*Progress In Electromagnetics Research, Vol. 112, 441–457, 2011*

# A ROBUST CAD TOOL FOR INTEGRATED DESIGN OF UWB ANTENNA SYSTEM

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**Abstract**—This paper proposes a robust Computer-Aided Design (CAD) tool for an Ultra-Wideband (UWB) antenna system which successfully integrates the design of the transmitting antenna, the receiving antenna and the shaping of the transmitted pulse. The distinctive features of this tool include: the efficient characterization of transfer function in terms of an analytical model, the effective evaluation from system point of view and the simultaneous optimization of multiple objectives. Using this tool, an automatic and efficient design can be realized to deliver the UWB antenna system upon the optimal performance.

## 1. INTRODUCTION

The recent interest in the UWB technology has revived the enthusiasm in the UWB antenna design. As a result,the UWB antenna [1–11] has already become one of the favorite topics in the field of antenna design. Rather than an independent transmitter or receiver, an antenna embedded in the UWB system plays a distinctive role in shaping the emission spectrum and maintaining the pulse fidelity [12]. In line with this role transition, the design of an UWB antenna system needs a new perspective. Instead of simply seeking to be an effective radiator or receiver, the design should set the goals upon the maximization of the

*Received 5 November 2010, Accepted 10 January 2011, Scheduled 25 January 2011*
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emission power under the Federal Communications Commission (FCC) mask and the minimization of the pulse distortion as well.

This new positioning of UWB antenna system raises challenges in every aspect of design. Firstly, the design needs to take every component into account, since the fulfillment of the above goals significantly depends on the collaboration of the whole system [12]. Secondly, the antenna system should be characterized and evaluated in terms of its ability in spectrum shaping and distortion reduction [13]. Rather than the traditional parameters such as VSWR and radiation pattern, the concept of transfer function [14–16] shows its potential of offering a proper evaluation of a UWB antenna system. However, for a system operating over the ultra wide band, determining the transfer function to a sufficient resolution is a challenging topic. Solutions to this difficulty have been extensively discussed, however, the way of reducing the discrete responses into an analytic model seems to be the best [17–20]. Firstly, it results in the significant reduction of computation cost. Secondly, it offers deeper insight into the temporal properties of the UWB antenna. Furthermore, it favors a continuous and analytical evaluation of the system, which is particularly suitable for the purpose of the design and the optimization of an UWB antenna system. However, the means of realizing an analytical model of transfer function mainly depends on the human efforts in repeatedly tuning the number and the locations of the samples. Thus, the treatment is far from an automatic process. While optimization becomes an indispensable part in present antenna design [21–25], the modeling, however, is expected to automatically proceed, for the need of working with a purely human-free optimization code. In our previous work [26], a new approach has been proposed, which automatically renders an analytical model of transfer function without any human input.

In the design of the UWB antenna system, another critical issue is how to strike a proper balance amongst the multiple objectives, since it is hardly possible to find a single "perfect" solution of simultaneously minimizing each objective to its fullest. In terms of the capability of handling the tradeoffs and even conflictions among the objectives, multi-objective optimization algorithms have been increasingly applied for the antenna designs [27, 28]. Fundamentally different from the single objective optimization that merely yields a single solution, multi-objective optimization generates a Pareto front constituted by a set of non-dominated solutions. For each solution, each objective has been optimized to the extent that if we try to optimize it any further, then the other objective(s) will suffer as a result. Recognizing that each one has its own merits, the ultimate choice would be decided by the specified preferences of the designers. Over the last two decades, multi-objective optimization has grown to a relatively mature level. A variety of algorithms have been developed including the Non-dominated Sorting Genetic Algorithm II (NSGA II) [29], Strength Pareto Evolutionary Algorithm (SPEA) [30], Pareto Archived Evolutionary Strategy (PAES) [31] and Multi-objective Particle Swarm Optimizer (MOPSO) [32]. By comparisons and reviews [29, 33], it is unfair to say which algorithm is the best in an absolute sense since there is no free lunch. However, amongst them, NSGA II has been recognized as one of the most mature algorithm in terms of its reliability of finding the well-spread Pareto front for most problems [29] and it has been successfully applied to a number of engineering designs [34–38]. In the proposed CAD tool, we will employ NSGA II as the optimizer of handling multiple objectives.

As a product of vast considerations, the design of a UWB antenna system is a rather tough task. In this paper, a robust CAD tool is proposed in effort to cope with the challenges confronted in the design of a UWB antenna system. A previous work on the construction of a CAD tool for UWB antenna system can be found in [39]. In this paper, some new features are added to improve the robustness of the tool. Firstly, in order to measure the extent to which the antenna system fulfills the given goals, the objective functions are redefined and established in terms of the transfer functions. For the convenience of incorporating with the optimization code, the approach proposed in [26] is applied to efficiently generate an analytical model of a transfer function. In the optimization block, a multi-objective algorithm, NSGA II [29] is adopted as the optimization solver. In the final section of the paper, a practical design of a UWB antenna system is implemented using this CAD tool. Structural parameters of a planar antenna model and the characteristic time of a differentiated Gaussian pulse are taken as the variables to be optimized. The numerical and experimental results are also given there.

## 2. DESCRIPTION OF THE CAD TOOL

The proposed CAD tool is developed in an optimization environment. The basic framework consists of four blocks: parametric modeling, characterization, evaluation and optimization. For the elements being optimized, the block of parametrical modeling is to establish a parameter set as the variable input for the optimization code. The block of characterization and evaluation is to define and determine the evaluative functions for estimating the fitness of each parameter set. The block of optimization is to utilize the useful operators and algorithms to explore the parameter set with the possibility of

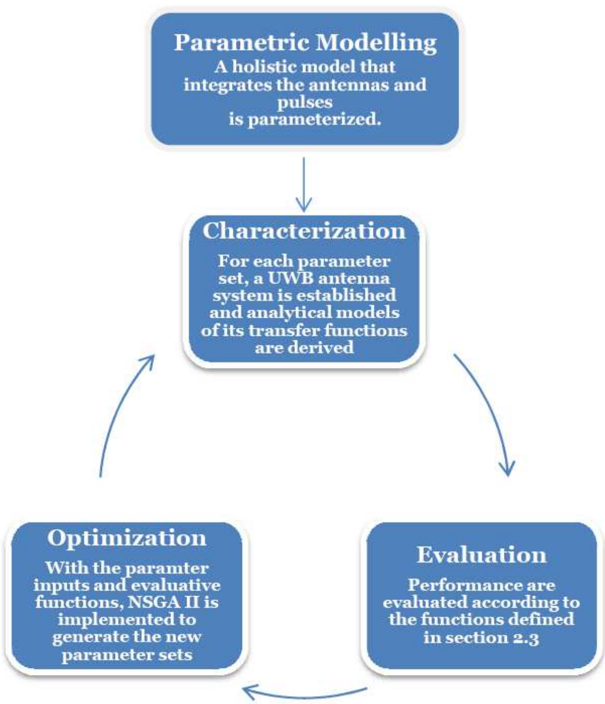


**Figure 1.** Overview of CAD design tool.

maximally enhancing the performance. Fig. 1 helps to illustrate the procedures of the CAD tool and the following topics give some details.

## 2.1. Parametric Modeling

At the first step, it is needed to properly parameterize the elements being optimized. It is based on the thorough study of which the prototype has the potential of realizing design goal and which parameters are of importance to be optimized. For the present purpose, the structural parameters of the transmitting and receiving antennas and the shaping factors of the transmitted pulse are chosen to be the input variables for optimization. Depending on the specific application and designer's preferences, the way of parametrization is varied. However, this design tool allows any alternative ideas simply via editing an independent input-file. In the final section, we present a choice of our own and the final results verify that it works well.

### 2.2. Characterization

As introduced above, a basic UWB antenna system can be fully characterized in terms of transfer functions. The transfer function is a numerical measure of the collective effects arising from a system and is defined as the ratio of the output to the input of the system. For giving a proper evaluation which we are going to discuss in Section 2.3, the transfer function of a whole UWB antenna system, $H(\omega)$ and the transfer function of the transmit antenna $H_{TA}(\omega)$ should be determined, which are defined as

$$H(\omega) = \frac{V_{out}(\omega)}{P(\omega)} \tag{1}$$

$$H_{TA}(\omega) = \frac{E_{rad}(\omega, \theta, \phi)}{P(\omega)} \tag{2}$$

where $\omega$ is the angular frequency, $V_{out}(\omega)$ and $P(\omega)$ are the spectrum of the output (received) and the input (transmitted) signal respectively, and $E_{rad}(\omega, \theta, \phi)$ is the radiated far field at the observation point $(\theta, \phi)$. As a major part of this tool, we incorporate the method proposed in [26] to facilitate the characterization of a UWB antenna system. As verified in [26], this method is particularly suitable for the optimized design of a UWB antenna system. Firstly, it is highly efficient, thus relieving the computation pressure of optimization typically involving a large number of iterations. Secondly, it is capable of automatically generating an analytical model of transfer function, thus offering a direct interface with optimization code. Additionally, it is applicable to an arbitrary antenna, thus allowing us to consider any antenna with any possibility of delivering the design to the optimal.

Due to limitations of space, full details of this method will not be discussed. In brief, this method is developed from the method of moment (MoM). Based on their formulations, it allows us to establish the transfer functions upon two independent components, namely, $Q_1$ and $Q_2$. Both of $Q_1$ and $Q_2$ are consistent with the classic descriptor of a single input single output dynamic system where impedance matrix, Z, constitutes the transformation matrix. Further development on segmentation process enables Z to be represented by a quadratic function in each segment, thus forming a second order system valid for each segment. Then, Q-Arnoldi method [40], a well-known model reduction method for second-order systems is adapted to estimate the dominant poles and residues associated to each segment. The last step is to compensate the truncated poles out of the band using an asymptotic function. Finally, a well-defined model is constructed as

(3).

$$Q(s) = \sum \frac{R_i}{s - s_i} + \sum \frac{R_i^*}{s - s_i^*} + \frac{T}{s} + E_0 + E_1 s + E_2 s^2 \tag{3}$$

where $R_i$ and $s_i$ are the residues and poles estimated by Q-Arnoldi method, and $T, E_0, E_1, E_2$ are the coefficients of the asymptotic function for compensating the truncated poles.

For the details and verifications of this method, please refer to [26]. Although developed in the context of MoM, the method is applicable to any computational method or software that is formulated by the electrical integral function.

### 2.3. Evaluation

From the interest of the whole communication system, this paper emphasizes two crucial aspects in evaluating a UWB systems. One is pulse distortion. An ideal UWB antenna system is the one of introducing zero distortion. The other is the radiated power spectrum. In UWB system, the FCC mask restricts the emission level to avoid any possible interference with other electronic systems. However, for improving the quality of communication such as the propagation range and the error rate, the transmitted power should be as high as possible. An optimal way is to make the radiated power fill up the permitted mask [12]. Based on the above considerations, the objectives of design have been established, which are to minimize pulse distortion and simultaneously to maximize the emission power yet without violating the FCC mask. According to the above objectives, the performance of a UWB antenna system needs to be quantified in terms of the proper measures.

At first, we need to assess the distortion of the received signal. In traditional practice, the pulse distortion is examined by the variance of the amplitude and the group delay of $H(\omega)$ with respect to the frequency. Generally speaking, the larger variation from the constant profile implies the larger distortion introduced. However, the degree of deterioration can not be appreciated quantitatively. In terms of their capability of offering a straightforward and quantified estimation, fidelity factor and stretch ratio [13] are employed to be the indicators of pulse distortion. Fidelity factor estimates the extent to which the received waveform $v_{out}(t)$ resembles the source $p(t)$. The fidelity factor is given as following.

$$F = \max_t \frac{\left| \int_{-\infty}^{\infty} v_{out}(t + t') p(t') dt' \right|}{\sqrt{\int_{-\infty}^{\infty} {v_{out}}^2(t') dt'} \sqrt{\int_{-\infty}^{\infty} p^2(t') dt'}} \tag{4}$$

If zero-distortion is introduced, F reaches the maximum of 1. Assuming the design as a minimization problem, we thus take (1-$F$) as the first evaluative function. The other crucial measure is the stretch ratio (SR) defined as

$$SR = \frac{W(v_{out})}{W(p)} \tag{5}$$

where $W(v_{out})$ and $W(p)$ are the pulse widths of the received signal, $v_{out}(t)$ and the transmitted signal, $p(t)$ of containing 90% of the total energy. Since distortion will broaden the pulse-width of the received pulse, smaller value of SR is desired. Therefore, the second evaluative function is defined by SR as shown in (5). The above two functions can be determined once $v_{out}(t)$ is known. $v_{out}(t)$ can be obtained via curl production of transfer function of the whole system $H(t)$ in the time domain, and transmitted pulse, $P(t)$. To be noted, $H(t)$ can be readily derived from the analytical model of $H(\omega)$, which is well defined in (3) of pole series.

$$V_{out}(t) = H(t) \otimes P(t) \tag{6}$$

Next, we turn to investigate the radiation power using

$$\Delta RP = \sqrt{\sum \left[PSD(\omega) - FCC(\omega) + 2|PSD(\omega) - FCC(\omega)|\right]^2} \tag{7}$$

where $PSD(\omega)$ defines spectrum density of the effective isotropic radiated power (EIRP) of a UWB antenna system and $FCC(\omega)$ corresponds to the maximal EIRP prescribed by FCC mask.$\triangle RP$ is a function of evaluating the deviation of $PSD(\omega)$ to $FCC(\omega)$. Basically, the deviation is expected to be as small as possible. However, exceeding the mask will be punished even though the deviation is sufficiently small. In view of that, the sum in parenthesis actually is a penalty function such that once the power spectrum density exceeds the mask, it will be given three times the weight compared with those with the same deviation but falling below the mask. $PSD(\omega)$ can be derived from $H_{TA}(\omega)$ and $P(\omega)$ as shown in (7), where the scaling factor of the signal rate T is omitted without any change of spectrum shape.

$$PSD(\omega) = |E_{rad}(\omega)|^2 = |H_{TA}(\omega)P(\omega)|^2 \tag{8}$$

In the design, we employ $1 - F$, $SR$ and $\triangle RP$ as the evaluative functions to evaluate the performance of a UWB antenna system. An ideal design is the one that simultaneously achieves the minimal value at each function. As discussed above, evaluative functions can be fully determined once the transfer functions, $H(\omega)$ and $H_{TA}(\omega)$ are obtained through the step of characterization.

### 2.4. Optimization

In this paper, the design involves three objectives, which are to simultaneously minimize the function of $(1 - F)$, $SR$ and $\triangle RP$. Therefore, it is a typical multiple objective optimization problem. As well-known for its robustness of handling multiple objectives in a single run, the NSGA II is programmed for the optimization. The process of characterization and evaluation as introduced above also should be programmed and incorporated into the optimization code in order to estimate the fitness of each antenna system. After inputting the variables to be optimized and specifying the parameters associated to the algorithm, the optimization code will start to explore the "optimal" design automatically.

## 3. PRACTICAL DESIGN AND NUMERICAL RESULTS

In terms of the remarkable potential for UWB applications, an antenna with planar configuration is chosen as the basic model for the design. Limited by the finite resolution of the mesh generator [41], we attempt to parameterize a planar antenna of arbitrary shape simply using 6 points. As shown in Fig. 2, these 6 points are defined by their polar coordinates $(\alpha_i, R_i)$. Assuming it is symmetric with the central axis, the contour of a planar antenna can be correspondingly determined by connecting them in sequence. Following specifications are given:

1) $\alpha_{i+1} = \alpha_i + 15; \quad \alpha_1 = 15^\circ \quad (i = 1, \ldots, 6)$
2) $R_{i+1} = R_i \cdot (1 + p_i); \quad p_i \in [-0.3, 0.3]; \quad R_i \in [0.005\,\mathrm{m}, 0.025\,\mathrm{m}]$

The former aims to avoid the ill-distribution by keeping the spacing of the polar angle constant at 15°. And the latter helps to maintain the smoothness of the contour in a way that the difference

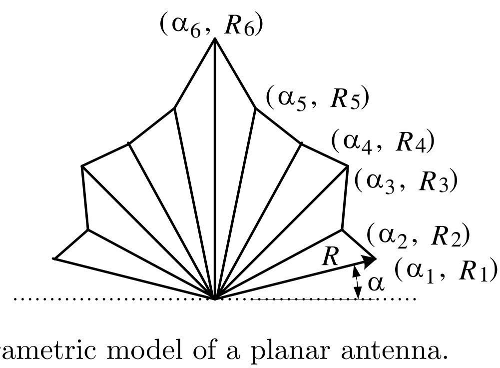


**Figure 2.** Parametric model of a planar antenna.

between $R_i$ and $R_{i+1}$ can not exceed the certain extent relative to the length of $R_i$. Additionally, the specifications of $p_i \in [-0.3, 0.3]$ and $R_i \in [0.005\,\mathrm{m}, 0.025\,\mathrm{m}]$ help to restrict the size of the antenna to a finite dimension. Thereby, the planar antenna can be fully determined by the variable parameters $R_1$ and $p_i(i{=}1,\ldots,5)$. Both antennas are parameterized in the same way and they are polarized in the same direction with a distance of 1 m apart.

Besides the design of the antennas, the proper shaping of the transmitted pulse can further enhance the system's performance. The well-known differentiated Gaussian mono-pulse is employed to be the transmitted pulse. The characteristic time of the pulse, $\sigma$, is another parameter to be optimized.

$$p(t,\sigma) = \frac{1}{\sigma^2} e^{-t^2/2\sigma^2} \qquad P(\omega,\sigma) = j\sqrt{2\pi}(\omega\sigma)e^{-(\omega\sigma)^2/2} \tag{9}$$

After parametrization and specification, an input file is generated and transferred to the CAD tool. The design proceeds through the procedures of characterization, evaluation and optimization. After 50 iterations, the CAD tool generates a database containing a large number of non-dominated solutions, the following criteria help to specify the one most desired.

1) Pulse fidelity should not be less than 85%;
2) Width stretch ratio should not exceed 1.5;
3) Deviation from FCC mask is minimal among ones that already reach the above two criteria.

Finally, antennas in Fig. 3 are selected as the pair for transmitting (the right) and receiving (the left). Their geometric parameters are listed in Table 1. The characteristic time of the pulse $\sigma$ found to be optimal for the antenna system is 23 ps.

**Table 1.** Parameters of antennas.

| Parameters | $R1$ | $P_i(i,\ldots,5)$ |
|---|---|---|
| Transmitting Antenna | 0.0121 | 0.0123,0.0107,−0.1316,0.0661,0.1000 |
| Receiving Antenna | 0.0079 | 0.2494,0.1657,−0.0322,0.0838,0.2775 |

This design achieves 91.43% fidelity of pulse and keeps stretch ratio less than 1.1338. EIRP achieved by this antenna system has the minimal deviation to FCC mask amongst the ones that already reaches the criteria for the pulse fidelity and the stretch ratio. On average, the deviation is less than 9 dB over the entire band and is even less than

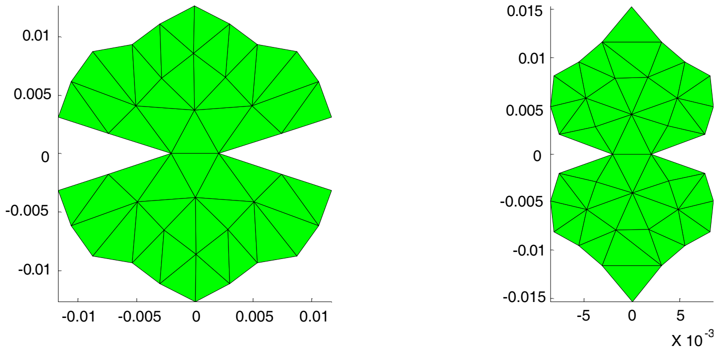


**Figure 3.** Transmitting and receiving antenna.

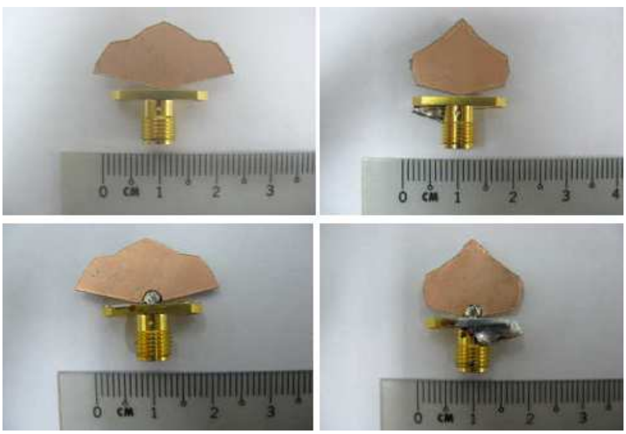

**Figure 4.** Fabricated antennas.

3 dB over the band of 3.1 GHz to 10.6 GHz which corresponds to the operation band of UWB communication.

The measurements are also conducted using a HP 8720ES network vector analyzer (VNA) in an anechoic chamber. The two sides of fabricated antennas and the measurement setup are given in Fig. 4 and Fig. 5 respectively.

$S_{21}$ parameters of the transmitting antenna and receiving antenna with spacing of 1m is used to measure $H(\omega)$. In order to achieve the experimental result of the $H_{TA}(\omega)$, two identical DRH-118 double ridged antennas firstly set up a standard antenna system. $S_{21}$ between them are measured and is referred to as $H_{ss}(\omega)$ [42]. Next, we replace the one of the standard antennas by the designed transmitting antenna

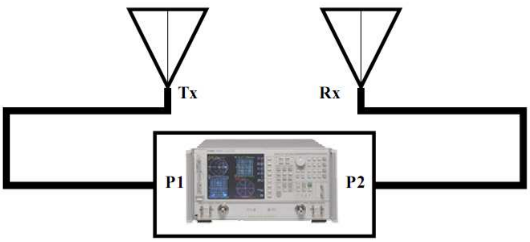


**Figure 5.** Measurement setup.

and then a new antenna system is built up while still keeping the standard antenna for receiving. Likewise, $S_{21}$ is measured and is taken as $H_{as}(\omega)$. By using their relationship, $H_{TA}(\omega)$ of the transmitting antenna can be derived as

$$H_{TA}(\omega) = \frac{H_{as}(\omega)H(\omega)}{H_{ss}(\omega)} \tag{10}$$

Based on the measurement result of $H_{TA}(\omega)$, we obtain the normalized EIRP of the radiated power and compare with the FCC mask within the UWB band from 3.1GHz to 10.6 GHz. As shown in Fig. 6, the measured EIRP follows closely to the FCC mask that implies that a desirable emission level has been achieved. Out of the UWB band, the normalized EIRP declines rapidly to avoid the interference with other communication system. Indeed, an ideal EIRP is expected to be exactly the same with FCC mask. In such a case, $H_{TA}(\omega)$ corresponds to a particular form which is far from the flat

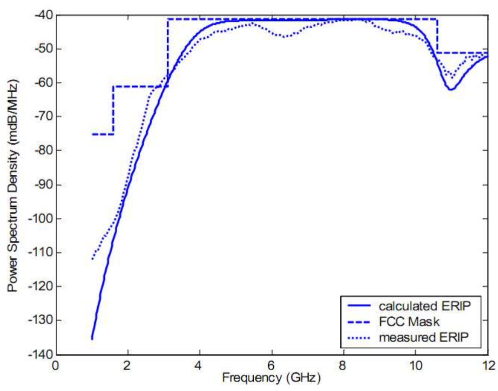


**Figure 6.** EIRP of antenna system.

response and thus introduce the distortion to the antenna system. Therefore, the design of the receiving antenna becomes more difficult in order to offset this intentional "distortion" brought by $H_{TA}(\omega)$. The shape of the pulse also has significant impact on the spectrum control. If using the different pulse, the transmitting antenna also should be redesigned so to achieve the desired radiated spectrum. This highlights the importance of considering the transmitting antenna, receiving antenna and transmit pulse together. Furthermore, the multi-objective optimization make it possible to strike a proper balance amongst multiple considerations.

Due to limitations in current experimental facilities, time domain measurements could not be undertaken. Therefore, we can not directly offer the experimental figures of the pulse fidelity and the stretch ratio. In this paper, we hope to give an intuitive estimation of the pulse distortion through investigating the amplitude and group delay of $H(\omega)$. As shown in Fig. 7, the amplitude of $H(\omega)$ is very flat over the UWB band except for a slight hump over 3.1 GHz–4 GHz. The phase of the $H(\omega)$ is another important parameter to estimate the performance of the antenna system. In Fig. 8, group delay of the modeled result is plotted. Though it is not as good as the simulated result, it still shows the relatively stable response and thus implies that proposed antenna system will not introduce the serious distortion to the signal.

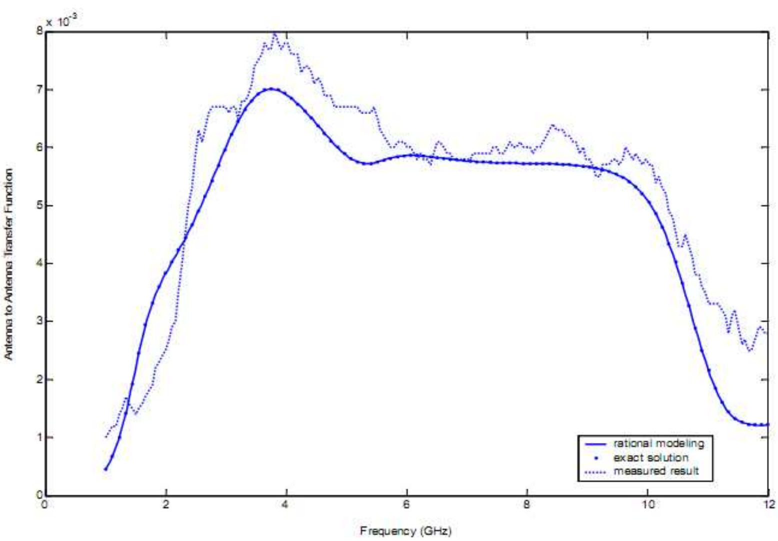


**Figure 7.** Amplitude of $H(\omega)$.

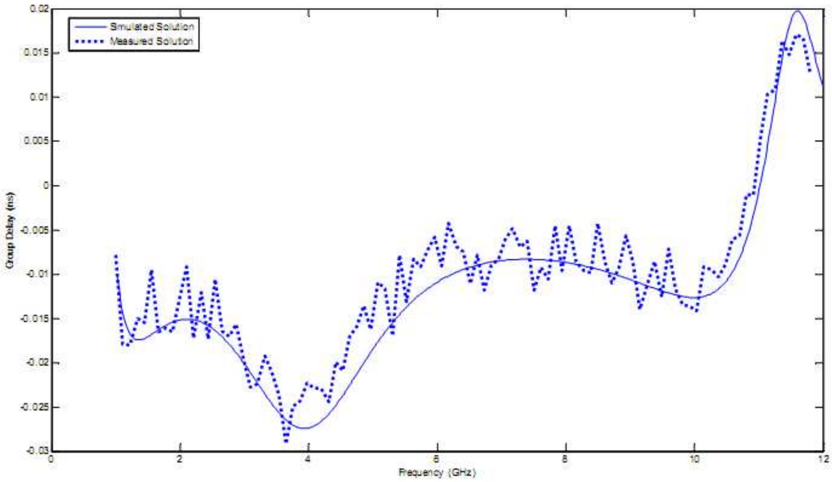


**Figure 8.** Group delay of $H(\omega)$.

## 4. CONCLUSIONS

In line with its distinctive role, a CAD tool for UWB antenna system is developed in this paper. The design integrates the transmit antenna, the receive antennas and the transmitted pulse. The objectives of design are redefined from the interests of the whole UWB radio system. An automatic model reduction of transfer functions is used to facilitate a direct interface with the optimization code. The multi-objective optimization method is employed to handle the trade-offs amongst multiple objectives. Using this CAD tool, a practical design of a UWB antenna system is presented and the results prove that good performance is achieved by the proposed design.

## ACKNOWLEDGMENT

The authors would like to thank the reviewers for their helpful comments and suggestions. They are really helpful to improve the quality of this paper and bring some new insights on our future work.

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