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UWB PRINTED SLOT ANTENNA WITH IMPROVED PERFORMANCE IN TIME AND FREQUENCY DOMAINS

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Abstract—A microstrip-fed slot antenna is proposed for short-range UWB communication. First, the characteristics of a conventional circular monopole UWB antenna, as a representative of a class of UWB antennas seen in the literature, are examined in time (pulse-shape) and frequency (reflection and transmission coefficients) domains. From these measurements, certain limitations of this class of antennas are brought out, which are not widely recognized. We then demonstrate that with proper optimization the traditional microstrip-fed slot antenna overcomes these defects and is an excellent candidate for UWB communication systems. This claim is justified with measurements in time domain and frequency domain.

1. INTRODUCTION

Ultra-wideband (UWB) technology has received considerable attention in recent years for high data-rate short distance communication in the 3.1 GHz to 10.6 GHz region [1]. A major challenge in the transmission of narrowband pulses is the antenna. From a systems point of view, the response of the antenna should cover the entire operating bandwidth, and the antenna should also be non-responsive to signals outside the specified band. It is not sufficient to evaluate the antenna performance solely through traditional frequency domain parameters such as return loss, radiation patterns and gain. Instead, for short-range high-speed low power UWB communication, it is important to evaluate the waveform distortion during the transient transmission, propagation and reception.

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Many different types of antennas have been recently proposed for UWB applications [2–4]. It can be seen that a circular monopole UWB antenna can be considered as a representative of a class of UWB antennas in the literature [4–6]. For these antennas, return loss and radiation patterns are presented in most of the references. More detailed frequency-domain studies are reported in [5, 6], and calculated impulse responses are reported in [7, 8]. However, actual transmission of UWB pulses and consequent changes in pulse-shape and spectrum have not been demonstrated for these antennas. In this paper, we carry out such studies and show that some of the deficiencies of these planar monopoles can be overcome by using a conventional microstrip-fed slot antenna with minor modifications.

In the comparison of UWB antennas, the primary guideline is the spectral mask recommended for UWB by FCC-USA [1]. The other guideline is the requirement that UWB should work up to 500 Mbps, requiring the received pulses to be < 2 ns in duration (i.e., the ringing should die down well before 2 ns).

The slot-antenna has been known for a long time. Several new ideas of these antennas can be found in [9, 10], but the recent 'slot antennas' are better described as 'aperture antennas'. The difference is that by 'slot' we mean a shape in a plane which is essentially one-dimensional (the length $\sim \lambda/2$) with the other dimension being very small (the width $\ll \lambda$), while an 'aperture' is not restricted. This is further clarified in Fig. 1.

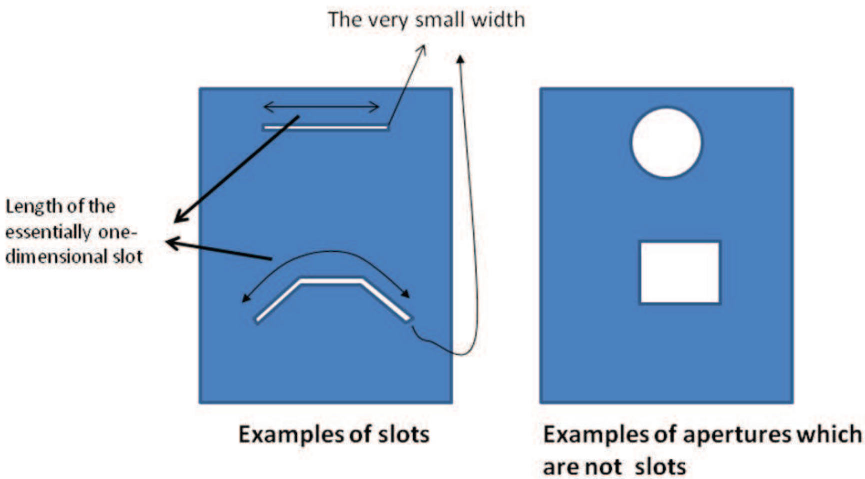


Figure 1. The difference between the terms 'slot' and 'aperture' as used in this work.

We discuss a true 'slot' antenna with very small width. This antenna has been studied since the 1950's but has not been used in UWB systems due to its limited impedance bandwidth. We demonstrate that the traditional impedance-bandwidth characterization is not quite appropriate for UWB communications. When more appropriate ways of characterizing the antenna are considered, the slot-antenna emerges as a very useful antenna. A detailed description of time-domain and frequency-domain properties and their impact on systems is given in [11].

The organization of this paper is as follows. In Section 2, a microstrip-fed circular monopole UWB antenna is described, and its characteristics and limitations are shown in frequency and time domains. Note that this is not a new antenna which we propose — it is discussed in order to bring out certain deficiencies of this class of antennas. In Section 3, design and optimization of the microstrip slot antenna is described. In Section 4, its superior performance along with limitations is presented.

2. CIRCULAR MONOPOLE UWB ANTENNA DESIGN

We mention at the outset that this is not a new antenna proposed by us, but a well-known type of UWB antenna [e.g., [4–7]]. The geometry of the proposed circular microstrip antenna is shown in Fig. 2. These particular dimensions do not belong to any one of the antennas from the references mentioned earlier, because all the required

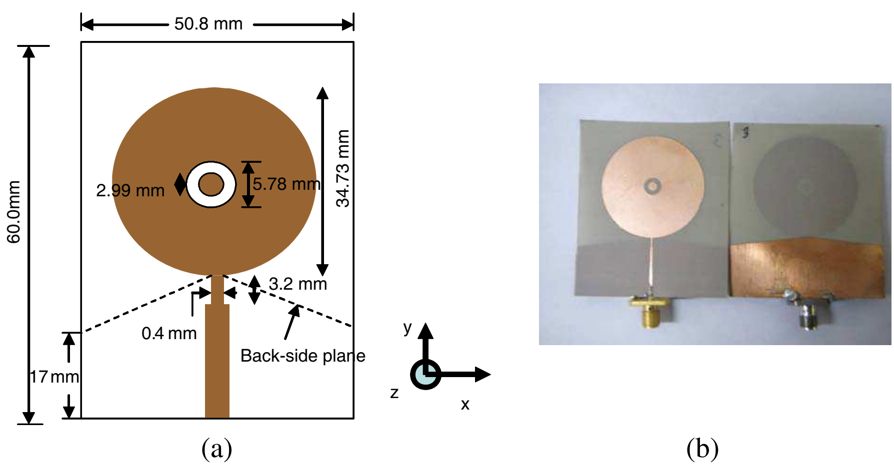


Figure 2. (a) Geometry of circular monopole UWB antenna and (b) fabricated structure (front and back views).

dimensions and other parameters were not given (or were inconvenient to reproduce) in those works to re-fabricate those antennas. However, it has very similar properties (return loss and radiation pattern) and can be considered as a representative of the class of printed monopoles. The antenna has dimension of $50.8 \times 60.0\,\text{mm}^2$ and was printed on substrate of 0.25 mm thickness and relative dielectric constant 2.2. The annular slot dimension and position on the patch and ground plane dimension were optimized using CST Microwave Studio, to obtain maximum impedance bandwidth.

The final optimized geometry of the antenna is shown in Fig. 2 considering the input matching to $50\,\Omega$ line.

2.1. Frequency Domain Properties

The measured and simulated return losses of the antenna are shown in Fig. 3. The 10-dB impedance bandwidth is from around 3 to 10.6 GHz which fulfills the FCC criterion. A small difference is a result of losses and additional SMA connector used in the measurements.

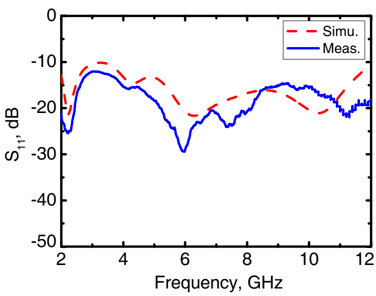


Figure 3. Measured and simulated return loss of circular monopole.

The transmit-receive antenna system can be considered as a two-port network. The transfer function can be measured in terms of S_{21}. The measured parameter S_{21} contains the effect of all the important system parameters as gain, impedance matching, polarization matching, path loss, and phase delay. It is actually the measured transfer function of the UWB communication channel.

The transmission between the two identical UWB antennas was examined in an anechoic chamber. Fig. 4 shows the simulated and measured S_{21} (including group delay) at $D = 300\,\text{mm}$. From Fig. 3 and Fig. 4, it is evident that the impedance bandwidth of the antenna, for 10 dB return loss, covers the whole UWB band very well, but the actual utility of this antenna is from 2–6 GHz and that too with a large gain variation ($\sim 15\,\text{dB}$) with frequency. Group delay was observed to

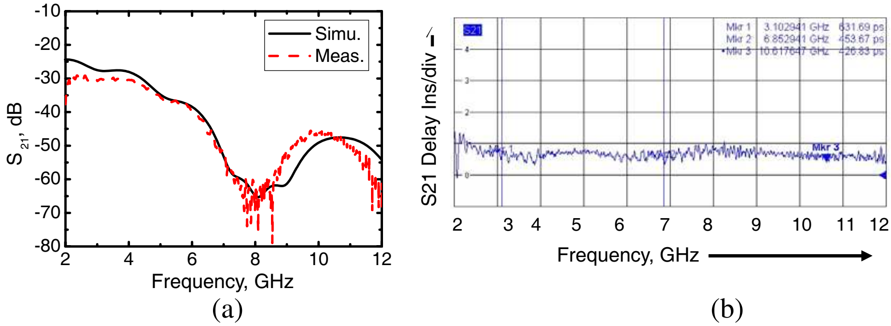


Figure 4. (a) Insertion loss $|S_{21}|$ with 30 cm inter-antenna spacing, and (b) group delay.

be quite flat in Fig. 4(b). This was seen to be true for all printed monopole and slot UWB antennas that were studied.

To explain the limited bandwidth, we turn to the radiation patterns. The radiation patterns for H-plane (normal to the feed line, i.e., x-z plane as in Fig. 2(a)) and E-plane (containing feed line and the normal to the substrate, i.e., y-z plane) are measured at frequencies of 4, 7, and 10 GHz. The simulated and measured H-plane and E-plane radiation patterns are shown in Fig. 5. We can see that at low frequencies, the radiation is primarily broadside, while at higher frequencies much of the radiation goes parallel to the substrate.

It is clear from this that the bandwidth is actually not fully evident from S_{11} alone and actually depends on the direction of maximum radiation as a function of frequency. These aspects have been mentioned in some references. For example, [6] has described an antenna with excellent gain flatness, although time-domain measurements were not described. However, references to UWB antennas can be seen to over-emphasize the impedance bandwidth aspect.

2.2. Time Domain Characteristics

The setup for overall transceiver characterization is shown in Fig. 6. A high-speed oscilloscope (Agilent DSA91304A) was used to observe the received pulses. The UWB pulse generating circuit has been described earlier in [12], and here only the final received pulse is shown in Fig. 7. The spectrum (see Eqs. (1) and (2) in Section 3) is shown in Fig. 8. The pulse shape of Fig. 7 can actually be further optimized by changing the dimensions of the antenna, and the effective received pulse duration can be brought down to ~ 1 ns.

To minimize ringing between the circuit and the antenna, a 10 dB attenuator was inserted between them. It is interesting to note that while the time-domain pulse shape appears acceptable, the spectrum is quite unsatisfactory. This is easily correlated with the antenna transfer function in Fig. 4(a). We next describe a new antenna which overcomes most of these issues.

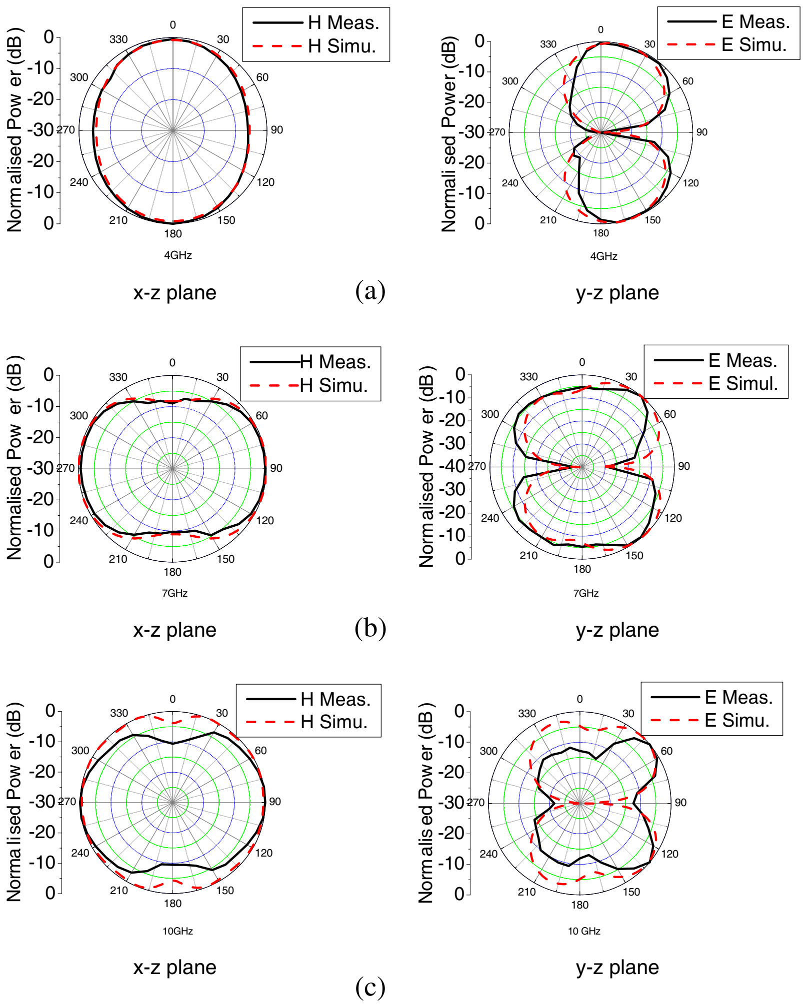


Figure 5. Simulated and measured *E*-plane and *H*-plane radiation pattern for the centre frequency (a) 4 GHz, (b) 7 GHz, and (c) 10 GHz. 0° is the broad-side direction.

3. UWB SLOT ANTENNA

The microstrip-fed slot antenna has been known for a long time [13], but has not been applied to UWB systems, because its 10-dB impedance bandwidth does not cover the 3–10 GHz band. However, we depart from the traditional starting point of impedance bandwidth when designing the antenna, and instead optimize the insertion loss between 2 antennas for the 3–10 GHz band (including low out-of-band response). Note that for UWB systems efficient radiation of available power is not a priority (power levels are often kept deliberately low) but proper spectrum utilization and low pulse distortion are crucial.

The antenna proposed is shown in Fig. 9. As can be seen from the dimensions, this is a true slot (see Fig. 1) with a width of 0.3 mm. As is the case for slot antennas, the performance is quite insensitive to the width. Many UWB antennas have been proposed which have circular or polygonal 2-D apertures in the ground plane, but relatively few use proper slots in this sense. The benefit will be shortly apparent. Apart from the parameters L_R and L_m (which are conventionally regarded as the primary dimensions governing the operation of the antenna) it was seen that the substrate dimension was also important.

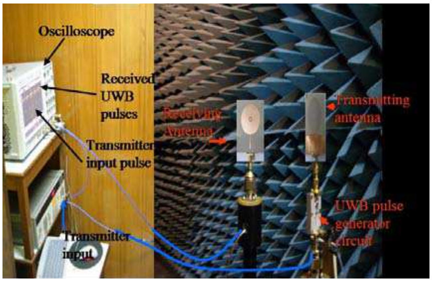


Figure 6. Measurement setup for time domain parameters.

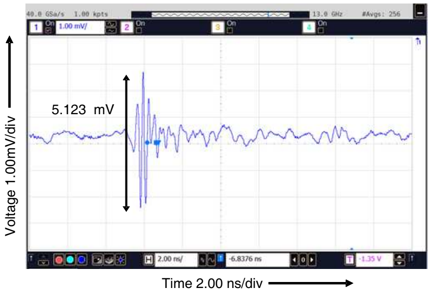


Figure 7. UWB pulse shape received.

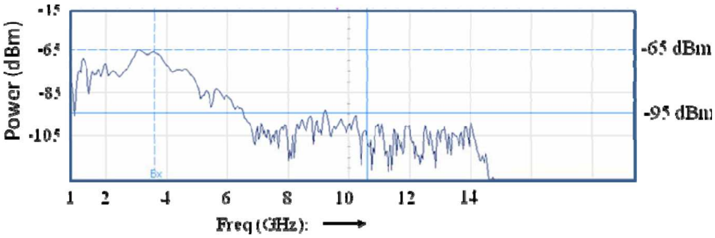


Figure 8. Spectrum of the received pulse.

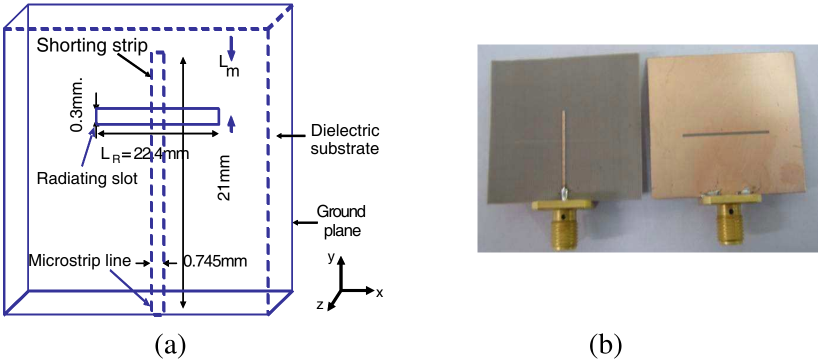


Figure 9. The slot antenna parameters and (b) the final fabricated antenna.

3.1. Microstrip UWB Slot Antenna Design

The printed slot antenna shown in Fig. 9 is designed to cover the UWB band of 3.1–10.6 GHz on a piece of dielectric substrate ($\varepsilon_r = 2.2$ and thickness $= 0.25$ mm) of size 30.4 mm × 35.4 mm. The simulation and optimization of the antenna is carried out using CST. The optimized dimensions are shown in Fig. 9.

Various structural parameters are systematically varied, one at a time, to improve the performance of antenna in terms of S_{21} as mentioned. A detailed analysis to study the effect of variations of various structural parameters on the antenna performance was carried out, but due to space constraints, only two samples results are shown here. Fig. 10 shows the variations of return loss of antenna as a function of frequency for various values of L_R. Note that the return loss is quite poor, especially at lower frequencies.

Figure 11 shows the variation of insertion loss from one antenna to another, as a function of frequency, for various values of L_m. It is observed that as L_m is increased, bandwidth is decreased.

The final optimized values were: $L_R = 22.4$ mm and $L_m = 6.15$ mm, using a symmetrically fed slot with substrate size as mentioned.

3.2. UWB Slot Antenna Measurements in Frequency Domain

The transmission between two identical optimized antennas was measured in an anechoic chamber. The antennas under test (AUT) were placed with slots parallel and facing each other, at a separation D. Fig. 12 shows simulated and measured $|S_{21}|$ or the distance

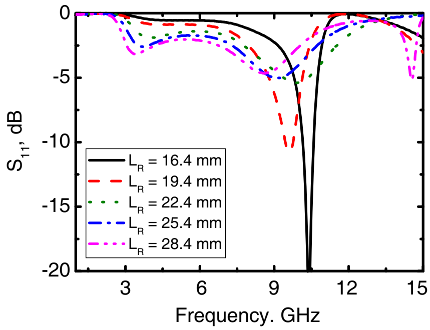


Figure 10. Return loss versus frequency characteristics for various values of L_R ($L_m = 6.15\,\mathrm{mm}$).

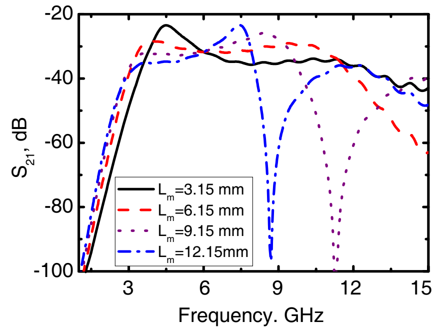
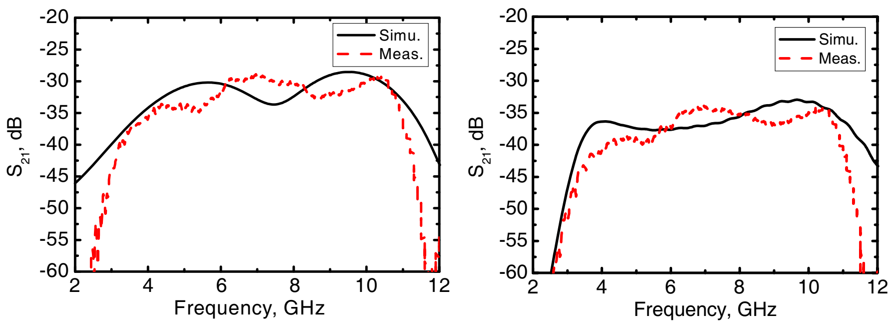


Figure 11. Insertion Loss versus frequency characteristics for various values of L_m ($L_R = 22.4\,\mathrm{mm}$).



(a) (b)

Figure 12. Simulated and measured $|S_{21}|$ for the distance (a) $D = 150\,\mathrm{mm}$, (b) $D = 300\,\mathrm{mm}$.

$D = 150\,\mathrm{mm}$ and $300\,\mathrm{mm}$. There is some discrepancy in the peaks and dips between the measured and simulated curves, which we believe is due to the co-axial connectors (mismatch as well as spurious radiation), but this is unconfirmed as of now.

The insertion loss $|S_{21}|$ between the slot antenna and a broad-band (0.8–18 GHz) horn antenna, separated by 0.5 m was also measured, as shown in Fig. 13. This is actually a measurement of just the transmitting characteristics of the slot antenna and confirms that the emissions are indeed within the permitted band, with very little out-of-band radiated signal.

Finally, we show the radiation patterns and gain for this antenna. The simulated and measured H-plane and E-plane radiation patterns are plotted in Fig. 14. It is evident from the figures that the pattern

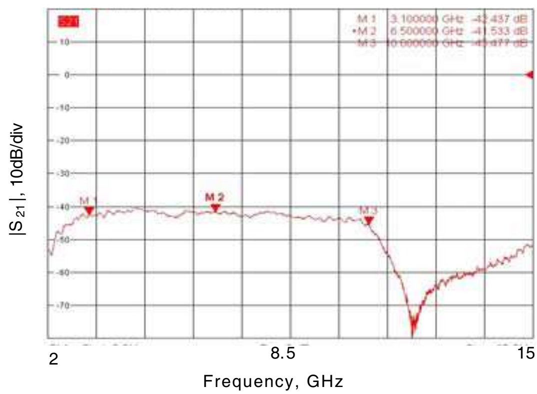


Figure 13. S_{21} between slot antenna and broadband horn antenna.

changes little across the band, in marked contrast to the circular monopole.

The measured gain (strictly speaking 'realized gain' which includes return loss as well as dissipative loss) is shown in Fig. 15. As we expect from Figs. 10–11, the poor return loss leads to a low value of gain at the lower frequencies. A low gain is of little concern in UWB systems, where power may actually be intentionally reduced to noise levels. More important is flat $|S_{21}|$ and group delay (which we have not shown here, but has been seen to be very flat, for the printed monopoles as well as slot antennas).

3.3. Time Domain Characteristics of UWB Slot Antenna

The setup for this measurement remains the same as in Fig. 6, only the antennas are now the UWB slots. The received pulses are shown in Fig. 16. It was observed that the ringing is difficult to reduce, and the effective pulse width is ~ 1.5 ns. Comparing the spectrum to Fig. 8, we can clearly see the benefit — significantly reduced powers below 3 GHz, and significant power received all the way to 9 GHz. Not that UWB standards are more specific about the spectrum than pulse-shape. A pulse duration of 1.5 ns is ample for data transmission at 500 Mbps.

If the generated pulse contains negligible energy below 3 GHz then this antenna would perhaps be inferior, but as has been noted in [14], generating such pulses requires sophisticated circuitry or filters — both of which are made redundant by this antenna.

For completeness, we mention here that by spectrum, we mean the Fourier transform of the waveform, defined in this case by the following

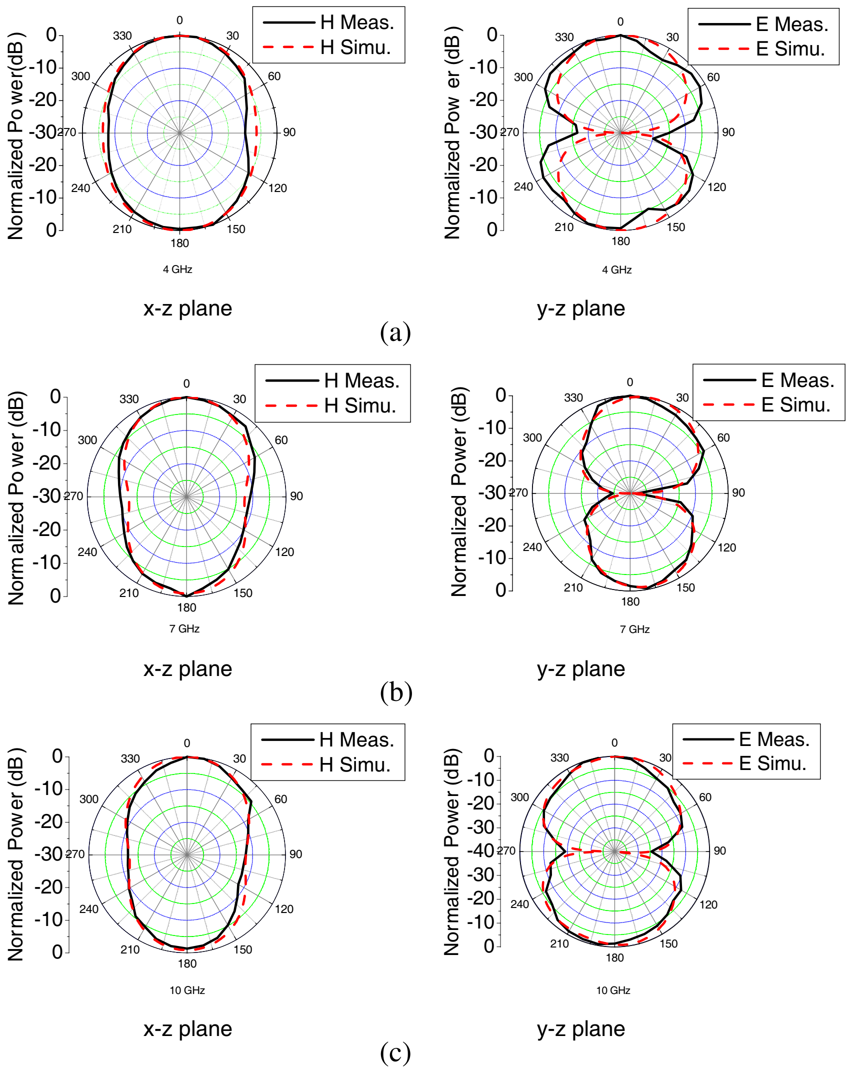


Figure 14. Simulated and measured H-plane and E-plane radiation pattern for the centre frequency (a) 4 GHz, (b) 7 GHz, and (c) 10 GHz. 0° is the broad-side direction.

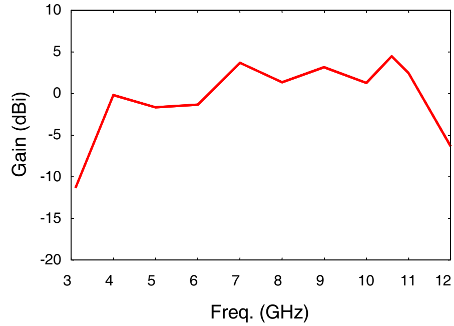
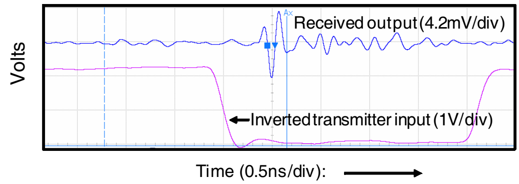
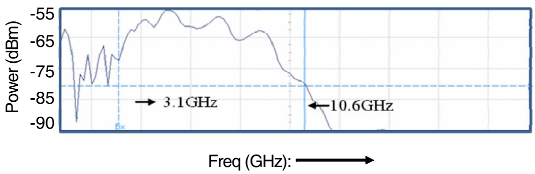


Figure 15. Measured gain of the UWB slot antenna.



(a)



(b)

Figure 16. (a) The received UWB pulse and (b) the frequency spectrum.

equation [14]:

$$V(f) = \frac{1}{T}\int_0^T v(t)e^{-j(2\pi f)t}dt \tag{1}$$

Its magnitude for $f > 0$ is plotted in dBm using the following expression:

$$V_{\text{dBm}}(f) = 10\log\left(\frac{2|V(f)|^2/50}{0.001}\right) \tag{2}$$

the factor of 2 being used to account for the power in negative frequencies. For an oscilloscope sampling rate of N samples/sec, and a data set of P points, T obviously comes out to (P/N) sec.

4. CONCLUSION

The microstrip-fed slot antennas has been proposed for UWB communications using narrow pulses. An optimized prototype has been fabricated, and its electrical characteristics have been measured. It has been demonstrated via simulated and measured results that the spectral response of this antenna is better than most of the printed monopoles proposed in the literature, at the cost of somewhat increased (but well within usable limits) pulse duration due to ringing.

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