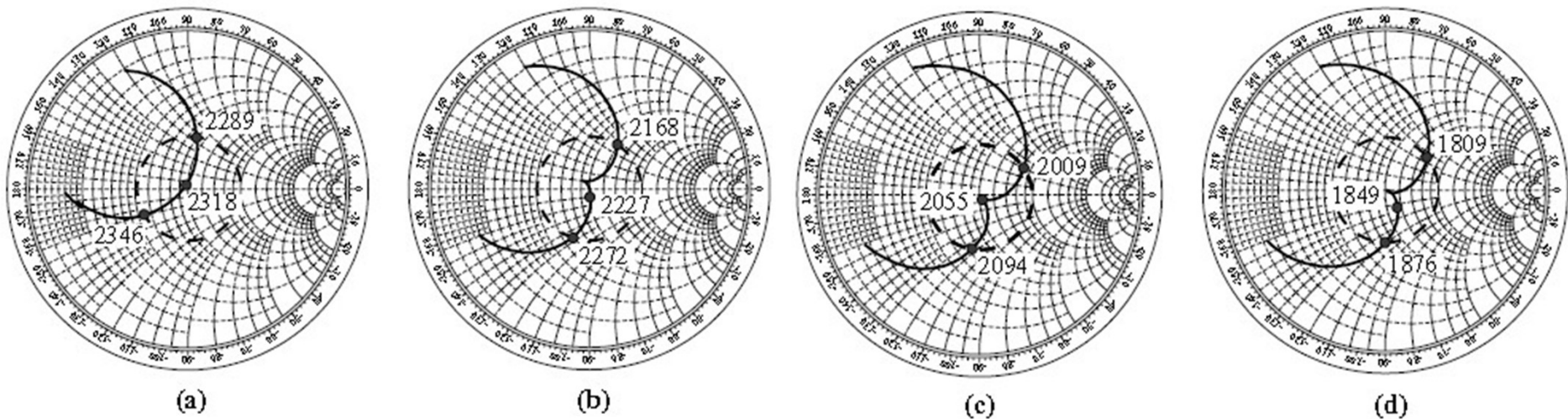


Figure (B) Measured input impedance for the antenna with slits of different lengths; $\epsilon_r = 4.4$, $h = 1.6$ mm, $L = 30$ mm, and feed at point C. (a) $l_x = l_y = 0$; (b) $l_x = 10$ mm, $l_y = 6.4$ mm; (c) $l_x = 15$ mm, $l_y = 13.1$ mm; (d) $l_x = 20$ mm, $l_y = 18.4$ mm.

3.3.1 With Four Inserted Slits

- For the case of $l_x = 20$ mm and $l_y = 18.4$ mm, the CP center frequency (see Figure (B)) decreases to about 1849 MHz [about 0.8 times that (2318 MHz) of the case without slits]. This corresponds to a patch size reduction of about 36% compared to the case using the conventional single-feed CP design. The measured radiation patterns in two orthogonal planes are plotted in Figure (C). No special distinction compared to the results obtained for conventional CP designs is observed.

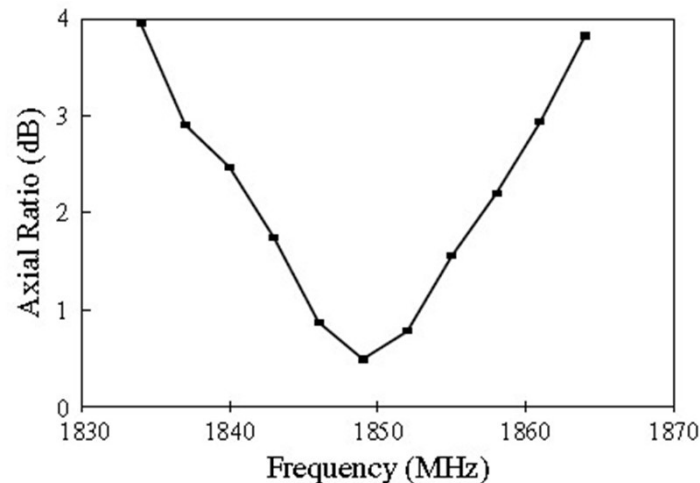


Figure (B) Measured axial ratio for an antenna with $l_x=20$ mm and $l_y=18.4$ mm; other parameters are given in Figure (A).

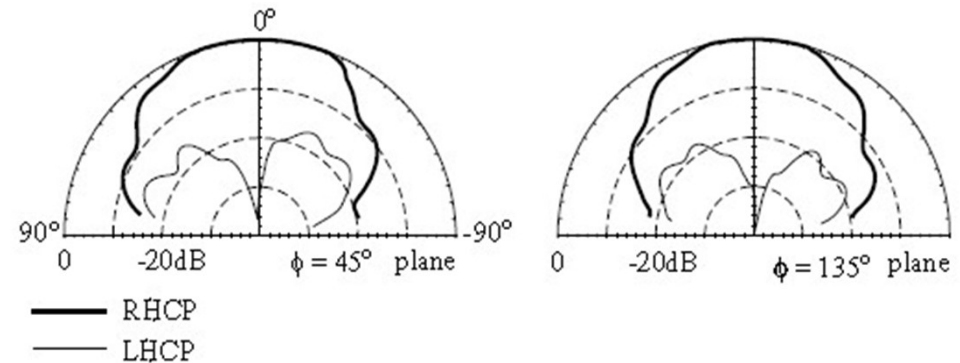


Figure (C) Measured radiation patterns for an antenna with $l_x=20$ mm and $l_y=18.4$ mm; $f=1849$ MHz. Other parameters are given in Figure (A).

3.3.1 With Four Inserted Slits

- Data for the cases in Figure (A) are listed in Table (a). It is seen that, for the case with a smaller slit length, the CP bandwidth is larger and the slit ratio is 1.553 for the case of $l_x = 10$ mm and $l_y = 6.4$ mm. This relaxes the fabrication tolerances compared to the case using conventional CP designs, where the aspect ratio of a design with a nearly square patch or with a patch with truncated corners is usually about or less than 1.05. Also note that the feed position $d_p (= AC/AB)$ for the present design is insensitive to the slit-length variation and is about (0.32–0.34) AB from the patch corner.

Slit Lengths l_x, l_y (mm)	Slit Ratio l_x, l_y	Feed Position $d_p = \overline{AC}/\overline{AB}$	f_c (MHz)	3-dB Axial-Ratio CP Bandwidth (%)
0, 0	—	0.36	2318	—
10, 6.4	1.563	0.32	2227	1.6
15, 13.1	1.145	0.32	2055	1.5
20, 18.4	1.087	0.34	1849	1.3

Table (a) CP Performance of the Antenna in (A)

3.3.2 With a Circular Patch

- Figure (A) shows the geometry of a compact circularly polarized circular microstrip antenna. The circular patch has a radius D , and four narrow slits equally spaced and inserted at the boundary of the circular patch lower the resonant frequency of the dominant TM_{11} mode. Several designs have been implemented.
- Figure (B) shows the measured input impedance for a right-hand circularly polarized circular microstrip antenna using the present compact CP design. Four designs (antennas 1–4 with parameters given in Table (a)) with different slit ratio l_x / l_y are shown.

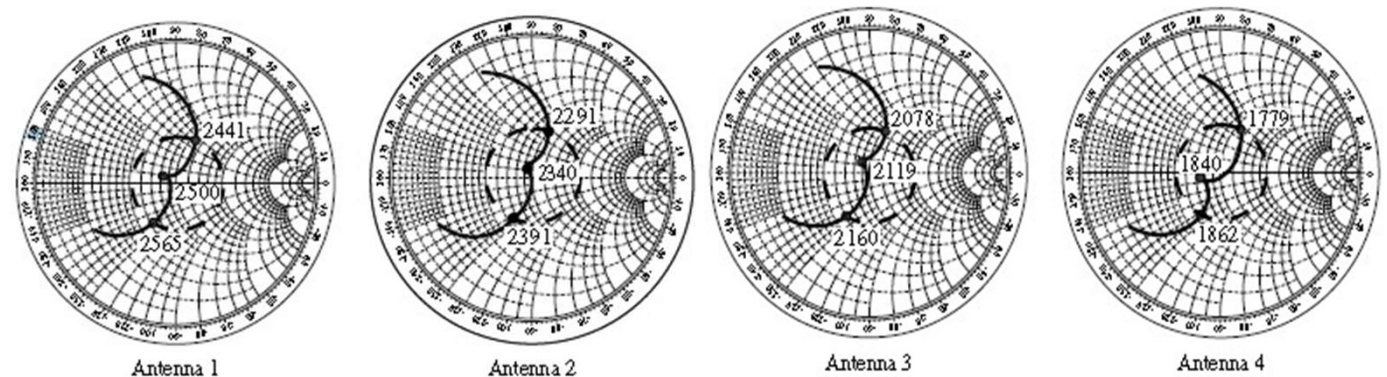
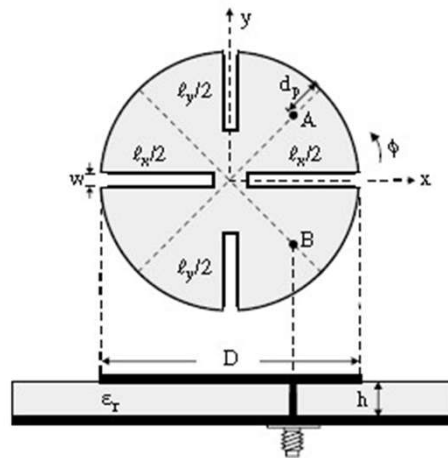


Figure (A) Geometry of a compact circular microstrip antenna with slits for CP radiation.

Figure (B) Measured input impedance for the antenna shown in Figure (A); parameters of antennas 1–4 are given in Table (a).

3.3.2 With a Circular Patch

- The corresponding measured results are presented in Figure (C). Detailed results of the CP performance for the four designs are listed in Table (a). From the results obtained, the optimal feed positions for various slit lengths are seen to be at about one-third the diameter away from the boundary of the circular patch and are closer to the patch center for the case with a larger slit length. With increasing slit length, the CP center frequency decreases with increasing slit length. For antenna 4, the center frequency decreases to only about 71% times that (2576 MHz) of the dominant resonant frequency for the simple circular patch without slits. This suggests that the present compact CP design can achieve a 50% antenna size reduction compared to conventional regular-size CP designs at a fixed operating frequency. Note that, to achieve CP radiation, the slit ratio quickly decreases with increasing slit length, and the CP bandwidth also decreases with increasing slit length. Radiation patterns in two orthogonal planes for antenna 4 were also measured, and good right-hand CP radiation was observed.

	Slit Lengths ℓ_x, ℓ_y (mm)	Slit Ratio ℓ_x/ℓ_y	Feed Position d_p/D	f_c (MHz)	3-dB Axial-Ratio CP Bandwidth (%)
Antenna 1	10, 5	2.00	0.28	2500	1.4
Antenna 2	15, 13	1.15	0.30	2340	1.2
Antenna 3	20, 18.75	1.07	0.33	2119	1.1
Antenna 4	25, 24.5	1.02	0.37	1840	1.0

Table (a)
CP Performance of the Antenna in Figure (A)

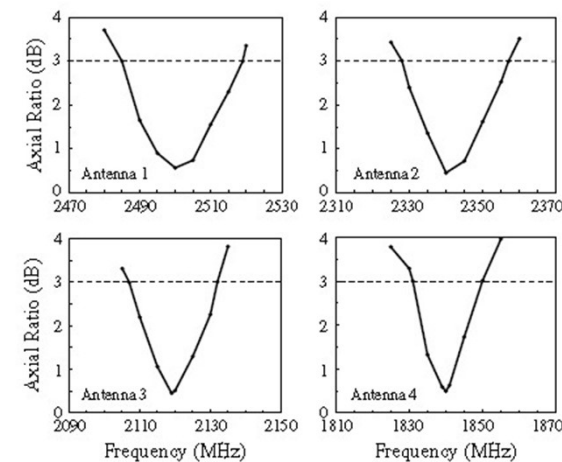


Figure (C) Measured axial ratio for the antenna shown in Figure (B); parameters of antennas 1–4 are given in Table (a).

3.3.3 With a Corner-Truncated Square Patch

- The method of producing single-feed CP operation of a square microstrip antenna by truncating a pair of patch corners has been widely used. Here we demonstrate that such a method can also be applied to a modified square microstrip patch with four inserted slits of equal lengths to achieve compact CP operation with relaxed manufacturing tolerances. The compactness of the proposed CP design is achieved due to the inserted slits at the patch corners of the square patch.
- These inserted slits result in meandering of the excited fundamental-mode patch surface current path, which effectively lowers the resonant frequency of the modified square patch, similar to the design using four inserted slits of different lengths at the boundary of a square patch (see Section 3.3.1). Instead of using different slit lengths for CP excitation, which usually requires a very small slit-length difference for a large reduction in antenna size, the present design uses the perturbation of truncating a pair of patch corners, with the inserted slits of equal lengths.
- Experimental results show that the required size of the truncated corners for CP operation increases with increasing reduction in antenna size. This behavior gives the present design a relaxed manufacturing tolerance for achieving a compact circularly polarized microstrip antenna.

3.3.3 With a Corner-Truncated Square Patch

- The proposed antenna geometry is shown in Figure (A). The square microstrip patch has a side length of L . The four slits have an equal length of l and a width of 1 mm and are inserted at the four patch corners along the directions of $\phi = \pm 45^\circ$. The truncated corners are of equal side length ΔL . The single probe feed is placed at point A on the y axis to achieve right-hand CP radiation. When the feed position is on the x axis, left-hand CP radiation is obtained. Figure (B) shows the measured return loss of constructed prototypes with $l = 16$ mm (denoted antenna 1), 14 mm (antenna 2), and 12 mm (antenna 3), with the side length of the square patch fixed to 28 mm.

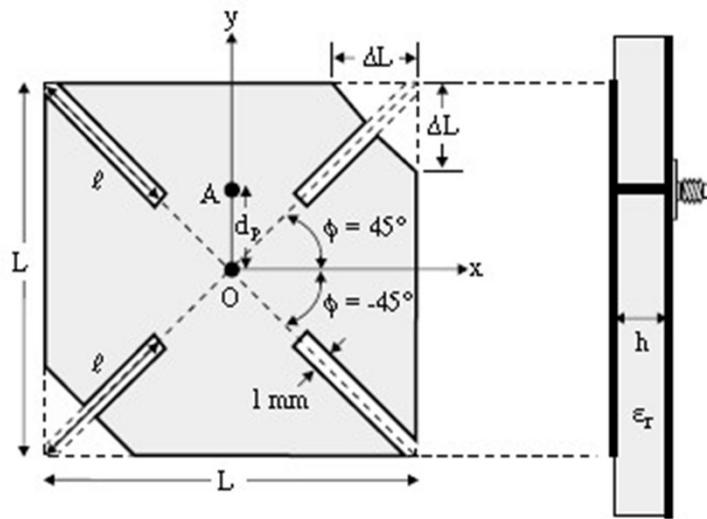


Figure (A) Geometry of a compact circularly polarized square microstrip antenna with four slits and a pair of truncated corners.

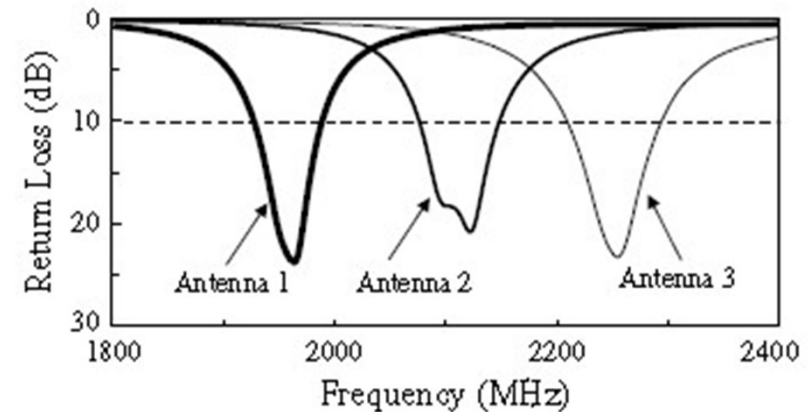


Figure (B) Measured return loss for the antenna shown in Figure 5.37 with various slit lengths; $\epsilon_r = 4.4$, $h = 1.6$ mm, $L = 28$ mm, and feed at point A. Antenna 1: $l = 16$ mm, $\Delta L = 6.3$ mm; antenna 2: $l = 14$ mm, $L = 4.5$ mm; antenna 3: $l = 12$ mm, $\Delta L = 2.9$ mm.

3.3.3 With a Corner-Truncated Square Patch

- The measured axial ratio in the broadside direction is shown in Figure (C). The corresponding CP performance is listed in Table (a). The CP center frequency f_c is 1970 MHz for antenna 1, 2101 MHz for antenna 2, 2262 MHz for antenna 3, and 2480 MHz for the reference antenna. In comparison to the reference antenna, the center frequency of antenna 1 is lowered by about 20%. The lowering in the center frequency corresponds to an antenna size reduction of about 36% by using the present design in place of the conventional CP design (reference antenna) at a fixed operating frequency. The required perturbation size of the truncated corners also increases with lowered center frequency. For the case of antenna 1 ($l = 16$ mm), the required area of the truncated corners is about four times that of the reference antenna. This suggests that, compared to the design using a square patch with slits of unequal lengths (Section 3.3.1) or a simple corner-truncated square patch, the present compact CP design has a very relaxed manufacturing tolerance for CP operation. Measured radiation patterns of the present design are plotted in Figure (D). Good right-hand CP radiation is observed for the present study with the feed position at point A.

	l (mm)	ΔL (mm)	d_p (mm)	f_c (MHz)	3-dB Axial-Ratio CP Bandwidth (%)	Antenna Gain (dBi)
Antenna 1	16	6.3	4.4	1970	0.80	1.4
Antenna 2	14	4.1	5.5	2101	0.81	2.0
Antenna 3	12	3.3	6.7	2262	0.84	2.8
Reference	0	3.2	7.8	2480	1.45	3.5

Table (a) CP Performance of the Antenna in Figure (A)

3.3.3 With a Corner-Truncated Square Patch

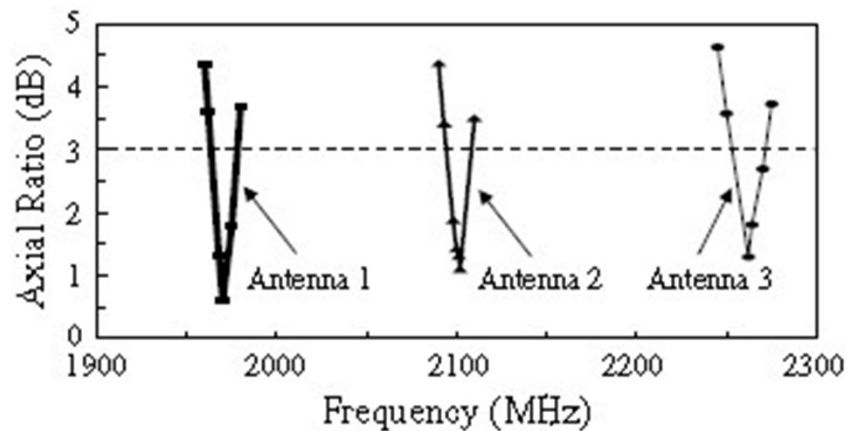


Figure (C) Measured axial ratio in the broadside direction for the antennas studied in Figure (B).

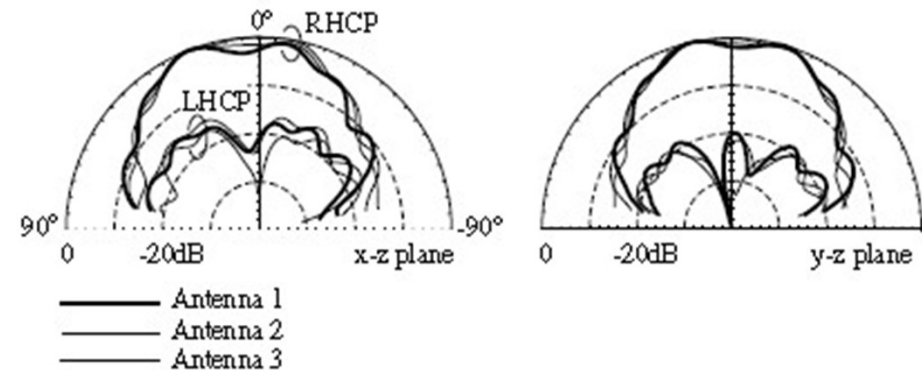


Figure (D) Measured radiation patterns for the antennas studied in Figure (B); antenna 1 at 1970 MHz, antenna 2 at 2101 MHz, and antenna 3 at 2262 MHz.

3.3.4 With a Chip-Resistor-Loaded Square Patch

- Figure (A) shows the antenna geometry studied here. The square patch has a side length of L . A single probe feed at point C gives right-hand CP radiation, and point D gives left-hand CP radiation. A narrow slit of length $l/2$ and width 1mm is inserted at the center of each patch edge. Note that the four inserted slits have equal lengths, and the total slit lengths in the x and y directions are the same, l . A chip resistor of resistance R is loaded along the positive y axis a distance S from the patch center. In this case, **the resonant frequency of the $\hat{y}$ -directed mode will be slightly larger than that of the $\hat{x}$ -directed mode**. By adjusting the distance S , these two orthogonal resonant modes can be excited with equal amplitudes, but with a 90° phase difference. With the present arrangement, compact CP operation with enhanced bandwidth can be obtained.

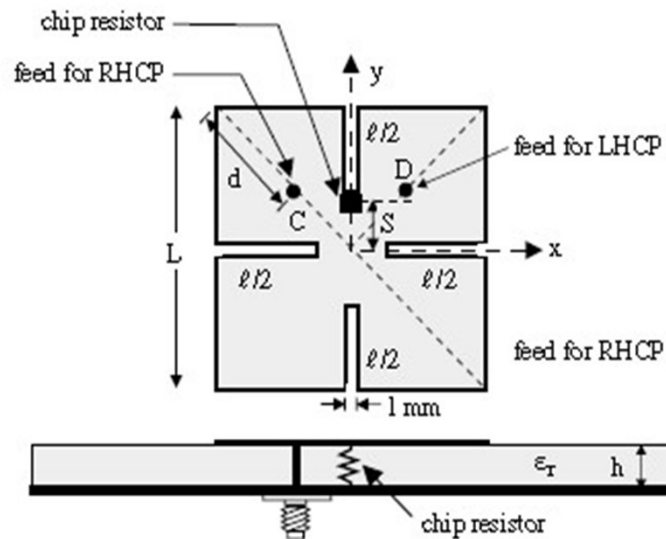


Figure (A) Geometry of a compact circularly polarized square microstrip antenna with slits and a chip resistor.

3.3.4 With a Chip-Resistor-Loaded Square Patch

- Figure (B) shows the measured return loss for a constructed prototype of the present design with $R = 4.7 \Omega$ and $l = 19$ mm. Two near-degenerate resonant modes are clearly seen to be excited. When there is no chip resistor present, only the lower resonant mode, at about 1855 MHz, is excited. The higher resonant mode, at about 1880 MHz, is excited owing to the loading of the $4.7\text{-}\Omega$ chip resistor. Figure (C) presents the axial ratio measurements. The corresponding CP performance is listed in Table (a). The results for the CP design using four slits of unequal lengths (Ref. Section 3.3.1) are shown in Table (a) as a reference. Note that a corresponding simple square patch antenna without chip-resistor loading and inserted slits has a fundamental resonant frequency of 2355 MHz.
- Since the antenna studied has a center frequency of 1867 MHz, a 20.7% lowering in the operating frequency compared to the conventional CP design using a simple square patch is thus obtained.

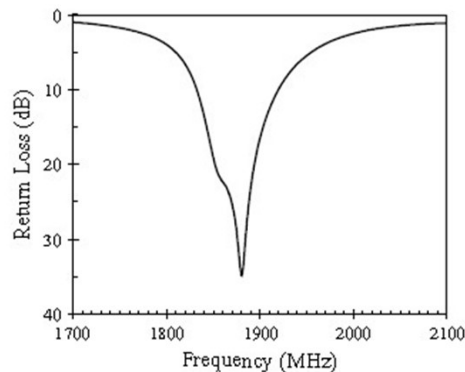


Figure (B) Measured return loss for the antenna shown in Figure (A) with right-hand CP operation (feed at point C); $\epsilon_r = 4.4$, $h = 1.6$ mm, $L = 30$ mm, $l = 19$ mm, $S = 4$ mm, $d = 14$ mm, and $R = 4.7$.

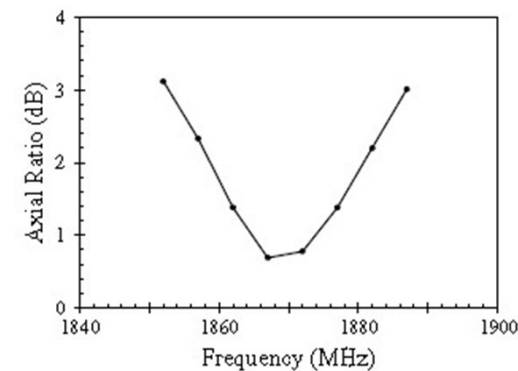


Figure (C) Measured axial ratio for the antenna studied in Figure (B)

3.3.4 With a Chip-Resistor-Loaded Square Patch

- Results show that the CP bandwidth is about 50% larger than that of the reference antenna shown in Table (a) (1.9% vs. 1.3%). This broadband characteristic is mainly due to the 4.7- Ω chip-resistor loading, and a much greater CP bandwidth can be obtained if a chip resistor of larger resistance is used for the present design. However, **it should be noted that the increase in CP bandwidth is at some expense of the antenna gain.**
- The maximum relative received power of the proposed antenna is 1.2 dBm less than that of the reference antenna. Finally, from the measured radiation patterns, good right-hand CP radiation is observed for the present proposed antenna.

	Slit Lengths on x, y Axes (mm)	f_c (MHz)	3-dB Axial-Ratio CP Bandwidth (MHz, %)	Maximum Received Power (dBm)
This study	19, 19	1867	35, 1.9	-52.5
Ref. 8	20, 18.4	1849	24, 1.3	-51.3

Table (a) CP Performance of the Antenna in Figure (A)

4 Designs With Truncated Corners

- The technique of truncating the patch corners of a simple square microstrip patch to obtain single-feed CP operation of microstrip antennas has been widely used in practical designs. In this section, we demonstrate that such a technique can also be applied to single-feed microstrip antennas with several kinds of patch.
- It is found that the required antenna size of these designs is smaller than that of the conventional design using a simple square patch at a fixed CP operation, and compact CP operation can be obtained. Experimental results of constructed prototypes of the designs are described in the following.

With a Triangular Patch

- Figure (A) shows the CP design of a single-feed, equilateral-triangular microstrip antenna with a truncated corner or tip.

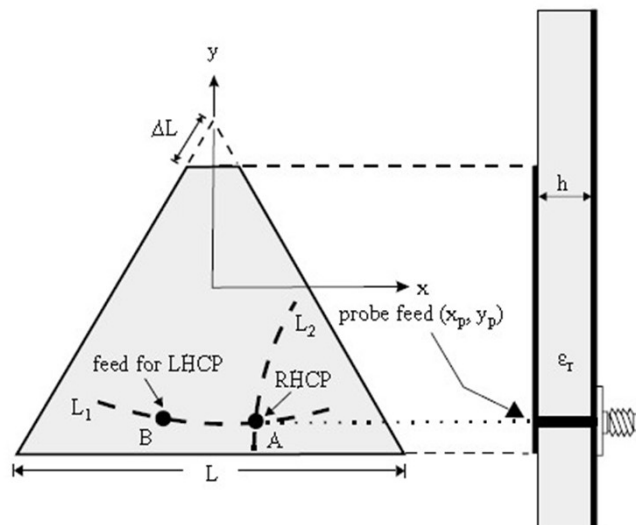


Figure (A) Geometry of a single-feed equilateral-triangular microstrip antenna with a truncated tip for CP operation.

With a Triangular Patch

- Experimental results for constructed prototypes of the present CP design are shown in Figures (B) and (C). Three different triangular patch dimensions were studied, with the feed at point A for right-hand CP radiation.

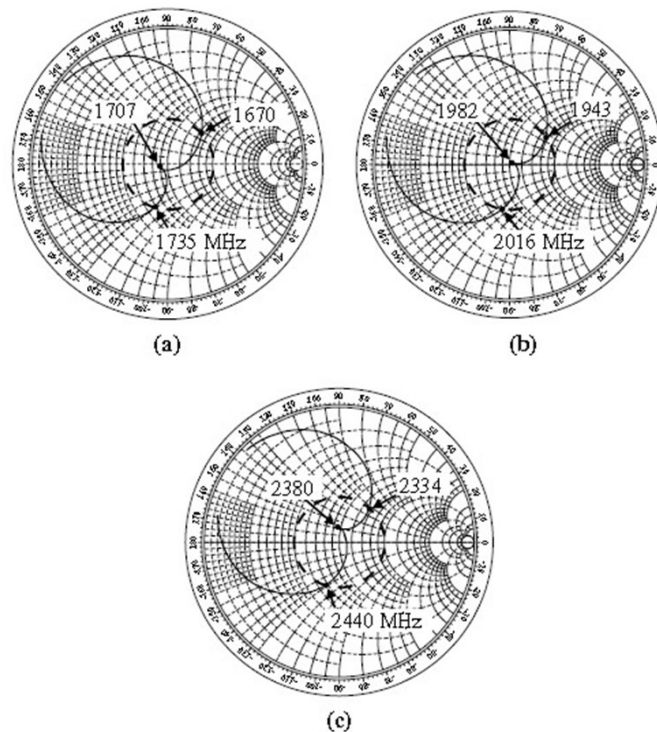


Figure (B) Measured input impedance for the antenna shown in Figure (A); $\epsilon_r = 4.4$, $h = 1.6$ mm, and feed at point A. (a) Antenna 1, (b) antenna 2, (c) antenna 3.

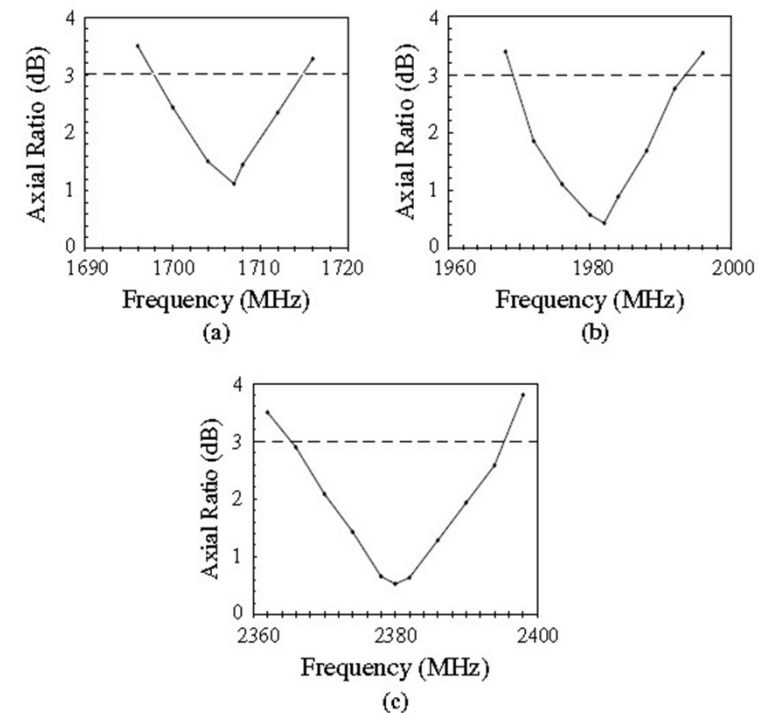


Figure (C) Measured axial ratio for the antennas studied in Figure (B).

With a Triangular Patch

- The corresponding CP performance is given in Table (a). It is found that, when the side length of the truncated tip is adjusted to be about 0.09 times that of the triangular patch, the dominant mode of the triangular patch is split into two near-degenerate orthogonal modes of equal amplitudes and a 90° phase difference, which results in CP radiation. Results show that the obtained CP bandwidths are about 1.0 –1.4%, which are largely dependent on the electrical thickness of the substrate, for the antenna parameters studied here. Radiation patterns at resonance of the prototypes were measured, and good right-hand CP radiation was observed.

	L (mm)	ΔL (mm)	Feed Position (x_p, y_p) (mm)	f_c (MHz)	3-dB Axial-Ratio CP Bandwidth (MHz, %)
Antenna 1	56	5.0	(7.3, -16.8)	1707	17, 1.0
Antenna 2	48	4.2	(7.2, -13.6)	1982	28, 1.4
Antenna 3	40	3.6	(3.8, -12.2)	2380	30, 1.3

Table (a) CP Performance of the Antenna in Figure (A)

5 Compact CP Designs With an Inset Microstrip-Line Feed

- A CP design for exciting a circularly polarized microstrip antenna using a 50- Ω inset microstrip-line feed has been reported. The proposed designs are shown in Figure (A). Figure (Aa) shows the case with a narrow slit (denoted design A), Figure (Ab) is for the case with two pairs of slits (design B), and the design in Figure (Ac) is with three pairs of inserted slits (design C). The 50- Ω inset microstrip line has a width w_c and an inset length ℓ_t . All the inserted slits are of length ℓ_s and width 1 mm, and the pairs of slits in Figures (Ab) and (Ac) are a distance d apart. The square patch has a side length L and a pair of truncated corners of dimensions $\Delta L \times \Delta L$. Because of the combined effects of the inset microstrip line and the slits, two orthogonal near-degenerate modes for CP radiation can easily be excited. Also, the excited patch surface currents are meandered in the present designs, and the obtained CP operating frequency is greatly lowered; thus, compact CP radiation can be achieved for the present designs.

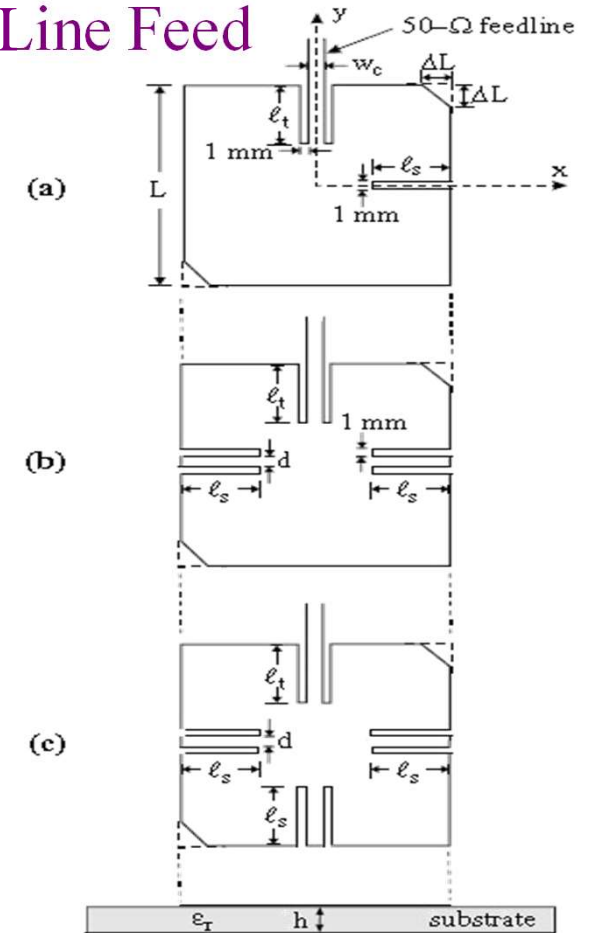


Figure (A) Geometries of inset microstrip-line-fed microstrip antennas for compact CP operation. (a) Design A: corner-truncated square patch with a slit; (b) design B: corner-truncated square patch with two pairs of slits; (c) design C: corner-truncated square patch with three pairs of slits. Designs A–C are all with right-hand CP radiation.

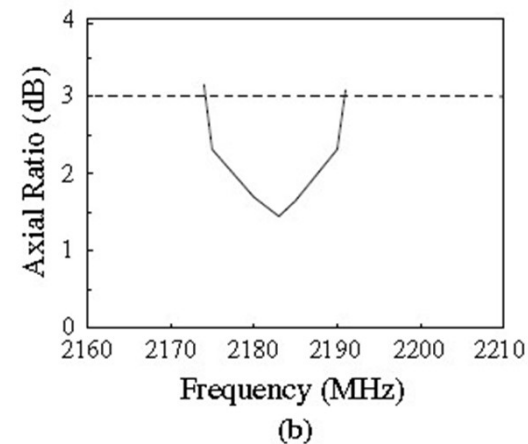
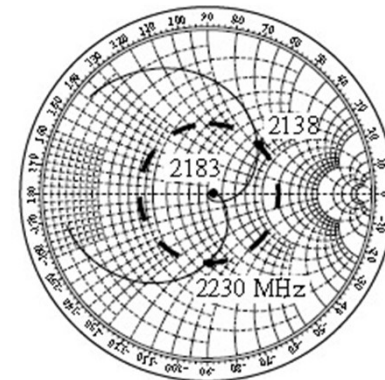
5 Compact CP Designs With an Inset Microstrip-Line Feed

- A conventional probe-fed, circularly polarized, corner-truncated square microstrip antenna was first constructed as a reference antenna. The dimensions of truncated corners, the CP bandwidth, and the CP center frequency f_c are shown in Table (a). Figure (B) presents the measured input impedance and axial ratio of design A; the corresponding results are given in Table (a).

	ℓ_s (mm)	d (mm)	ℓ_t (mm)	ΔL (mm)	f_c (MHz)	3-dB Axial-Ratio CP Bandwidth (%)
Design A	9.7	—	7.4	3.3	2183	0.8
Design B	9.8	3.0	10.8	3.6	1775	0.8
Design C	10.8	3.0	10.8	3.9	1653	0.7
Reference	—	—	—	3.2	2480	1.4

Table (a) CP Performance of the Antenna in Figure (A)

Figure (B) Measured (a) input impedance and (b) axial ratio of the antenna shown in Figure (Aa) (design A); $\epsilon_r = 4.4$, $h = 1.6$ mm, $L = 28$ mm, $L = 3.3$ mm, $s = 9.7$ mm, $t = 7.4$ mm, $w_C = 3.0$ mm, and ground-plane size = 60×60 mm².



5 Compact CP Designs With an Inset Microstrip-Line Feed

- It is observed that two near-degenerate resonant modes with good impedance matching are excited [see Figure (Ba)], and the CP bandwidth [see Figure (Bb)] is 17 MHz, or about 0.8% with respect to the center frequency at 2183 MHz. Note that the center frequency is lowered by about 12% compared to that (2480 MHz) of the reference antenna. This corresponds to an antenna size reduction of about 23% for design A in place of the reference antenna at a fixed frequency. Measured radiation patterns are plotted in Figure (C), and good right-hand CP radiation is obtained. For designs B and C, parameters are given in (a). The CP center frequencies of designs B and C occur, respectively, at 1775 and 1653 MHz, which are lowered by about 28% and 33% compared to that of the reference antenna. That is, an antenna size reduction about 49% or 55% can be expected at a fixed frequency by replacing the reference antenna with design B or C, respectively. Measured radiation patterns of designs B and C indicate that good CP radiation is observed.

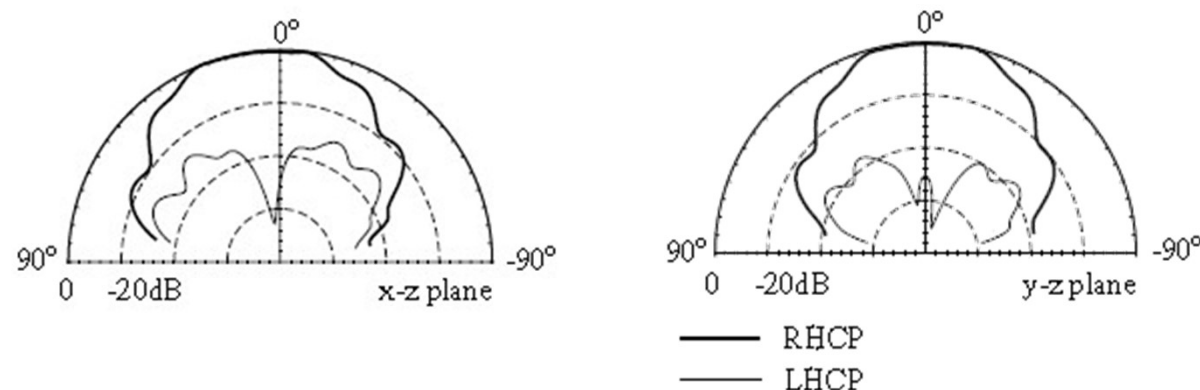


Figure (C) Measured radiation patterns for the antenna studied in (B) with $f = 2183$ MHz.



Chapter 5 Part II Microstrip antenna

- Compact Broadband MSA
- Dual-frequency and dual-polarized MSA
- Compact circularly polarized MSA
- **Broadband planar monopole antennas**

1. Introduction

- As we observed, the BW of the MSA increases with an increase in the substrate thickness and a decrease in the dielectric constant of the substrate .
- But too much increase in the substrate thickness decreases the efficiency of the MSA and increases cross-polar levels ,and also, a long coaxial probe is required to feed the radiating metallic patch suspended in air at a large height h as shown in Figure (A). The large h increases the probe inductance, and the input impedance becomes too inductive to obtain impedance matching.

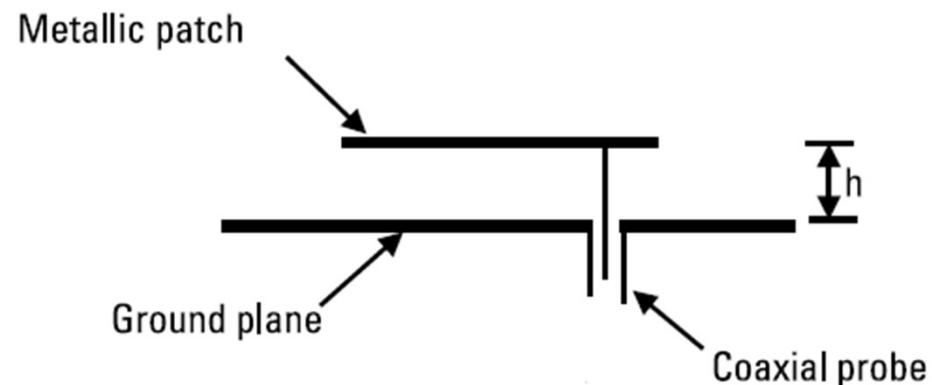


Figure (A) MSA suspended in air at a large height h .

1. Introduction

- To take care of the large inductive input impedance, a shorter probe of length p as shown in Figure (B) is used to feed the patch. In this case, the patch is fed along the periphery and an additional perpendicular ground plane is required.
- If h is very large, the bottom ground plane would have a negligible effect and hence can be removed. This configuration becomes similar to that of a planar monopole antenna, as shown in Figure (C).

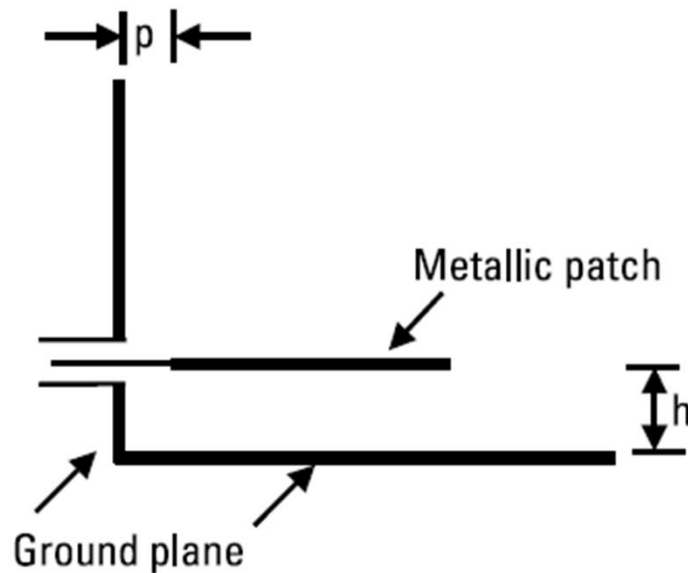


Figure (B) Modified MSA with side feed

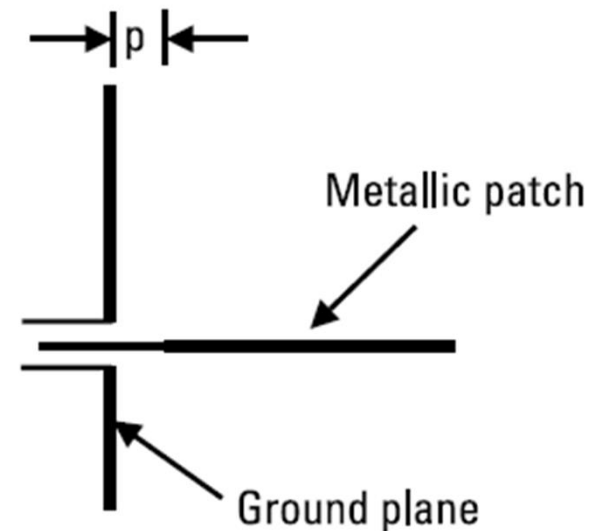


Figure (C) Planar monopole antenna

1. Introduction

- The planar disc monopole antennas yield a very large-impedance BW, which can be explained in the following two ways:
 - 1. A monopole antenna generally consists of a thin vertical wire mounted over the ground plane, whose BW increases with an increase in its diameter. A planar monopole antenna can be equated to a cylindrical monopole antenna with a large effective diameter.
 - 2. The planar monopole antenna can be viewed as a MSA on a very thick substrate with $\epsilon_r = 1$, so a large BW is expected. In the radiating metallic patch, various higher order modes will get excited.
 - Since all the modes will have a larger BW, these will undergo a smaller impedance variation. The shape and size of these planar antennas can be optimized to bring several modes within the VSWR = 2 circle in the Smith chart, leading to very large-impedance BW.
- This chapter describes various planar monopole antennas, including square, rectangular, triangular, hexagonal, circular, and elliptical disc monopoles.

2 . Various planar monopole antennas

2.1 Planar Rectangular and Square Monopole Antennas

2.1.1 RMSA Suspended in Air with Orthogonal Ground Plane

- A planar rectangular monopole antenna can be thought of as a variation of the RMSA, in which the horizontal ground plane is considered to be located at infinity. The side and the front views of a rectangular radiating patch with $L = W = 12$ cm made of a copper plate of thickness 0.1 cm with two orthogonal ground planes are shown in Figure(A). The patch is fed with a 50-SMA connector of probe length p through a fixed ground plane and the orthogonal ground plane is moveable.

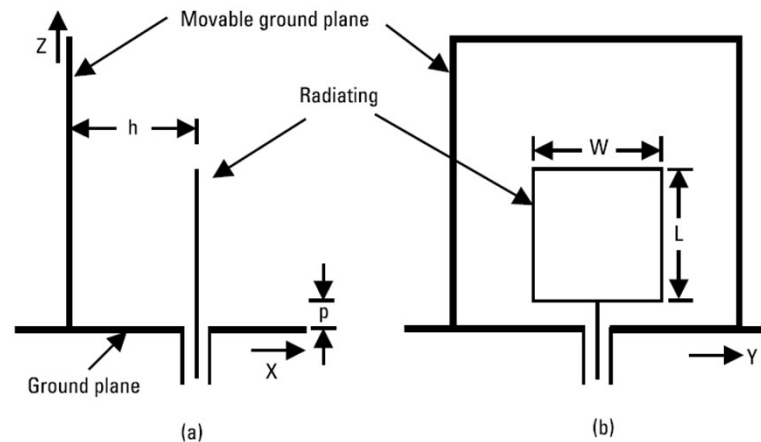


Figure (A)

(a) Side and (b) front views of modified RMSA with orthogonal ground planes.

- This structure can be thought of as an MSA on an air dielectric with an additional perpendicular ground plane. The theoretical resonance frequency for the fundamental mode can be calculated using:
- L_e = effective resonant length; $f_0 = c / (2L_e)$
- c = velocity of light in free space.
- The extension of length L due to the fringing fields is applicable only for one side, and on the other side, it is restricted to p due to the orthogonal ground plane.

2.1.1 RMSA Suspended in Air with Orthogonal Ground Plane

For the moveable ground plane spacing $h = 3$ cm from the radiating patch and the probe length $p = 0.4$ cm, the measured input impedance and VSWR plots are shown in Figure (B). Multiple loops occur due to the excitation of various higher order modes of RMSA. The impedance plot shows less inductive shift due to the smaller value of the feed probe length p , so the value of p is increased to 1 cm to shift the impedance plot in the clockwise direction.

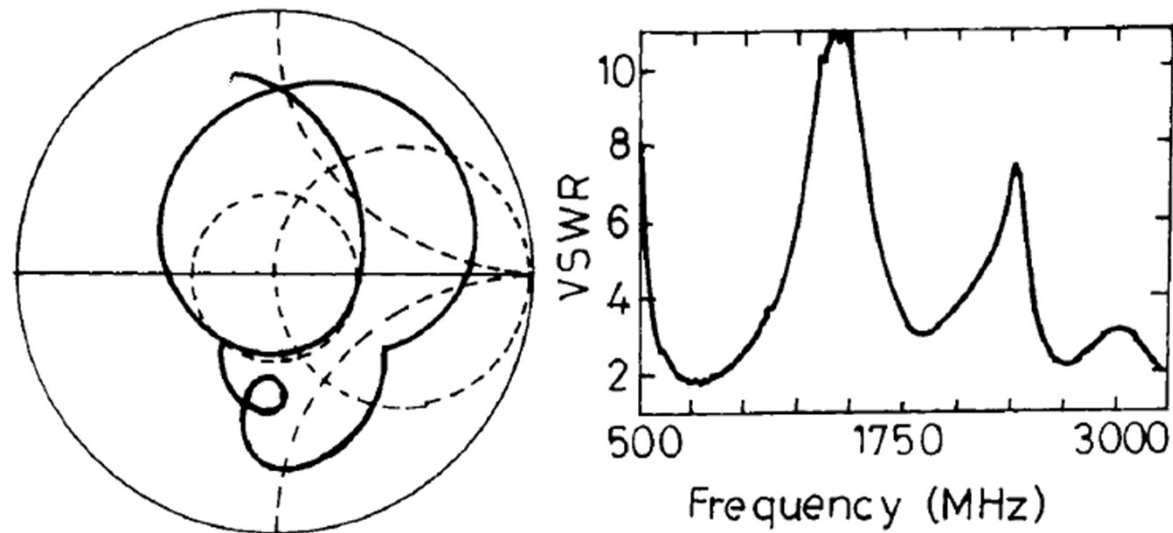


Figure (B) .Measured input impedance and VSWR plots

2.1.1 RMSA Suspended in Air with Orthogonal Ground Plane

- The effect of increasing h on BW of the antenna is considered. For different values of h with $p = 1.0$ cm, the measured lower and upper frequencies corresponding to $VSWR = 2$ are given in table 2.1.

Table 2.1

Resonance Frequency and Percentage BW of RMSA with $L = W = 12$ cm for Different Values of h

h (cm)	Measured Results for $VSWR \leq 2$			Theoretical Frequency (MHz)
	f_L (MHz)	f_H (MHz)	% BW	
3	858	988	14.1	937 ^a
6	752	934	17.7	789 ^a
18	515	1,081	70.3	484 ^a , 483 ^b
∞	501	1,154	81.2	0 ^a , 483 ^b

2.1.1 RMSA Suspended in Air with Orthogonal Ground Plane

- As h increases, the measured lower resonance frequency decreases because of the increase in L due to the large fringing fields. For smaller values of h , there is a reasonable agreement between the theoretical frequency obtained from (2.1) and the measured center frequency. As h increases, the theoretical frequency is close to the measured lower frequency corresponding to $VSWR = 2$. For two different values of h [i.e., 18 cm (large) and ∞ (bottom ground plane removed)], the measured input impedance and VSWR plots are shown in Figure(C).

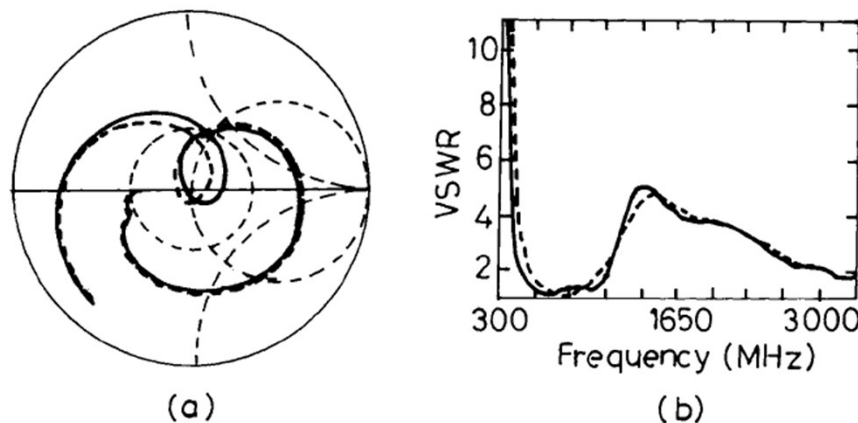


Figure (C) . Measured (a) input impedance and (b) VSWR plots of RMSA for two values of h : (- - -) 18 cm and (—) ∞ .

- For these two values of h , the input impedance and VSWR plots are nearly the same. Therefore, for a large h tending to infinity, the MSA configuration reduces to that of a planar monopole antenna.

2.1.2 Effect of Various Parameters of Planar Rectangular Monopole Antennas

- The BW of these antennas depends mainly on the width W of the plate, the diameter d of the feeding probe, and the length of the probe p . The SMA connector is generally used above 1 GHz for feeding the antenna, and hence, d is kept fixed at 0.12 cm. When the height L of the monopole antenna increases (or decreases), the lower edge frequency decreases (or increases), which is quite obvious. Therefore, the effects of width W and probe length p on the performance of the antenna are described.
- The effect of p is described.
- The RM and square monopole (SM) antennas are analyzed using IE3D software. Keeping $L = W = 4.5$ cm, the input impedance and VSWR plots for two values of p are shown in Figure (D).

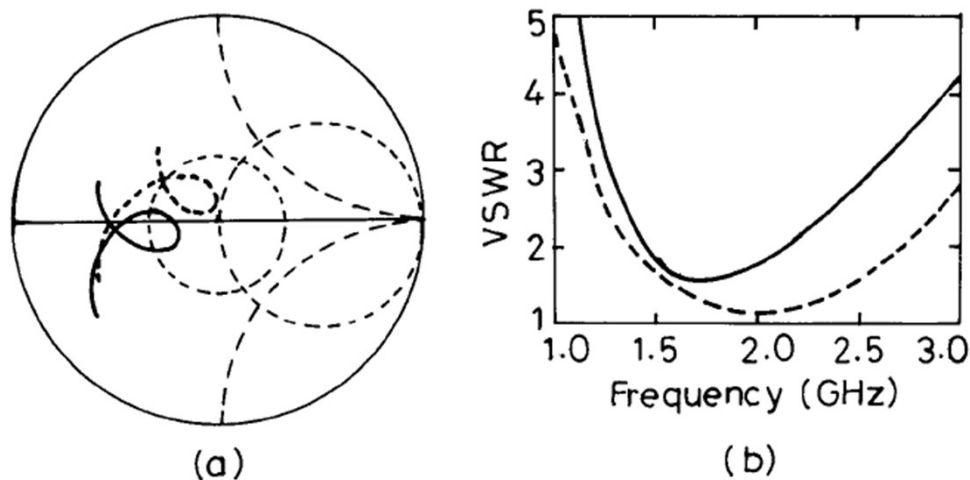


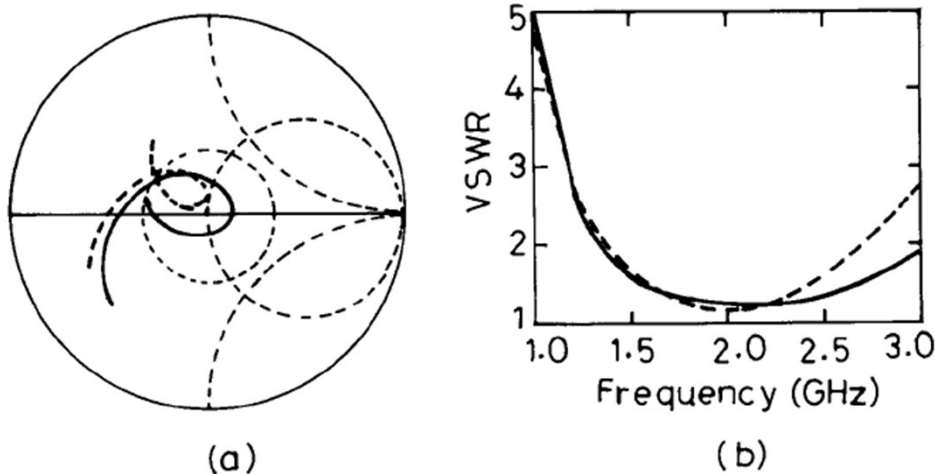
Figure (D)
Input impedance and (b) VSWR plots of
RM antenna for two values of p [(—)
0.05 cm and (---) 0.2 cm]

2.1.2 Effect of Various Parameters of Planar Rectangular Monopole Antennas

- As p is increased from 0.05 cm to 0.2 cm, the input impedance plot shifts up in the clockwise direction. This is because with an increase in p , the probe inductance increases and therefore the input impedance becomes more inductive. A broad BW of 1335 MHz (68%) is obtained for $p = 0.2$ cm, compared to the BW of 668 MHz (40%) for $p = 0.05$ cm.

2. The effect of w is described.

The input impedance and VSWR plots for two values of W (4.5 cm and 3.5 cm) with $L = 4.5$ cm and $p = 0.2$ cm are shown in Figure(E).



• Figure (E). (a) input impedance and (b) VSWR plots with $L = 4.5$ cm and $p = 0.2$ cm for two values of W [(- - -) 4.5 cm and (—) 3.5 cm].



2.1.2 Effect of Various Parameters of Planar Rectangular Monopole Antennas

With a decrease in W , the size of the loop in the impedance plot increases and the plot shifts toward the right in the Smith chart. Since the lengths of these RMs are kept fixed at 4.5 cm, the lower band-edge frequency remains almost unchanged; this is predominantly determined by the length L of the planar monopole antenna. As W decreases from 4.5 cm to 3.5 cm, the BW increases from 1,335 MHz to 1,715 MHz due to an increase in loop size.

2.1.3 Radiation Pattern of RM Antennas

The theoretical radiation pattern of the square monopole antenna ($L=W=4.5$ cm) is obtained using IE3D for infinite ground plane. For comparison, the radiation pattern of a thin (narrow width $W=0.5$ cm) RM antenna with the same length $L=4.5$ cm is also computed in the same frequency range. The E- and H-plane radiation patterns of both the antennas at 1.5 GHz and 2.5 GHz are shown in Figure (A).

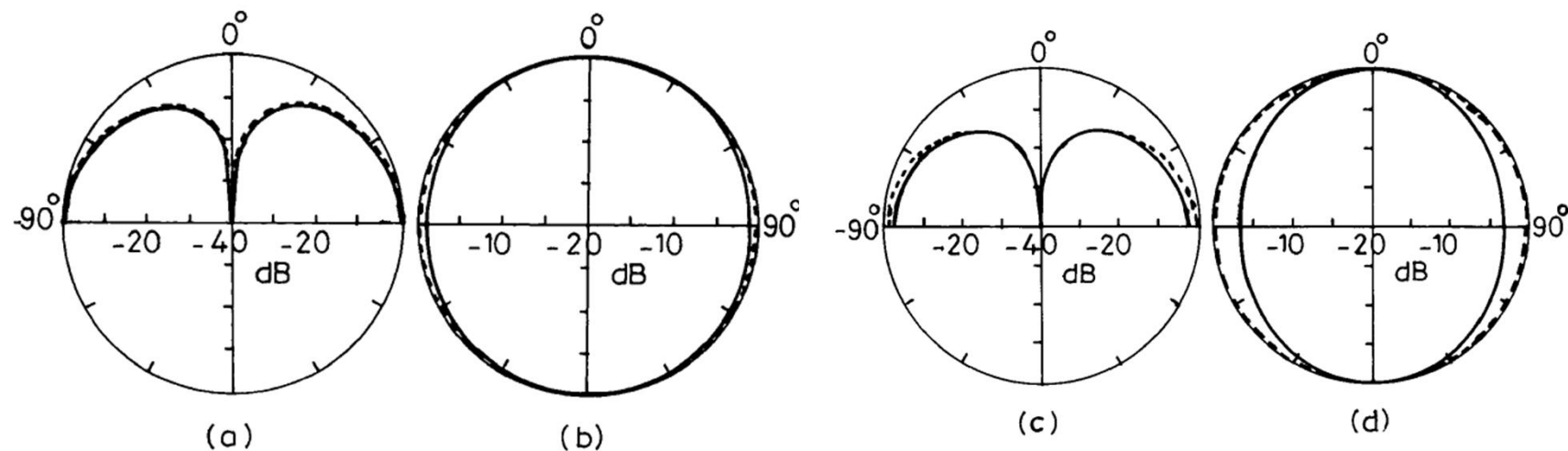


Figure (A) Radiation patterns of the two monopole antennas at 1.5 GHz (a) E-plane and (b) H-plane. Radiation patterns at 2.5 GHz and the (c) E-plane and (d) H-plane. [(- - -) thin RM and (—) SM].



2.1.3 Radiation Pattern of RM Antennas

These two frequencies are within the BW for $VSWR = 2$ of the SM antenna. In the E-plane, the radiation pattern of the SM is similar to that of the thin monopole antenna . With an increase in frequency from 1.5 GHz to 2.5 GHz, the variation in the azimuthal pattern (H-plane) increases from 1 dB to 3 dB for SM, because of the asymmetry in the X- and Y-planes of the structure as compared to the thin monopole antenna.

2.1.4 Various Planar RMs with Equal Areas

The dimensions L and W of RM are chosen such that their surface areas are equal. The SM is fed in the middle of the one side by a SMA connector as shown in Figure A(a), whereas RM is fed in two different ways as shown in Figure A(b, c). The RMs with feeds in the middle of the smaller and larger dimensions are coined RMAs and RMBs, respectively.

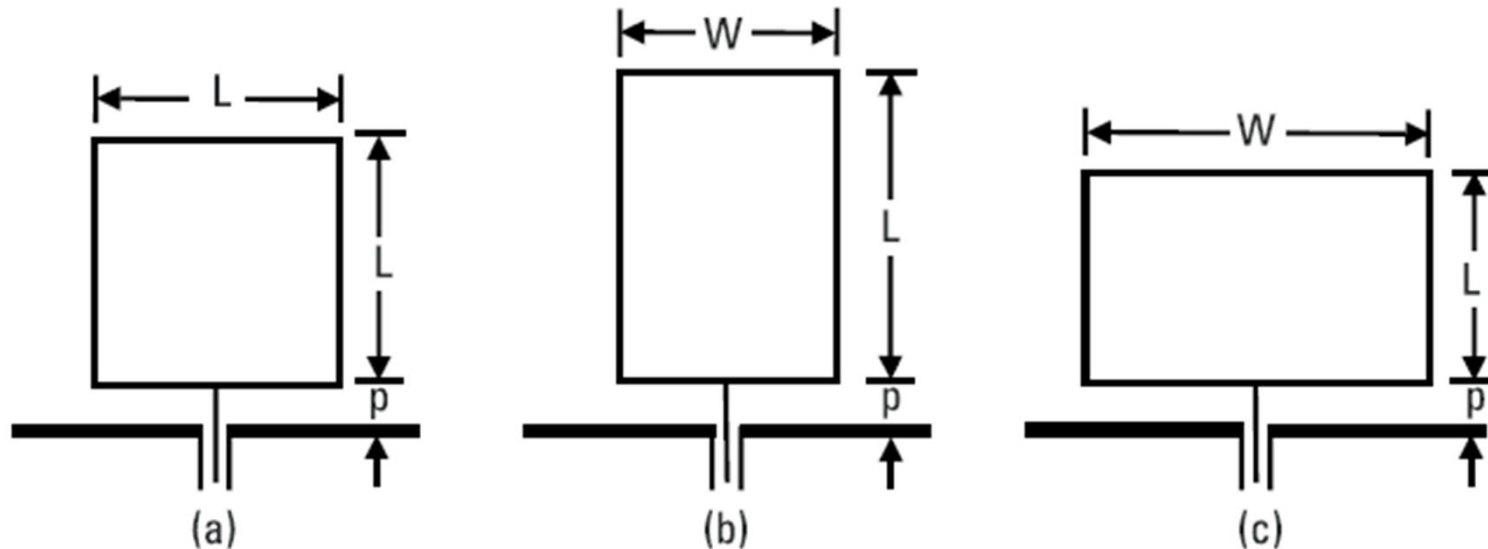


Figure (A) (a) Square monopole antenna. RM antennas with feed in the middle of (b) smaller W and (c) larger W .

2.1.4 Various Planar RMs with Equal Areas

The dimensions and VSWR BW of these configurations are listed in table 2.2.

Table 2.2

Comparison of Square, Rectangular, triangular, and Hexagonal Monopole Antennas

Configuration	$L \times W$ (cm $\times$ cm)	Measured Frequency f_m Range for VSWR ≤ 2 (GHz)	f_L (GHz)	Measured BW Ratio	Percentage Error in Frequency
SM	4.5×4.5	1.27 to 2.81	1.354	1:2.2	+6.6
RMA	4.6×4.2	1.38 to 2.75	1.341	1:2.0	-2.8
RMB	4.2×4.6	1.40 to 2.02	1.431	1:1.4	+2.2
MB	5.9×6.8	1.07 to 1.11	1.101	1:1.04	+2.9
HMA	4.8×5.6	1.37 to 2.68	1.282	1:1.9	-6.5
HMB	5.6×4.8	1.20 to 3.92	1.147	1:3.2	-4.4

- The f_L of RMB is higher than that of the RMA, because the height of the RMB is smaller than that of the RMA.

2.1.4 Various Planar RMs with Equal Areas

The measured VSWR plots of SM, RMA, and RMB are given in Figure B.

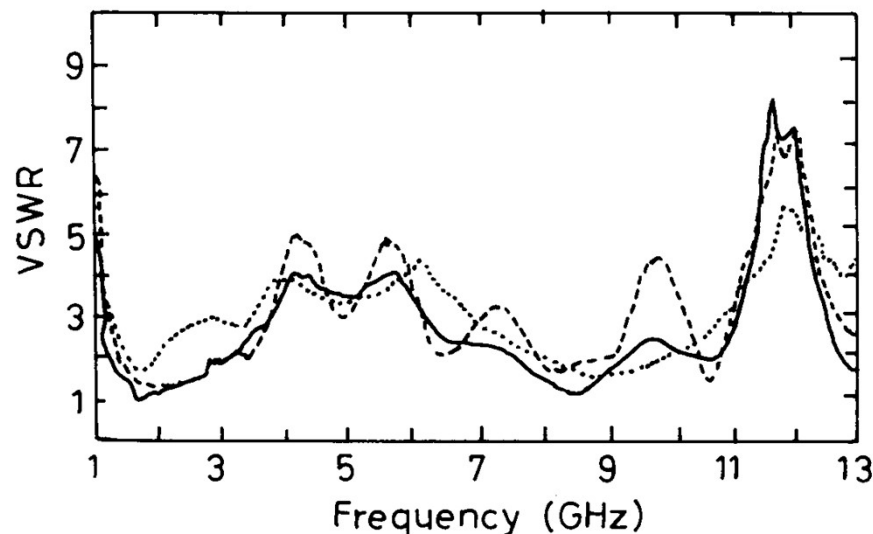


Figure B Measured VSWR plots for three monopole antennas: (—) SM, (- - -) RMA , and (. . .) RMB.

The VSWR values fluctuate from as high as 8 to as low as 1.05 in the frequency range of 1–13 GHz. The measured BW ratios of SM, RMA, and RMB in the lower range of frequency are 1:2.2, 1:2.0, and 1:1.4, respectively. By adjusting the dimensions of the patches and length of the probe, these configurations can be optimized to operate within selected frequency bands.

2.2 Planar Triangular and Hexagonal Monopole Antennas

2.2.1 Planar Equilateral Triangular Monopole

The side length of the equilateral triangular patch is calculated to be 6.84 cm, so that its area is equal to that of the SM described in the previous section. Two feed configurations, TMA and TMB, are considered as shown in Figure A(a, b). The TMA is fed at the middle of the side while the TMB is fed at the vertex.

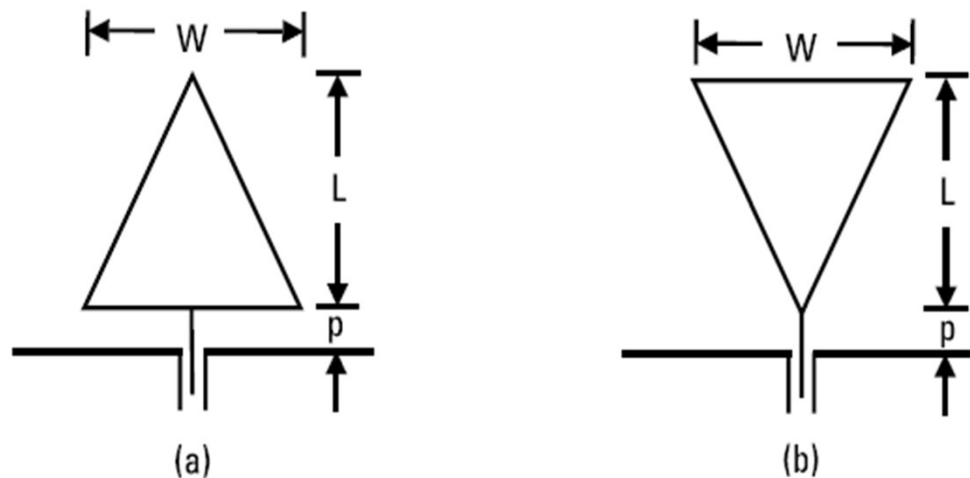


Figure A Triangular monopole antenna fed (a) in the middle of the side and (b) at the vertex.

2.2.1 Planar Equilateral Triangular Monopole

•For TMA, the VSWR is always greater than 2, as there is no input impedance matching at any frequency. However, for TMB, which is like a half-bowtie dipole, matching is obtained at some frequencies. The results for the TMB are summarized in table 2.2. The f_L of this antenna is the least amongst all the other configurations of the same area because it has the largest height. The measured BW is smaller as compared to the corresponding RM and SM antennas.

Table 2.2

Comparison of Square, Rectangular, triangular, and Hexagonal Monopole Antennas

Configuration	$L \times W$ (cm $\times$ cm)	Measured Frequency f_m Range for VSWR ≤ 2 (GHz)	f_L (GHz)	Measured BW Ratio	Percentage Error in Frequency
SM	4.5×4.5	1.27 to 2.81	1.354	1:2.2	+6.6
RMA	4.6×4.2	1.38 to 2.75	1.341	1:2.0	-2.8
RMB	4.2×4.6	1.40 to 2.02	1.431	1:1.4	+2.2
MB	5.9×6.8	1.07 to 1.11	1.101	1:1.04	+2.9
HMA	4.8×5.6	1.37 to 2.68	1.282	1:1.9	-6.5
HMB	5.6×4.8	1.20 to 3.92	1.147	1:3.2	-4.4

2.2.2 Planar Hexagonal Monopole

The side length l of the hexagon is obtained by equating its area with SM, and its value is calculated to be 2.8 cm. In this case also, two feed configurations, HMA and HMB, are used as shown in Figure B(a, b). The HMA and HMB are fed in the middle of the side and at the vertex, respectively.

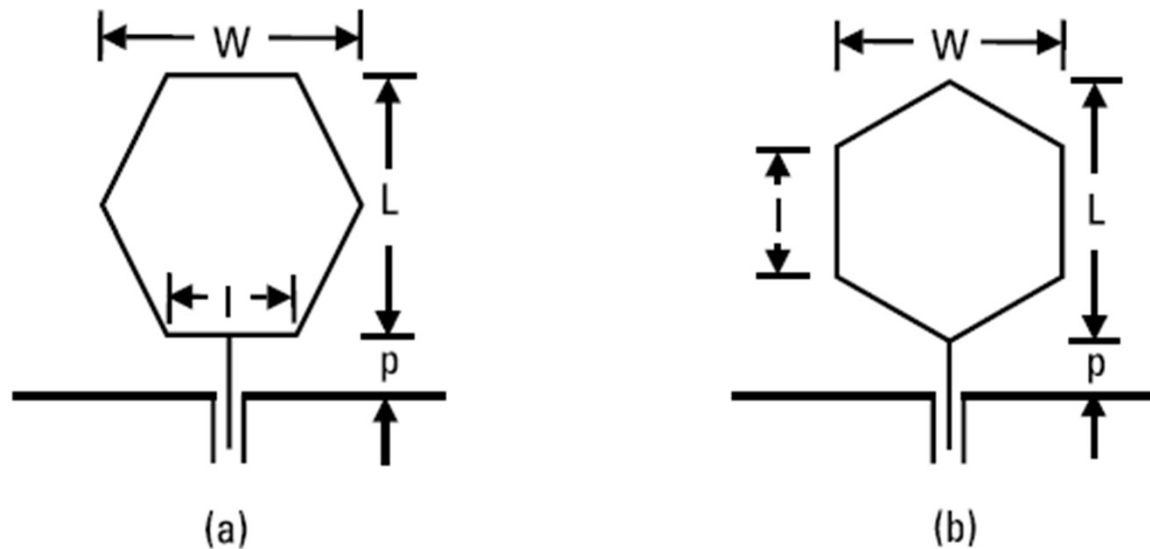


Figure B Hexagonal monopole antenna fed (a) in the middle of the side and (b) at the vertex.

2.2.2 Planar Hexagonal Monopole

- The VSWR plots for these two configurations are shown in Figure C, and the results are summarized in Table 2.2. The f_L of HMB is lower than that of HMA because of its larger height L . The HMB has a larger BW than the HMA. This can be understood from the analogy that the HMB feed is similar to that of the TMB, which yields better matching than the TMA. The HMA feed is similar to the feed for the TMA and hence yields a smaller BW. The HMB provides a wider BW than the square and the RMs, as it is closer to the circular configuration, which has a very large BW as described in the next section.

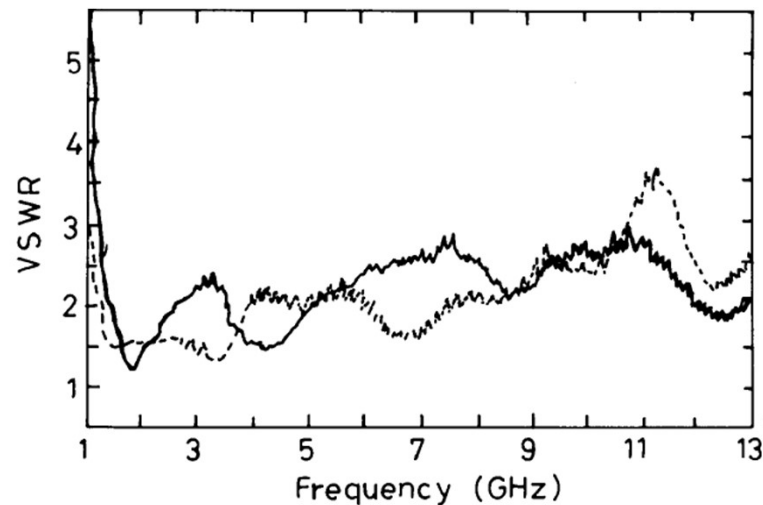


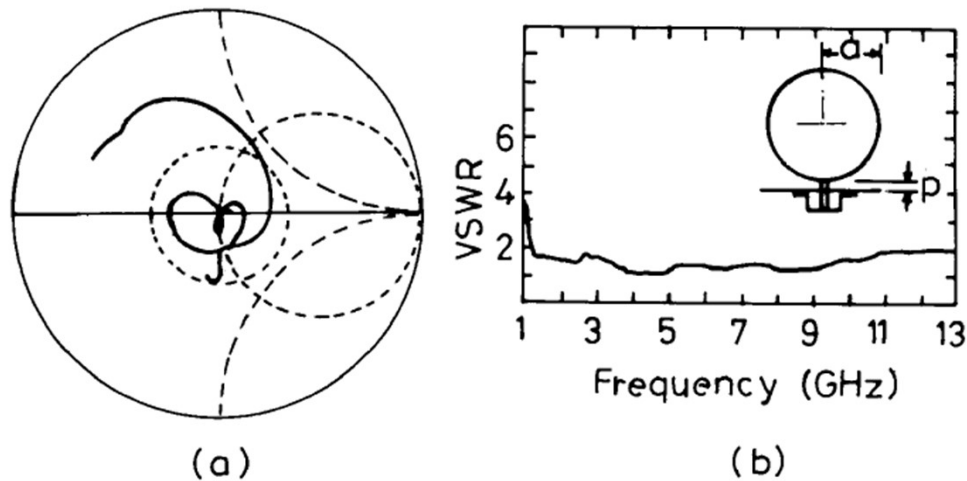
Figure C Measured VSWR plots of two-feed configurations of hexagonal monopole antennas: (—) HMA and (---) HMB.

Table 2.2
Comparison of Square, Rectangular, triangular, and Hexagonal Monopole Antennas

Configuration	$L \times W$ (cm $\times$ cm)	Measured Frequency f_m Range for VSWR ≤ 2 (GHz)	f_L (GHz)	Measured BW Ratio	Percentage Error in Frequency
SM	4.5×4.5	1.27 to 2.81	1.354	1:2.2	+6.6
RMA	4.6×4.2	1.38 to 2.75	1.341	1:2.0	-2.8
RMB	4.2×4.6	1.40 to 2.02	1.431	1:1.4	+2.2
MB	5.9×6.8	1.07 to 1.11	1.101	1:1.04	+2.9
HMA	4.8×5.6	1.37 to 2.68	1.282	1:1.9	-6.5
HMB	5.6×4.8	1.20 to 3.92	1.147	1:3.2	-4.4

2.3 Planar Circular Monopole Antennas

A planar circular monopole (CM) antenna yields very broad BW. A CM of radius a is shown as inset in Figure A.



For $p = 0.1$ cm, the BW for $VSWR \leq 2$ is from 1.17 GHz to 12 GHz, which corresponds to a BW ratio of 1:10.2.

Figure A Measured (a) input impedance and (b) VSWR plots of CM antenna.

2.3 Planar Circular Monopole Antennas

The radius a is taken equal to 2.5 cm, so that its surface area is approximately equal to that of the other monopole antennas given in Table 2.2.

Table 2.2

Comparison of Square, Rectangular, triangular, and Hexagonal Monopole Antennas

Configuration	$L \times W$ (cm $\times$ cm)	Measured Frequency f_m Range for $VSWR \leq 2$ (GHz)	f_L (GHz)	Measured BW Ratio	Percentage Error in Frequency
SM	4.5×4.5	1.27 to 2.81	1.354	1:2.2	+6.6
RMA	4.6×4.2	1.38 to 2.75	1.341	1:2.0	-2.8
RMB	4.2×4.6	1.40 to 2.02	1.431	1:1.4	+2.2
MB	5.9×6.8	1.07 to 1.11	1.101	1:1.04	+2.9
HMA	4.8×5.6	1.37 to 2.68	1.282	1:1.9	-6.5
HMB	5.6×4.8	1.20 to 3.92	1.147	1:3.2	-4.4

The BW of the CM is larger than all the monopole antennas described earlier. This could be interpreted in terms of various higher order modes of the circular patch. The BW associated with the various modes is very large because the disc is in the air ; accordingly, the change in the input impedance from one mode to another mode is very small. This can also be noted from the impedance plot shown in Figure A(a), which has multiple loops corresponding to the various modes. Since these loops are within the $VSWR = 2$ circle, a large BW is obtained.

2.4 Planar Elliptical Monopole Antennas

2.4.1 Planar Elliptical Monopole Antennas

An elliptical monopole (EM) antenna is a generalized case of the circular monopole, wherein the major axis is not equal to the minor axis. The dimensions of EM (i.e., major axis length = $2a$ and minor axis length = $2b$) are calculated, keeping its area equal to that of the CM. The ellipticity ratio is chosen as $a/b = 1.1$, which is named as EM1. The EM is fed either along the minor axis (EMA) or the major axis (EMB) as shown in the insets of Figure A.

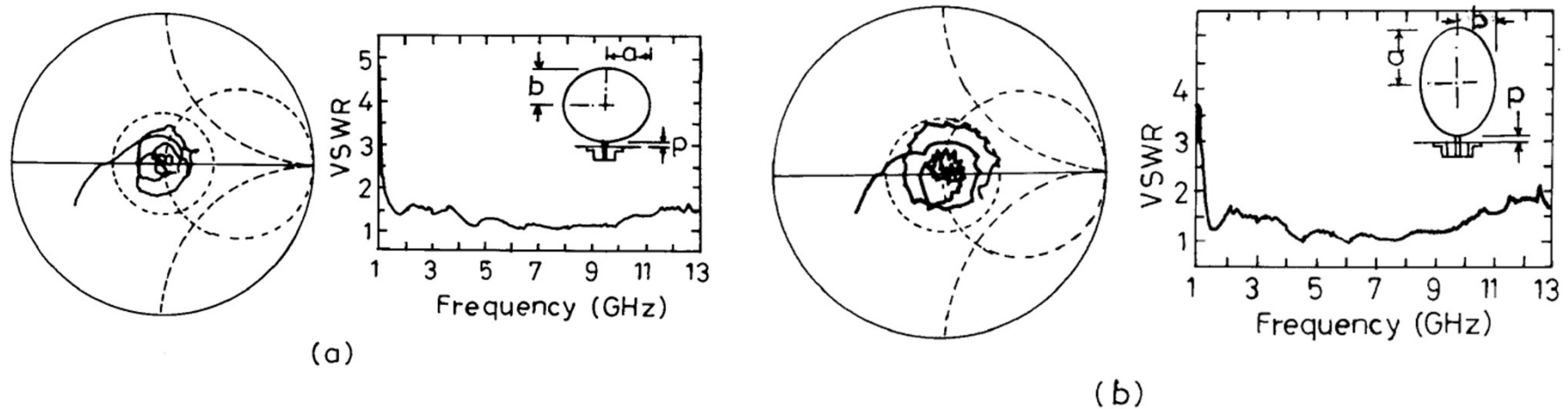


Figure A .Measured input impedance and VSWR plots of (a) EM1A and (b) EM1B.

2.4.1 Planar Elliptical Monopole Antennas

- Three elliptical disc monopoles with different ellipticity ratios are considered by keeping the area same as before. For these three monopoles, the values of a/b are chosen as 1.2 (EM2), 1.3 (EM3), and 1.4 (EM4). The measured VSWR plots of EM2, EM3, and EM4 in configurations “A” and “B” are compared in Figure B.

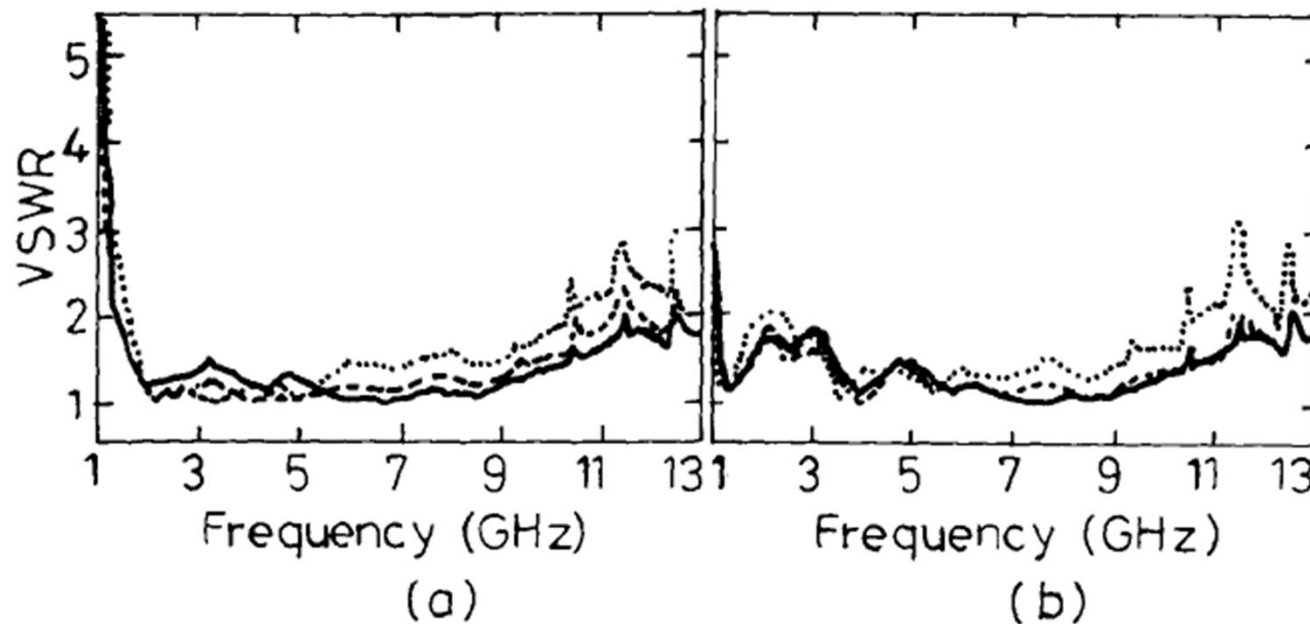


Figure B. Measured VSWR plots of (a) EMA and (b) EMB for different a/b ratios: (—) 1.2, (---) 1.3, and (····) 1.4.

2.4.1 Planar Elliptical Monopole Antennas

The dimensions and measured VSWR BWs for EM2, EM3, and EM4 in configurations “A” and “B” are summarized in able 2.3.

Table 2.3
Comparison of VSWR BW of CM and Various EMs

Configuration	(cm)	b (cm)	Measured Frequency Range (GHz)	Theoretical f_L (GHz)	Percentage Error in f_L
CM	2.5	2.5	1.17 to 12.0	1.258	+7.5
EM1A	2.6	2.4	1.21 to 13*	1.297	+7.2
EM1B	2.6	2.4	1.20 to 12.50	1.220	+1.7
EM2A	2.7	2.3	1.38 to 11.49	1.340	-2.9
EM2B	2.7	2.3	1.13 to 12.00	1.185	+4.9
EM3A	2.8	2.2	1.37 to 11.30	1.385	+1.1
EM3B	2.8	2.2	1.08 to 11.43	1.152	+6.7
EM4A	2.9	2.1	1.58 to 10.45	1.433	-9.3
EM4B	2.9	2.1	1.09 to 10.45	1.121	+2.8

- The f_L of EMBs is always smaller than that of the EMAs because of its larger height . As the ellipticity ratio a/b increases from 1.1 to 1.4, BW decreases. In comparison with the measured f_L , the theoretical f_L is within $\pm 7.5\%$ for most of the cases as shown in able 2.3.

2.4 .2 Radiation Pattern of Circular and Elliptical Monopole Antennas

Among all these broadband monopole configurations, the CM and EM1A antennas provide a maximum BW. The measured radiation patterns of these two configurations at frequencies 2.5 GHz and 9 GHz are shown in Figure C.

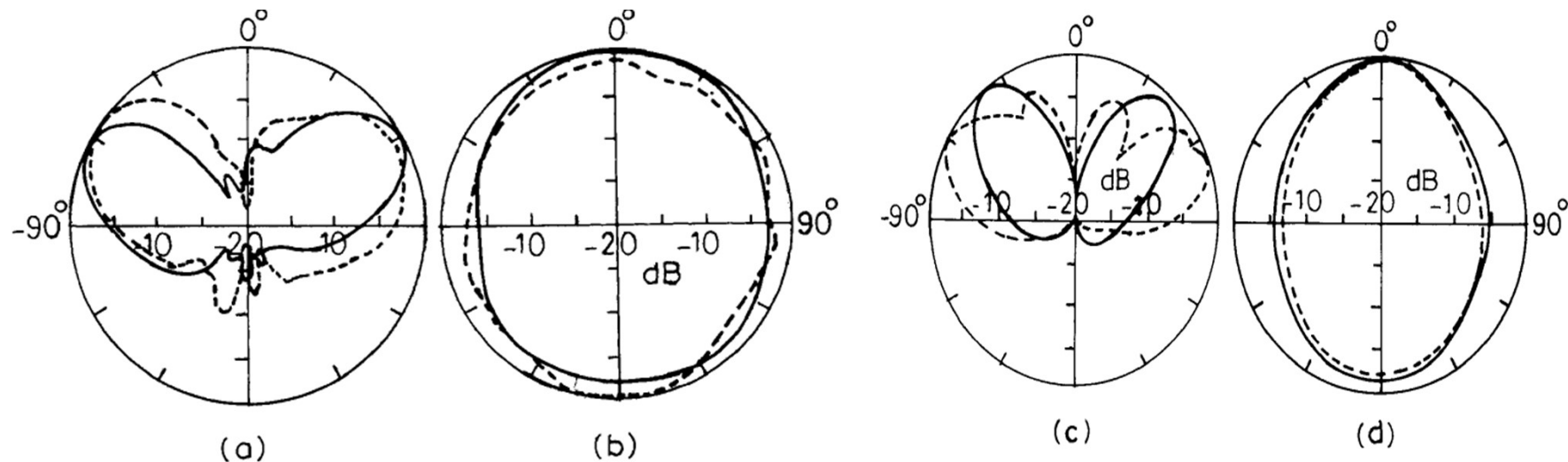


Figure C. Radiation pattern of two monopole antennas at two frequencies: (a) E- and (b) H-planes at 2.5 GHz and (c) E- and (d) H-planes at 9.0 GHz. [(—) CM and (---) EM1A.]

2.4 .2 Radiation Pattern of Circular and Elliptical Monopole Antennas

- The results are summarized as follows:
- At 2.5 GHz, the E-plane (elevation) pattern is conical, whereas the H-plane (azimuthal) pattern is nearly omni-directional with a maximum variation of 4 dB. The pattern is similar to that of a vertical 0.4 linear monopole antenna (which is approximately the equivalent height of the antenna at this frequency) on a finite ground plane.
- At 9 GHz, the effective height of the disc monopole is $3/2$, the E-plane pattern resembles to that of a $3/2$ vertical linear monopole antenna. The maximum variation of 7 dB is observed in the azimuthal pattern.