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A NOVEL OMNIDIRECTIONAL BROADBAND PLANAR MONOPOLE ANTENNA WITH VARIOUS LOADING PLATE SHAPES

S. M. Mazinani and H. R. Hassani

Electrical & Electronic Engineering Department
Shahed University
Tehran, Iran

Abstract—A novel, low profile and broadband plate loaded planar monopole antenna is investigated. The proposed antenna consists of a rectangular planar monopole with small plates attached to its radiating edges. Two types of plates, rectangular and cylindrical shapes are fabricated and tested. The characteristics of the antennas are investigated in both frequency and time domains. The study shows that the proposed antennas are capable of achieving broadband and omnidirectional radiation characteristics within 2.9–17.9 GHz with the cylindrical loading plates and 2.9–16.7 GHz for the rectangular loading plates with a gain of up to 7 dBi.

1. INTRODUCTION

Advances in wireless communication technologies are placing greater demands on higher antenna impedance bandwidth and smaller antenna size. The design of broadband antennas has received the attention of many antenna researchers due to their various applications, including wireless UWB communication.

It is quite challenging to design a suitable antenna for broadband communication systems. The requirements include a broad impedance bandwidth, omnidirectinal radiation patterns, constant gain and group delay, a stable transmit-receive transfer response and low pulse distortion, [1–5]. Among the many types of antennas that can provide wideband performance, the planar metal monopole antenna [8–19] exhibit excellent bandwidth as well as pattern performance. Broadband planar monopole (PM) antennas have found wide spread application in wireless communication services due to their attractive

Corresponding author: H. R. Hassani (hassani@shahed.ac.ir).

features like simple geometry, low profile, ease of fabrication, very low cost and omnidirectional pattern, but they usually show the directional radiation property at high operating frequencies due to their structural asymmetry.

In this paper, a novel approach to achieve a broadband omnidirectional planar monopole antenna is introduced. This is obtained by loading the rectangular planar monopole with a pair of parallel small plates placed on the two radiating sides of the monopole antenna. The addition of the plates increases the upper edge frequency significantly resulting in a bandwidth of 2.9–17.9 GHz. The monopole metal plate antenna has a small width, 12 mm, placed over a small circular ground plane of radius 50 mm. These dimensions are smaller than those reported in the literature [6–16]. Two types of plate loading shapes, rectangular and cylindrical, are simulated via software package CST, and samples are fabricated and tested. The impedance and radiation characteristics as well as the time domain (TD) and frequency domain (FD) parameters of the proposed PM antennas are examined. Application of the proposed antenna for UWB communication system is discussed.

2. ANTENNA DESIGN

The study of the current flow on a rectangular planar monopole (RPM) antenna reveals that its bottom edge will hardly contribute to the radiation and radiation occurs in the two vertical edges, Fig. 1. Thus, the vertical edge can be considered as a radiation resistance of the antenna [17]. In wire monopole antenna, adding multiple-arm to the antenna changes its radiation resistance [18]. Implementing this idea to the planar monopole, two loading plates are added to the radiating side edges. The loading plate introduces parasitic capacitance and inductance, that affect the antenna impedance match.

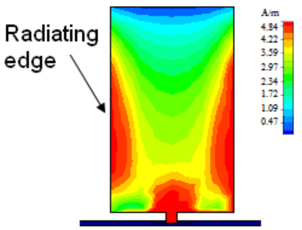


Figure 1. Current flow on a rectangular planar monopole.

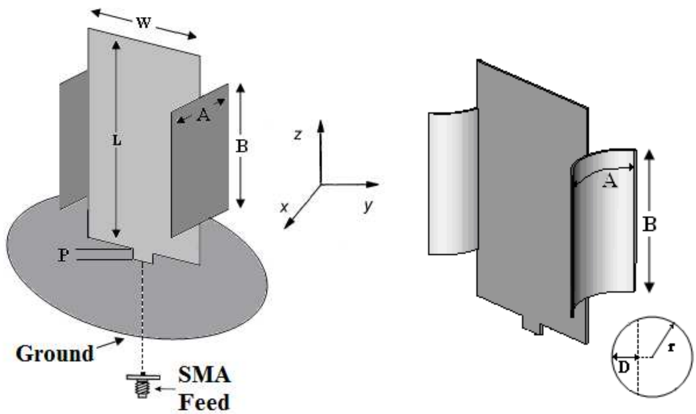


Figure 2. Planar monopole antenna loaded with a pair of (a) rectangular and (b) cylindrical plates.

The geometry of the proposed antenna with its parameters is depicted in Fig. 2. It consists of a rectangular planar metal monopole antenna with dimensions L and W that excited at the middle of its base by a narrow metal strip connected to a $50\,\Omega$ coaxial feed. The antenna is placed at a height, P over a small circular ground plane of radius 50 mm. This planar monopole antenna is loaded at its two radiating edges by small plates.

Two geometries for the loading plates are used in this paper:
Rectangular loading plate: Fig. 2(a) shows the geometry of the planar monopole antenna loaded with a pair of rectangular plates of dimension A and B.
Cylindrical loading plate: Fig. 2(b) shows the structure of the planar monopole antenna loaded with a pair of cylindrical plates. These plates are a cut through a cylinder of radius $r = 4$ mm. The depth D is set according to:

$$D = r\ (1 - \cos(A/2r)) \tag{1}$$

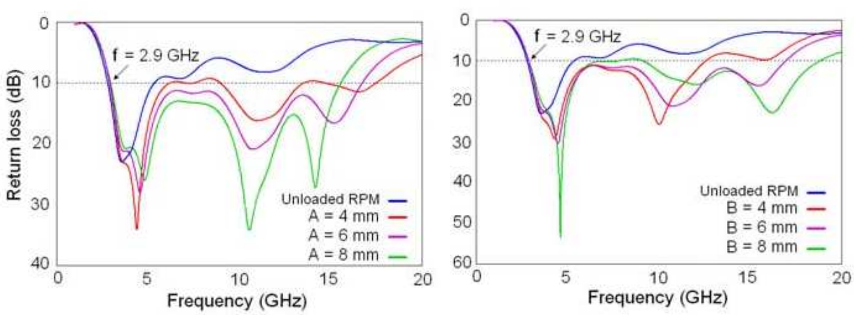
The loading plate surface area in Fig. 2(a) is equal to that in Fig. 2(b).

The proposed planar monopole antenna with rectangular and cylindrical plate loading has been simulated through the Finite Integration Technology (FIT) in CST Microwave package. Initially, an unloaded rectangular monopole plate with dimensions L and W was simulated. As given in [19], the theoretical lower limit frequency band, f_l, is according to (2) below. The dimensions $L = 20$ mm and $W = 12$ mm were chosen according (2), in order to have the f_l around

3 GHz. The space between the metal monopole and the ground plane P is set at 1 mm. This antenna shows a bandwidth of 2.9 to 5.3 GHz.

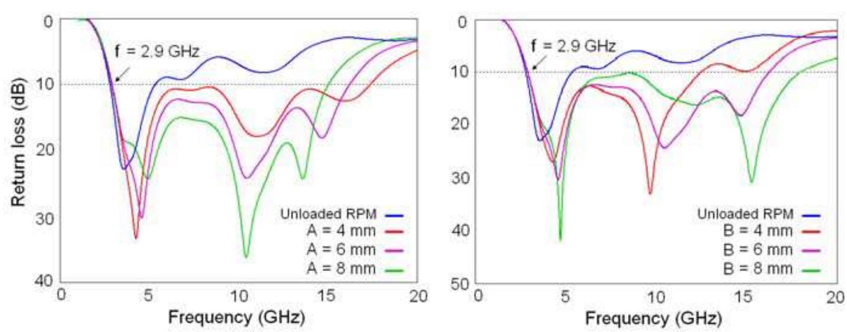
$$f_l = \frac{7.2}{\left(L + \frac{W}{\pi} + p\right)} \tag{2}$$

The effect of the size of a pair of rectangular loading plate A and B on the frequency of operation and bandwidth are then considered. Fig. 3(a) shows the return loss of the proposed antenna loaded with a pair of rectangular plates with dimension of the plate B fixed at 12 mm while A changes. The return loss for a rectangular plate loading with fixed value of side A set at 6 mm, and various values of side B is shown in Fig. 3(b). Similarly, the return loss for a pair of the cylindrical plate loaded monopole antenna for various values of A and B are shown in



(a) (b)

Figure 3. Return loss of RPM loaded with a pair of rectangular plates with (a) $B = 12$ mm and various A, (b) $A = 6$ mm and various B.



(a) (b)

Figure 4. Return loss of RPM loaded with a pair of cylindrical plates with (a) $B = 12$ mm, and different A, (b) $A = 6$ mm and various B.

Fig. 4. From the results shown in Fig. 3 and Fig. 4, as expected, the plate loading has no effect on the lower resonant frequency, constant in all cases at f_l.

From the results of Fig. 3 and Fig. 4 it is obvious that the size of the plate loading has a pronounce effect on the upper resonant frequency and thus on the impedance bandwidth of the monopole antenna. For the rectangular and cylindrical plate loading, with small values of A the return loss shows multiband behavior and with a good choice for B a wideband behavior can be obtained. Based on a return loss of 10 dB, the effect of the plate loading dimension on frequency and bandwidth are listed in Table 1 for rectangular and in Table 2 for the cylindrical loading plates. From these Tables, it is seen that for the rectangular loading plates with $A = 6\,\text{mm}$ and $B = 12\,\text{mm}$ the upper frequency limit is 16.7 GHz while for the cylindrical loading plates with $A = 6\,\text{mm}$ and $B = 14\,\text{mm}$ the upper limit is 17.9 GHz. Based on a 10 dB return loss as well as wide bandwidth, the ideal dimension of rectangular and cylindrical loading plates are found to be $A = 6\,\text{mm}$ and $B = 12\,\text{mm}$ which shows that $A = 1/2W$ and $B = 3/5L$.

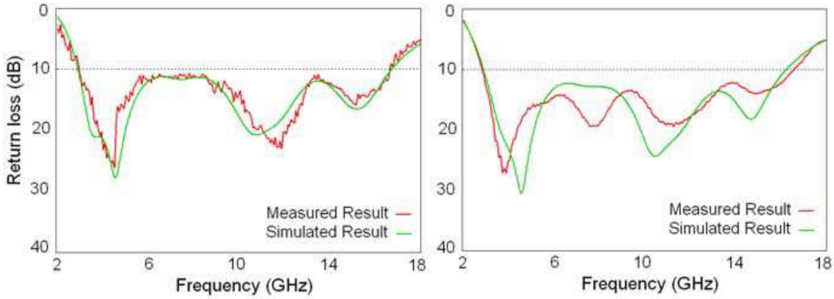
Two prototypes of the RPM antenna loaded with rectangular and cylindrical plates made of copper with thickness 0.2 mm and size $A = 6\,\text{mm}$ and $B = 12\,\text{mm}$ have been fabricated and tested. Fig. 5

Table 1. Dimensions and bandwidth for rectangular loading plates.

Size of A parameter (mm)	Size of B parameter (mm)	Bandwidth (GHz)
4	12	2.9–6.2, 8.9–13.5, 14.7–17.5
6	12	2.9–16.7
8	12	2.9–15.6
6	10	2.9–6.7, 9.2–18.5
6	14	2.9–12.5

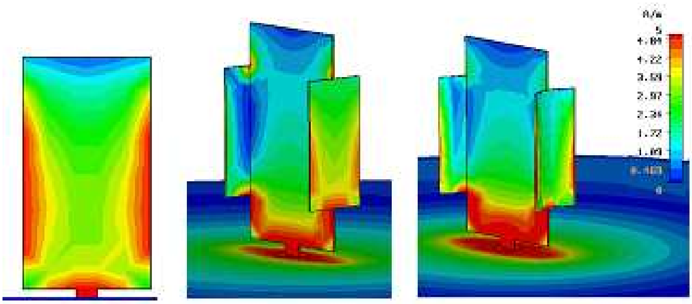
Table 2. Dimensions and bandwidth for cylindrical loading plates.

Size of A parameter (mm)	Size of B parameter (mm)	Bandwidth (GHz)
4	12	2.9–17.4
6	12	2.9–16.2
8	12	2.9–17.4
6	10	2.9–17.9
6	14	2.9–12.5



(a) (b)

Figure 5. Simulated and measured return loss of RPM antenna with $A = 6\,\mathrm{mm}$ and $B = 12\,\mathrm{mm}$ loaded with (a) rectangular, (b) cylindrical plates.



(a) (b) (c)

Figure 6. Current amplitude distribution at 4 GHz (a) RPM antenna, (b) RPM loaded with rectangular plates, (c) RPM loaded with cylindrical plates.

shows the measured and simulated return loss of these two antennas.

The effect of the presence of the loading plates can be seen through a study of the current flow on the planar monopole antenna. Fig. 6 shows the simulated current distribution on a basic planar monopole antenna as well as on the rectangular and cylindrical loaded plates at frequency of 4 GHz. Fig. 6(a) shows that a concentration of current takes place around the feed point as well as along the two sides of the planar monopole parallel to the feed. The currents on these two sides are responsible for most of the radiation. As can be seen from Fig. 6, when a pair of plates is placed on these two side edges of the planar monopole, current flows on the loading plates and a concentration of current on the loading plate edges takes place. The use of the loading plate adds extra modes to the original structure. Since the loading plates chosen are smaller in size than the main monopole plate antenna, modes of higher resonances are created, resulting in an increase in the overall bandwidth of the antenna.

3. FREQUENCY DOMAIN CHARACTRESTRICS

3.1. Radiation Patterns and Uniformity

The measured normalized E and H-plane radiation patterns of the proposed RPM antenna loaded with a pair of rectangular plates at 4, 10, and 16 GHz, respectively, is shown in Fig. 7. Also the measured radiation patterns for a pair of cylindrical plate loaded monopole antenna are shown in Fig. 8. The E-plane radiation pattern of the PLMP antenna is similar to those of the RPM antenna. With increase in the frequency of operation, a dip in the main beam in the E-plane pattern is in evidence, due to the large electrical size of the antenna. In H-plane, the patterns of both antennas are similar and show a good acceptable omnidirectional behavior at all frequencies. At higher frequencies, in the usual RPM antennas, due to the asymmetry

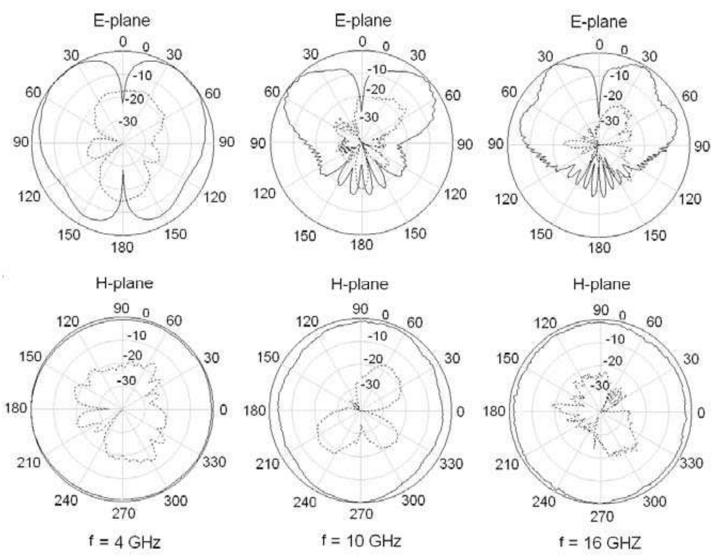


Figure 7. Measured radiation pattern of RPM antenna loaded with a pair of rectangular plates at 4 GHz, 10 GHz and 16 GHz.

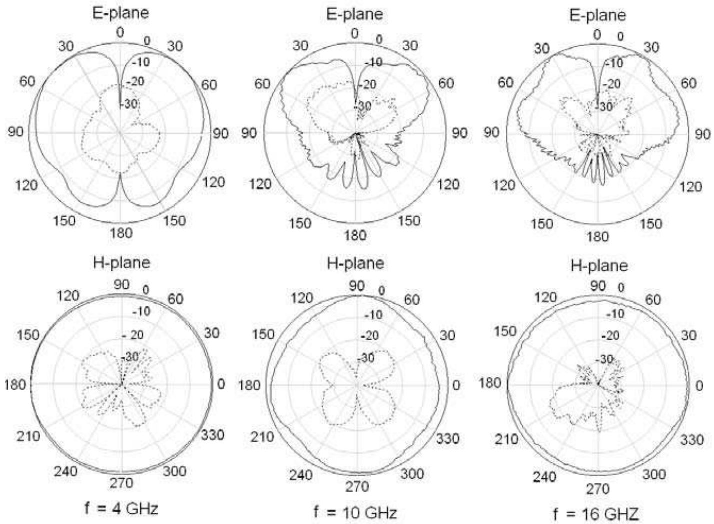


Figure 8. Measured radiation pattern of RPM antenna loaded with a pair of cylindrical plates at 4 GHz, 10 GHz and 16 GHz.

in the configuration of the antenna in the two orthogonal planes omnidirectional pattern is not achievable, whereas, by adding the loading plates to the RPM antenna and choosing $2A = W$, the antenna's radiated fields in the x and y directions will be expected to have about the same amplitude, thereby causing much improved omnidirectional radiation characteristics in the azimuthal plane.

To achieve a more comprehensive understanding of the radiation patterns over the entire band, we define uniformity to quantitatively describe the performance of the radiation patterns over bandwidth, as given by (3).

$$Uniformity\,(f) = \frac{\begin{array}{l}\textit{No. of measured pattern points that their deviation}\\ \textit{from the maximum value are less than 6 dB}\end{array}}{\textit{No. of total measured pattern points in a } \sin \textit{gle plane cut}}(f) \quad (3)$$

The uniformity is a statistical parameter related to the normalized measured radiation patterns, and is defined as the probability that the deviation of the radiation pattern from its maximum value is less than 6 dB at specific plane cut and frequency. With the uniformity, the dependence of the radiation patterns on frequencies can then be easily observed. As is usual [17], only the co polarized component in H-plane is taken into account in the following discussion. Fig. 9 illustrates the uniformity of the two proposed RPM antennas in the H-plane. From the figure, we observe that the uniformity curve for PM antenna loaded with rectangular plates is greeter than 80% and for antenna loaded with cylindrical plates is greeter than 75%. Thus, the uniformity of PM antenna loaded with rectangular plates is better than that loaded with cylindrical plates. It means that PM antenna with rectangular plates has a better omindirectional pattern in the frequency band of interest.

Figure 10 shows the RPM antenna gain variation with frequency for the antenna loaded with a pair of rectangular and cylindrical plates. At lower frequencies the two shapes of plate loading result in similar gain but at higher frequencies the rectangular plate gives higher gain. It is known that a single planar monopole antenna has less than 4.5 dBi of gain. Thus, plate loading has increased the gain especially at higher frequencies where gain of 7 dBi is noted.

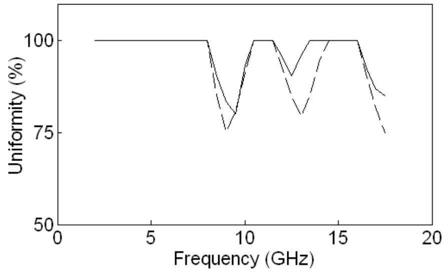


Figure 9. Uniformity of the RPM antenna loaded with rectangular plates (solid), cylindrical plates (dash).

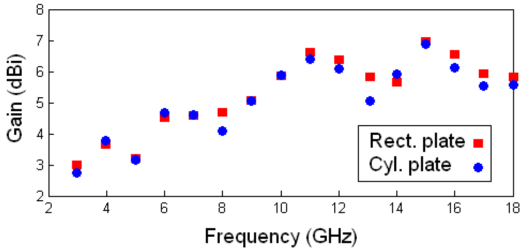


Figure 10. Measured gain of RPM antenna loaded with rectangular and cylindrical plates.

3.2. Antenna Transfer Function

Pulse distortion through the proposed antenna can be checked in the frequency domain through the analysis of the antenna transfer function. A Transmit/Receive antenna communication system can be described as a two-port network in terms of scattering parameters, as shown in Fig. 11. The system transfer function, S_{21}, as defined in [20] is the ratio of the received to the transmitted signal:

$$\begin{aligned} S_{21}(\omega) &= \frac{V_r(\omega)}{V_t(\omega)} = \left| \sqrt{\frac{P_r(\omega)}{P_t(\omega)} \frac{Z_L}{4Z_O}} \right| e^{-j\phi(\omega)} = \left| S_{21}(\omega) \right| e^{-j\phi(\omega)} \\ \phi(\omega) &= \phi_t(\omega) + \phi_r(\omega) + \frac{\omega d}{c} \end{aligned} \tag{4}$$

in which P_r and P_t are the received and transmitted powers, Z_L and Z_o are the load and generator impedances, c is the velocity of light, d is the space between the two antennas and $\varphi_t(\omega)$ and $\varphi_r(\omega)$ are the phase variations related to the transmitting and receiving antennas, respectively.

The transfer function is determined by the characteristics of both transmitting and receiving antennas, such as impedance matching, gain, polarization matching and the distance between the antennas. Therefore, it can be used to evaluate the performance of the antenna systems. To minimize the distortions in the received signal waveform, the transfer function is required to have flat magnitude and linear phase response over the operational band.

To evaluate the antenna transfer function, a pair of identical antennas has been placed 250 mm from each other (antennas are in the far field of the each other) in two different orientations in the free space, face to face and side by side, as shown in Fig. 12. These orientations were selected based on the knowledge of the radiation patterns of the planar monopoles [20].

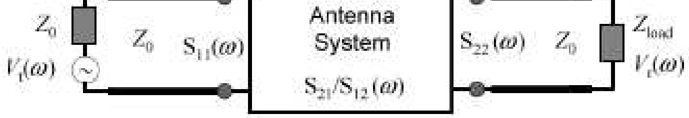


Figure 11. Schematic diagram of an antenna system in UWB radio systems.

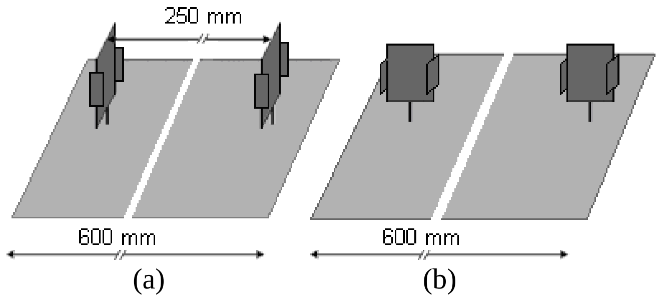


Figure 12. (a) Face to face, (b) Side by side antennas.

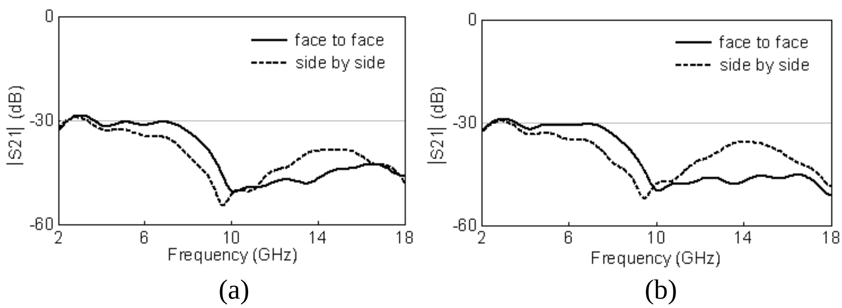


Figure 13. Transfer function of the RPM antenna with (a) rectangular, (b) cylindrical loading plates.

In Fig. 13, the magnitudes of the transfer parameters $|S_{21}|$ gainst frequency are illustrated for the two shapes of the loading plates. Fig. 13(a) shows that for face to face orientation, the antenna with rectangular loading plates has a flat magnitude of around -30 dB over the UWB band (3.1–10.6 GHz), but at higher frequencies is degraded and has a value around -45 dB. For the side by side scenario, the variation in the $|S_{21}|$ is larger than face to face. Fig. 13(b) shows the transmission performance for the antenna with cylindrical loading plates. It is seen that this antenna has much higher variation at higher frequencies than the antenna with rectangular loading plates for both orientations. Therefore, the antenna with rectangular loading plate may be a good solution for omnidirectional applications in comparison to the antenna with cylindrical loading plate.

The phase response of the transfer function can be obtained through the group delay which is defined as the rate of change of the total phase shift with respect to angular frequency. Ideally, when the phase response is strictly linear, the group delay is constant. Fig. 14

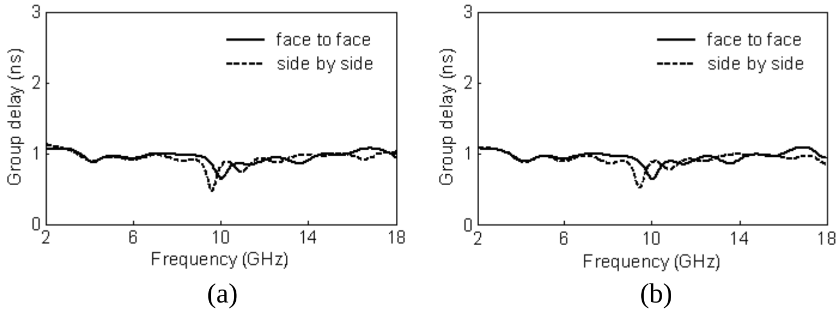


Figure 14. Group delay of the RPM antenna with (a) rectangular, (b) cylindrical loading plates.

shows the group delay results for rectangular and cylindrical loaded RPM antennas. The results shows that the group delay variations of the two antennas are less than 0.6 ns and are almost flat.

4. TIME DOMAIN CHARACTRESTRICS

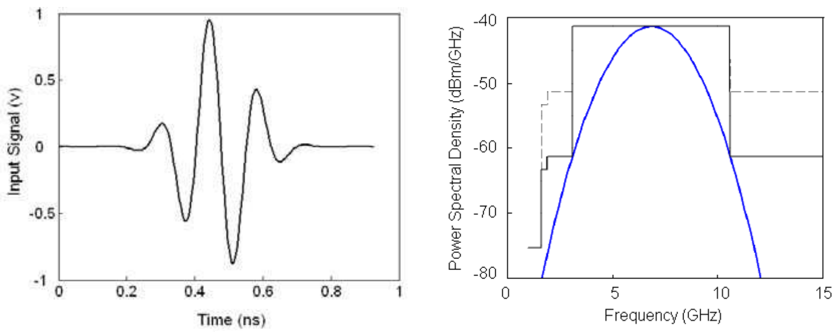
As shown in previous section the proposed antennas have very wide bandwidth. However, having a wide band frequency domain response does not necessarily ensure that antenna behaves well in the time domain as well; that is, a narrow time-domain pulse is not widened by the antenna.

Figure 13 clearly reveals that the antenna does not have a flat transfer function over the bandwidth. Therefore, in order to ensure the usefulness of the proposed antenna, the time domain response of antenna must also be examined. Based on the previous results, the proposed antenna is assumed to be excited by two wideband signals corresponding to UWB (3.1–10.6 GHz) and higher-band (11–18 GHz).

The Federal Communication Commission (FCC) released the regulations for UWB technology [21]. Two main schemes, the single-band operation and the multiband operation, have been proposed by the FCC to exploit the UWB band. The single-band operation follows the conventional way to utilize the whole frequency band and transmits subnanosecond pulses, whereas the multiband operation divides the allocated spectrum into subchannels to transmit much broader pulses and eases the challenge in hardware implementations [22]. Only the single-band operation, which is much more sensitive to the choice of the antenna, will be considered in this paper. For UWB communications the ultra-wideband pulse should comply with FCC emission mask. Thus, we assume the antennas are excited by the derivatives of a

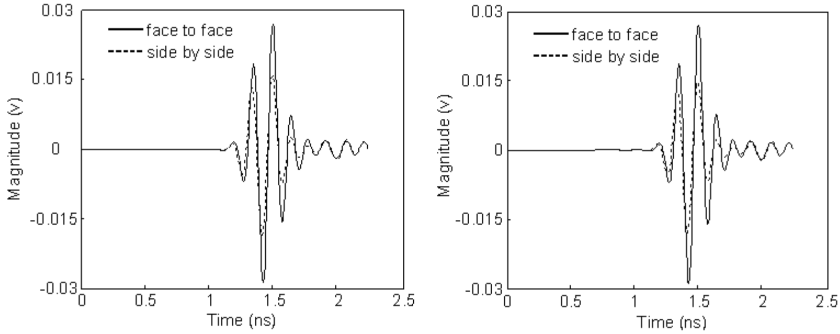
Gaussian pulse. The pulse signal and its power spectral density (PSD) are shown in Fig. 15. The results of the output pulses at the terminal of the antenna for the two loading plate types are shown in Fig. 16. The waveforms for the two antennas are unchanged for the two orientations, face to face and side by side, but, the maximum magnitude of the waveform for the side by side is 40% lower than that for the face to face case. The power spectrum density of the received signals in both orientations for both proposed antennas has been depicted in Fig. 17.

To determine the correlation coefficient between signal at the terminals of the receiving antenna $S_2(t)$ and the input signal $S_1(t)$ at the transmitter end, referred to as fidelity, the following equation is



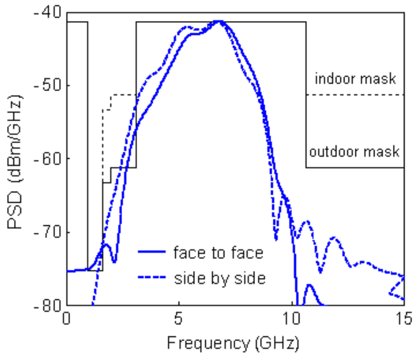
(a) (b)

Figure 15. (a) Input signal for UWB, (b) power spectral density of input signal (blue), FCC's indoor mask (dash) and FCC's outdoor mask (black solid).

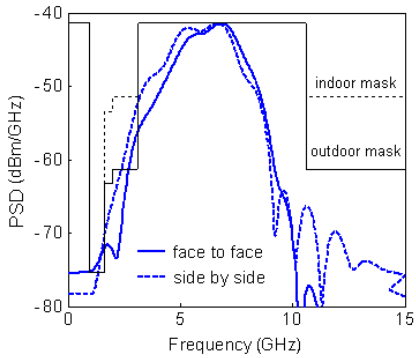


(a) (b)

Figure 16. Received UWB waveform at the RPM antenna loaded with (a) rectangular, (b) cylindrical plates.



(a)



(b)

Figure 17. Power spectral density of received waveform at the RPM antenna loaded with (a) rectangular, (b) cylindrical plates.

Table 3. The values of the fidelity.

Monopole antenna with	Fidelity face to face	Fidelity side by side
rectangular loading plate	0.84	0.75
cylindrical loading plate	0.85	0.73

used [23]:

$$Fidelity = \max_{\tau} \left\{ \frac{\int S_1(t)\, S_2(t-\tau)\, dt}{\sqrt{\int S_1^2(t)\, dt} \sqrt{\int S_2^2(t)\, dt}} \right\} \quad (5)$$

The fidelity reaches unity as the two pulses are exactly the same in shape, which means the receiving antenna does not distort the incident pulse at all. The values of the fidelity obtained for each antenna at UWB are summarized in Table 3. From this table, it can be concluded that the change in the magnitude of the antenna system response does not severely distort the waveforms.

The input signal for the higher-band (11–18 GHz) is shown in Fig. 18. The relevant signals at the receiving antenna terminals for the two loading plate types are shown in Fig. 19. The fidelity factor between Input signal and received signal for the two antenna types are shown in Table 4.

Upon comparing the results for the two loading plate types, it is observed that the rectangular loading plate provides lower distortion than the antenna with cylindrical loading plates.

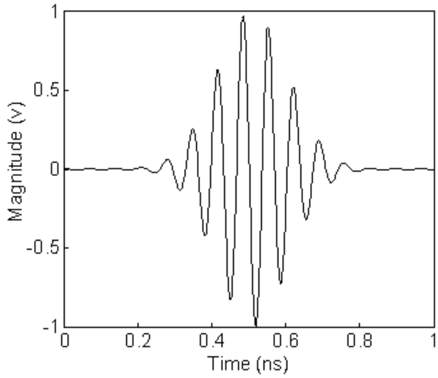
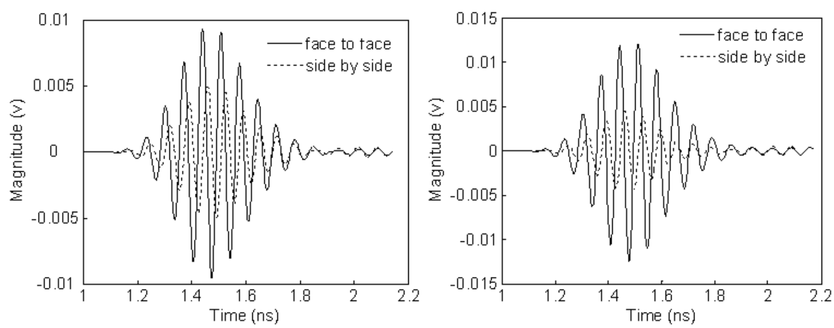


Figure 18. Input signal for higher-band.



(a) (b)

Figure 19. Received higher-band waveform at the RPM antenna loaded with (a) rectangular, (b) cylindrical plates.

Table 4. The values of the fidelity.

Monopole antenna with	Fidelity face to face	Fidelity side by side
rectangular loading plate	0.97	0.94
cylindrical loading plate	0.96	0.92

5. CONCLUSION

A low profile broadband planar metal monopole antenna loaded with plates at its radiating edges has been proposed. The presence of the loading plates increases the upper resonance frequency and with proper choice of the loading plate dimensions either multiband or very broadband behavior is achievable. It has been shown that the rectangular loading plate provides 2.9–16.7 GHz and the cylindrical loading plate 2.9–17.9 GHz bandwidth. The frequency and time domain analysis of both loading plate types shows that, although the cylindrical loading plate gives a higher bandwidth, the rectangular loading plate provides a slightly higher gain, more omnidirectional pattern and lower pulse distortion.

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