Parametric Studies for the Optimum Design of a Hexagonal Plate Monopole Antenna

Seong-Bae Park · Joung-Min Park · Bierng-Chearl Ahn · Kyung-Seok Kim

Abstract

In this paper, we present parametric studies for the optimum design of a hexagonal plate monopole antenna. The dependence of the antenna performance on various geometric parameters is investigated using a commercial electromagnetic software, from which an optimum design of a hexagonal plate monopole antenna is derived. Guidelines for determining initial parameter values are given. The diameter of the circular ground plane is minimized to 1/5 wavelength at the lowest operating frequency. The antenna impedance matching is controlled by adjusting the gap between the plate and the ground plane, the plate base width, and the base bevel angle. The antenna proposed in this paper shows a reflection coefficient less than −10 dB and a 2.0~6.2 dBi gain over 3~20 GHz frequencies.

Key words : Hexagonal Pate Monopole, Ultra-Wdeband Antenna, Parametric Studies.

Ⅰ. Introduction

Considerable research efforts have been under way in the area of ultra-wideband antennas[1]~[5]. With emerging reconfigurable and software-defined wireless networks, there are also growing demands for antennas covering multiple bands[6]~[8]. As one of ultra-wideband antennas, the plate or planar monopole has received considerable interests in recent years[9]~[26]. Among advantages of the plate monopole are the small size and the structural simplicity.

The plate monopole is usually implemented in a printed form[9],[10] or in an erected form[11]~[26]. In the former case, the monopole is printed on a thin substrate and usually fed either by a microstrip line[9] or by a coplanar waveguide[10]. The ground plane, in this case, is parallel to the monopole surface. In the latter case, the monopole is placed vertically on a horizontal ground plane and fed by a coaxial probe.

The erected form of a plate monopole was first discussed in an open literature by Dubost and Zisler in a monograph published in 1976[11]. The first practical application of the erect plate monopole was presented by Honda and co-workers in 1992[12]. They employed a disc monopole for the reception of television signals at 90~770 MHz. In 1993, Hammoud and co-workers[13] analyzed the circular plate monopole using the method of moments and found the optimum feed gap for a wideband impedance matching. Agrawall and co-workers[14] experimentally studied the impedance characteristics of plate monopoles of various shapes such as circular, elliptical, square, rectangular, and pentagonal ones. They used a 30×30 cm ground plane and changed only the shape of the monopole to compare impedance bandwidths. With a feed gap of 1 mm and an ellipticity ratio of 1.1(a 2.6-cm major axis and a 2.4-cm minor axis), they obtained a 10.7 : 1 bandwidth (1.21~13.0 GHz) by feeding the monopole along the minor axis. They also proposed a simple formula for predicting the frequency corresponding the lower edge of the bandwidth.

Ammann[15],[16] experimentally studied the square plate monopole and applied the Agrawall's formula to compare lower operating frequencies. The simple square monopole has a bandwidth ratio of about 2. The bandwidth of a rectangular plate monopole can be enhanced mostly by modifying the geometry of the plate base such as the use of beveling[17]~[19], a shorting pin[20],[21], a double[22] or triple[23] feed, a semi-circular base[24], and a stepped base[25].

The first published result on the bandwidth improvement of the rectangular plate monopole was given by Evans and Ammann[17]. They obtained a bandwidth ratio of 10 : 1 by beveling the plate base to form a pentagonal monopole. Lee and co-workers[18] extended the bandwidth of a rectangular plate monopole by using a shorting pin and by adjusting the plate width. When a shorting pin is employed, an additional mode is excited below the fundamental mode and the lower frequency of the bandwidth is decreased resulting in a significant reduction of the monopole length. Another useful technique for reducing the monopole length is the folding of

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the monopole tip[27]. A shorting pin can be employed simultaneously with a bevel[26]. A band-notched monopole[28] is a variant of the rectangular plate monopole, where a half-wavelength slot formed on the plate acts as a single-element band-rejection filter.

In this paper, we present parametric studies for the optimum design of a hexagonal plate monopole fed by a coaxial probe through a small circular ground plane. A thorough parametric study on the pentagonal plate monopole has not yet been published in the open literature. Especially parametric studies on the base width and the ground plane diameter are included. Microwave Studio(MWS)® by Computer Simulation Technologies[29], a widely-known commercial electromagnetic software, is used for the numerical simulation of the antenna performance variation with respect to geometrical parameters, from which an optimum antenna design is derived. The designed antenna is fabricated and its performance is measured in order to validate the proposed design.

Ⅱ. Antenna Design

Fig. 1 shows the geometry and design parameters of a hexagonal plate monopole. As depicted in the figure, the ground plane is quite small. Evans and Ammann studied a pentagonal monopole on a large ground plane [17]. In this paper, we investigate a hexagonal monopole, where the base width B can be used as an additional parameter for the optimization of antenna performances. Also in this paper, to make the antenna as small as possible, the diameter of the circular ground plane is reduced to a minimum value in so far as the antenna performance is not appreciably degraded.

Initial dimensions of the antenna are calculated in terms of the wavelength at the lowest operating frequency f_L(3 GHz in this paper). The length L of the monopole is set to be approximately 1/4 wavelength at f_L. Specifically the monopole length can be estimated using following formulas[14] for the rectangular plate monopole on a large ground plane.

$$L = 0.24\lambda F \tag{1}$$

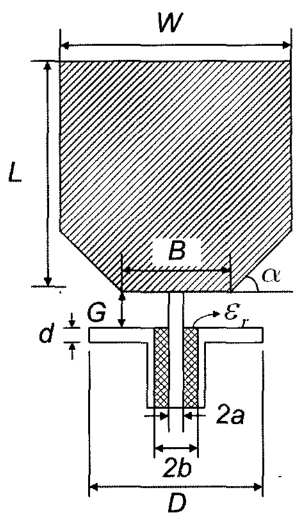
where F is the length-to-radius correction factor given by

$$F = \frac{L/r}{1+L/r} \tag{2}$$

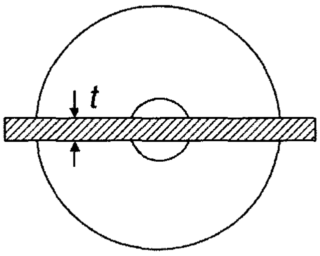
In Eq. (2), r is the radius of an equivalent cylindrical monopole, which is defined by

$$2\pi r L = S \tag{3}$$

where S is the area of the monopole plate. From Eqs. (1)~(3), we obtain an approximating formula for the first resonant frequency of the monopole



(a) Side view



(b) Top view

Fig. 1. Geometry and design parameters of a hexagonal plate monopole.

$$f_R(\mathrm{GHz}) = \frac{72}{L + S/(2\pi L)} \tag{4}$$

where dimensions are in millimeters. It is empirically found that the first resonant frequency is approximately equal to the lowest operating frequency, which is the minimum frequency where the reflection coefficient is less than −10 dB[14].

The highest operating frequency of a square plate monopole is about twice the lowest operating frequency. The highest operating frequency of a rectangular monopole can be increased by reducing the capacitance between the monopole plate and the ground plane[17], which can be realized by beveling the plate base at an angle α as shown in Fig. 1. The lowest operating frequency, in this case, is almost unaffected by the introduction of bevels.

The width of a plate monopole is determined considering the impedance bandwidth and the uniformity of the radiation pattern versus the frequency. A small plate width leads to a narrow bandwidth although the radiation pattern uniformity is better for smaller plate widths.

The effect of the diameter D of a circular ground plane on the performance of a thin wire monopole has been extensively investigated by Weiner[29]. The direction of maximum radiation is near the horizontal direction (θ=90°) for $\pi D/\leq 1.5$, while for $1.5 < \pi D/\leq 5.5$ it is rapidly moved toward the zenith (down to θ=35°). For values of πD larger than 5.5, the direction of maximum radiation is gradually moved back toward the horizon. Referring to Weiner's results, we choose to minimize the ground plane size so that the maximum radiation is near the horizontal direction and the antenna becomes as compact as possible, although the antenna gain is reduced accordingly.

Some typical values are initially chosen for other design parameters of the monopole: for example, B=0.25 W, α=35°, d=3 mm, G=1 mm, t=0.8 mm. The monopole is fed by the probe of a widely-used SMA connector ($2a$=1.3 mm, $2b$=4.1 mm, ε_r=2.08).

To arrive at an optimum antenna design, parametric studies are carried out using MWS®. Firstly we investigate the dependence of the lowest operating frequency f_L on the monopole length. Fig. 2 shows the reflection coefficient of the monopole for various values of the monopole length L.

With a monopole length of 25 mm, the lowest operating frequency f_L is 3.0 GHz, while Eq. (4) yields f_L =2.53 GHz. Besides the fact that Eq. (4) is an approximating formula, a small ground plane introduces a substantial upward shift in the monopole resonant frequency. When the monopole length L is increased, the lowest operating frequency f_L is decreased as expected.

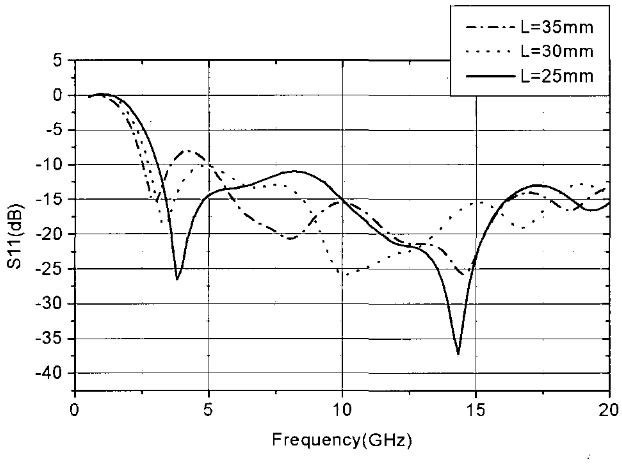


Fig. 2. Monopole reflection coefficient for various values of the monopole length(W=25 mm, t=0.8 mm, d=3 mm, D=20 mm, G=1 mm, α= 35°, B=6 mm).

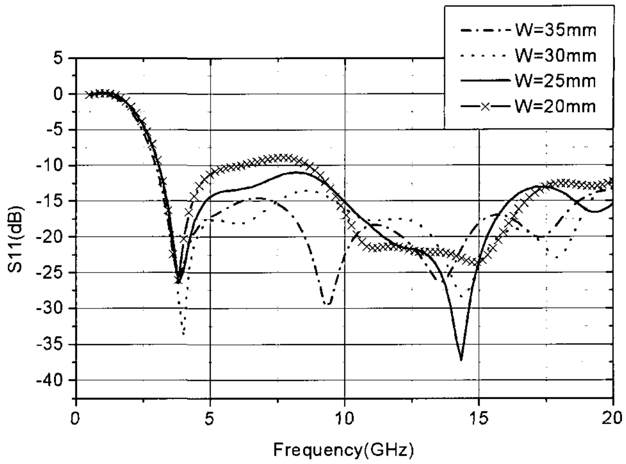


Fig. 3. Monopole reflection coefficient for various values of the monopole width(L=25 mm, t=0.8 mm, d=3 mm, D=20 mm, G=1 mm, α=35°, B=6 mm).

Next we investigate the dependence of the reflection coefficient on the monopole width W. Fig. 3 shows the monopole reflection coefficient for various values of the monopole width. The reflection coefficient is moderately dependent on the monopole width. For the frequently-used square plate(W=25 mm), the reflection coefficient is less than −10 dB at 3~20 GHz frequencies. The square shape in the rectangular plate monopole is thus a well-founded choice. The lowest operating frequency remains almost unchanged with changing values of W.

Next we investigate the dependence of the reflection coefficient on the ground plane diameter. Fig. 4 shows the result. The ground plane diameter is gradually reduced until the reflection coefficient does not exceed some specified level(*e.g.*, −10 dB). From this analysis we find that the diameter D of the ground plane can

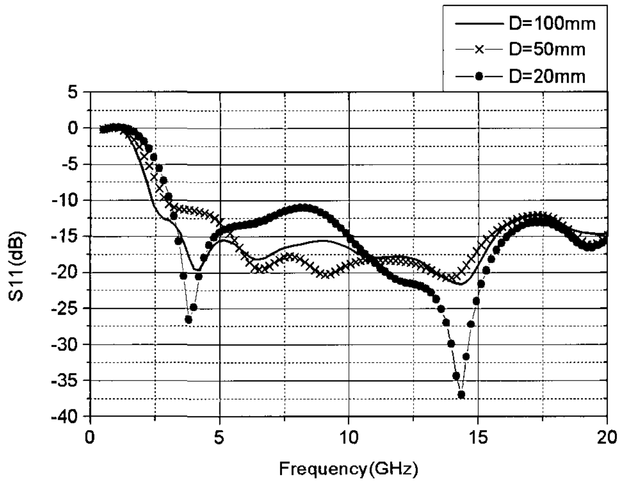


Fig. 4. Monopole reflection coefficient for various values of the ground plane diameter(W=L=25 mm, t=0.8 mm, d=3 mm, G=1 mm, α=35°, B=6 mm).

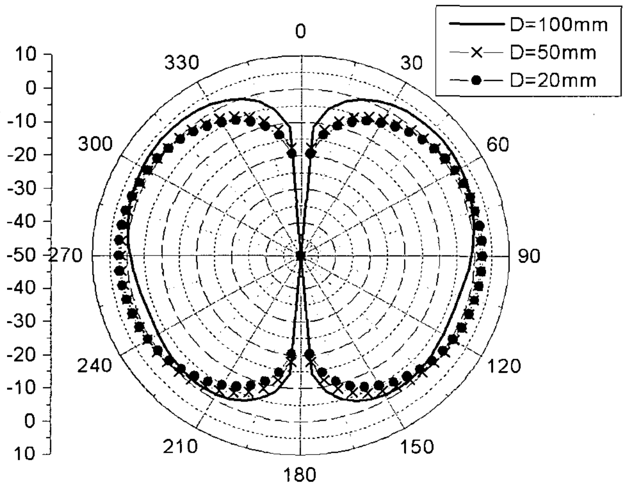
be decreased to 20 mm, which is 0.2 λ at 3 GHz so that $\pi D/\lambda=0.63$. We observe in Fig. 4 that the lowest operating frequency can be reduced by increasing the ground plane diameter.

Fig. 5 shows the dependence of the radiation pattern on the ground plane diameter D. As the ground plane diameter is increased, the maximum radiation direction moves from the horizon toward the zenith and the gain at $\theta=90°$ decreases. With $D=20$ mm, the maximum gain is 2.3 dBi and occurs at $\theta=90°$. With $D=50$ mm, the maximum gain is 1.8 dBi and occurs also at $\theta=90°$. With $D=100$ mm, the maximum gain is 3.2 dBi and occurs at $\theta=47°$. In this case, the gain at $\theta=90°$ is -0.9 dBi.

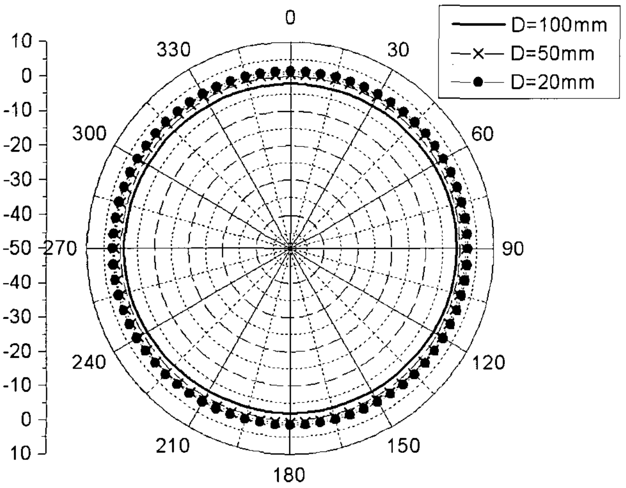
Next we investigate the effect of the base taper angle α on the reflection coefficient. Fig. 6 shows the result. The reflection coefficient is moderately dependent on the taper angle α when α ranges from 30° to 45°. An optimum performance is obtained when $\alpha=45°$. The rectangular plate monopole with no taper($\alpha=0°$) has a bandwidth of only about 2 : 1[16]. The bandwidth in excess of 10 : 1 was obtained by shaping the plate in a pentagonal form[17].

Next we study the effect of the feed gap G on the reflection coefficient. Fig. 7 shows the result. The reflection coefficient is sensitively dependent on the feed gap. Detailed analyses reveal that both the real and imaginary parts of the antenna input impedance depend upon the feed gap especially at higher frequencies. The best performance is obtained when $G=1$ mm.

Finally we investigate the dependence of the reflection coefficient on the base width B. Fig. 8 shows the



(a) E-plane



(b) H-plane

Fig. 5. Dependence of the monopole radiation pattern on the ground plane diameter($f=3$ GHz), ($W=L=25$ mm, $t=0.8$ mm, $d=3$ mm, $G=1$ mm, $\alpha=35°$, $B=6$ mm).

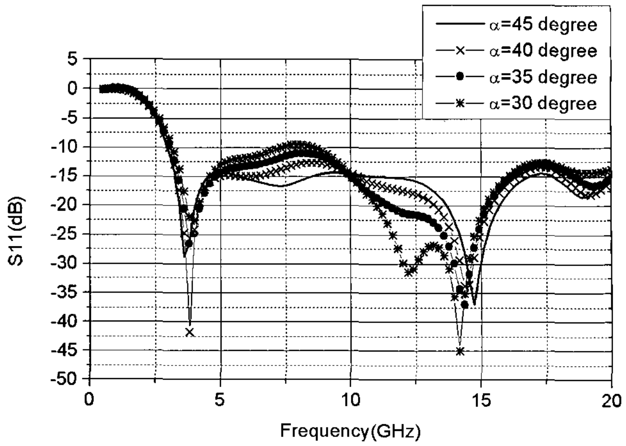


Fig. 6. Effect of the taper angle on the monopole reflection coefficient($W=L=25$ mm, $t=0.8$ mm, $d=3$ mm, $G=1$ mm, $D=20$ mm, $B=6$ mm).

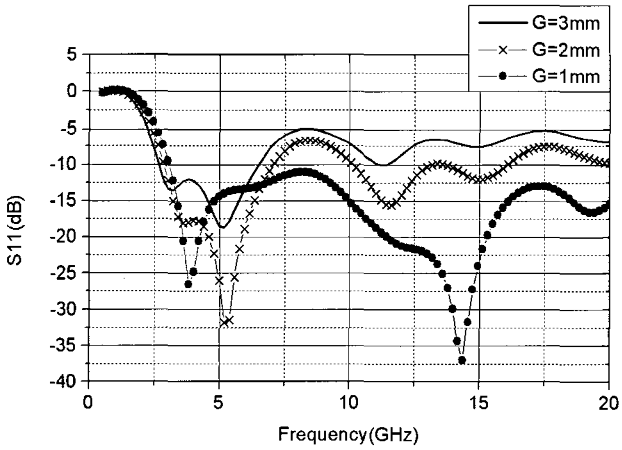


Fig. 7. Effect of the feed gap on the monopole reflection coefficient($W=L=25$ mm, $t=0.8$ mm, $d=3$ mm, $G=1$ mm, $D=20$ mm, $\alpha=35°$, $B=6$ mm).

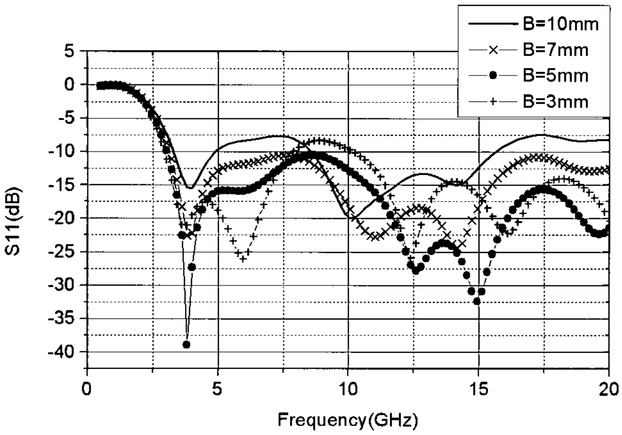


Fig. 8. Effect of the base width on the monopole reflection coefficient(W=L=25 mm, t=0.8 mm, d=3 mm, G=1 mm, D=20 mm, α=35°)

simulated reflection coefficient for various values of B. We observe that the reflection coefficient is rather sensitively dependent on the base width. An optimum performance is obtained when B=6 mm.

Based on foregoing parametric studies, we have simulated many cases to arrive at a final design: W=L=25 mm, t=0.8 mm, d=3 mm, G=1 mm, D=20 mm, α=45°, B=6 mm. Fig. 9 shows the monopole input impedance $Z_{in}=R_{in}+jX_{in}$ over 1~20 GHz at the coaxial aperture of the probe. Over 1~20 GHz frequencies, the real part of the impedance ranges from 30 to 70 ohms while the imaginary part ranges from −20 to 20 ohms. Other performance characteristics of the designed monopole are presented in Chapter III along with measurements.

III. Antenna Fabrication and Measurements

The designed antenna is fabricated using standard machining processes. Fig. 10 is a photograph of the fabricated antenna. The plate monopole is fed by the coaxial probe of an SMA connector. The probe is soldered to the lower edge of the plate monopole. For the plate material, a piece of a high-frequency circuit board with a dielectric thickness of 0.787 mm, a 1/2 oz. copper cladding, a dielectric constant of 2.5, and a dielectric loss tangent of 0.002 is employed. As shown in Fig. 10, four screw threads are machined on the ground plane in order to attach the SMA connector to the back side of the ground plane. Screw threads have negligible effects on the antenna performance.

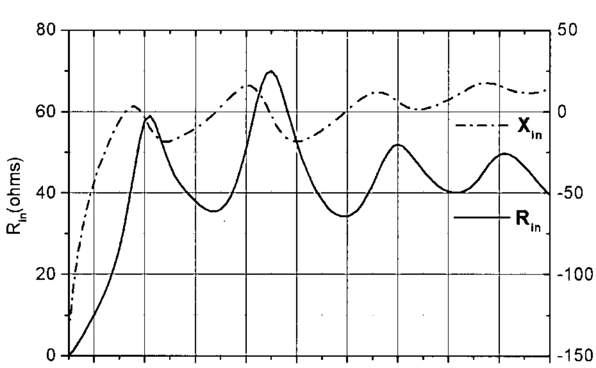


Fig. 9. Monopole input impedance at the coaxial aperture of the probe.

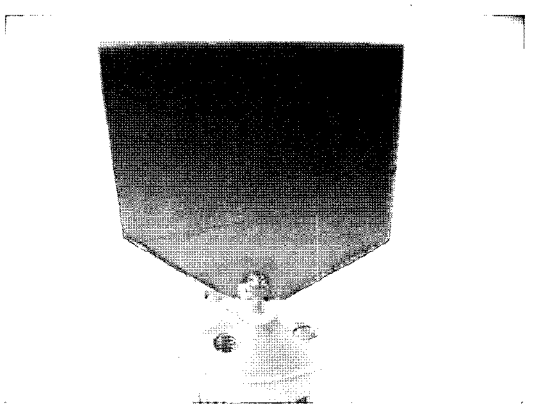


Fig. 10. Photograph of the fabricated antenna.

Electrical performances of the fabricated antenna are measured and compared with the simulation. Fig. 11 shows the reflection coefficient of the fabricated antenna. The measured reflection coefficient of the antenna is less than −10 dB over 3~20 GHz. The agreement between the measurement and the simulation is good. The antenna has low values of the reflection coefficient even above 20 GHz. The occurrence of many pattern nulls beyond 20 GHz limits the usefulness of the antenna.

Figs. 12~15 show antenna radiation patterns at 3, 8,

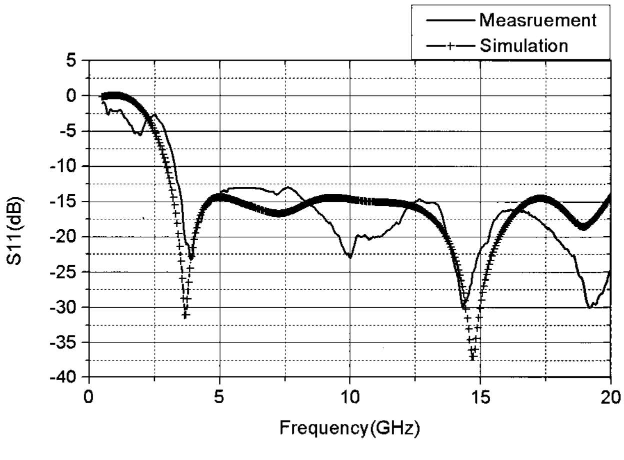
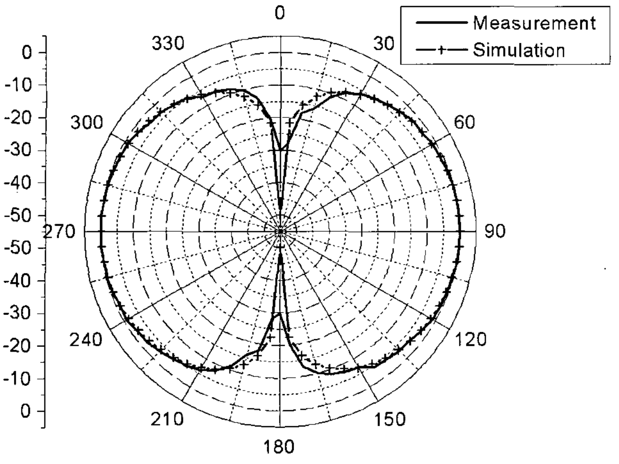
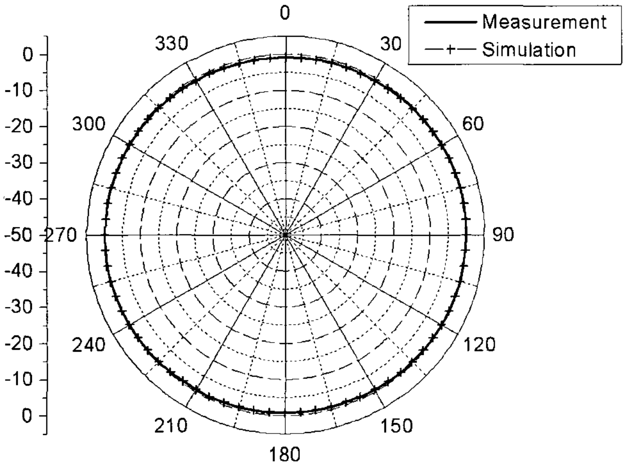


Fig. 11. Reflection coefficient of the fabricated antenna.

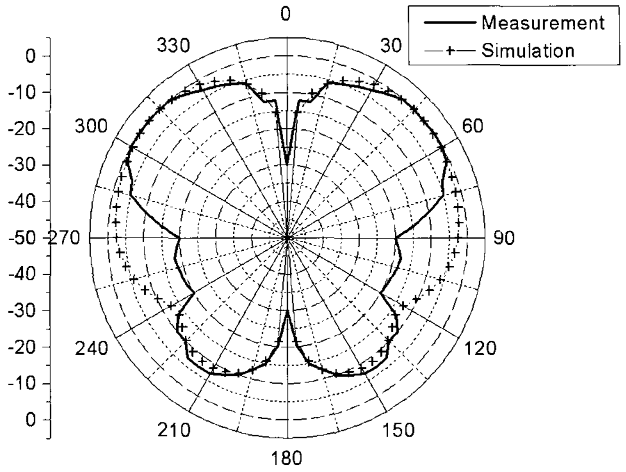


(a) E-plane

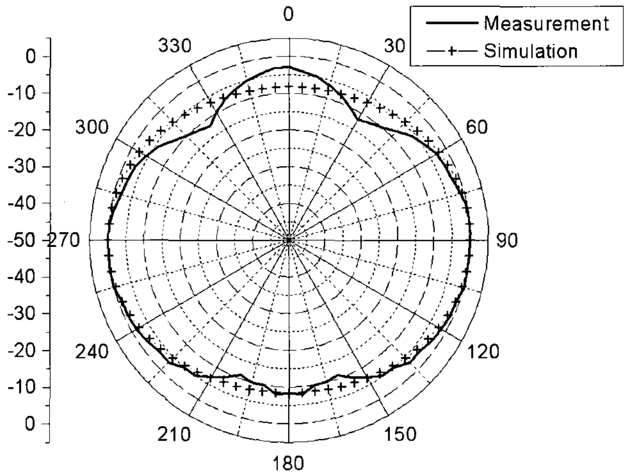


(b) H-plane

Fig. 12. Antenna radiation pattern at 3 GHz.



(a) E-plane



(b) H-plane

Fig. 13. Antenna radiation pattern at 8 GHz.

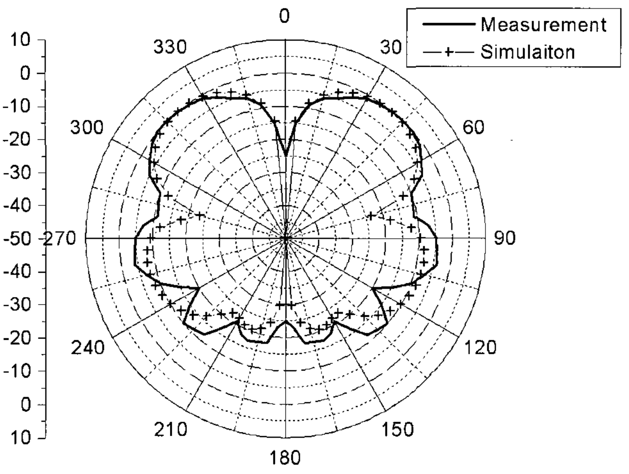
13 and 18 GHz, respectively. In these figures, the E-plane is orthogonal to both the plate and ground plane and the H-plane is parallel to the ground plane surface. The 0° angle in the E-plane corresponds to the zenith direction, while the 0° angle in the H-plane corresponds to the direction normal to the plate surface.

In Figs. 12~15, we observe that the radiation pattern is gradually distorted with many nulls as the frequency increases. This places a fundamental limit on the ultra-wideband radiation-pattern performance of all monopole antennas made of a single plate. The pattern distortion in the azimuth direction can be largely overcome by using a pair of crossed plates[31], while that in the elevation direction is more difficult to correct. Recent publications indicate that the pattern distortion in the elevation plane can be reduced by using a structure with steps along the monopole length[32],[33]. The problem of the pattern stability in the wideband monopole is a separate research topic in itself and may as well be treated in other articles.

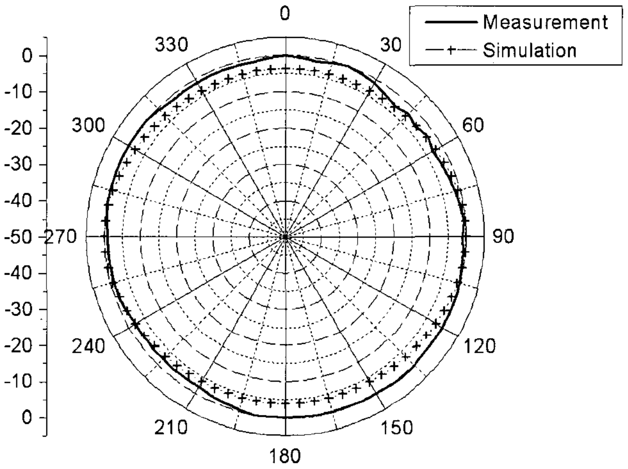
At 8 GHz, there is a noticeable disagreement between measured and simulated patterns. As in the case of the antenna gain described below, this is believed due to an unbalanced current flowing on the outer surface of the coaxial cable feeding the antenna.

Next the antenna gain is measured at various frequencies and is shown in Fig. 16. Over 3~20 GHz frequencies, the antenna gain ranges from 2.0 dBi to 6.2 dBi. Over 2~10 GHz frequencies, the gain monotonically increases with the frequency. Beyond 10 GHz, the gain tends to reach a saturated value, which is due to the occurrence of pattern distortions explained above.

The measured gain deviates from the simulated value by a maximum error of 1.5 dB. The discrepancy between the measurement and the simulation is believed due to the use of a small ground plane, which introduces a current flowing on the outer surface of the coaxial cable feeding the antenna. This unbalanced

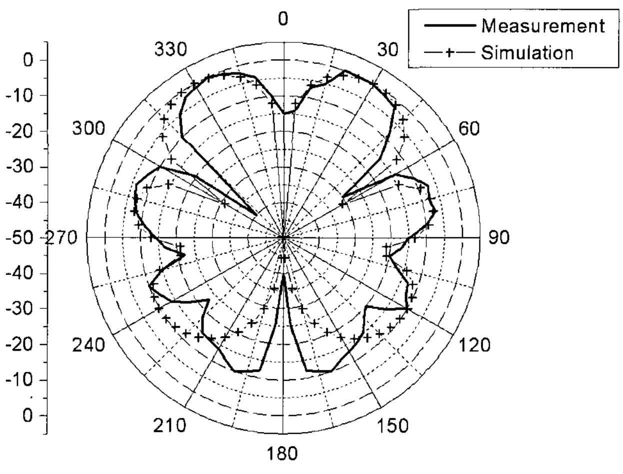


(a) E-plane

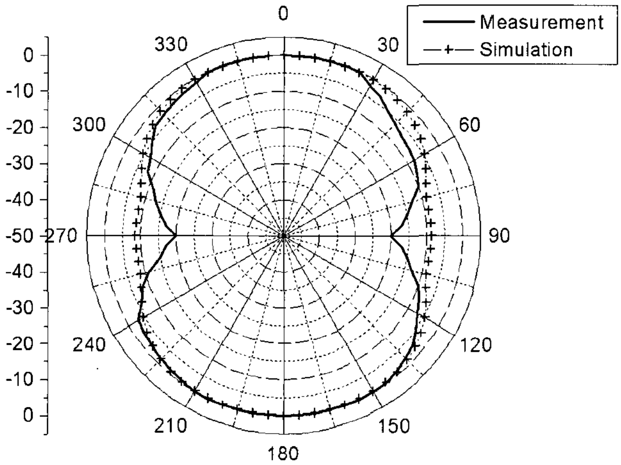


(b) H-plane

Fig. 14. Antenna radiation pattern at 13 GHz.



(a) E-plane



(b) H-plane

Fig. 15. Antenna radiation pattern at 18 GHz.

current leads to a reduced gain. The instrumentation error is estimated to be less than ±0.3 dB.

Ⅳ. Conclusions

In this paper, we presented parametric studies of a hexagonal plate monopole. The dependence of the antenna performance on various geometric parameters of the antenna is investigated, from which an optimum design is obtained. The height of the monopole is about 1/4 wavelength at the lowest operating frequency. The reflection coefficient can be tuned by adjusting the feed gap and can be further optimized by a proper choice of the patch base width and the base taper angle. It is shown that the ground plane diameter can be reduced to 1/5 wavelength at the lowest operating frequency without appreciably deteriorating the antenna performance. Measurements of the fabricated antenna show good performance characteristics: a 3~20 GHz operating frequency range, a 2.0~6.2 dBi gain, and a reflection coefficient less than −10 dB. The proposed antenna can be used in applications where multi-band or ultra-wideband signal transmissions are required.

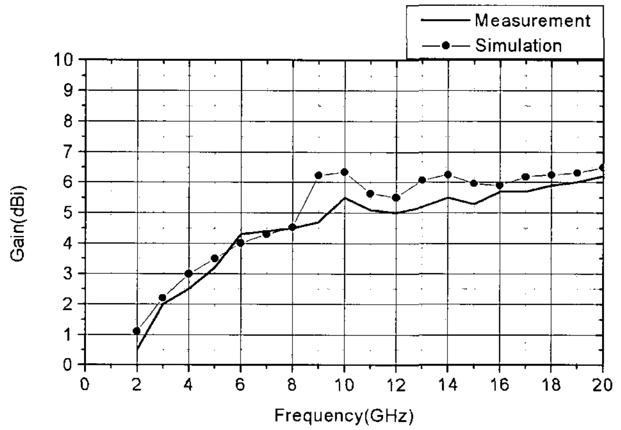


Fig. 16. Antenna gain versus the frequency.

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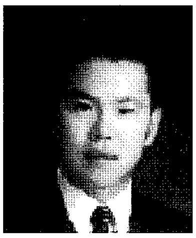

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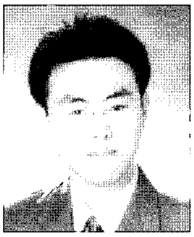

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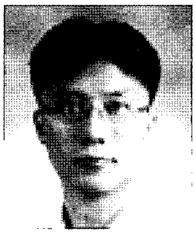

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