

Broadband Planar Monopole Antennas

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Abstract

Monopole antennas have several advantages but for their narrow bandwidth. Broadband planar monopole antennas have all the advantages of the monopole in terms of their cost, and ease of fabrication besides, yielding very large bandwidths. For many applications large bandwidth is required. Recently, many techniques to tailor and optimize the impedance BW of these antennas have been investigated. These include the use of bevels, slots and shorting posts. These antennas are becoming popular, and have been proposed for modern and future wideband wireless applications. The radiation performance is also shown to be acceptable over a wide range of frequency. Various planar configurations such as circular, triangular, rectangular and annular ring monopoles have been studied. Circular wire mesh monopole with peripheral strip and annular ring monopole give similar performance as compared to solid disc monopole and have light weight and less wind loading. Combinations of shorting pin and optimization of the feed point location can achieve very compact configurations. Also these antennas can provide band-notching characteristics. These antennas have been reported to provide multi band characteristics too. More recently, it has been shown that, although the square monopole (SM) provides smaller BW than the circular monopole (CM), its radiation pattern suffers less degradation within the impedance BW. Investigations on planar monopoles of different geometrical shapes, such as the ellipse, rectangle, bow tie, diamond and trapezoid have since been conducted. Until now, the achieved impedance BW for VSWR = 2:1 have usually reached about 10:1 for an elliptical planar monopole and 80% for the other planar monopoles.

1. Introduction

Modern and future wireless systems are placing greater demands on antenna designs. Many systems now operate in two or more frequency bands, requiring dual or triple band operation of fundamentally narrow band antennas [10]. These include, satellite navigation systems, cellular systems, wireless LAN and combination of these systems. One of the most popular antennas employed in mobile communication systems is the monopole antenna and its family. The monopole antennas are convenient to match to 50 ohms, and are unbalanced. This eliminates the need for a balun, which may have a limited bandwidth (BW). The simplest member of the family is the quarter wave monopole above a perfect ground plane. The impedance BW achievable for the quarter wave monopole antenna is dependent on the radius of the cylindrical stub, and increases with increased radius. This is true up to a point where the stepped radius from the feed probe to the cylindrical element becomes abrupt. Tapering this transition is often used in wide band elements, such as biconical dipoles and conical monopoles. Typically, fractional impedance BW (10 dB return loss) for length to radius factors of 20 and 100 is approximately 25% and 16% respectively, in the frequency range of 1-6GHz[10]. A simpler technique, with lower cost, is to replace the cylindrical stub of a conventional monopole with a planar element, yielding a planar monopole. Meinke and Gundlach, who mentioned it as a variant of the cylindrical and conical monopoles, first described the planar monopole in a textbook, in 1968. Dubost and Zisler described it more in details in 1976. They observed the wide impedance characteristics of this antenna. Later a number of different shapes have been studied which fit into this category of broadband planar monopoles antennas. Agrawal, who proposed a formula for predicting the

frequency corresponding to lower edge of the impedance BW for these antennas [3], also studied circular and elliptical disk monopoles in 1998.

A planar monopole may be realized by replacing the wire element of a conventional monopole with a planar element. The planar element is located at a distance h above the ground plane [19]. The replacing of wire element with planar element, with various shapes, increases the surface areas of the monopoles, there by having a direct impact on BW. Planar monopole antennas have long been used in mobile communications. Several planar monopoles such as circular, elliptical, square, rectangular, hexagonal and pentagonal, have been analyzed, providing wide impedance BW. Among all these configurations, the circular monopole [1,2] and the elliptical monopole fed along the major axis were reported to yield maximum bandwidth [3]. More recently, it has been shown that, although the square monopole provides smaller bandwidth than the circular monopole, its radiation pattern suffers less degradation within the impedance BW [3]. Planar monopole antennas can be optimized to provide extremely wide impedance BW with acceptable radiation performance. Also in reconfigurable radio systems, planar monopole antennas provide maximum flexibility by radiating over radio terminal's entire frequency range [10]. They can be developed to cover frequency extremities from GSM900/NADC through GSM1800/PCS1900, IMT-2000, the 2.45GHz and 5.8GHz ISM bands and including UWB (1.9GHz – 10.6 GHz).

The broadband planar monopoles can also be understood by considering it as a modified MSA. MSA in their original configurations cannot yield multi octave BW because of their resonant nature. In MSAs increasing the substrate height or decreasing the substrate dielectric constant increases the BW. Now if a rectangular patch without the substrate is fed by a coaxial feed with a perpendicular ground plane, it will result into effective dielectric constant of one and a substantial increase in height h . Both these factors will yield a large BW.

2. Theoretical explanation on planar monopole antenna

In case of microstrip antennas (MSAs), with thick substrate and low dielectric constants, bandwidth of 5 to 15 % is obtained. Any further increase in the substrate thickness decreases the efficiency of the MSA and increases cross-polar levels. The increase in substrate thickness will result in corresponding increase in probe height too. The increase in probe length will also result in increase in probe inductance, and as a result of this the input impedance will become too inductive to obtain impedance matching. This configuration is shown in fig 1(a). This large inductive input impedance can be taken care of by feeding the patch with a shorter probe of length p as shown in Fig 1(b). In this case, since the patch is fed along the periphery, hence an additional perpendicular ground plane is required. If h were very large, the bottom ground plane would have negligible effect, and hence can be removed. This configuration becomes similar to that of a planar monopole antenna, as shown in Fig 1(c)[1-4]. The planar disc monopole antennas yield very large impedance bandwidth, which can be explained in the following two ways:

(a) The planar monopole can be equated to the cylindrical monopole antenna with large effective diameter. A monopole antenna generally consists of a thin vertical wire mounted over the ground plane, whose bandwidth increases with increase in its diameter [5].

(b) The planar monopole antenna can be viewed as a MSA on a very thick air substrate; its large impedance BW is understandable. For these radiating patches, various higher order modes will get excited, and since all the modes will have larger bandwidth, these will undergo smaller impedance variation. The shape and size of these planar antennas can be optimized to bring all the modes within $VSWR = 2$ circle in the Smith chart, leading to very large impedance bandwidth. Hence resulting in to a broadband planar monopole antenna.

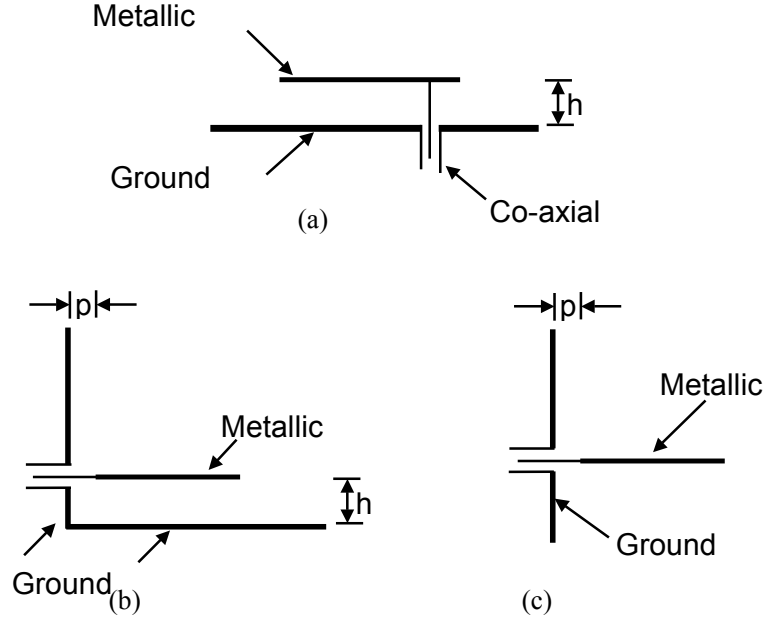


Fig 1. (a) MSA suspended in air. (b) Modified MSA with side feed. (c) Planar monopole antenna.

Hence planar rectangular disc monopole antenna can be thought of as a variation of rectangular MSA (RMSA), as described above, in which the horizontal ground plane is considered to be located at infinity. The following discussions bring out this analogy.

3. Rectangular Microstrip Antenna Suspended in Air with Orthogonal Ground Plane

A rectangular Microstrip antenna (RMSA) radiating with $L = W = 12$ cm made of copper plate of thickness 0.1 cm with two orthogonal ground planes (forming an L shaped ground plane) with a 50Ω , SMA connector are shown in Fig 2 (a) and (b), respectively. The patch is fed with a probe of length p through a fixed ground plane and the orthogonal ground plane is moveable. 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 Fig 2 (c) and (d), respectively. Multiple loops are seen, which are due to excitation of various higher order modes of RMSA. The impedance plot shows less inductive shift due to the smaller value of feed probe length p , so the value of p is increased to 1.0 cm to shift the impedance plot in the clockwise direction. The results are summarized in Table 1. The measured bandwidth for $VSWR \leq 2$ is from 858 to 988 MHz.

For analysis purpose, this structure can be thought of as a microstrip antenna on air dielectric with an additional perpendicular ground plane. The analytical methods valid for microstrip antennas could be applied to this configuration with suitable modifications.

The formula for RMSA is used to calculate the resonance frequency of this antenna. Since the dielectric medium for all the cases under consideration is air, the effective dielectric constant ϵ_e is equal to 1. The theoretical resonance frequency for the fundamental mode can be calculated using Equation (1).

$$f_o = \frac{c}{2L_e \sqrt{\epsilon_e}} = \frac{15}{L_e \sqrt{\epsilon_e}} \quad (1)$$

$$\text{i.e. } f_0 = c / (2 L_e) \quad (2)$$

Where, L_e = effective resonant length.
 c = velocity of light in free space

For two orthogonal ground planes, $L_e \simeq L + \Delta L + p$, because the extension of length ΔL 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. For large width of the patch ($W/h > 10$) with $\epsilon_r = 1$, ΔL is approximately equal to h . The theoretical resonance frequency, calculated using Equation (2) for $p = 1.0$ cm, is 937 MHz, which is close to the measured center frequency of 923 MHz.

Next, the effect of increasing h on bandwidth of the antenna is considered. For different values of h with $p = 1.0$ cm, the measured lower and upper frequencies (f_L and f_H) corresponding to VSWR = 2 are given in Table 1. With increase in h from 3 cm to infinity (∞), the percentage bandwidth of the antenna increases from 14.1 % to 81.2 %.

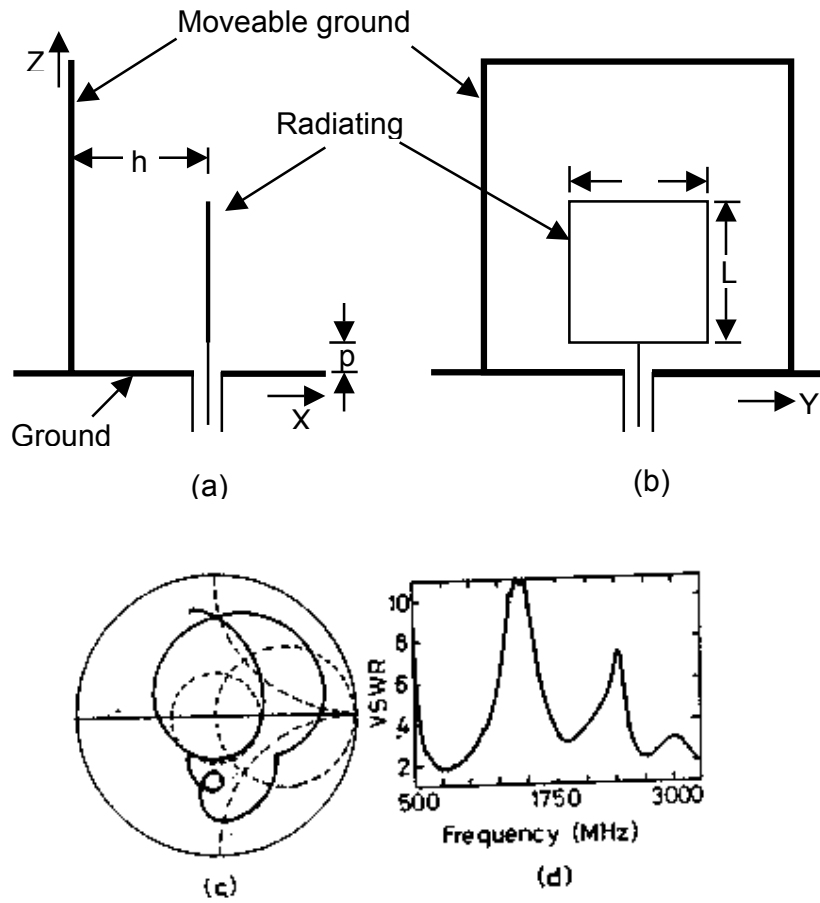


Fig 2. (a) Side and (b) front views of modified RMSA with orthogonal ground planes. Measured (c) input impedance and (d) VSWR plots.

As h increases, the measured lower resonance frequency decreases because of the increase in ΔL due to the large fringing fields. For smaller values of h , there is a reasonable agreement between the theoretical frequency obtained from Equation (2) and the measured center frequency. As h increases, the theoretical frequency is close to the measured lower frequency corresponding to VSWR = 2.

Table 1.
Resonance Frequency and % BW of RMSA with $L = W = 12$ cm for Different 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*
6	752	934	17.7	789*
18	515	1081	70.3	484*, 483#
∞	501	1154	81.2	0*, 483#

* Calculated using Equation (2)

Calculated using Equation (9)

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 Fig 3 (a) and (b), respectively. As h increases from 18 cm to ∞ , the measured lower frequency decreases slightly from 515 to 501 MHz. For these two values of h , the input impedance and VSWR plots are nearly same. Therefore, for large h tending to infinity, the MSA configuration reduces to that of a planar monopole antenna.

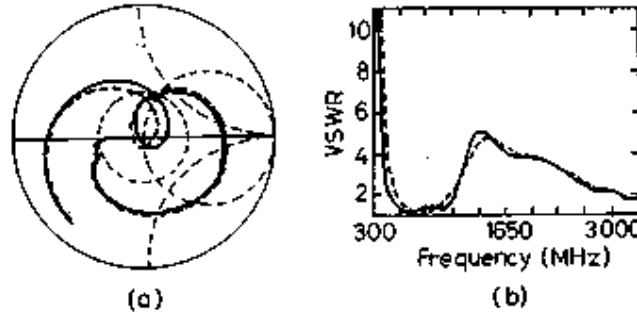


Fig 3 Measured (a) input impedance and (b) VSWR plots of RMSA for two values of h . (---) 18 cm, (—) ∞ .

4. Characteristics of Broadband Planar Monopole Antennas

The broadband planar monopole antennas have proved to be excellent radiators over very large BW. They are finding their place in numerous applications. Some of their characteristics are as mentioned below: -

- Very large impedance bandwidths. For example until now, the achieved impedance BW for $VSWR = 2:1$ have reached about 10:1 for an elliptical planar monopole and 80% for other planar monopoles [3,18].
- Provide maximum flexibility in reconfigurable radios [14].
- Stable monopolar radiation patterns with a return loss in excess of 10dB over an extremely wide frequency range [10].
- Capable of multi band operations and posses omni directional radiation patterns in azimuth plane for all operation bands [11].
- Low fabrication cost and ease of manufacture.
- Compact size, linear phase response and acceptable radiation efficiency [13].
- Electrical heights less than $\lambda/4$ achieved [13,17].
- Can provide interference immunity with existing wireless networking technologies by using band-notched planar monopole antenna [13].

5. Various shapes investigated

Researchers to optimize various parameters have investigated a number of different shapes so far. From every shape investigated a number of inferences have been drawn and these results used, to further fine-tune the designing of these antennas. The shapes investigated so far are as given below: -

- Planar rectangular and square monopole antennas.
- Planar Rectangular Monopoles (RM) with equal areas.
- Planar triangular and hexagonal monopole antennas.
- Planar circular monopole antennas.
- Planar elliptical monopole antennas.
- Wideband orthogonal square monopole antennas with semi circular base.
- Shorted planar monopole with bevel.
- Bow tie shaped planar monopole antennas.
- Circular wire mesh monopole antenna.
- Annular ring monopole antenna.
- Compact wide band planar rectangular monopole antenna.

To further optimize the radiation patterns and to achieve increased BWs, a number of modified shapes of the above-mentioned shapes have also been investigated and the field is still being explored to add something new everyday. In the next section, various planar monopole antennas such as square, rectangular, triangular, hexagonal, circular and elliptical disc monopoles are described.

6. Inferences drawn from investigations on various shapes

Planar monopole antennas yield large impedance BWs [3,4]. The BW mainly depends on the width W of the plate, diameter d and length of the feeding probe p . Also any variations in the height L of the monopole will have an inverse effect on lower edge frequency. Also from the comparison of radiation patterns of Square Monopole (SM) and a thin monopole of $L = W = 4.5$ cm and $L = 4.5$ cm and $W = 0.5$ cm respectively, in the same frequency range it is seen that in the E-plane, the radiation pattern of the SM is similar to that of the thin monopole antenna [6]. With increase in frequency from 1.5 to 2.5 GHz, the variation in the azimuthal pattern (H-plane) increases from 1 to 3 dB for SM. This happens because of the asymmetry in the X and Y planes of the structure as compared to the thin monopole antenna.

The location of feed point has a direct bearing on the BW of the square monopoles. This is as a direct consequence of excitation of additional modes as the feed is moved away from the center [5]. Since all these modes have a large BW, the overall BW is increased. Having SM with a semi circular base can further increase the BW. A circular disc monopole antenna gives an impedance BW of 1:10.2. The radiation pattern of circular disk monopole (CDM) has been computed and found to be conical in elevation plane and omni directional in azimuth [1,2]. This is symmetrical to the radiation pattern of a cylindrical monopole antenna over the ground plane.

To counter the wind loading effect in case of a CDM, a circular wire mesh with grid size kept to 3 mm x 5 mm and with a copper rim yielded nearly the same impedance BW as that of CDM. Hence this configuration has been able to negate the disadvantages of the CDM and still provide the same BW. Amongst the other geometries studied the elliptical disc monopole with ellipticity ratio=1.1 yielded maximum BW of 1:10.7. This was possible because of overlapping of their various resonant modes [3,5]. The radiation pattern of various shapes reported did not remain omnidirectional at all frequencies because of asymmetry of the configuration in two orthogonal planes. This problem has been countered by modifying the basic shapes. One of them, which makes azimuth pattern omnidirectional at all frequencies, is orthogonal SM with semi circular base [5]. The radiation pattern of SM suffers less

degradation with in the impedance BW. The impedance BW of a SM has been shown to increase dramatically by combining beveling and a shorting technique. Such a monopole can cover frequencies from 800MHz to greater than 10.5GHz.

Also the antennas have been reported to provide band notched characteristics for the ultra wide band (UWB)[13]. This antenna offers significant attenuation in the notched band without affecting the antenna operation outside the band. The dual band operation has been achieved using planar rotated F and T shaped monopole antennas coupled with a shorted L wire [12]. This antenna can provide good impedance matching in 2.4/5.2 GHz bands.

Planar antennas have been reported to provide multi frequency operations, having a height of only about 0.05 times the wavelength of the lowest operating frequency and having omnidirectional radiation for all operation bands [11]. It has also been investigated and analysed that both the frequency responses of the input impedance and the parallel resonance vary greatly for slant angles of 67.5 degrees. The increase in slant angle increases Q-value significantly, there by decreasing the BW rapidly [14].

Annular planar monopole antenna achieves nearly same BW as that of circular planar without any hole, typically of the order of >8:1 for both VSWR =2:1 and 3:1. The introduction of the hole has been shown to have no effect at lower frequencies and to have acceptable effect at higher frequencies. With the increase in inner diameter beyond a threshold, the BW starts decreasing [18]. It also been realized that as is typical for the monopole antennas, the lower edge frequency of the impedance BW is inversely proportional to the over all length of the element. In case of planar monopoles overall length (i.e. $l = L + h$) includes the feed gap height. The length of the square monopole corresponds to about 0.21 of a free space wavelength at the lower edge frequency [10]. This is shorter than a quarter wavelength monopole. Also from various studies it is seen that feed gap needs to be optimized to achieve maximum BW.

A significant increase in impedance BW can be achieved by trimming the square edge near the ground plane, yielding either an asymmetrical or a symmetrical pentagonal monopole. Also use of a shorting post reduces the lower edge frequency by introducing an extra mode, which results in reduction of over all height of the antenna [5,10].

It has also been realized that a combination of shorting posts and bevel can yield an impedance BW of 800 MHz to 11GHz, which is suitable for combination of cellular and UWB systems [10,14].

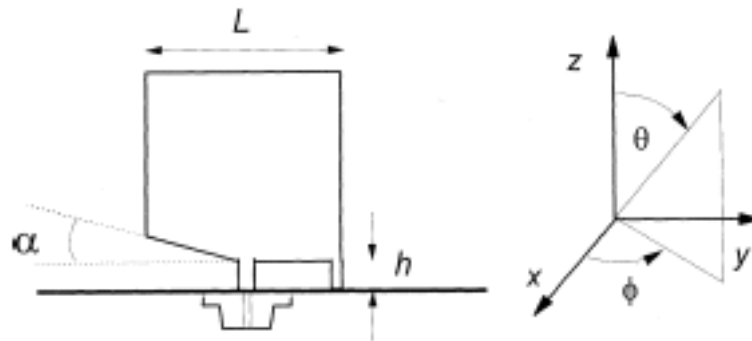


Fig 4. Square planar monopole with bevel and shorting post

This is shown in the fig 4. The investigation of slots on planar elements has shown to lower the cost, reduce the wind loading and to slightly reduce the lower edge frequency, with little effect on radiation performance or impedance BW. When a shorting pin is added to a rectangular monopole antenna and the dimensions are optimized, a compact wide band

antenna can be constructed [19]. Addition of a shorting pin excites additional lower modes. As the feed point is moved towards the shorting point, additional modes are excited, which result in further lowering the lower resonant frequency.

7. Calculation of Lower Frequency of Planar Monopole Antenna

For a planar monopole antenna, the lower frequency corresponding to $VSWR = 2$ can be approximately calculated by equating its area (in this case, a rectangular disc monopole) to that of an equivalent cylindrical monopole antenna of same height L and equivalent radius r , as described below [3, 4]:

$$2 \pi r L = W L \quad (3)$$

Which gives $r = W / (2 \pi)$ (4)

The input impedance of a $\lambda/4$ monopole antenna is half of that of the $\lambda/2$ dipole antenna. Thus, the input impedance of an infinitesimally thin monopole antenna is $36.5 + j 21.25 \Omega$, which is inductive. The real input impedance is obtained when a slightly smaller length of the monopole is used as given by [5]:

$$L = 0.24 \lambda F \quad (5)$$

Where,

$$F = (L / r) / (1 + L / r) = L / (L + r) \quad (6)$$

From the Equations (1.4) and (1.5), the wavelength λ is obtained as:

$$\lambda = (L + r) / 0.24 \quad (7)$$

Therefore, the lower frequency f_L is given by:

$$f_L = c / \lambda = (30 \times 0.24) / (L + r) = 7.2 / (L + r) \text{ GHz} \quad (8)$$

Equation (3.6) does not account for the effect of the probe length p , which increases the total length of the antenna thereby reducing the frequency. So, this equation is modified to

$$f_L = 7.2 / (L + r + p) \text{ GHz} \quad (9)$$

Where, L , r and p are in cm.

The theoretical frequency of 483 MHz for $h = \infty$ (monopole antenna) obtained using Equation (9) is close to the measured f_L of 501 MHz. For $h = 18$ cm, the theoretical frequencies obtained using MSA and monopole concepts are very close to each other. Thus, an interesting transition in antenna characteristics (with respect to resonance frequency) is observed, as the ground plane spacing h is increased. For smaller h , the measured resonance frequency is close to the theoretical frequency determined by the expressions applicable to the MSA and for larger h , it is close to the frequency obtained using expressions for a monopole antenna.

8. Effect of width W of the plate, diameter d of the feeding probe, and length of the probe p

The bandwidth of planar monopole antennas depends mainly on the width W of the plate, 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. The decrease or increase in height L of the monopole antenna inversely affects the lower edge frequency of the antennas. The RM and square monopole (SM) antennas are analyzed using IE3D software [6]. Initially, the effect of p is described by keeping $L = W = 4.5$ cm. The input impedance and VSWR plots for two values of p are shown in Fig 5 (a) and (b), respectively.

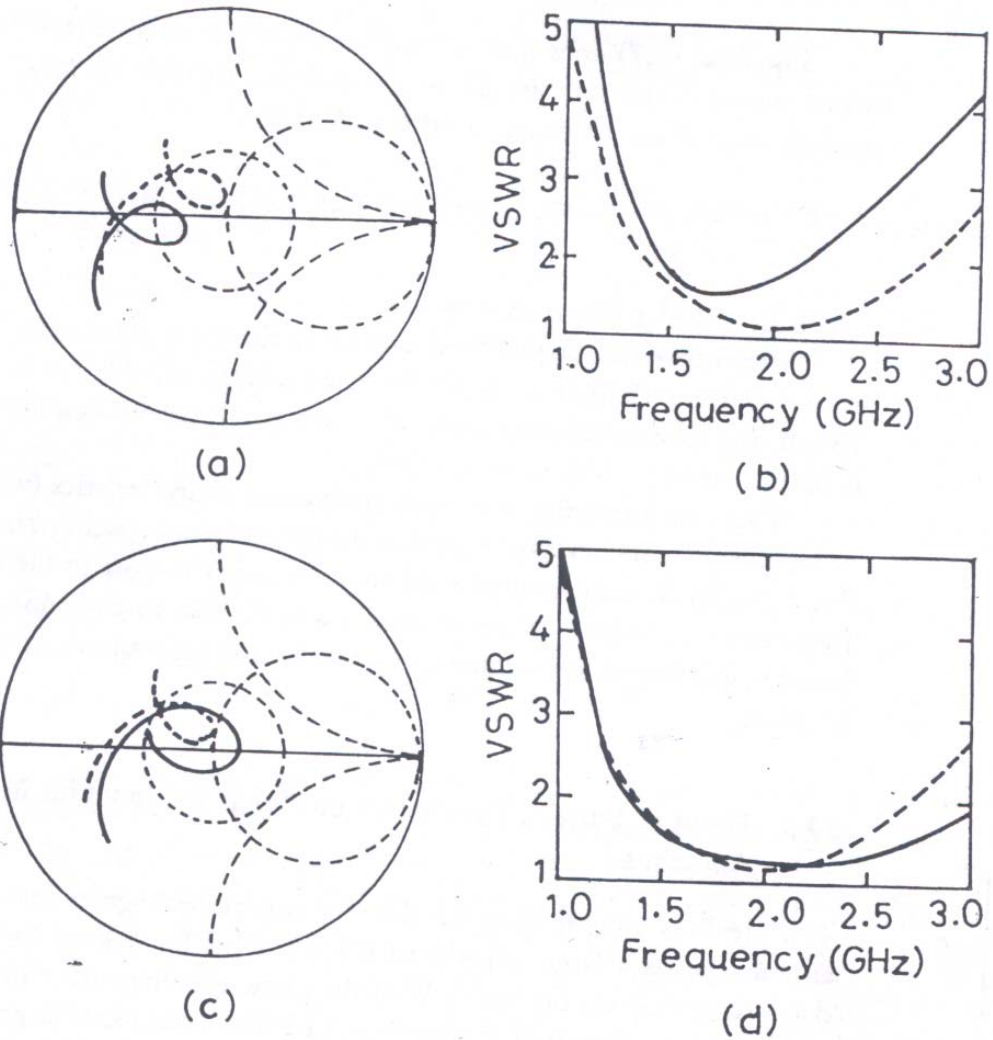


Fig 5. (a) Input impedance and (b) VSWR plots of rectangular monopole antenna for two values of p . (—) 0.05 cm, (---) 0.2 cm. (c) Input impedance and (d) VSWR plots with $L = 4.5$ cm and $p = 0.2$ cm for two values of W . [(---) 4.5 cm, (—) 3.5 cm].

As p is increased from 0.05 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 become more inductive. A broad bandwidth of 1335 MHz (68%) is obtained for $p = 0.2$ cm, compared to the bandwidth of 668 MHz (40%) for $p = 0.05$ cm. Also the effect of W has been investigated by keeping other parameters fixed. The input impedance and VSWR plots for two values of W (4.5 and 3.5 cm) with $L = 4.5$ cm and $p = 0.2$ cm are shown in Fig 5 (c) and (d), respectively. With decrease in W , the size of the loop in the impedance plot increases and the plot shifts towards 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, which is predominantly determined by the length L of the planar monopole antenna. As W decreases from 4.5 to 3.5 cm, the bandwidth increases from 1335 to 1715 MHz due to increase in loop size. Hence any increase in probe length will result in increase in BW and vice versa for width W .

9. Techniques to tailor impedance BW

There are various ways in which the BW of planar monopoles can be increased. A significant increase in impedance BW can be achieved by trimming the square edge near the ground plane yielding either an asymmetrical or symmetrical pentagonal monopole [10]. Fine control of the impedance BW was achieved by varying the trim angle of the cut. The impedance BW ratios in this way varied from 2.4:1 for the simple square element, to greater than 6.6:1 for an element with an optimized pentagonal geometry as shown in the fig 6(a) and (b).

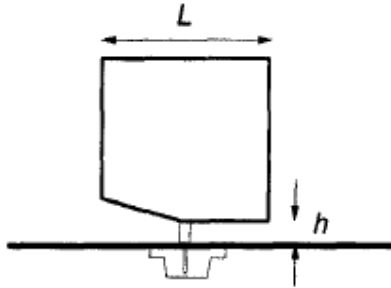


Fig 6. (a) Square planar monopole with asymmetrical beveling

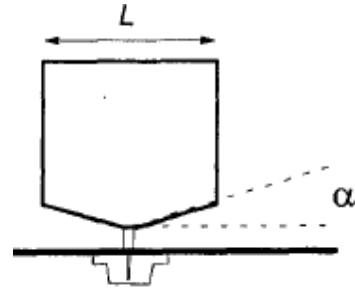


Fig 6. (b) Square planar monopole with symmetrical beveling

Measured values of upper and lower edge frequencies of a planar monopole (25mm x 25mm) with various bevel angles α , on one and both sides of the feed probe are tabulated in the table3.1. This showed good control of the upper edge frequency. The lower edge frequency remained fairly constant at around 2.10-2.35 GHz, but the upper edge frequency could be varied from 4.95-12.5 GHz, depending on the value of the bevel angle.

Also the shorting pin as shown in fig 7, has been shown to reduce the lower edge frequency by introducing an extra mode. This also makes the antenna smaller in height. The shorting strip is located at one corner of the planar element, and is generally about 1mm diameter or a strip of width 2mm. Also the feed gap as already discussed needs to be optimized to get optimum BW [10], since it greatly affects the impedance characteristics. Also in general larger the feed gap lower will be the frequency corresponding to the lower edge of the passband.

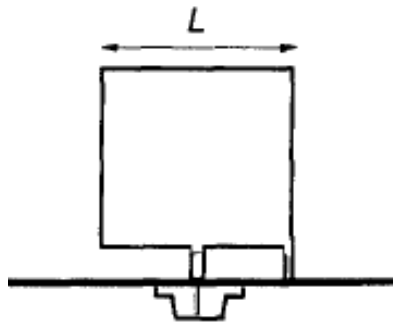


Fig 7. Square planar monopole with shorting pin

The asymmetries in the geometrical shape of the element can also produce some distortions in the radiation pattern. A combination of the shorting post and bevel can yield an impedance BW of 800 MHz to 11 GHz. Lastly any increase in the surface area will result in corresponding increase in the impedance BW.

Table 2. Measured impedance BW for a square element with both asymmetrical and symmetrical bevels of various angles show an increase in upper edge frequency with an increase in bevel angle.

Trim angle α (degrees)	2:1 VSWR BW (GHz) Asymmetrically Trimmed	2:1 VSWR BW (GHz) Symmetrically Trimmed
No trimming	2.35-4.95	2.35-4.95
10	2.20-5.30	2.12-5.95
20	2.19-5.75	2.11-6.75
30	2.17-5.97	2.10-7.25
40	2.17-6.00	2.10-12.50

10. Radiation performance of broadband planar monopole antennas

The radiation pattern for these antennas are typically monopolar, and show little change with frequency over the impedance BW for simple square planar monopole, which is typically 80%. For increase in impedance BW beyond 100%, changes in radiation pattern are noticeable with a change in frequency. The theoretical radiation pattern of the square monopole antenna ($L = W = 4.5$ cm) is obtained using IE3D for infinite ground plane [6]. For comparison, the radiation pattern of a thin (narrow width $W = 0.5$ cm) rectangular monopole antenna with same length $L = 4.5$ cm is also computed in the same frequency range.

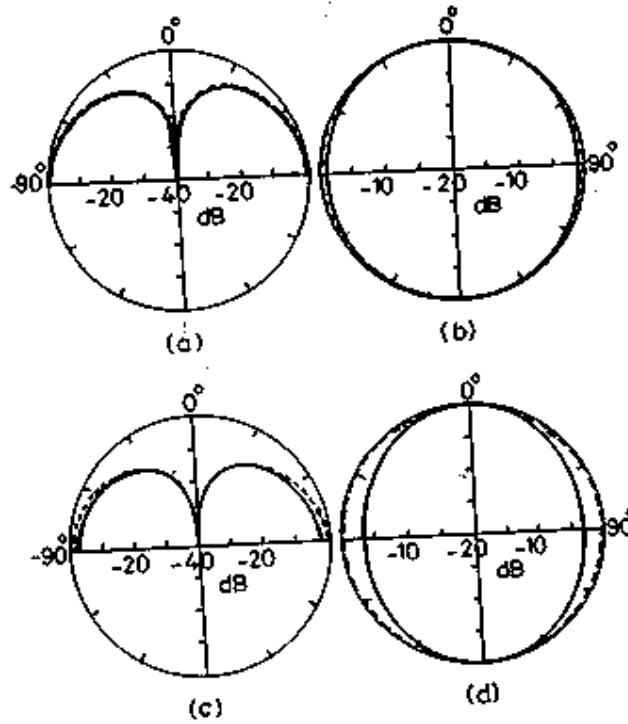


Fig 8. Radiation patterns of the two monopole antennas at 1.5 GHz (a) E- plane and (b) H- plane. Radiation patterns at 2.5 GHz. (c) E-plane and (d) H-plane. [(- - -) Thin RM, (—) SM]

The E and H plane radiation patterns of both the antennas at 1.5 and 2.5 GHz are shown in Fig 8. These two frequencies are within the bandwidth 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 increase in frequency from 1.5 to 2.5 GHz, the variation in the azimuthal pattern (H-plane)

increases from 1 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.

11. Effects of slots and circular holes concentrically cut from circular elements of the planar monopole antennas

The impedance and radiation characteristics of annular planar monopole antennas have been experimentally investigated. The annular planar monopole antenna is shown in fig 9.

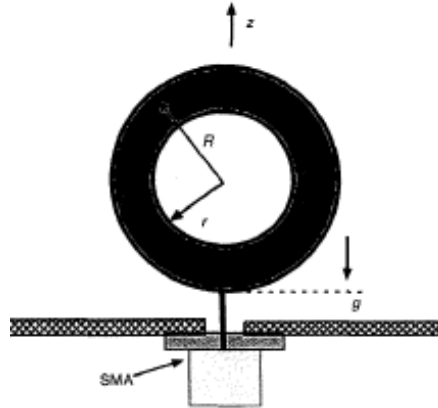


Fig 9. Annular planar monopole antenna

The effects of the circular hole concentrically cut from the circular elements of planar monopole antennas on the impedance bandwidth, the frequency corresponding to the lower edge of the pass band (FLEPB), and the radiation patterns are first discussed [18]. The measurements show that, as compared to a circular planar monopole without any hole, the proposed annular monopole antennas still achieve extremely broad impedance bandwidths, typically of the order of $> 8:1$ for both $VSWR = 2:1$ and $3:1$. The introduction of the hole is shown to have little or no effect on the radiation pattern at lower frequencies and to have acceptable effects at higher frequencies. Owing to the introduction of the hole to the planar element, the weight, volume (also height), wind resistance and cost of the antenna are greatly reduced. These are desirable features, especially at low frequencies. The slots do tend to reduce the lower edge frequency slightly.

The other point is that the hole cut from the circular element also has a significant effect on the impedance matching conditions. The antennas attain remarkably broad bandwidths of $> 6.5:1$ for $VSWR = 2:1$ or $> 8.5:1$ for $VSWR = 3:1$, when the radii of the holes are less than 15mm. It is particularly interesting to note that the antennas still possess almost the same highpass feature even when 64% of the area ($r = 15\text{mm}$) has been removed from the circular element [18]. The effect of introducing a hole of radius $r = 15\text{mm}$ was found to be negligible on the radiation patterns at low frequencies. At low frequencies, the antenna exhibited typical omnidirectional monopolar patterns with a maximum gain of 4.8dBi, which was found to be constant to within ± 0.5 dB over polar angles from $\theta = 48^\circ$ to $\theta = 63^\circ$. The half power beam widths were 48° in both the $\phi = 0^\circ$ and $\phi = 90^\circ$ planes. The gain in the ground plane ($\theta = 90^\circ$) was 0.3 dBi. The introduction of the hole had no effect on the maximum gain at this frequency.

With the increase in frequency, a slight increase in directivity was observed, accompanied by a reduction in the half power beam widths in the vertical planes. The gain in the ground plane ($\theta = 90^\circ$) also fell. The effect of the hole on the patterns became more pronounced and tended to offset the gain reduction in this plane. This can be seen in Figs 10, which illustrate the radiation patterns in the $\phi = 0^\circ$ and $\phi = 90^\circ$ cuts.

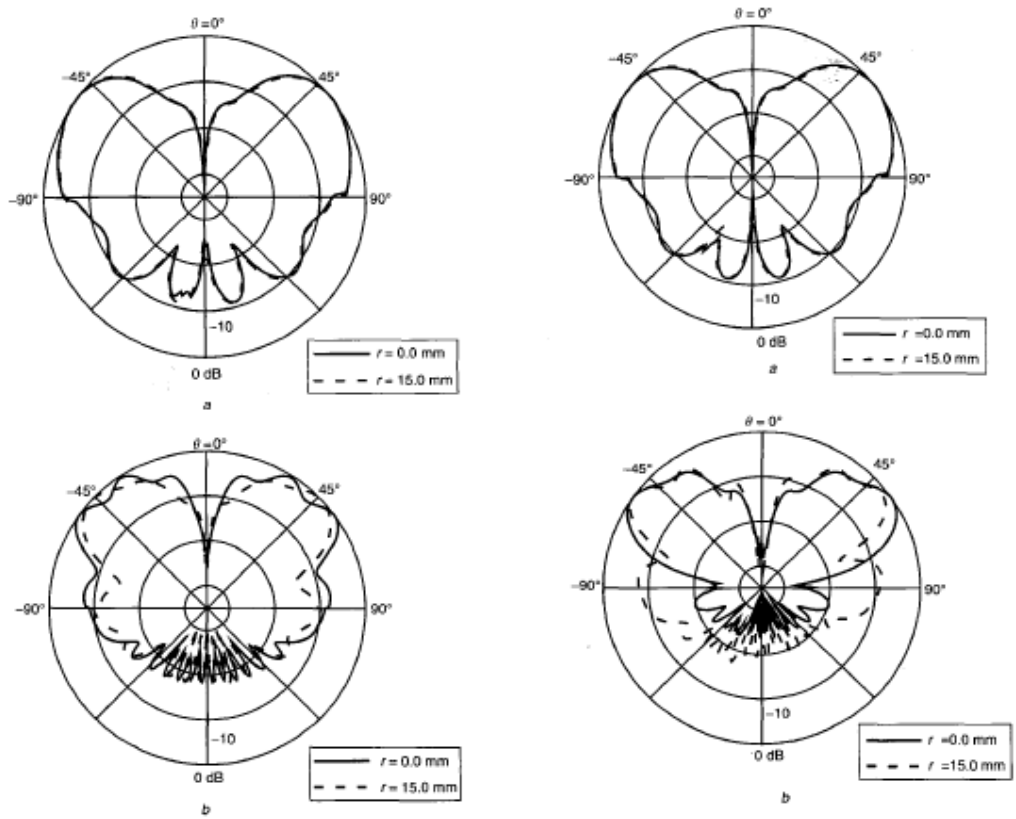


Fig 10. Measured radiation pattern in $\phi=0^0$ and $\phi=90^0$

12. Effect of ellipticity ratio

The quest for increase in the impedance BW has made researchers study various possible geometrical shapes. The elliptical planar monopole antennas, the achieved impedance BW for $VSWR=2:1$ have usually reached about 10:1. Three elliptical disc monopoles with different ellipticity ratios are considered by keeping their areas same. For calculating f_L of the elliptical antenna, the L and r of the effective monopole are determined by equating its area as:

$$2\pi rL = \pi ab \quad (10)$$

For EMA (fed along minor axis), $L=2b$ and $r=a/4$, and for EMB (fed along major axis), these parameters are $L=2a$ and $r=b/4$. For these three monopoles, the values of a/b are chosen as 1.2 (EM2), 1.3 (EM3), and 1.4 (EM4) [3]. The measured VSWR plots of EM2, EM3 and EM4 in configurations 'A' and 'B' are compared in Fig 11 (a) and (b), respectively. The dimensions and measured VSWR bandwidths for all these cases are summarized in Table 3. The f_L of EMBs is always smaller than that of the EMAs, because of its larger height. As the ellipticity ratio a/b is increased from 1.1 to 1.4, bandwidth decreases. In comparison with the measured f_L , the theoretical f_L obtained using Equations (9) and (108) is within $\pm 7.5\%$ for most of the cases as shown in Table 3.

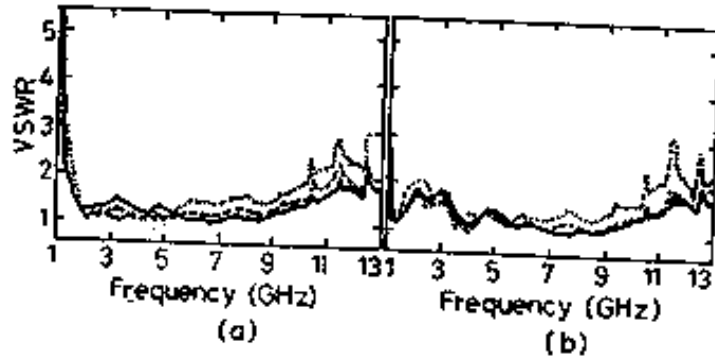


Fig 11. Measured VSWR plots of (a) EMA and (b) EMB for different a/b ratio. (—) 1.2, (- - -) 1.3, (· · ·) 1.4.

Table 3. Comparison of VSWR Bandwidth of CM and Various EMs [3]

Configuration	a (cm)	b (cm)	Measured freq. range (GHz)	Theor. f_L (GHz)	% 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 EM2B	2.7	2.3	1.38 to 11.49	1.340	-2.9
	2.7	2.3	1.13 to 12.00	1.185	+4.9
EM3A EM3B	2.8	2.2	1.37 to 11.30	1.385	+1.1
	2.8	2.2	1.08 to 11.43	1.152	+6.7
EM4A EM4B	2.9	2.1	1.58 to 10.45	1.433	-9.3
	2.9	2.1	1.09 to 10.45	1.121	+2.8

- Gives VSWR < 2 above 13 GHz also.

13. 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 previous section. Two feed configurations, TMA and TMB, are considered as shown in Fig 12 (a) and (b), respectively. The TMA is fed at the middle of the side while TMB is fed at the vertex. The TMB configuration is equivalent to one half of broadband bow-tie dipole antenna [5].

For calculating f_L of the TMA and TMB antenna using Equation (9), the values of L and r of the effective cylindrical monopole are determined as

$$L = \sqrt{3} W / 2 \quad (11)$$

$$r = W / (4 \pi) \quad (12)$$

Where W is equal to the side length of the equilateral triangle.

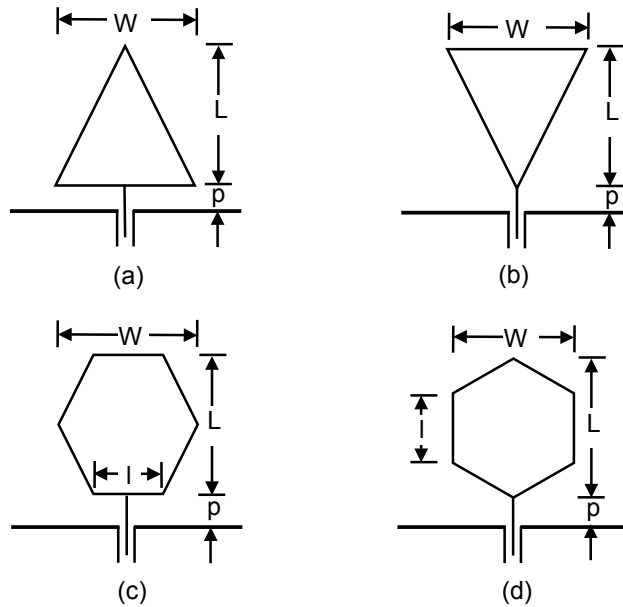


Fig 12. Triangular monopole antenna fed (a) in the middle of the side and (b) at vertex. Hexagonal monopole antenna fed (c) in the middle of the side and (d) at vertex.

14. 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 Fig 13 (a) and (d), respectively. The HMA and HMB are fed in the middle of the side and at the vertex, respectively. The theoretical lower frequencies corresponding to VSWR = 2 are calculated separately for the HMA and HMB antennas as given below. For the HMA, the L and r -values of the equivalent cylindrical monopole antenna are obtained by equating their areas as follows:

$$L = \sqrt{3} l \quad (13)$$

$$r = 3 l / (4 \pi) \quad (14)$$

The parameters for the HMB are:

$$L = 2 l \quad (15)$$

$$r = 3\sqrt{3} l / (8 \pi) \quad (16)$$

For these values of L and r , the lower frequency f_L is computed from Equation (9). The VSWR plots for these two configurations are shown in Figure 4.3. The f_L of HMB is lower than that of HMA because of its larger height L . The HMB has a larger bandwidth than the HMA. This can be understood from the analogy that HMB feed is similar to that of TMB, which gives a better matching as compared to TMA. The HMA feed is similar to the feed for the TMA and hence yields smaller bandwidth. The HMB provides wider bandwidth than the square and the rectangular monopoles, as it is closer to the circular configuration, which has very large bandwidth.

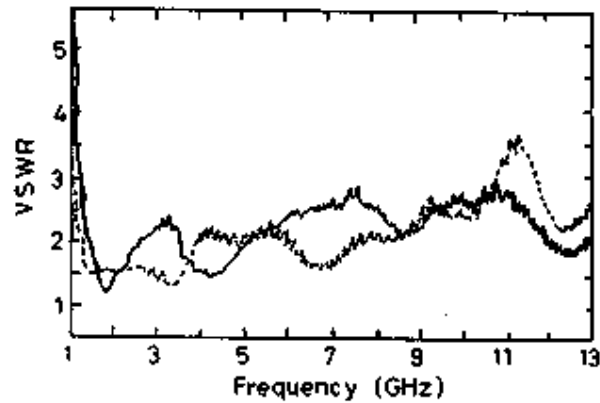


Fig 13. Measured VSWR plots of two feed-configurations of hexagonal monopole antennas. (—) HMA, (---) HMB.

15. Effect of increase in flaring angle, vertex truncation and effect of moving feed away from center in case of a triangular planar monopole

The effects of increase in flaring angle α were analysed using IE3D software. Simulations were carried out on infinite ground plane. By keeping the height of the triangular sheet and height of the probe constant. By varying the flaring angle α , it was noticed that antenna yielded maximum BW at an angle 120 degrees and at 130 degrees antenna started resonating at multiple bands. Since triangular sheet with flaring angle 120 degrees becomes too bulky, the antenna was analysed truncating its vertex [20]. The impedance loops for equilateral triangular monopole are in the higher impedance region in the smith chart and the impedance at the vertex is very high. This implies that if the vertex is chopped off partially, the matching of the antenna will improve. Equilateral triangular monopole with height 60 mm and base $b = 69.3$ mm was studied. It was found that as the vertex width was increased loop moved from higher impedance to lower impedance side in the smith chart. Further increase in the vertex results in to opening of the loop.

The moving of the feed point from the center results in to excitation of the higher modes. This results into increase in the BW. The optimized vertex truncated triangular monopole yielded ultra broadband width above 8786 MHz. Hence though the vertex chopping does improve the BW, but its optimization is a must. The planar triangular monopole and truncated equilateral triangular monopole are as shown in fig 14. The effect of shorting one of the corners of equilateral triangular monopole was studied. The shorting results into excitation of the lower modes below fundamental. The shorting reduces the lower resonance frequency also. When the feed point was moved away from the shorting pin, the impedance loop moved towards higher impedance side. The shorted configuration yielded impedance BW from 1158MHz to 2108 MHz where as non-shortened did not yield any impedance bandwidth. Moving the feed point could further control the impedance variations.

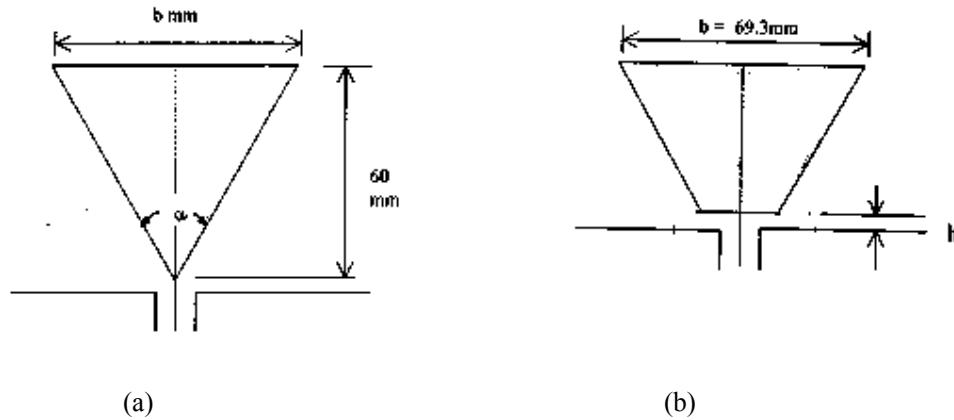


Fig 14. (a) Planar Triangular monopole antenna and (b) Truncated equilateral triangular monopole antenna.

16. Planar Circular Monopole Antennas

A planar circular monopole (CM) antenna yields very broad bandwidth [1, 2]. The radius a is taken equal to 2.5 cm. The size of the ground plane is kept same as 30 cm x 30 cm. For the CM, the values L and r of the equivalent cylindrical monopole antenna are given by:

$$L = 2a \quad (17)$$

$$r = a/4 \quad (18)$$

For $p = 0.1$ cm, the measured input impedance and VSWR plots are shown in Fig 15 (a) and (b), respectively. The bandwidth for $VSWR \leq 2$ is from 1.17 to 12 GHz, which corresponds to bandwidth ratio of 1:10.2.

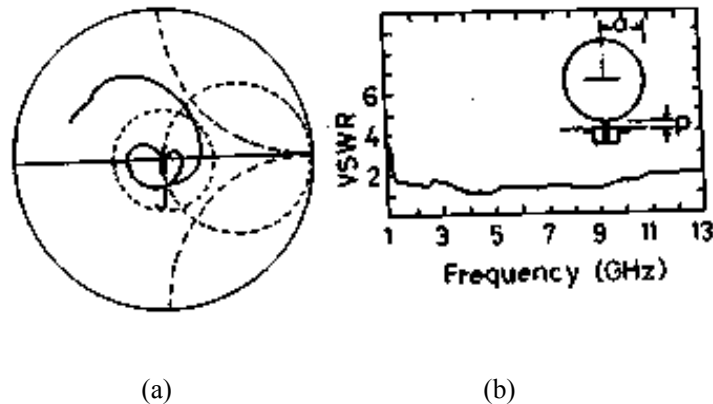


Fig 15. Measured (a) input impedance and (b) VSWR plots of CM antenna

The bandwidth of the CM is larger than all the monopole antennas described earlier. This could be interpreted in terms of various higher order modes of circular patch. Unlike the various modes of rectangular resonator, modes of the circular resonator (characterized by the roots of the derivative of the Bessel function) are closely spaced. Since the BW associated with the various modes is very large because the disc is in the air, so 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 Fig 15. (a).

17. Multi-band planar monopole antenna

The planar monopole antenna reported for multi bands for handsets is only about 0.05 times the wavelength of the lowest operating frequency. This antenna is not only capable of multi-band operations, but also possesses omnidirectional radiation patterns for all operation bands. The impedance BW covers almost all the present wireless systems of GSM (880-960MHz), including Digital Communication Systems (DCS, 1720-1880MHz), Personal Communication Systems (PCS, 1850-1990MHz) Universal Mobile communication systems (UMTS, 1920-2170MHz) and Industrial Science Band (ISM, 2400-2484MHz)[11]. Its desired characteristics, such as low cost, ease of manufacture, compact size, very wide BW, acceptable radiation efficiency, and omnidirectional radiation patterns, makes the proposed antenna very attractive for mobile communications. The antenna as designed is shown in fig 16.

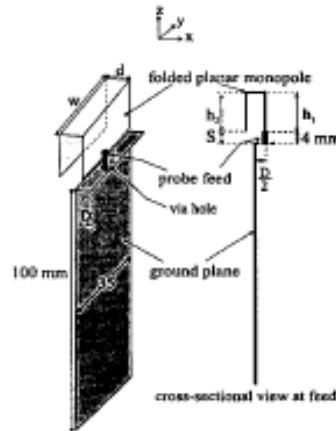


Fig 16. Multi-band folded planar monopole antenna

It mainly consists of a folded rectangular planar monopole and an inverted L-shaped ground plane. The rectangular monopole is bended into three parts; two parallel vertical plates with dimensions of $w \times h_1$ (plate 1) and $w \times h_2$ (plate 2) and one horizontal part with dimension $w \times d$ (plate 3). The combined plate length can be denoted as (h_1+h_2+d) . The distance between bottom edge of the plate and ground plane is denoted as S . In this experiment the combined length is fixed to be about one eighth wavelength of the lowest operating frequency. For impedance matching a gap G of probe feeding is needed to compensate the capacitive effect due to parallel plates of the planar monopole. Otherwise an additional ground plane with length D is needed for holding radiation patch.

The feed also influences the impedance matching and lowest feeding height of 4mm is needed to insure inclusion of GSM band in operating BW. Even all other dimensions too affect the impedance matching. The performance for the proposed antenna with various dimensions is shown in table 4. Also the measured and simulated return loss and radiation patterns for various bands are shown in fig 17. The radiation patterns at x-y, y-z and x-z planes for center frequency of GSM (920MHz), ISM band (2450MHz), DCS (1800MHz), PCS (1920MHz) and UMTS (2050MHz) are represented in fig 18.1, 18.2 and 18.3 respectively. The measured results show that the radiation patterns at vertical planes of y-z and x-z are conical, and in horizontal plane, the patterns are nearly omnidirectional for all measured frequencies. It is also noted that the gain variation from 880MHz to 2485 MHz is less than 3 dB.

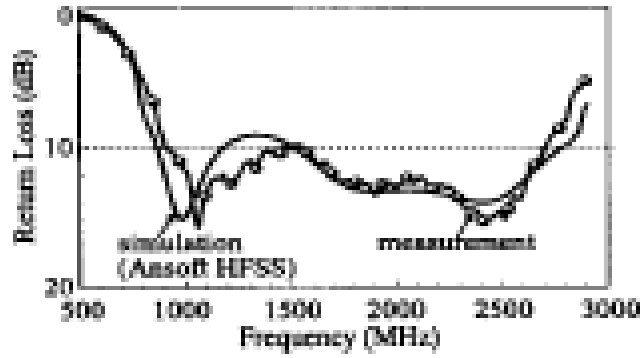


Fig 17. (a) Measured and simulated return loss for multi-band planar monopole antenna

Table 4: Performance for the proposed multi-band folded planar monopole handset with various antenna dimensions; $G=4\text{mm}$, $h_2=(30-h_1)$ mm, and $S=(2h_1-26)$ mm. the impedance BW is determined by 10dB loss.

d mm	W mm	h_1 mm	D mm	f_L MHz	BW MHz
8	35	15	6	923	923-1260; 1625-2675
10	35	15	6	880	880-2680;
12	35	15	6	850	850-2640
10	30	15	6	1005	1005-1160; 1700-2740
10	25	15	6	1030	1030-1180; 1745-2750
10	35	13	6	925	925-1660
10	35	14	6	920	920-1325; 2100-2535
10	35	16	6	870	870-1235; 1505-2770
10	35	17	6	865	865-120; 1540-2825
10	35	15	8	960	960-1180; 2100-2200
10	35	15	10	1025	1025-1175; 2105-2260

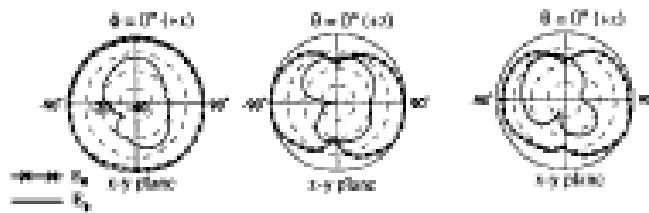


Fig 18.1. Measured radiation pattern at 920 MHz

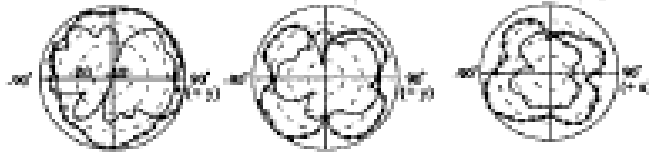


Fig 18.2. Measured radiation pattern at 2450 MHz

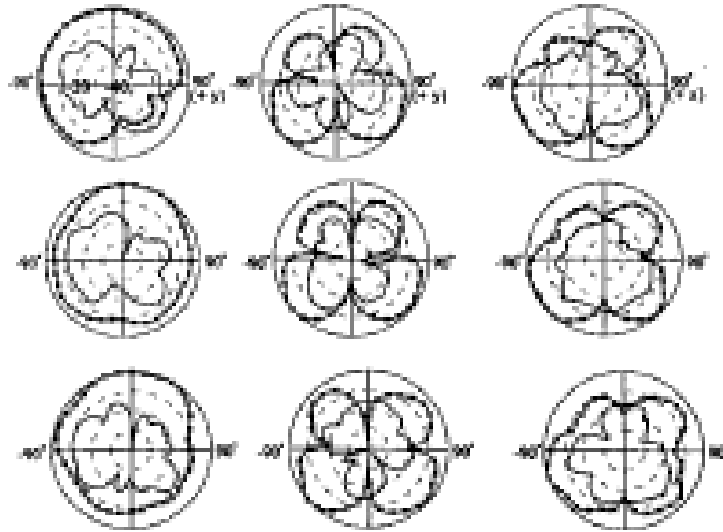


Fig 18.3. Measured radiation pattern at 1800 and 1900 MHz
and at 2050 MHz

18. Planar monopole antennas for 2.4/5.2 GHz dual band application

Two new designs of planar monopoles with a shorted parasitic inverted L wire for achieving dual band operation has been studied. One is a rotated F planar monopole driven patch coupled with a shorted inverted L wire and the other is a T shaped planar monopole driven patch coupled with a shorted inverted L wire. The antenna can be fed with a 50 ohms microstrip line on the same substrate. On the other side there is a ground plane below the microstrip feed line [12]. Both the antennas have same areas. Fig 19(a) and (b) show the configurations of two proposed small planar monopole antennas for dual band operation.

Both the driven monopole and the shorted parasitic inverted L wire are designed to operate as a nearly quarter wavelength antenna. The lower operating frequency is determined by the shorted inverted L wire and the upper frequency determined by the planar driven patch. The measured return losses of the antenna 1 in the case of length $L_1=10\text{mm}$ and antenna 2 in case of length $L_2=10\text{ mm}$ are shown in the fig 20. Also the measured radiation pattern of the antenna 2 at 2.45 and 5.2 GHz in the case of length $L_2=10\text{ mm}$ are shown in fig 21. The dual-band operation is achieved by the planar rotated F antenna and T shaped monopole antenna coupling with a shorted inverted L wire. The antenna's impedance BW in the two bands meets the BW requirements for applications in WLAN and HIPERLAN.

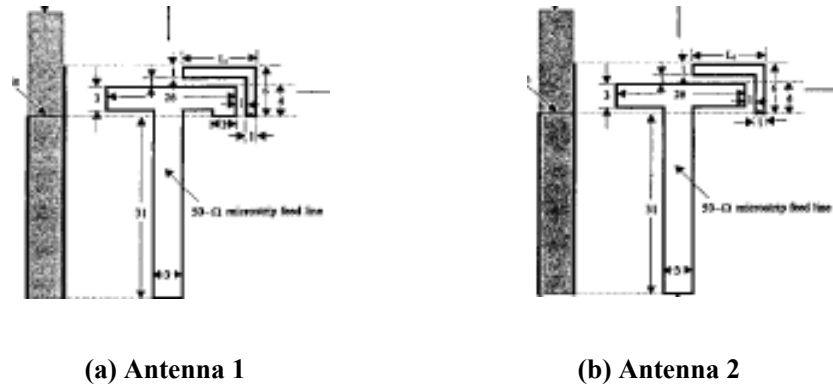


Fig 19. Proposed configuration of planar monopole antenna for dual-band operation. In this figure SP is shorting pin.

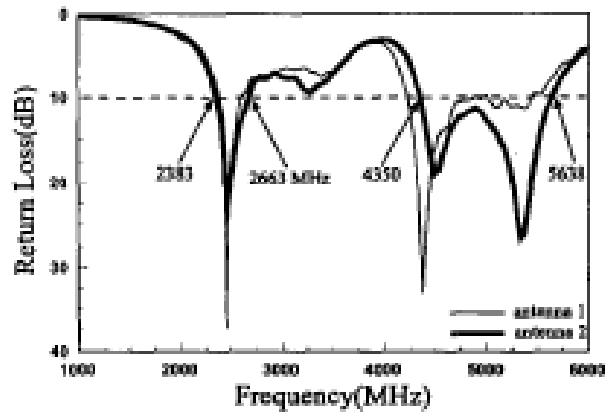


Fig 20. Measured return loss of antenna 1 in case of the length $L_1=10\text{mm}$ and antenna 2 in case of length $L_2=10\text{mm}$

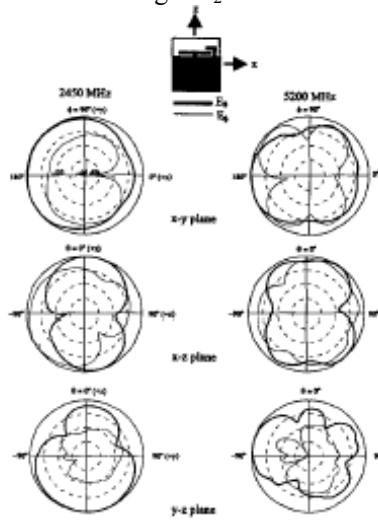


Fig 21. Measured radiation pattern of antenna 2 at 2.45 and 5.2 GHz in case of the Length $L_2=10\text{ mm}$

19. Design Example of Monopole Antenna for 225 to 400 MHz

To cover the frequency range of 225 to 400 MHz for defense applications, an inverted disc cone monopole antenna is typically used, which is structurally not very convenient. There is a need for simple planar monopole antenna, which can be easily fabricated and installed. This bandwidth can be achieved with the planar rectangular monopole antenna described in Section 3. Initially, the length L of the rectangular monopole antenna is obtained as 27.6 cm for $f_L = 0.225$ GHz by using Equations (4) and (8) by choosing $W = L$. It has been shown in Section 3.2, that the broader BW is obtained when W is smaller than L without significantly affecting the lower resonant frequency. To keep the margin in f_L , L is chosen as 28 cm and the width is chosen as 22 cm. These dimensions can be approximately obtained by using frequency-scaling technique from the dimensions given in Section 3.2. Also, in this frequency range, N-type connector is typically used instead of SMA connector, which helps in supporting large size monopole antenna. Hence, the diameter of the probe is taken as 0.4 cm. For $p = 0.7$ cm, the theoretical input impedance and VSWR plots are shown in Fig 22 (a) and (b), respectively. In the desired frequency range of 225 to 400 MHz, VSWR is less than 2. The maximum variation of the pattern in the azimuthal direction is 2 dB at the higher frequency.

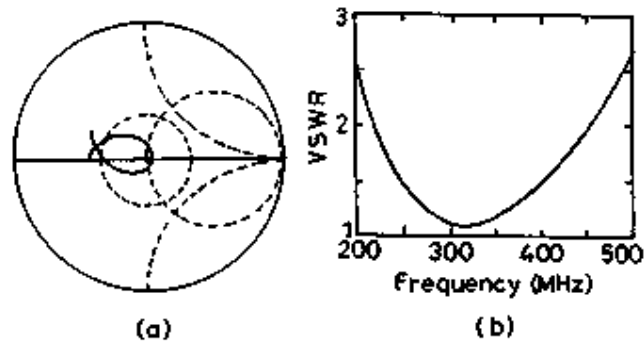


Fig 22. Theoretical (a) input impedance and (b) VSWR plots of RM with $L = 28$ cm, $W = 22$ cm, and $p = 0.7$ cm.

20. Conclusion

Various planar monopole antennas, such as rectangular, square, triangular, hexagonal, circular, and elliptical disc monopoles have been reported for very large VSWR BW. A suspended microstrip patch in air and fed at its periphery through a perpendicular ground plane becomes a planar monopole antenna, when the bottom ground plane is removed. Simple equations are given to predict the lower frequency corresponding to $VSWR = 2$ for these antennas. The square, rectangular, triangular, and hexagonal monopole antennas give lesser bandwidth than the circular and elliptical monopoles, but these bandwidths are large enough for many applications, so these antennas can be used because of the ease of fabrication. Circular and elliptical disc monopoles yield multi-octave bandwidth, which is extremely useful for broadband applications. Elliptical disc with ellipticity ratio of 1.1 provides maximum bandwidth of more than 1:11 for $VSWR \leq 2$.

Various techniques to tailor the impedance BW of planar monopoles and the effect of slots and circular holes on the impedance BW of planar monopole antennas investigated have been discussed. The radiation pattern at various frequencies in the E and H planes of these antennas is similar to that of a cylindrical monopole antenna of equivalent height on a finite ground plane. The planar monopole antennas can also provide band-notching characteristics, multi band operation and are useful in dual and triple band applications. Work is continuing on planar monopoles in regard to downsizing, pattern stability with change of frequency, the use of dielectric and reactive loading and folding. Design example of planar monopole antenna is presented using simple design equations to cover 225 to 400 MHz frequency bands.

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