Time-Domain Investigation of a Family of Symmetrically Modified Square Plate Monopole Antennas for UWB Applications

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Abstract

Here we investigate the UWB performance of a family of symmetrically modified square plate monopole (SPM) antennas. The time domain results on the prototypes of three members of the family viz., Symmetrically Bevelled SPM (SB-SPM) antenna, Symmetrical Smoothed SPM (SS-SPM) antenna and Symmetrically Notched SPM (SN-SPM) antenna are presented. The time-domain UWB characteristics in terms of received pulse waveform and fidelity factor are analysed.

1. Introduction

Ultra-wideband (UWB) wireless technology appears to be a promising solution for short-range personal networks as well as for microwave imaging for the identification of abnormal tissue lesions etc [1].By making use of the UWB pulses, coupled with the dielectric contrast, the location of abnormal tissue legions can be estimated by processing the reflected echo. Thus, use of UWB radar for non-invasive imaging of biological objects is fastly gaining momentum [7]. In all UWB applications, antennas are important components as they can act as filters. Thus, it is imperative to design antennas to meet the UWB operational requirements. Mainly, it is essential that the antennas have ultra-wideband performance particularly with respect to impedance bandwidth (< -10 dB), have omni-directional radiation characteristics and have minimal signal dispersion. It is widely reported in recent antenna literature [2-4, 8] that a broadband planar monopole antenna can be a good candidate for UWB. The antenna shape differs from a basic wire monopole in the way that the element provides a smooth taper relative to the ground plane. By optimizing this taper broadband impedance matching can be obtained quite easily.

Based on this, we have, in the past, proposed a family of symmetrically modified SPM antennas (SB-SPM antenna, SS-SPM antenna and SN-SPM antenna) for UWB operation and presented the antenna performance in terms of impedance bandwidth and radiation characteristics [10]. In this paper, our aim is to present the results of time domain investigation on the UWB characteristics for this family of symmetrically modified SPM antennas.

2. Antenna Design

The schematic diagrams of the symmetrically modified SPM antennas (SB-SPM antenna, SSCB-SPM antenna and SN-SPM antenna) are shown in Fig. 1. We differ from the asymmetrical antenna counterparts [2-4], and apply the modifications both at the bottom and the top of the square plate monopole antenna element symmetrically, thus the name symmetrically modified SPM antennas. For these antennas, the symmetrical plane is the one paralleled to the *x*-*y* plane and crossing the mid-height section of the square plate.

We have made extensive studies by empirically optimising the dimensions of the proposed antennas for impedance bandwidth and radiation pattern performance. The final optimised dimensions are BH = 7mm and BW = 15mm for SB-SPM antenna (Fig. 1 (a)), radius R = 13mm for SS-SPM antenna (Fig. 1 (b)) and NH = 3mm, NW = 7mm for SN-SPM antenna (Fig. 1 (c)), respectively. Other geometry dimensions are set as a = b = 30mm and c = d = 100mm with identical height of 1.5mm between the antenna element and the ground plane.

3. Time-Domain Investigation

To investigate the time-domain UWB characteristics, the essence is to compare the transmitted UWB pulse with the received UWB pulses for a pair of identical antennas. Once the shape of received UWB pulse is guaranteed to be similar to that of the transmitted pulse without losing information, one can say that the antenna under test has low signal dispersion. For this test, the proposed symmetrically modified SPM antennas are theoretically investigated using the commercially available software package High-Frequency Structure Simulator (HFSS®) for time-domain characteristics. To obtain the time-domain characteristics, antennas are arranged in such a way shown in Fig. 2 to form a wireless link. It is a conventional two-antenna light-of-sight (LOS) gain measurement configuration [5], which needs that both

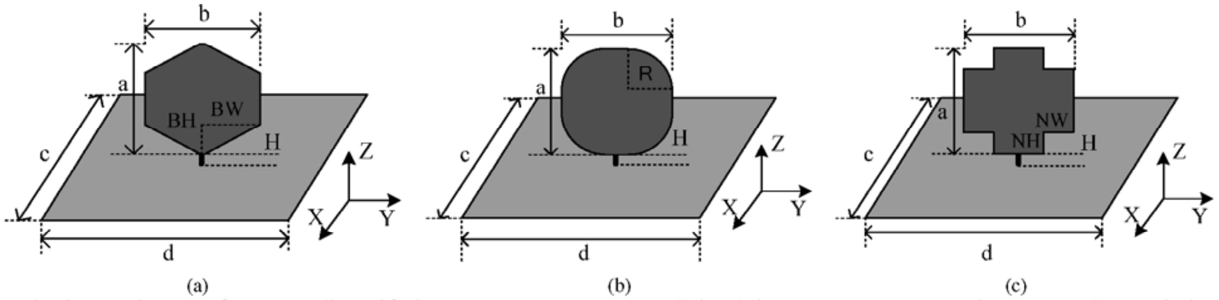


Fig. 1 Schematic diagrams of symmetrically modified SPM antennas. (a) Symmetrically beveled SPM (SB-SPM) antenna; (b) symmetrically smoothed SPM (SS-SPM) antenna and (c) symmetrically notched SPM (SN-SPM) antenna.

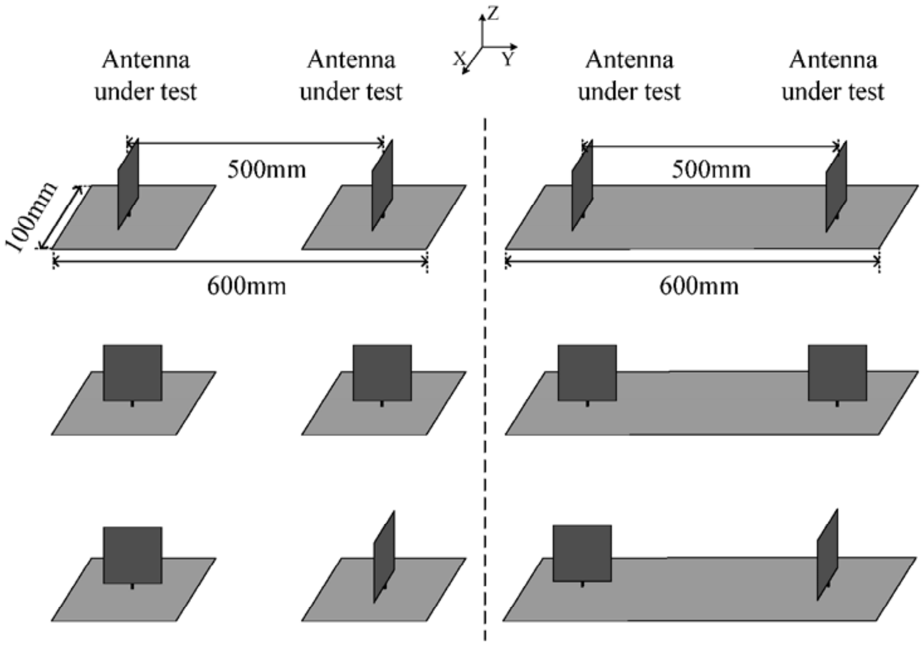


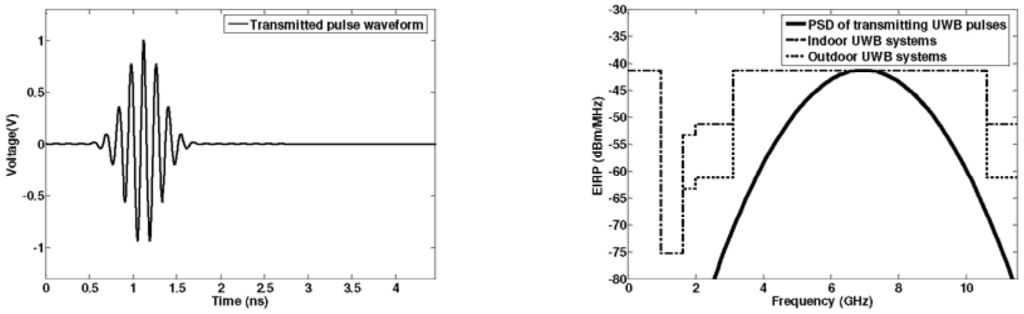
Fig. 2 The schematic of antenna positioning schemes for a 3-D link using both separate ground planes and a single ground plane: (a) Face to face; (b) Side by side and (c) Face to side. For simplicity, a bare square plate monopole (SPM) antenna is depicted here only for illustration.

antennas are in the far-field of each other. The calculated far-field distance is given by [6]:

$$R_{\max} = \frac{2D^2}{\lambda_{\min}} = \frac{2\times 30^2}{28.3} = 63.6mm \quad (1)$$

where $\lambda_{\min}$ is the wavelength at 10.6GHz, which is the higher end of the UWB band.

In our investigations, two of the identical antennas (viz., SB-SPM antenna, SS-SPM antenna and SN-SPM antenna) were arranged in such a way that the distance between their centre points are away at 500mm, which is larger than the maximum far-field distance for these antennas. The antennas under test have different facets. When these antennas are used in a far-field link, the consistency in including all the facets is important as it can influence the energy received which in turn dictates the antenna transfer function therefore has a bearing on the received pulses. Hence, the investigations into the influence of antenna positioning on time-domain characteristics have been carried out. The other aspect is the ground plane of the monopole antennas which plays a crucial role. We have observed that two of the proposed antennas can be mounted on either two separate ground planes or use a single contiguous ground plane for both the measurement and the simulations. Therefore, to include all these possible variations, different investigations with different relative positions that include all possible ground plane configurations between two of the antennas under test have been taken into account for forming a 3-D wireless link for obtaining the time-domain characteristics. In this paper, six typical scenarios as shown in Fig. 2 are used, viz.: face to face, side by side and face to side, on both separate ground planes as well as a single ground plane between two of the antennas under test.



(a) (b)

Fig. 3 (a) Waveform of input pulse and (b) power spectral density of the input pulse normalized to the FCC indoor and out door EIRP masks.

In these investigations, the input is considered to be a modulated Gaussian pulse given by:

$$x(t) = e^{-\frac{(t-4\tau)}{\tau^2}} \sin(2\pi f_0(t-4\tau)) \qquad (2)$$

where f_0 = 7GHz and τ = 280ps. The waveform and normalized power spectral density (PSD) of this pulse are illustrated in Figs. 3 (a) and (b) respectively. It is observed that the spectrum of this source pulse has a peak near 7GHz and a bandwidth of around 5.8GHz, which is sufficiently covered by the UWB band as per FCC mask.

The wireless links formed by a pair of antennas under test has theoretically been investigated by frequency-domain solver HFSS®, therefore it is necessary to perform some signal processing to obtain the UWB characteristics for the antennas under test in time domain. It is well known [6-8], that a system, which is comprised of a transmitting antenna (with non-magnetic media), free space transmission media and a receiving antenna (with non-magnetic media), can be considered as a linear time-invariant (LTI) system. For a LTI system, the system transfer function (here is the antenna transfer function) is independent of the input and output signals. Thus, it would be appropriate to theoretically investigate the UWB characteristics of the antennas under test in time domain using the antenna transfer function obtained from a frequency domain solver.

It is observed that UWB antennas act like a band-pass filter within the band ranging from 1.5GHz to 11.5GHz. We obtained the antenna characteristics within this frequency range by using HFSS® with a frequency resolution of 0.2GHz. Therefore, the highest frequency component of the output signal can be determined by the upper end of the antenna transfer function, which is 11.5GHz in these investigations. The system output $y(t)$ can be obtained using:

$$y(t) = IFT\left[FT\left[x(t)\right]\cdot H(f)\right] \qquad (3)$$

where *IFT* denotes the inverse Fourier transform and *FT* the Fourier transform. Parameters of system input $x(t)$ is given above in eq(2) and the system transfer function (antenna transfer function) $H(f)$ is calculated using HFSS.

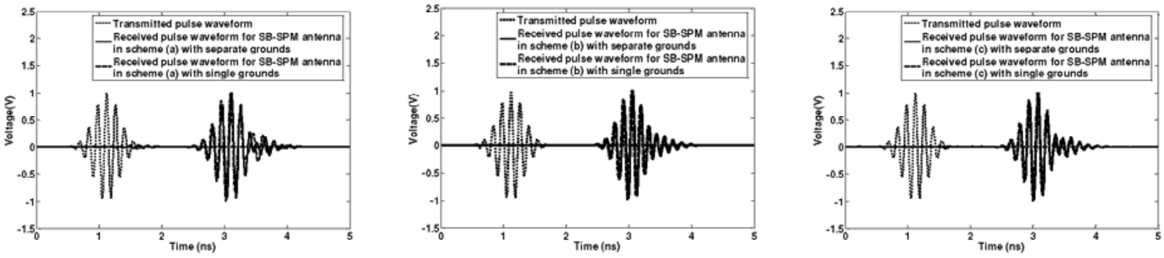
In order to efficiently obtain the time-domain characteristics in these investigations, fast Fourier transform (FFT) technique is used. In our investigations, as the system input $x(t)$ is a band limited signal that is sufficiently covered by the UWB band defined by FCC, and the system performs as a band-pass filter with upper end at 11.5GHz, therefore, in order to reconstruct the system output $y(t)$ without losing information, the sampling frequency for the FFT process should be $f_s \geq 2f_m$ = 23GHz.

Another important issue in the FFT process is to match the frequency domain resolution of Fourier transform of $x(t)$ with the one of antenna transfer function $H(f)$. As stated earlier, system transfer functions (antenna transfer functions) were calculated by using HFSS® in the frequency range between 1.5GHz and 11.5GHz with a frequency resolution of 0.2GHz. Therefore, the FFT of $x(t)$ should also have a resolution of 0.2GHz in frequency domain to make it consistent.

Consequently in the calculation setup, with the above concerns, parameters were set as f_s = 183GHz ≥ 23GHz and T = 1/0.2GHz = 5ns respectively for the FFT processing, where T determines the maximum time value for $x(t)$ accounted in FFT processing. Therefore, with the FFT processing of $x(t)$ and $H(f)$ through the relationship indicated by equation (3), time domain responses $y(t)$ have been calculated for the symmetrically modified SPM antennas in the configuration schemes as shown in Fig. 2. The results are plotted in Figs. 4, 5 and 6 respectively.

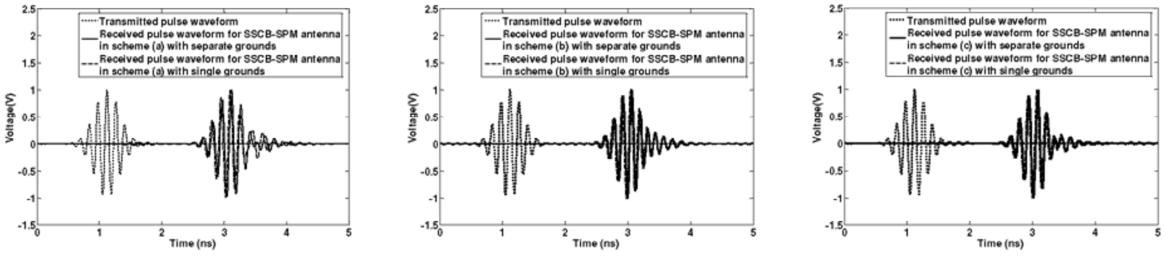
4. Time-Domain UWB Characteristics

As can be observed in Figs. 4-6, the calculated received pulses are well behaved. The performance of late time ringing appears to be within acceptable limits. For SN-SPM antenna as per the configuration scheme (a) of Fig. 2, the late ringing appears to be larger than the others. These results can confirm the suitability of the symmetrically modified SPM antennas for UWB systems including the imaging systems.



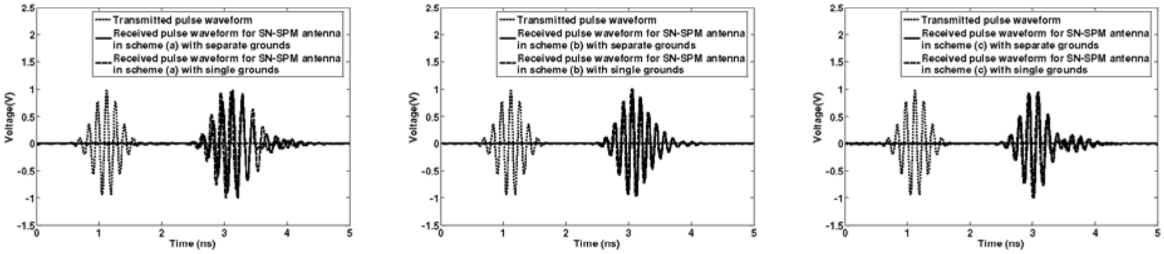
(a) (b) (c)

Fig. 4 Normalized received waveforms of UWB pulses for the SB-SPM antenna for configurations shown in Figs. 2. The dotted waveforms at the left indicate the normalized transmitted UWB pulse.



(a) (b) (c)

Fig. 5 Normalized received waveforms of UWB pulses for the SS-SPM antenna for configurations shown in Figs. 2. The dotted waveforms at the left indicate the normalized transmitted UWB pulse.



(a) (b) (c)

Fig. 6 Normalized received waveforms of UWB pulses for the SN-SPM antenna for configurations shown in Figs. 2. The dotted waveforms at the left indicate the normalized transmitted UWB pulse.

In order to further characterize the time-domain characteristics of symmetrically modified SPM antennas, a well-defined parameter known as 'fidelity factor' is presented to evaluate the capability of pulse detection of an antenna [6]. It is reported that fidelity factor is a measure of how accurately the transmitted waveform reproduces the time derivative of the voltage applied to the antenna terminals or, equivalently, how accurately the received voltage available at the antenna terminal reproduces the transient field incident upon it [7, 9]. However, it is noted that fidelity factor for an antenna is waveform specific [9].

The fidelity factor can be calculated using:

$$Fidelity = \max_{\tau} \int_{-\infty}^{\infty} \hat{y}_r(t-\tau)\,\hat{x}(t)\,dt \qquad (4)$$

where $\hat{y}_r(t)$ is the normalized received pulse and $\hat{x}(t)$ is the normalized transmitted pulse [6]. Therefore, the definition of fidelity factor corresponds to the maximum magnitude of the cross-correlation between the normalized transmitted and received pulses. Here, it is noted that a fidelity factor = 1 indicates a perfect match between $\hat{y}_r(t)$ and $\hat{x}(t)$, which means that the transmitting and receiving antennas do not distort the input pulse at all. For the chosen input pulse given by the eqn (2), the fidelity factor for the symmetrically modified SPM antennas (for the configurations shown in Fig.

TABLE 1: SUMMARY OF FIDELITY FACTOR BETWEEN THE TRANSMITTING AND RECEIVING UWB PULSES FOR THE FAMILY OF SYMMETRICALLY MODIFIED SPM ANTENNAS FOR THE CONFIGURATIONS AS SHOWN IN FIG. 2

Configuration scheme	(a) with separate grounds	(a) with a single ground	(b) with separate grounds	(b) with a single ground	(c) with separate grounds	(c) with a single ground
SB-SPM antenna	0.94829	0.87475	0.92909	0.94369	0.97083	0.96538
SSCB-SPM antenna	0.93741	0.87475	0.90996	0.93944	0.94893	0.94593
SN-SPM antenna	0.79125	0.64541	0.89519	0.9031	0.92831	0.94524

2) have been calculated and the results are summarized in Table 1.

According to the above table, the fidelity factor is mostly greater than 0.9 for the symmetrically modified SPM antennas for most of the configurations as shown in Fig. 2. However, for SN-SPM antenna for the configuration (a) for both the cases of separate ground planes as well as a single ground plane, it is observed that the fidelity factor has slightly degraded, which is an indication that signal dispersion can become significant for these specific scenarios. Otherwise, the results for all the other cases can be considered above satisfactory. These results further confirm the superior low dispersion performance of the proposed family of symmetrically modified SPM antennas for the transmission and reception of UWB signals.

5. CONCLUSION

In this paper, the time-domain UWB characteristics of a family of symmetrically modified square plate monopole (SPM) antennas were theoretically investigated using a frequency-domain solver. The well-behaved time domain responses demonstrate that the antennas under test substantiate their applicability in UWB systems that include microwave imaging applications as they introduce very low distortion. The symmetrically modified SPM antennas are compact and can be fabricated at low-cost which make them highly suitable for compact UWB applications. Further, they can be easily extendable into arrays which would be highly suitable for imaging applications.

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