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# Design and System Characterization of Ultra-Wideband Antennas With Multiple Band-Rejection

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**ABSTRACT** This paper presents system modelling and characterization of multiple-band notched ultra-wideband (UWB) antennas using the singularity expansion method (SEM). Multiple-band notches in a classical UWB coplanar disc monopole antenna are achieved by introducing systematic defection slots in the coplanar ground structure solely. The antenna uses two dual-band meander ground-defects to create quadruple band notches to avoid possible interference with pre-existing standard services. The SEM with an improved pole-residue extraction scheme is developed to precisely characterize the band-notched antenna in the time and frequency domains. The improved matrix pencil method is applied to the bore sight impulse response of the proposed notched-band UWB antenna to precisely recognize the band-notches and extract the complex poles and residues at the operating bands between the reject-bands. This procedure is validated by reconstructing the impulse response of the antenna from the extracted poles and residues. The obtained simulation and measurement results are in a very good agreement and demonstrate the reliability of the proposed antenna model and characterization method.

**INDEX TERMS** Ultra wideband antennas, transfer functions, time domain analysis, frequency domain analysis.

## I. INTRODUCTION

One of the important parts of any ultra-wideband (UWB) communication system is the antenna. UWB antenna design has drawn significant attention and contributions from the antenna engineering researchers in the last decade. The main problem with UWB communication systems is its susceptibility to electromagnetic interference from already existing narrowband communication systems. The co-existing narrowband communication systems are mainly the wireless local area network (WLAN) 2.4GHz (2.4-2.48), worldwide interoperability for microwave access (WiMAX) 2.5/3.5 GHz (2.5-2.7 and 3.4- 3.69 GHz), WiMAX 5.8GHz (5.25-5.825GHz, and international telecommunication union (ITU) 8 GHz (8.025-8.4 GHz) bands. In order to eliminate interference of these pre-existing bands, the UWB antennas with reject-band notches have been proposed in the past few years [1]–[8]. The classical disc monopole coplanar waveguide (CPW) antenna designs presented in [2]–[5] have several appealing advantages over microstrip based antennas such as the lower dispersion at high frequencies, practical unipolar configuration, ease of integration with passive and active devices, and lesser dependency on the substrate thickness [3], [9], [10]–[13].

A compact planar UWB antenna with quadruple band-notch characteristics is analyzed and presented in [1] where C-shaped and nested C-shaped slots in the radiating patch and a U-shaped slot in the feed lines are introduced to achieve the quadruple band-notch characteristics at frequencies of 2.5, 3.7, 5.8 and 8.2 GHz. In [2], a compact CPW fed UWB monopole antenna with triple band-reject is presented. The antenna uses three open-ended quarter-wavelength slots in the radiator element to create triple band-notch characteristics for the WiMAX, WLAN, and for downlink of the X-band satellite communication systems, respectively. A modified compact UWB monopole antenna with triple controllable band-notches are presented in [3]. That proposed antenna consists of a modified stair case V-shaped radiating element and a partial ground plane to achieve the triple band notches.

In [4], an UWB antenna with multiple band rejection is presented. The proposed antenna utilized a C-shape ground plane and two electromagnetic band-gap (EBG) structures to create the notched bands. Carefully designed defected ground structures (DGS) has been used to introduce band pass and band stop characteristics in radio frequency (RF) passive circuits [14]–[17]. Therefore, DGS is a good candidate to provide band rejection at specified frequencies in UWB antenna. A U-shaped DGS is utilized in [12] to achieve single band notch, while in [13] DGS symmetrical-slits has been proposed to get single band notch at specified frequency of UWB antennas.

The singularity expansion method (SEM) has been recently used to characterize UWB and resonant antennas [16], [18]–[22]. The SEM models the time response of an antenna by utilizing physical poles and residues of the antenna. The physical poles are aspect independent, and depends only on the antenna characteristics. Subsequently, the poles allow us representing the antennas in a distinct way.

Since its introduction, the matrix pencil (MP) method [23] has been widely used to extract poles and residues of different waveforms. In [16] and [18], SEM has been used with MP method to characterize UWB Vivaldi antennas as well. It has been shown that it is possible to generate frequency domain patterns from the pole residue model of the antenna's effective height model. The main constraint of the proposed model in [16] and [18], is that it is virtuous only to characterize classic UWB antennas. The robustness of the matrix pencil (MP) method and the Cauchy's method were compared in [24]. It is shown that, in presence of noise, the MP method is more accurate in extraction of poles from the radiated fields of a dipole antenna and two bowtie antennas. In [25], the SEM is used to model and reconstruct the field backscattered from a high gain wide-band helical antenna. The SEM is, also, used to identify resonances of the dipole antennas in [20]–[22]. Simple dipole antennas are considered and the matrix pencil method is applied on its backscattered fields to identify the resonance of each antenna. An UWB antenna design using optimized curvature element and an elliptically tapered coplanar line is presented in [26]. A single notch is achieved by a $\omega$-shaped slot on the surface of the radiating element. The pole-residue model of the original UWB antenna was obtained from the scattering parameters of the link response of identical antennas in that paper.

In actuality, the number of physical poles of antenna that are bounded in far-field-impulse-response are unknown. Mostly, the number of physical poles are overvalued by the classical MP method. This results in the extraction of non-physical poles in conjunction with the physical ones. In case of multiband rejection antennas, SEM model suffers due to existence of low energy non-physical poles at the multi rejection/stop bands of the antenna. In order to model and characterize UWB multiband rejection antennas using SEM, there is a need of accurate poles extraction scheme, capable of eliminating the non-physical poles.

In this paper we present design and system characterization of a disc monopole UWB antennas. The designed antenna has quadruple band notch characteristic. The band-rejection at specified frequencies is achieved by using well-designed band-stop DGS. The proposed design of the notch-band ground-defect resonators is direct and systematic. It can be easily repeated to achieve multiple band rejection at specified frequencies. Two pairs of DGS resonators are used to get the quadruple band notches at selected frequencies. The designed antenna is then accurately characterized and modeled in the time and frequency domains using the singularity expansion (SEM) method. In order to extract the physical poles and residues of the antenna that describe the operating bands and identify the reject bands accurately, an improved matrix pencil (MP) scheme has been proposed. The accuracy of the presented model has been examined for two cases of the designed UWB antenna. The poles residues for the original UWB antenna and the UWB antenna with the quadruple band notches are extracted and compared. The original impulse responses for the notched and the un-notched UWB antenna are reconstructed in order to validate the model.

In section III of this paper, the design of the coplanar DGS-based UWB antenna with quadruple band notches is introduced. Section IV includes the description and implementation of the improved MP method with a pre-scaled filtering parameter to detect the band pass and the band reject regions of the proposed UWB band-notch antenna from its impulse response. In section V, the pole-residue of the measured and simulated impulse responses demonstrate that the developed MP method provides accurate detection of the antenna band pass and band-reject regions.

## II. THE SINGULARITY EXPANSION METHOD (SEM)

According to the definition of SEM [27], the impulse response of any antenna can be modeled as [28]:

$$h(t) = \sum_{m=1}^{M} R_m e^{s_m t} \tag{1}$$

$$H(s) = \sum_{m=1}^{M} \frac{R_m}{s - s_m} \tag{2}$$

where $h$(t) is the response, $s_{\mathrm{m}} = \sigma_{\mathrm{m}} + j\omega_{\mathrm{m}}$ represents the complex poles, $\sigma_{\mathrm{m}}$ is the damping factor, $\omega_{\mathrm{m}}$ is the angular frequency, $R_{\mathrm{m}}$ is the corresponding residue, and $M$ is the number of poles. In the frequency domain, SEM allows modeling of the transfer function $H$(s). It is clear from Equations (1) and (2) that SEM requires extraction of complex poles and corresponding residues in order to model the antenna in time and frequency domains.

### A. IMPROVED MATRIX PENCIL METHOD

The matrix pencil (MP) method is normally used to estimate parameters (complex poles and residues) of potentially damped and/or un_damped sinusoids wave forms. Besides MP, Prony's method and Cauchy's method are used for extracting the pole pairs and their residues. Among these methods, the matrix pencil (MP) method is known to be efficient and effective. One of the major advantage of MP method is that it can extract complex poles and residues from noisy wave forms [24].

For multiple notched-band antennas where the operating bands are located among non-operating stop-bands, SEM model suffers from the contamination of the non-physical poles between the matched bands of the antenna. In this case, the extracted physical poles are very susceptible to the out-of-resonance nonphysical poles. Therefore, the antenna response is usually corrupted by the contribution of the nonphysical poles and their corresponding residues. To model multi notched antennas in time and frequency domain using SEM, an attentive and accurate pole extracting scheme is required.

In this paper we use a modified MP scheme that relies on an adjusted filtering parameter ($F$) to accurately detect the congested pass bands and the reject bands of the multiply frequency notched UWB antenna. The pre-scaled $F$ will improve the accuracy of the MP method in extracting physical poles of the antenna.

After the application of singular value decomposition (SVD) in the MP method on the generated matrix, an additional procedure is added to the classical MP method for physical pole extraction. For this purpose, the filtering parameter $F$ of the MP method is pre-scaled on the basis of the energies of the singular values. A reduced singular values matrix is reconstructed using only the rows corresponding to the dominant singular values. The singular vectors that are related to lower-energy singular values are discarded.

The filtering parameter $F$ is selected on the basis of energy of the extracted poles. The energy ($E$) of the pole pair is proportional to the square of the residues of the pole and inversely proportional to the damping factor [29]:

$$|E| \approx \frac{|R|^2}{Damping\ Factor} \tag{3}$$

where $R$ is the residue of the pole. Typically, low energy poles have lower residues and high damping factors. The key advantage of the pre-selection of $F$ is to provide a better control over frequency and time domain resolution. Higher values of $F$ provide higher resolution and sensitivity in time domain. The classical MP method extracts poles of wave forms, with value of $F$ that depends on the ratio of the highest singular value $\gamma_{\mathrm{Max}}$ to a critical singular value $\gamma_{\mathrm{c}}$ [23] according to:

$$\frac{\gamma_c}{\gamma_{Max}} \approx 10^{-F} \tag{4}$$

where $F$ is the filtering parameter applied to the frequency domain data. The number of the extracted poles in the classical MP is roughly proportional to $F^2$. Some of the extracted poles could be out of band nonphysical poles. The energies ($E$) of each pole pair is calculated using Equation (3) to get accurate knowledge of the number of physical poles of the UWB antenna. Once the number of physical poles are known

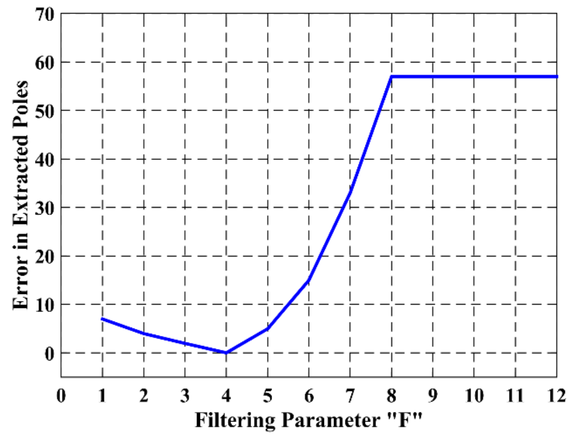


**FIGURE 1.** Filtering parameter *F* as a function of extracted poles.

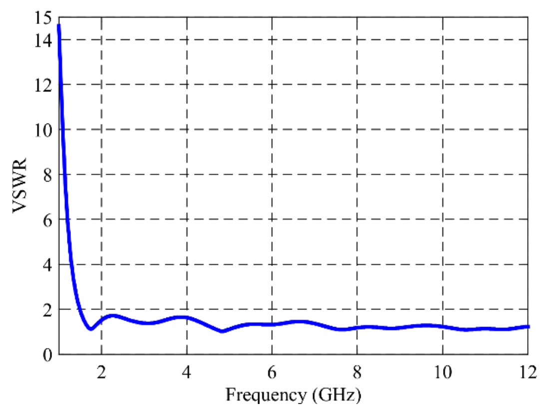


**FIGURE 2.** VSWR of the original antenna without band-rejection characteristics.

then the value of the filtering parameter $F$ is swept from 1 to 12 in the improved MP method to reach the optimum value of $F$ for the classical UWB disc monopole. At the optimum value of $F$, the number of the extracted poles equals the number of the physical poles. The error in the number of the extracted pole-pairs with $F$ for a typical UWB disc monopole antenna is shown in Fig. 1.

For an optimum value of $F$, the total number of the extracted poles is equal to the physical poles of the tested antenna. In the proposed MP scheme, the correct filtering parameter $F$ is treated as a function of the total operating bandwidth of the modeled antenna.

## III. ANTENNA DESIGN AND ANALYSIS

In this section, the design of the coplanar DGS-based UWB antenna with quadruple band notches is introduced. An optimized design of a typical disc monopole UWB coplanar waveguide (CPW) antenna is simulated and the voltage standing wave ratio (VSWR) is shown in Fig. 2. The antenna is directly matched to 50 Ohms feed line. The antenna has been simulated on a dielectric substrate with thickness of 1.54 mm, relative dielectric constant of 2.2, and loss tangent of 0.02. The circular radiating patch and the half ground plane result

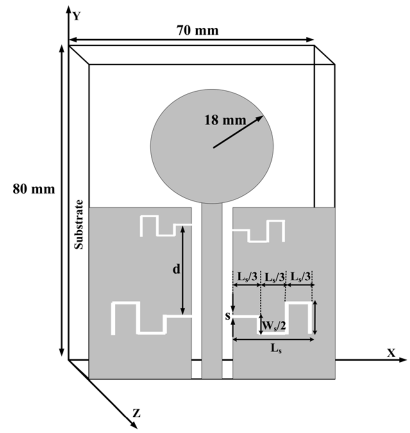


**FIGURE 3.** Geometry of the proposed UWB antenna with dual band rejection meander shaped DGS slots.

in a good impedance match over a wide frequency range. The parameters of the antenna are optimized to get VSWR less than two for a frequency range between 1.5 to 12 GHz.

A meander shaped symmetric band-reject DGS slots shown in Fig. 3 are etched in the ground plane of the CPW antenna. The self-resonance frequencies of the DGS resonators depend on their physical dimensions. The DGS resonator behaves as a parallel inductance capacitance (LC) circuit. An increase in the total length of the slot will increase the inductance while a decrease in the width of the slot increases its capacitance. The frequency of the notched band ($f\_notch$) can be approximated using the dimensions of the DGS slot as:

$$f\_notch = \frac{c}{4(L_{Total}\sqrt{\varepsilon_e})} \tag{5}$$

where $L_{\mathrm{Total}}$ is the total length of the DGS slot, $\varepsilon_e$ is the effective dielectric constant, and $c$ is the speed of light in free space. In the presented structure, the slot width ($s$) is kept constant to 0.2 mm, while the $L_{\mathrm{Total}}$ of the DGS slot is used to control the resonant frequency. $L_{\mathrm{Total}}$ of the slot can be calculated as:

$$L_{\mathrm{Total}} = L_s + \frac{3}{2}W_s \tag{6}$$

where $L_s$ and $W_s$ are the dimensions of the meander shaped slot shown in Fig. 3. The proposed meander shaped DGS pair provides dual band reject response. The ratio between the two frequencies is roughly about 2.4. The lower slot in Fig. 3 has $L_s = 6$mm and $W_s = 10.5$mm to get dual band rejection at 2.4 GHz and 5.6 GHz. The upper slots are designed at dimensions, $L_s = 4.5$ and $W_s = 7.5$ to produce dual band notches at 3.4 GHz and 8.35 GHz. The results of the upper and lower slots are compared in Fig. 4 (a). The position and dimensions of the DGS slots are optimized to minimize the coupling effects between them. The DGS slots are placed in sequence with a separation distance of $d = 15$mm as shown in Fig. 3.

Each pair of the dual band notch DGS slot operates at different frequencies and does not disturb the UWB antenna bandwidth except at the notch locations. The main advantage of the proposed antenna is the strong band rejection in the stop bands using only two pair of simple slots in the ground plane without any complex etching on the surface of the antenna itself. The band reject frequencies can be easily adjusted by changing the size of the meander shaped DGS slots.

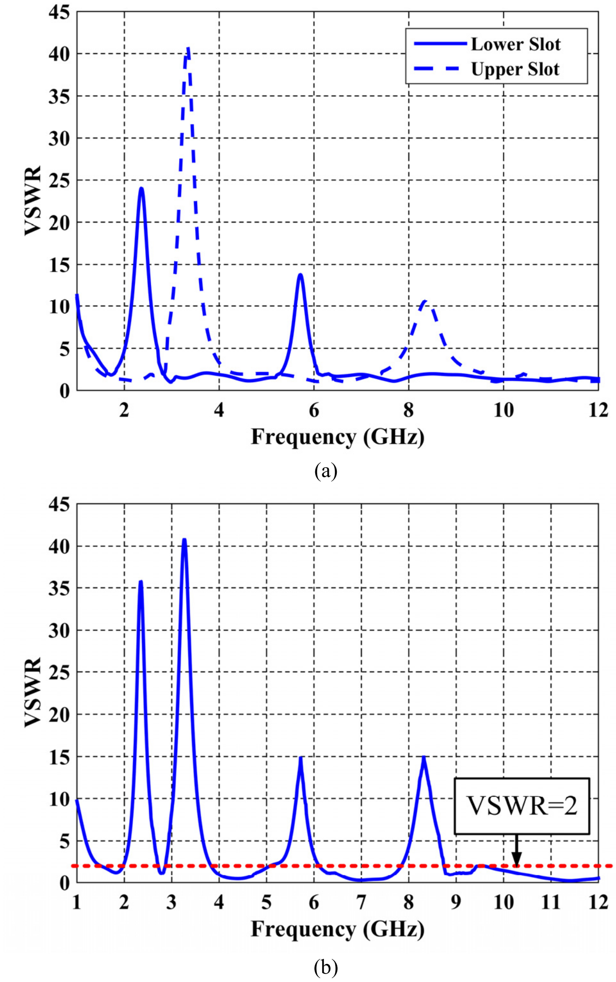


**FIGURE 4.** Simulated VSWR for: (a) the UWB antenna with upper or lower slots. (b) the UWB antenna with quadruple band notches.

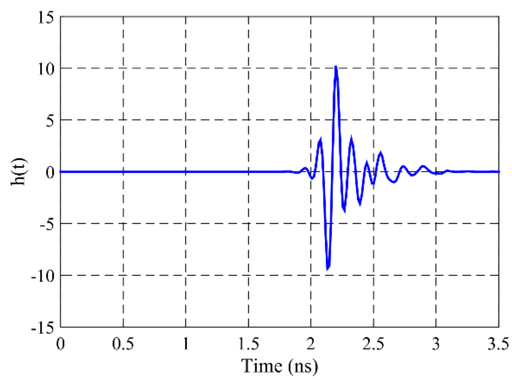


**FIGURE 5.** Impulse response of the UWB antenna without band notches.

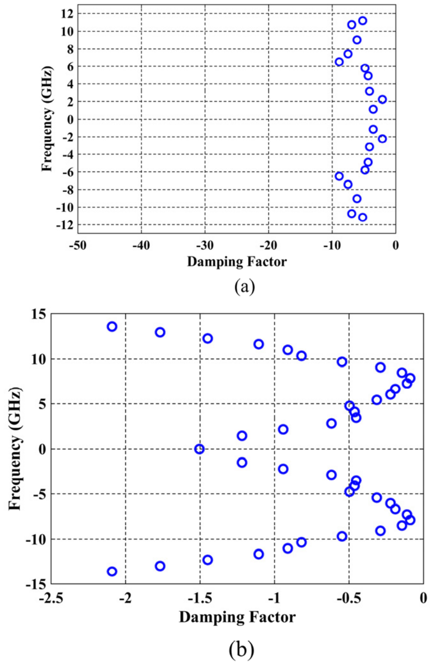


**FIGURE 6.** Location of extracted poles with damping factor of original UWB antenna. (a) Using improved MP method. (b) Using classical MP.

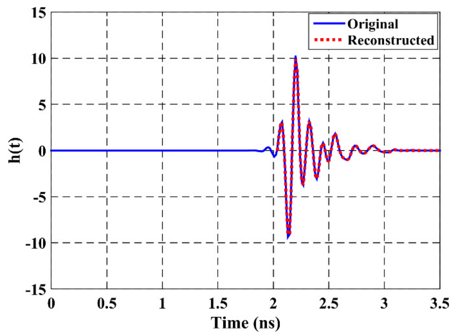


**FIGURE 7.** Comparison of the reconstructed impulse response with the original for the UWB antenna.

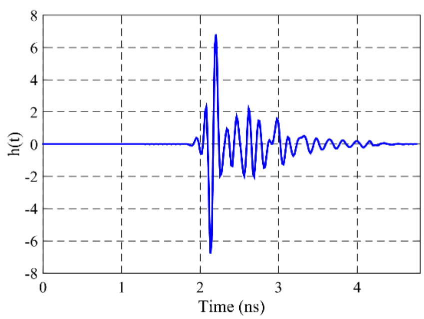


**FIGURE 8.** Impulse response of UWB antenna with quadruple band notches.

Fig. 4 (b) shows the simulated VSWR curve with frequency for UWB notched antenna shown in Fig. 3. The bandwidth of the proposed antenna is from 1.5 to 12 GHz for VSWR < 2 with four stop bands in the frequency ranges of 2.15-2.65, 3-3.7, 5.45-5.98, and 8-8.68 GHz. These four band notches can avoid interference with the existing standards like 2.5/3.5 GHz Wi-MAX, IEEE 802.11a WLAN, and ITU 8 GHz frequency bands.

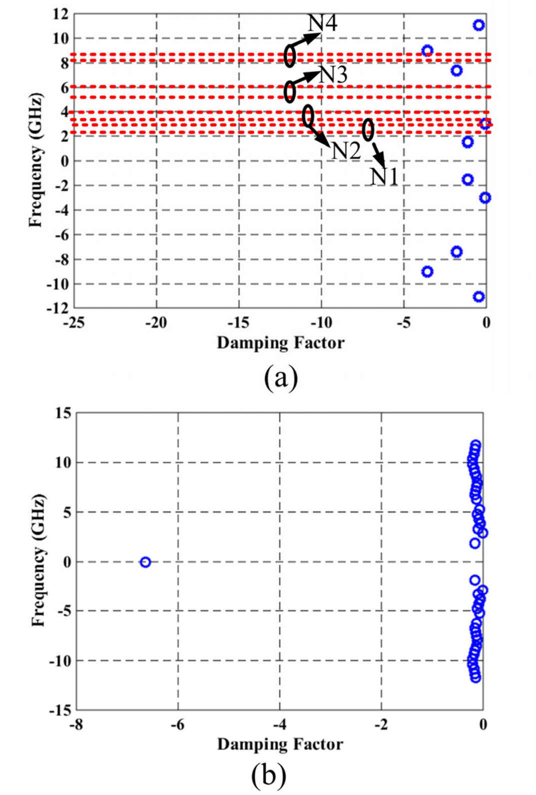


**FIGURE 9.** Location of extracted poles with damping factor of the proposed band notched UWB antenna. (a) Using improved MP method. (b) Using classical MP.

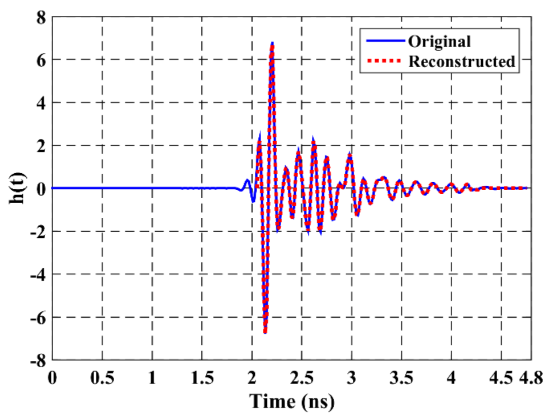


**FIGURE 10.** Sample Comparison of the reconstructed impulse response with the original for the proposed quadruple band notched UWB antenna.

## IV. CHARACTERIZATION OF THE PROPOSED ANTENNA USING SINGULARITY EXPANSION METHOD (SEM)

The improved matrix pencil (MP) method is applied to the bore sight impulse response of the proposed notched-band UWB antenna to precisely recognize the band-notches and

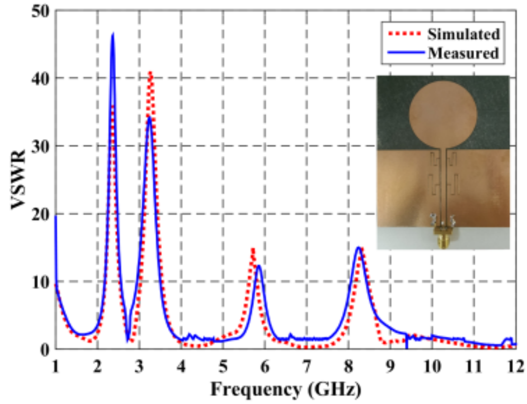


**FIGURE 11.** Comparison of the simulated and measured VSWR and photograph of the UWB antenna with quadruple band notches.

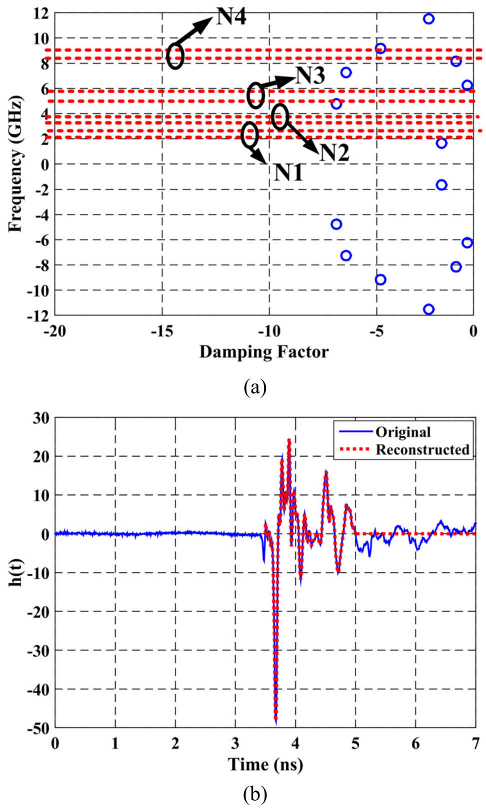


**FIGURE 12.** The measured results for the UWB antenna with quadruple band notched characteristics. (a) The location of the extracted poles versus damping factor. (b) The reconstructed impulse response and the original measured impulse response.

extract the complex poles and residues at the operating bands between the reject-bands. We consider only the late time response in order to avoid the nonphysical poles caused by the early time response. The early time response can be approximated as [24]:

$$Early\ Time \approx \frac{D}{c} + Pulse\ Duration \tag{7}$$

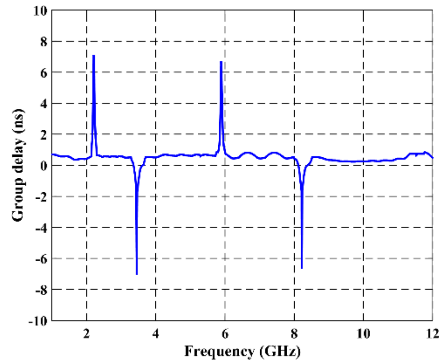


**FIGURE 13.** Simulated group delay of the proposed antenna.

where $D$ is the largest dimension of the antenna, and $c$ is the speed of light in free space. The far field impulse response of UWB antenna without band notches is shown in Fig. 5. The filtering parameter that determines the resolution of the MP algorithm is pre-scaled to take the value of 4. It can be examined from Fig. 1, that at $F = 4$ the error between the extracted and physical poles is zero.

Utilizing the improved MP with $F = 4$, there are totally ten pairs of physical poles extracted from the impulse response. For comparison the poles versus the damping factor for improved MP method and classical MP method are plotted in Fig. 6 (a) and (b) respectively. In Fig. 6 (a), the poles are located over the entire wide band of the antenna from 1.5 GHz to 12 GHz. To validate the sufficiency and accuracy of the extracted ten pairs of poles of improved MP method, the impulse response is reconstructed from these poles using the SEM model in Equation (1). The reconstructed impulse response is compared to the original one in Fig. 7.

The impulse response of the UWB antenna with quadruple band notched characteristics of Fig. 3 is plotted in Fig. 8. The impulse response of the UWB antenna with quadruple band notches is directly applied to the proposed MP and classical MP algorithm. The poles versus damping factor for improved MP and classical MP algorithm of the notched UWB antenna are shown in Fig. 9 (a) and (b) respectively.

There are total of five pairs of extracted poles representing the pass band as shown in Fig. 9 (a). The four reject bands in the frequency ranges of 2.15-2.65, 3-3.7, 5.45-5.98 and 8-8.68 GHz result in the elimination of five poles at these bands. The locations of the mentioned stop bands are highlighted in Fig. 9(a) as $N_1$ (2.15-2.65), $N_2$ (3-3.7), $N_3$ (5.45-5.98), and $N_4$ (8-8.68). All the poles in the ranges of $N_1$, $N_2$, $N_3$, and $N_4$ are filtered out due to the rejection bands provided by the DGS slots. The extracted poles with damping factor for notched-band antenna using classical MP method is shown in Fig. 9(b). It can be perceived from Fig. 9 (b) that the notches of the UWB antenna cannot be discriminated.

To validate the extracted poles using improved MP algorithm, the impulse response of the proposed notched UWB antenna is reconstructed using the extracted five pairs

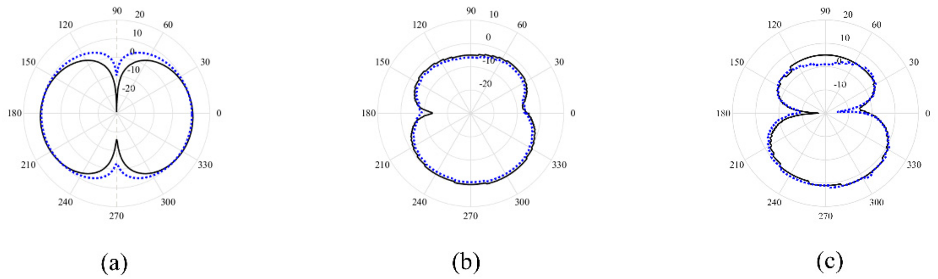

**FIGURE 14.** Simulated and measured radiation patterns at 1.80 GHz of the UWB antenna with quadruple band notches. Solid black line: simulated, dashed line: measured, (a) xy-plane. (b) yz -plane. (c) xz-plane.

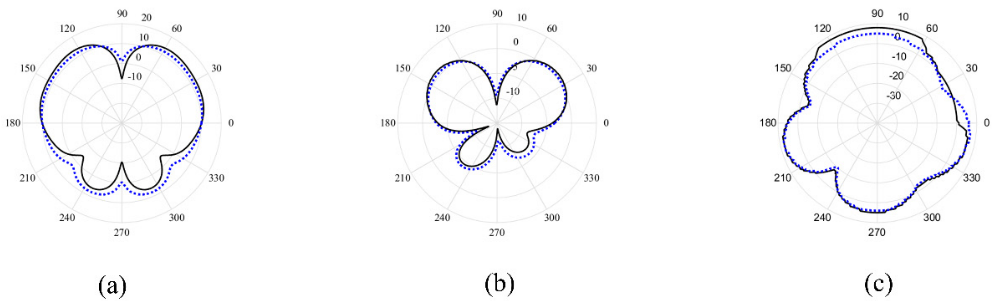

**FIGURE 15.** Simulated and measured radiation patterns at 4.50 GHz of the UWB antenna with quadruple band notches. Solid black line: simulated, dashed line: measured, (a) xy-plane. (b) yz -plane. (c) xz-plane.

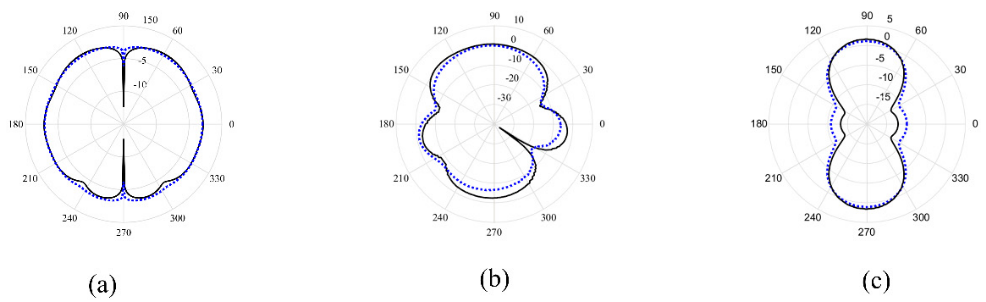

**FIGURE 16.** Simulated and measured radiation patterns at 7.0 GHz of the UWB antenna with quadruple band notches. Solid black line: simulated, dashed line: measured, (a) xy-plane. (b) yz -plane. (c) xz-plane.

of poles. The reconstructed impulse response is compared to the original response in Fig. 10. Utilizing these new results in characterization of the band notched UWB antennas enables representing this type of intricate antennas in both the frequency and time domains with only one set of parameters.

## V. MEASURED RESULTS

The proposed quadruple band notched monopole disc UWB antenna based on DGS is printed on a substrate with dielectric constant of 2.2 and height of 1.54 mm. The photograph of the fabricated antenna and comparison of the measured and the simulated VSWR is shown in Fig. 11. The measured VSWR matches well with the simulated results.

The measured impulse response of the proposed UWB antenna with quadruple band notches is directly applied to the developed MP method. The late time impulse response from 3.6 ns to 6.5 ns is considered for the input of the MP method to avoid delayed background reflections. The poles versus damping factor are shown in Fig. 12 (a). The same regions $N_1$, $N_2$, $N_3$, and $N_4$ are highlighted in Fig. 12 (a). The four reject band regions ($N_1$, $N_2$, $N_3$ and $N_4$) can be observed in Fig. 12 (a). To validate the extracted poles, the measured impulse response is reconstructed using the extracted seven pairs of poles. Fig. 12 (b) shows that the reconstructed response is in a good agreement with the original response.

Group delay of the proposed antenna is shown in Figure 13. The variation of the group delay of the quadruple band notched UWB antenna is about 0.5 ns across the whole bandwidth except at the notched bands. The simulated and measured radiation patterns of the proposed quadruple band

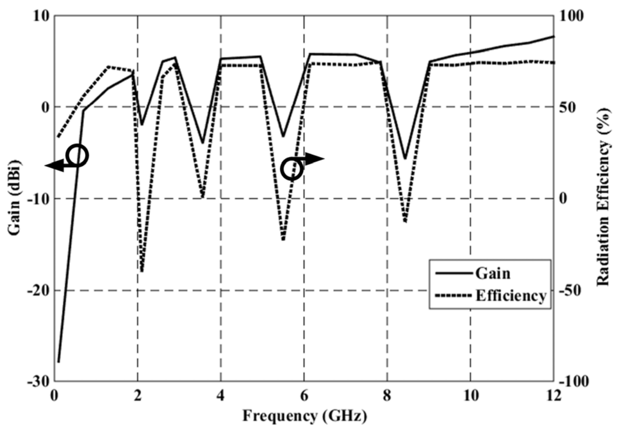


**FIGURE 17.** Simulated gain and radiation efficiency of the proposed antenna.

notched UWB antenna are plotted in Figs. 14-16 at three frequencies (1.8GHz, 4.5GHz, 7GHz). From Figs. 11-16 a good agreement can be observed between simulations and measurements.

The gain of the proposed antenna is shown in Fig. 17. From Fig. 17 it can be noted that there is a drop in the peak gain at the four notched bands. The gain falls down below 0 dBi at the notches, which confirms that antenna does not radiate at notched bands. The proposed antenna demonstrates a good radiation efficiency across the entire radiating band but not at the notched bands as depicted in Fig. 17.

## VI. CONCLUSION

This paper present new design and characterization methods for ultra-wideband (UWB) antennas with multiple reject-bands. The band notches for the proposed structure are achieved by using simple meander shaped defected ground structure (DGS) slots in the ground plane. The structure of the antenna is simple and repeatable to obtain band rejection at selected frequencies. An improved matrix pencil (MP) method with a predesigned filtering scheme is used to accurately extract the physical complex poles and their residues for the singularity expansion method (SEM) antenna model. This method is applied to the bore sight impulse response of the proposed notched-band UWB antenna to precisely recognize the band-notches and extract the complex poles and residues at the operating bands between the reject-bands. Utilizing these new results in the characterization of band notched UWB antennas enables representing this type of intricate antennas in both the frequency and time domains with only one set of parameters. The proposed notched UWB antenna is fabricated and tested. To validate the extracted complex poles and their corresponding residues, the measured and the simulated impulse responses of the antenna are reconstructed using the SEM model. The reconstructed impulse response match well with the original measured and simulated data.

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