LINEAR SYSTEM APPROACH TO ULTRAWIDEBAND ANTENNA DISTORTION ANALYSIS

Pedro Luis Carro
Electronics Engineering and Communications
University of Zaragoza, Spain

Jesus de Mingo
Electronics Engineering and Communications
University of Zaragoza,Spain

ABSTRACT

Since the Federal Communications Commission (FCC) approved rules for the commercial use of ultrawideband (UWB) radio applications, UWB antenna structures have been an intensive research field in order to satisfy the spectrum requirements of this technology. There are some differences between narrowband and UWB antennas. First of all, the design process in UWB antennas is more difficult than in narrowband cases since the antenna has to radiate in an extreme bandwidth. Because of this fact, UWB antennas may distort waveforms, in contrast to narrowband systems. The contribution to distortion comes from two different points: radiation patterns and mismatch. In this paper, the distortion introduced by UWB antennas is analysed using a linear system approach which takes into account both contributions. In order to compare two antennas and show the method suitability, measured transfer functions obtained from to UWB geometries are used, computing metrics dependent on the communication direction.

I. INTRODUCTION

Ultrawideband (UWB) technologies have been a focus of intense research over the last few years. The UWB antenna element design, considered one of the bottle-necks in a UWB wireless communication systems, is one of the keys in order to achieve good performances. Broadband applications require the radiating structure to have a good impedance matching and high radiation efficiency in the whole band. The Federal Communication Commission (FCC) has established a frequency range from 3.1 GHz to 10.6 GHz for UWB, that is, a bandwidth ratio around 3.3:1. Accomplishing all UWB antenna requirements is extremely difficult, but some geometries have been proposed [1-5]. Typicall examples include printed monopoles and dipoles on substrates.

As well as the good electrical performance in the UWB sense, there are some additional problems which are not necessary to be considered in a narrowband design. Antenna distortion becomes important when high bandwidths are involved in the communication process. Therefore, antenna parameters as group delay or transfer functions must be study. In addition, a time domain approach in contrast to the classical frequency domain analysis is required to characterize carefully the antenna behaviour.

In order to study the distortion introduced by the antennas, correlation methods have been used [6-8].In this paper, the transmitter and receiver antennas are considered as a linear system modelled by differential equations. By this approach, it is easily identified the error terms, and thus, the antenna distortion, without working out any correlation. This may have some advantages, since correlation methods are associated to signal waveforms. The problem that we try to answer is, therefore ,given two UWB antennas, A and B, which one will introduce more distortion in the system regardless the input waveform. On the other hand, it is important to notice that correlation analysis it is needed in order to compute with accuracy the distorted waveform.

This paper is organized as follows. The antenna distortion mathematical analysis is presented in the next section. Afterwards, transfer functions of in-house UWB printed dipole antennas measured in the anechoic chamber are presented. Finally, the formalism , applied to a set of UWB printed antennas using the experimental results is presented, obtaining conclusions about the distortion.

II. UWB ANTENNA DISTORTION MODELLING AS A LINEAR SYSTEM

A. *General modelling*

Fig. 1 shows the typical structure of a UWB antenna system. It consists in one UWB antenna working as transmitter and other working as receiver. Due to the linearity of Maxwell equations, the system can be modelled as a linear system and therefore, the system output can be computed as a convolution between the input waveform and the overall system transfer function.

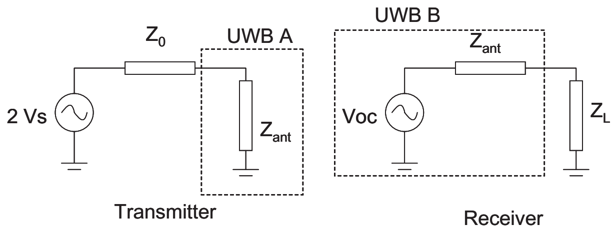

Figure 1: UWB Transceiver simple model

If a linear system does not introduce distortion in the transmitted signal, it should obey:

$$y(t) = \alpha_0 x(t - t_0) \quad (1)$$

where α may be seen as a gain or, more usually, as a attenuation due to the propagation, and t_0 is related to the propagation time of the waveform in free space. Here we will assume that real signals are involved, and therefore that coefficients are real. If the system introduces distortion, the output signal in direction Ω can be expressed, provided no feedback, as:

$$y(t, \Omega) = \alpha_0 x(t - t_0, \Omega) + \alpha_1 \frac{dx(t - t_0, \Omega)}{dt}$$

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$$+ \ldots + \alpha_n \frac{dx^n(t - t_0, \Omega)}{dt^n} \quad (2)$$

Therefore, the terms of the derivatives may be considered as distortion terms if compared with equation (1). Let us assume that $t_0 = 0$ with no loss of generality. Applying a Fourier Transform to (2), the transfer function becomes:

$$H_t = \alpha_0 + \alpha_1 j\omega + \alpha_2 (j\omega)^2 + \ldots \quad (3)$$

On the other hand, it is possible to compute the transfer function of two-antenna system by using the concept of the effective length [9-10]:

$$S_{21}(\omega, \Omega) = 2\frac{j\omega\mu}{Z_0} h_r(\omega, \Omega) h_t(\omega, \Omega) \frac{e^{-j\beta r}}{4\pi r} \quad (4)$$

where β is the propagation constant, and h_r, h_t correspond to the realized effective length, that takes into account the mismatch between generator, receiver load, and antennas. Thus:

$$h_t(\omega, \Omega) = \frac{2}{1 - S_{11}(\omega)} \left(\mathbf{r} \times \mathbf{r} \times \int_V \vec{J}(\vec{r'}) e^{j\beta \hat{\mathbf{r}} \vec{\mathbf{r}}'} dV' \right) \quad (5)$$

Let us consider two antennas, A and B, and a reference antenna (REF). Transfer functions between REF and A, and REF and B may be obtained either by simulation or experimentally. Applying (4) to each configuration:

$$h^A = \frac{S_{21}^{A-Ref} Z_0 2\pi r e^{j\beta r}}{\mu h_{REF}} \quad (6)$$

$$h^B = \frac{S_{21}^{B-Ref} Z_0 2\pi r e^{j\beta r}}{\mu h_{REF}} \quad (7)$$

Therefore:

$$\frac{h^A}{h^B} = \frac{S_{21}^{A-Ref}(\omega, \Omega)}{S_{21}^{B-Ref}(\omega, \Omega)} \quad (8)$$

Taking into account eq. 3 , each S_{21} may be modelled in this way, and the quotient between transfer functions may be expressed as:

$$\frac{h^A}{h^B} = \frac{S_{21}^{A-Ref}(\omega, \Omega)}{S_{21}^{B-Ref}(\omega, \Omega)} \simeq \frac{\alpha_0}{\delta_0} \frac{1 + \frac{\alpha_1}{\alpha_0} j\omega + \ldots + \frac{\alpha_n}{\alpha_0}(j\omega)^n}{1 + \frac{\delta_1}{\delta_0} j\omega + \ldots + \frac{\delta_n}{\delta_0}(j\omega)^n} \quad (9)$$

If the antennas do not introduce distortion, this quotient should be

$$\frac{h^A}{h^B} \simeq \frac{\alpha_0}{\delta_0} \quad (10)$$

and therefore, it may be defined a Distortion Factor (DF) as:

$$DF = \frac{1 + \frac{\alpha_1}{\alpha_0} j\omega + \ldots + \frac{\alpha_n}{\alpha_0}(j\omega)^n}{1 + \frac{\delta_1}{\delta_0} j\omega + \ldots + \frac{\delta_n}{\delta_0}(j\omega)^n} \quad (11)$$

Looking at (10), we conclude that if $\alpha_0 > \delta_0$,since the test has been performed using the same transmission power, Antenna A is, on average, more directive in UWB than antenna B, as this term is related to the received power in the load.

B. *First Order Test from Distortion Factor*

In order to extract some conclusions from DF, a hypothesis will be adopted to simplify this factor: it will be considered derivatives of higher order than one have little influence in the distortion factor. This hypothesis is logic since higher order coefficients will decrease as long as the order derivative is increased. As a result, distortion factor is written as:

$$DF \simeq \frac{1 + \frac{\alpha_1}{\alpha_0} j\omega}{1 + \frac{\delta_1}{\delta_0} j\omega} = \sqrt{\frac{1 + \frac{\alpha_1^2}{\alpha_0^2}\omega^2}{1 + \frac{\delta_1^2}{\delta_0^2}\omega^2}} e^{j\left(\arctan \frac{\alpha_1}{\alpha_0}\omega - \arctan \frac{\delta_1}{\delta_0}\omega\right)} \quad (12)$$

Supposing $\delta_1/\delta_0 j\omega << 1$ since is a error term, DF becomes:

$$DF \simeq \left(1 + \frac{\alpha_1}{\alpha_0} j\omega\right)\left(1 - \frac{\delta_1}{\delta_0} j\omega\right) \quad (13)$$

or

$$DF \simeq 1 + \left(\frac{\alpha_1}{\alpha_0} - \frac{\delta_1}{\delta_0}\right) j\omega + \frac{\alpha_1}{\alpha_0}\frac{\delta_1}{\delta_0}\omega^2 \quad (14)$$

If the system is ideal, then DF should be equal to one, and then, some conclusions are obtained:

- if $\frac{\alpha_1}{\alpha_0} > \frac{\delta_1}{\delta_0}$ then antenna A is worse in a distortion sense than B, since its contribution to the error in (14) is higher.
- if $\frac{\alpha_1}{\alpha_0} = \frac{\delta_1}{\delta_0}$ this first order test fails, and more derivatives in time domain will be needed because the contribution in a first order DF is the same for A and B.
- if $\frac{\alpha_1}{\alpha_0} < \frac{\delta_1}{\delta_0}$ then, as the same reason as before antenna B is worse in a distortion sense than A, since its contribution to the error in (14) is higher.

Coefficients involved in the test may be computed from the measurements done in an anechoic chamber. These criteria may be used in a very wide range of situations , and it will be applied in the following sections to some cases. Note that in the above procedure no correlation or waveform is used, as the transfer function is considered enough to describe the whole system.

III. Antenna Geometries and Measured Transfer Functions

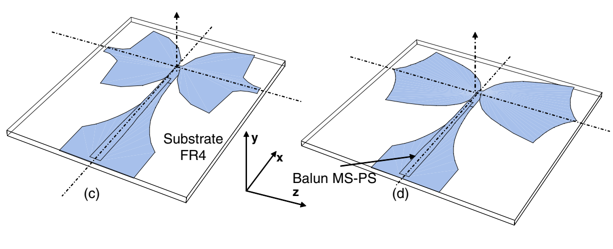

Figure 2: Coordinate Reference System in antenna measurements

Three UWB band antennas working from 3.1 GHz to 10.6 GHz have been used in order to prove the capability of the algorithm. These antennas are depicted in Fig. 3,4. As seen, they consist on printed strips on FR4 substrate. The structure is the same in all three but different shapes provide different transfer functions. Although its performance as far as the return losses are concerned are nearly the same, distortion depends on the radiation patterns and there may be one geometry that could be more suitable from the distortion point of view.

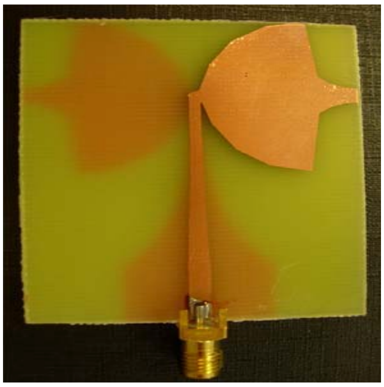

Figure 3: Reference Antenna used to measure transfer function

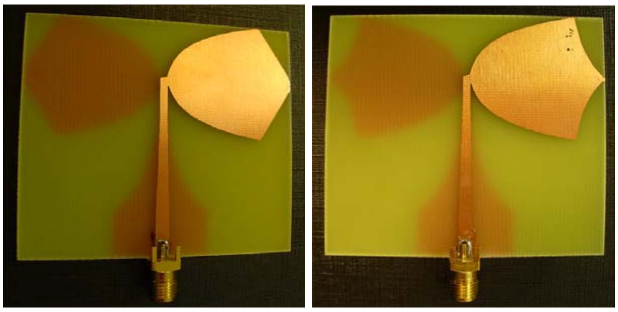

Figure 4: A and B test beds

The measured return losses for these radiators are presented in Fig. 5. according to the reference system in Fig.3. As presented, these results are close in the frequency band to the usual constrain of -10dB and fulfill the requirement of $VSWR < 2$ (equivalent to $S_{11} < -9.5dB$). The design process for these radiating structures is described in [11]. Measured transfer functions have been obtained using the best antenna in the sense of return losses.

Transfer functions have been measured in an anechoic chamber (see Fig 6) using a calibration on feeding and receiving points so that cable effects are removed. In order to reduce the multipath effect, the data have been processed by windowing these components. The scattering parameter S_{21} has been measured in several antenna orientations (0, 45 and 90 approximately) for both antennas using the network analyzer ANRITSU 37247D. It has been obtained in a frequency band from 2GHz to 12GHz, using 1601 points in the measure.

Transfer functions in H-plane are presented in Figs. 7-8. These figures show that the transfer functions are different for each angle, and therefore distortion is dependent on direction. It should be stressed out that although the mathematical approach from section I is applied for two different antennas, it

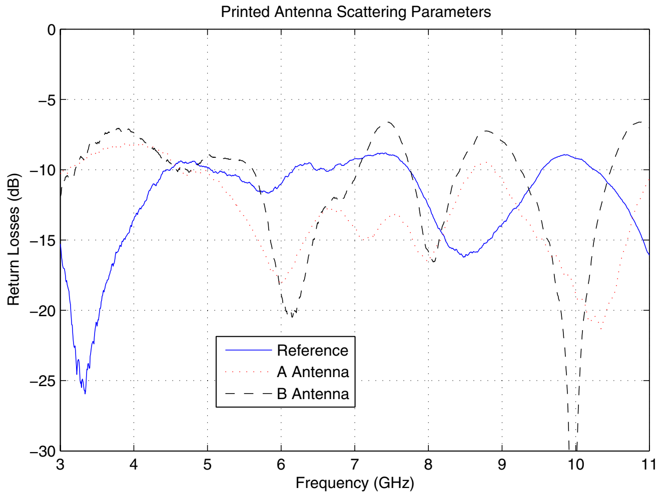

Figure 5: Return loss of PS-antennas.

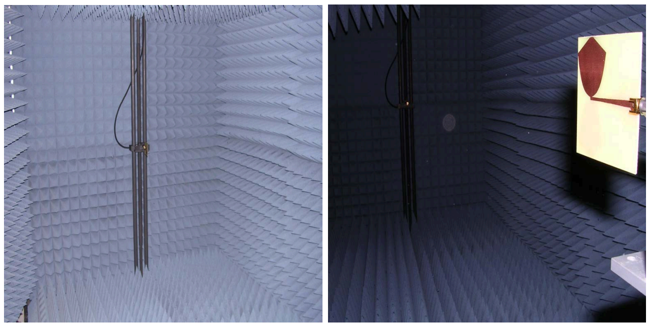

Figure 6: Reference Antenna and overall test system.

can be applied to the same antenna but in different directions. In this case, this analysis will lead to a best direction in order to establish communications from the distortion point of view.

IV. Experimental Analysis

Measurements results and their comparison to modelled results using a 4th order approximation are presented in Figs. 9 and 10. A linear approach as equation (3) has been applied to each S-parameter in order to compute the modelling coefficient values. Table I shows this computed values.

TABLE 1: MODEL COEFFICIENTS

DIR./ COEF.$\times 10^{-5}$	α_0	α_1	α_1/α_0
ANTENNA A	α_0	α_1	α_1/α_0
0	2.015	0.017	**851.3**
$\pi/4$	2.059	0.019	**947.9**
$\pi/2$	1.93	0.019	**970.1**
ANTENNA B	δ_0	δ_1	δ_1/δ_0
0	2.72	0.024	**869.2**
$\pi/4$	2.56	0.025	**984.4**
$\pi/2$	2.13	0.021	**969.8**

From those, several conclusions may be obtained. First of

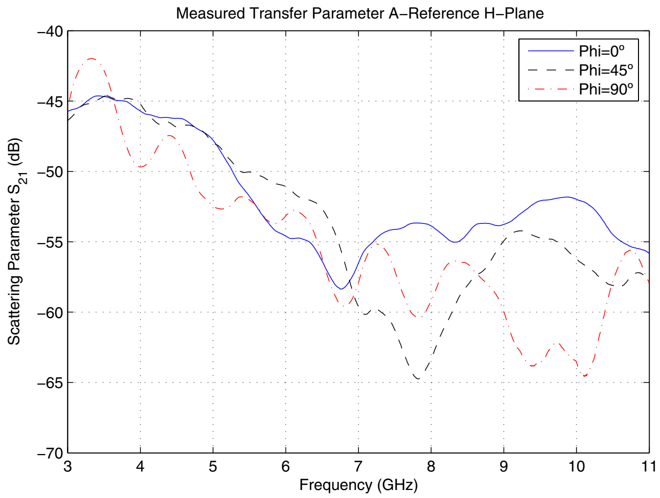

Figure 7: Measured Scattering Parameter S_{21} A

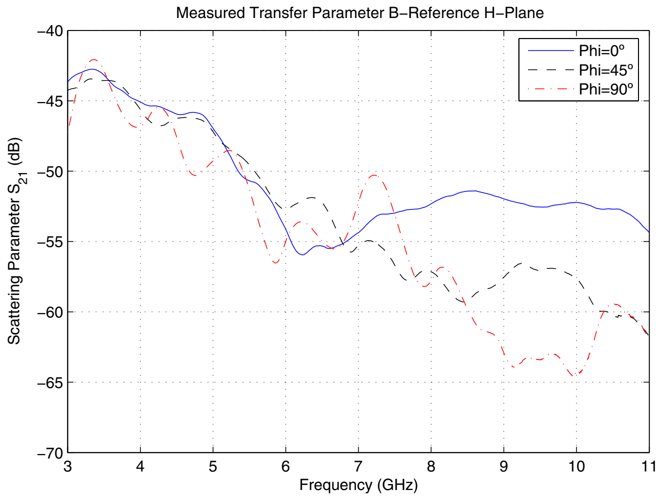

Figure 8: Reference Antenna and overall test system.

all, a comparison between antennas reveals that antenna A is better in two directions that antenna B. Besides, this metrics is very similar to the case of $\pi/2$ so, the Antenna A has better perfomance in terms of distortion than antenna B. However, regarding the independent coefficient, it is clear that the one corresponding to antenna B is higher than antenna A. This means that, provided a receiver sensibility constant with frequency, antenna B can reach more distance. Therefore, a tradeoff between distance and distortion can be expected.

A second analysis is related to a direction analysis. Results suggest that as the angle increases, the distortion increases. This can be confirmed by looking at the measured results, since these curves are more uniform in low angles. These behaviour is concerned with radiation pattern.

Besides, transfer function measurements allows us to study the group delay. This parameter is computed as:

$$\tau_g = -\frac{d\phi}{df} = -\frac{dS_{21}(f)}{df} \tag{15}$$

As seen, group delay is very stable in direction 0 and is de-

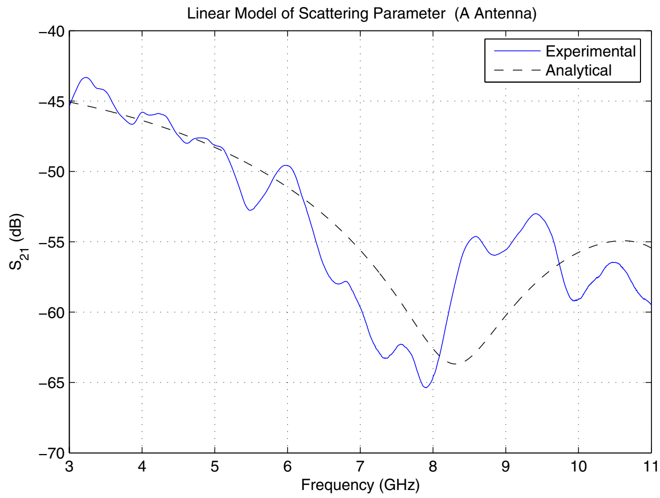

Figure 9: Absolute Value of Transfer Parameter S_{21} for Antenna A

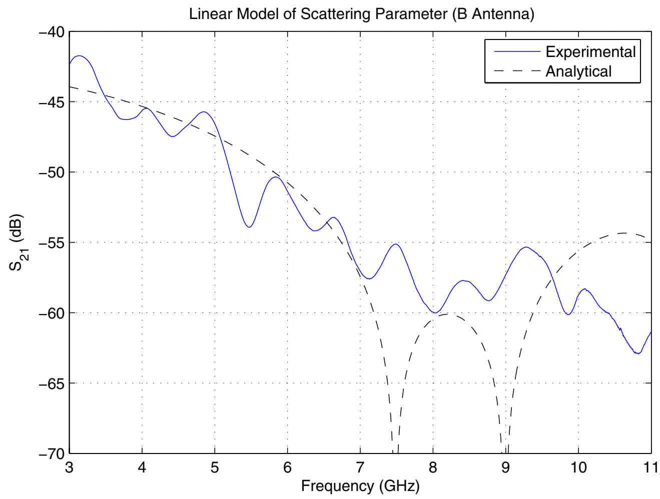

Figure 10: Absolute Value of Transfer Parameter S_{21} for Antenna B

grading as the angle increases for both antennas. Despite, it is quite uniform in the whole band. This is due to the fact that these antennas present a good phase center stability. However, the variation may be quite large in other antennas such as log-periodic type antennas.

V. Conclusions

A procedure based on linear system modelling for antenna transfer functions in UWB has been developed in order to study distortion introduced by the antenna in a UWB communication system. This procedure is developed so that two different antennas can be compared without the need of computing any correlation. It has been applied to two radiating structures showing that antenna distortion depends on the transmission direction. This degradation is quantified by means of the model coefficients used in the process. In addition the method allows contrasting the tradeoff between distance and distortion in a simple

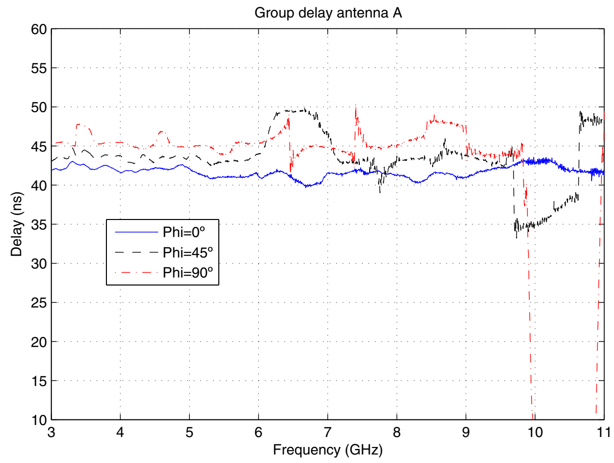

Figure 11: Group Delay in different directions antenna A

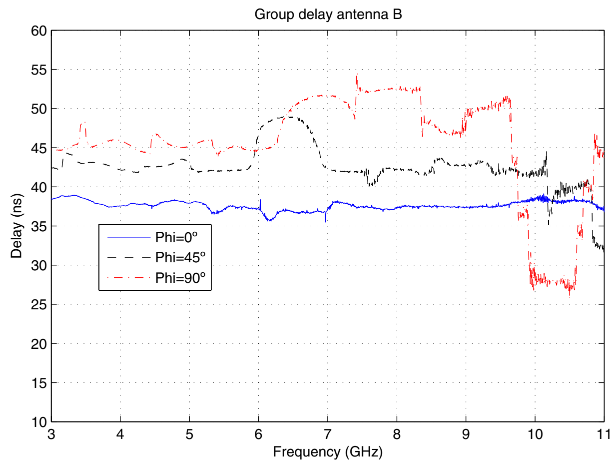

Figure 12: Group Delay in different directions antenna B

way.

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References

[1] Guofeng Lu; von der Mark, S.; Korisch, I.; Greenstein, L.J.; Spasojevic, P.; "Diamond and rounded diamond antennas for ultrawide-band communications", Antennas and Wireless Propagation Letters, Volume 3, Issue 1, 2004 Page(s):249 - 252

[2] Jianxin Liang; Chiau, C.C.; Xiaodong Chen; Parini, C.G.;"Study of a printed circular disc monopole antenna for UWB systems", IEEE Transactions on Antennas and Propagation, Volume 53, Issue 11, Nov. 2005 Page(s):3500 - 3504

[3] Seong-Youp Suh; Stutzman, W.L.; Davis, W.A.;"A new ultrawideband printed monopole antenna: the planar inverted cone antenna (PICA)" IEEE Transactions on Antennas and Propagation, Volume 52, Issue 5, May 2004 Page(s):1361 - 1364

[4] Tzyh-Ghuang Ma; Chao-Hsiung Tseng;"An ultrawideband coplanar waveguide-fed tapered ring slot antenna", IEEE Transactions on Antennas and Propagation, Volume 54, Issue 4, April 2006 Page(s):1105 - 1110

[5] Low, Z.N.; Cheong, J.H.; Law, C.L.; "Low-cost PCB antenna for UWB applications" Antennas and Wireless Propagation Letters, Volume 4, 2005 Page(s):237 - 239

[6] Telzhensky, N.; Leviatan, Y.; "Novel method of UWB antenna optimization for specified input signal forms by means of genetic algorithm", IEEE Transactions on Antennas and Propagation, Volume 54, Issue 8, Aug. 2006 Page(s):2216 - 2225

[7] Do-Hoon Kwon; "Effect of antenna gain and group delay variations on pulse-preserving capabilities of ultrawideband antennas", IEEE Transactions on Antennas and Propagation, Volume 54, Issue 8, Aug. 2006 Page(s):2208 - 2215

[8] Dissanayake, T.; Esselle, K. P.; "Correlation-Based Pattern Stability Analysis and a Figure of Merit for UWB Antennas" ,IEEE Transactions on Antennas and Propagation ,Volume 54, Issue 11, Part 1, Nov. 2006 Page(s):3184 - 3191

[9] Licul, S.; Davis, W.A.; "Unified frequency and time-domain antenna modeling and characterization" , IEEE Transactions on Antennas and Propagation ,Volume 53, Issue 9, Sept. 2005 Page(s):2882 - 2888

[10] Shlivinski, A.; Heyman, E.; Kastner, R.; "Antenna characterization in the time domain" ,IEEE Transactions on Antennas and Propagation,Volume 45, Issue 7, July 1997 Page(s):1140 - 1149

[11] Carro, P.L.; Gracia,R. ,de Mingo, J.; "Parallel-Strip-Fed Antenna designs in Ultrawideband applications", IEEE Antennas and Propagation Society International Symposium 2007