Planar Ultrawideband Antennas With Multiple Notched Bands Based on Etched Slots on the Patch and/or Split Ring Resonators on the Feed Line

Yan Zhang, Wei Hong, Chen Yu, Zhen-Qi Kuai, Yu-Dan Don, and Jian-Yi Zhou

***Abstract*—Three types of ultrawideband (UWB) antennas with triple notched bands are proposed and investigated for UWB communication applications. The proposed antennas consist of a planar circular patch monopole UWB antenna and multiple etched slots on the patch and/or split ring resonators (SRRs) coupled to the feed line. Good agreement is achieved between the simulated and measured results. These techniques are significant for designing UWB antennas with multiple narrow frequency notched bands or for designing multiband antennas.**

***Index Terms*—Notched band, split ring resonator (SRR), split ring slot, ultrawideband (UWB) antenna.**

I. Introduction

In recent years, ultrawideband (UWB) system has been required for many applications because of its plenty of advantages, such as low complexity and low cost, resistant to severe multipath and jamming, etc. [1]. As one of main issues of UWB systems, UWB antenna has received increased attention. In literature [2], Chen *et al.* have given an overview of planar wideband antennas with different configurations exhibiting good impedance matching, stable radiation patterns, and high efficiency over bandwidths suitable for use with UWB system.

The UWB radio system occupies an UWB frequency band, i.e., 3.1–10.6 GHz approved by Federal Communications Commission (FCC) [3], in which there might potentially exist several narrow band interferences caused by other wireless communication systems, such as IEEE 802.11a wireless local area network (WLAN) in the frequency band of 5.15–5.825 GHz, and fixed broad wideband access (FBWA) mainly around 3.5 GHz. Therefore, it is necessary for UWB antennas performing band-notched function in those frequency bands to avoid potential inferences.

Lately, a number of antennas with band-notched property have been discussed in [4]–[25] and various methods have been used to achieve the function. The widely used methods are etching slots on the patch or on the ground plane, i.e., straight, triangular, C-shaped, H-shaped, U-shaped, and pie-shaped slot in [4]–[19]. Particularly, slot-type split ring resonators (SRRs) have been etched on the patch to obtain better performance in [20], [21]. Adding parasitic elements is another method to generate notched band, i.e., L-shaped and ring shaped parasitic elements designed on the bottom of the substrate in [22], [23], respectively. A novel antenna with band-notched filter realized by a strip bar has been proposed in [24]. Recently, an ultrawideband monopole antenna with folded strip to achieve band-notched function has been reported in [25]. However, all of these antennas mentioned above have concerned no more than two notched bands and most of them only have one notched band. Although the antenna in [19] can perform two notched bands, it only covers a frequency band from 2 to 6.5 GHz.

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The authors are with the State Key Laboratory of Millimeter Waves, School of Information Science and Engineering, Southeast University, Nanjing 210096, China (e-mail: yanzhang@emfield.org; weihong@seu.edu.cn).

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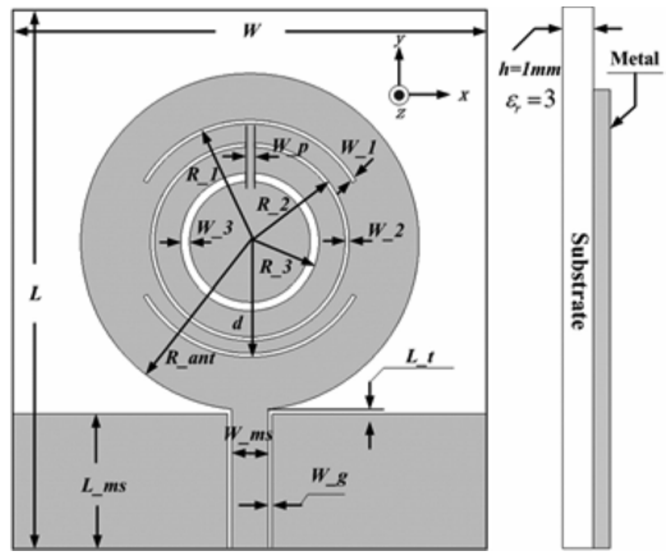


Fig. 1. The configuration of proposed antenna Type-I.

Moreover, it has been designed on a non-planar configuration with large size that couldn't meet the demand of integrating with planar printed circuits nowadays.

In this paper, three types of novel planar UWB antennas with multiple notched bands are proposed. Three narrow band interferences are considered to be notched, i.e., frequency bands centered on 2.4, 3.5, and 5.8 GHz. Type-I of the proposed antenna has several slots etched on the patch to generate multiple notched bands, while Type-II combines a special feed line with band-notched function with an UWB antenna to achieve the same performance. Type-III is synthesized by former two types, included both a slot etched on the patch and a feed line with band-notched property. All of these antennas with triple notched bands are fabricated and experimentally verified. Good agreement between the measured data and simulated results which are obtained using a time-domain finite integration technique (CST Microwave Studio) is achieved.

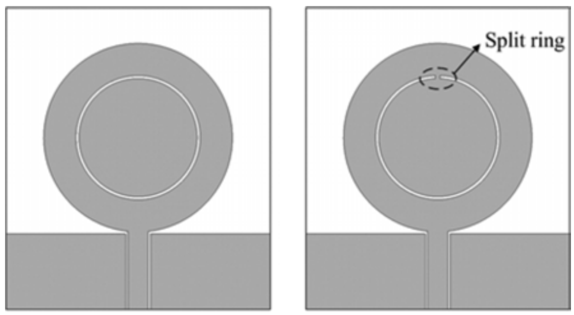
The configuration and guideline of all these antennas are firstly introduced in Section II. The proposed antennas were fabricated and measured, and the corresponding measured results are shown in Section III. Radiation patterns, gains, and time domain characteristics are also presented. The conclusion is made in Section IV.

II. Antenna Configurations

A. Antenna With Etched Slots On the Patch

To achieve band-notched characteristic, slots have been etched on UWB antenna patch as discussed in [4]–[21]. The etched slots would resonant in certain frequencies upon which the antenna performs band-notched characteristics. According to this concept, the antenna with triple notched bands has been proposed as shown in Fig. 1, noted as Type I. Two split ring slots and two arc slots have been etched on the patch to generate triple notched bands. Two split ring slots are used to generate notched bands with central frequency of 2.4 and 3.5 GHz, respectively, while the couple arc slots with the same radius are corresponding to the notched band centered on 5.8 GHz.

Slots with different shape, such as rectangular, circular, and elliptical or any other shapes can either be etched on the patch to generate notched bands. Through full-wave EM simulation, we have found that,



(a) (b)

Fig. 2. (a) Proposed antenna with circular slot, (b) proposed antenna with split ring slot.

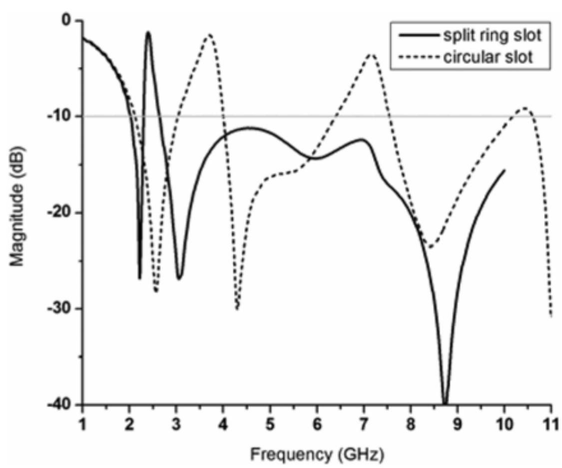
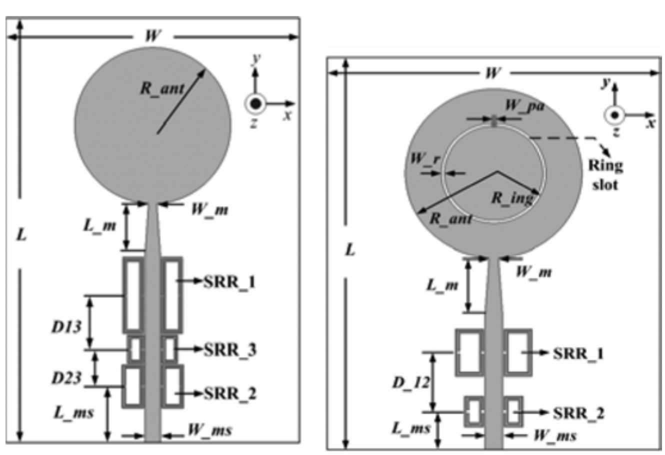


Fig. 3. Simulation of proposed antenna with circular slot compare to antenna with split ring slot.



(a) (b)

Fig. 4. UWB antennas combined with notched band filter.

in particular, a slot with the similar shape of the antenna patch can generate a stronger resonance than any other shape due to the current distribution is concentrated at the edge of the patch. In this case, the antenna performs a narrower and stronger band-notched property. Consequently, the circular slot has been chosen as a basic resonant element to be etched on the patch, as shown in Fig. 2(a). The simulation result shown in Fig. 3 indicates that a notched band occurred in vicinity of 3.7 GHz; however, a spurious notched band emerged in vicinity of undesired frequency 7.2 GHz simultaneously. This phenomenon wouldn't be encountered when the notch band centered on 5.8 GHz is only considered. To eliminate the spurious resonance, as seen in Fig. 2(b), a split ring slot was used to supplant the former circular slot, and the corresponding simulation result shown in Fig. 3 remains the notched band of 2.3–2.65 GHz ($|S11| > -10\ \mathrm{dB}$) with the spurious notched bands eliminated. It was found that the length of slot is corresponding to the notched frequency in [7], so it is convenient for adjusting the length of the slot to control the notched frequency. The notched frequency f_r can be empirically approximated by

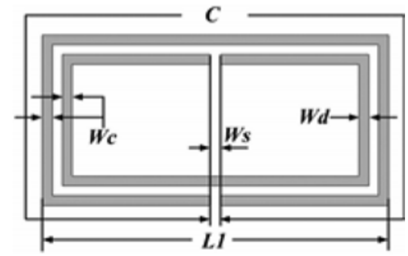


Fig. 5. Rectangular SRR.

$$fr \approx \frac{c}{\sqrt{\varepsilon_{\mathrm{eff}}}\cdot\lambda_g} \approx \frac{c}{\sqrt{\varepsilon_{\mathrm{eff}}}\cdot 2\cdot l\_ring} \tag{1}$$

$$l\_ring \approx 2\cdot\pi\cdot R\_ring \tag{2}$$

$$\varepsilon_{\mathrm{eff}} \approx \frac{\varepsilon_r + 1}{2} \tag{3}$$

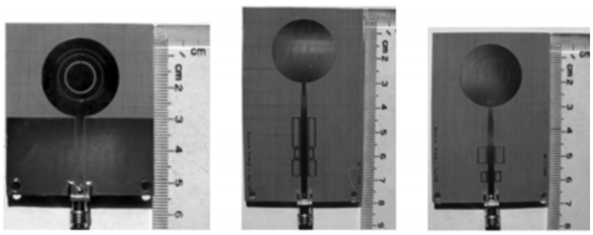
where c and $\varepsilon_{\mathrm{eff}}$ are the speed of light and the approximated effective dielectric constant, respectively; *R_ring* and *l-ring* are the radius and length of the split ring slot respectively. *l-ring* can be estimated as (2) when the width of the split is extremely small. Another point worth mentioning is that the notched bandwidth can be tuned slightly though adjusting the width of the slot. Thus, a specified notched band can be obtained through tuning the radius and width of the slot. It is obviously that combining several split ring slots with different radius and width etched on the patch can generate more notched bands, whereas the slots will be limited by the shape and size of the patch. In addition, there is mutual coupling among each slot that should be considered and an optimization method should be involved in during the design process to acquire optimal antenna's dimension. What's more, with the notched frequency increases, according to (1)–(3), slot's radius will decrease dramatically which results in a weaker notch, because the slot is very far from the edge of the patch on which the current mainly distributes. Therefore, instead of the split ring slot, a couple of arc slots with a large radius are used in high frequency to achieve a strong notch as shown in Fig. 1. The length of arc slots is also corresponding to $\lambda_g/2$ of the notched frequency. For estimating the notched frequency f_s of the arc slots, (2) should be changed as following:

$$l\_ring \approx 2\cdot\pi\cdot R\_ring\cdot\frac{\alpha}{360^\circ} \tag{4}$$

where *R_ring*, *l_ring* and (Unit: degree) are the radius, length and flare angle of the arc slot respectively. A little shifting was added to the arc slot below to avoid spurious resonances occurring on unwanted frequency with no shifting added to the top one. A coplanar waveguide (CPW) with 50-Ω characteristic impedance is used as the feed line.

B. Antennas With Band-Notched Filter

Another method to realize UWB antenna with multiple notched bands is connecting a multiple band-notched filter to the antenna.



(a) (b) (c)

Fig. 6. Photographs of proposed antennas: (a) Type-I, (b) Type-II, (c) Type-III.

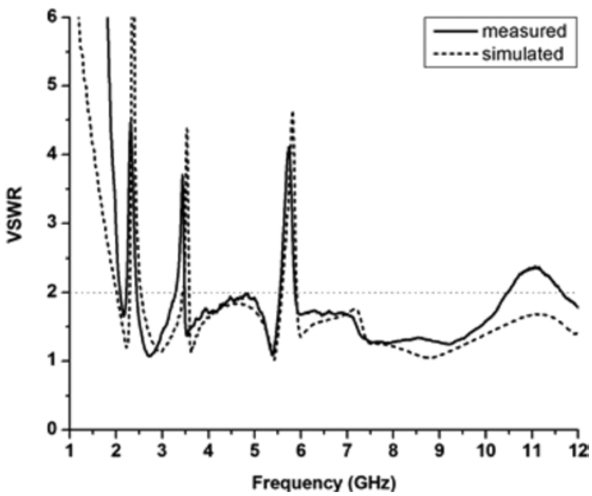


Fig. 7. VSWR of the antenna Type-I. $R\_ant = 12.5\ \mathrm{mm}$, $R\_1 = 9.06\ \mathrm{mm}$, $R\_2 = 6.84\ \mathrm{mm}$, $R\_3 = 5.11\ \mathrm{mm}$, $W\_1 = 0.2\ \mathrm{mm}$, $W\_2 = 0.25\ \mathrm{mm}$, $W\_3 = 0.65\ \mathrm{mm}$, $d = 7.76\ \mathrm{mm}$, $W\_m = 2.7\ \mathrm{mm}$, $W\_g = 0.2\ \mathrm{mm}$, $L\_m = 24\ \mathrm{mm}$, $W\_p = 0.2\ \mathrm{mm}$, and $\alpha = 120°$.

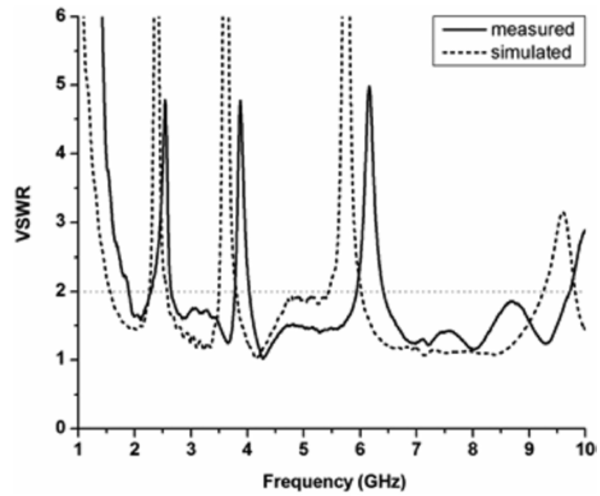


Fig. 8. VSWR of the antenna Type-II. $R\_ant = 12.5\ \mathrm{mm}$, $W\_ms = 2.48\ \mathrm{mm}$, $L\_ms = 14.39\ \mathrm{mm}$, $W\_m = 1.25\ \mathrm{mm}$, $L\_m = 8\ \mathrm{mm}$, $D13 = 8.55\ \mathrm{mm}$, $D23 = 5.95\ \mathrm{mm}$, SRR_1: $C\_1 = 31\ \mathrm{mm}$, $L1\_1 = 12.2\ \mathrm{mm}$, $Wc\_1 = Wd\_1 = Ws\_1 = 0.2\ \mathrm{mm}$, SRR_2: $C\_2 = 21\ \mathrm{mm}$, $L1\_2 = 7\ \mathrm{mm}$, $Wc\_2 = Wd\_2 = Ws\_2 = 0.2\ \mathrm{mm}$, SRR_3: $C\_3 = 14.2\ \mathrm{mm}$, $L1\_3 = 4.5\ \mathrm{mm}$, and $Wc\_1 = Wd\_3 = Ws\_3 = 0.2\ \mathrm{mm}$.

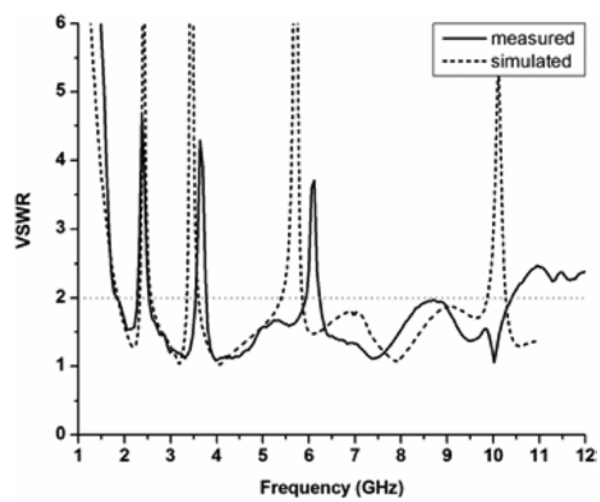


Fig. 9. VSWR of the antenna Type-III. $R\_ant = 12.5\ \mathrm{mm}$, $R\_ring = 7.385\ \mathrm{mm}$, $W\_r = 0.2\ \mathrm{mm}$, $W\_pa = 0.2\ \mathrm{mm}$, $W\_ms = 2.48\ \mathrm{mm}$, $L\_ms = 10.63\ \mathrm{mm}$, $W\_m = 1.25\ \mathrm{mm}$, $L\_m = 8\ \mathrm{mm}$, $D12 = 8.75\ \mathrm{mm}$, SRR_1: $C\_1 = 22\ \mathrm{mm}$, $L1\_1 = 7\ \mathrm{mm}$, $Wc\_1 = Wd\_1 = Ws\_1 = 0.2\ \mathrm{mm}$, SRR_2: $C\_2 = 14.4\ \mathrm{mm}$, $L1\_2 = 4.5\ \mathrm{mm}$, and $Wc\_2 = Wd\_2 = Ws\_2 = 0.2\ \mathrm{mm}$.

In this section, we have proposed antennas with a special feed line coupled by SRRs, which acts as a multiple band-notched filter as shown in Fig. 4.

Originally proposed by Pendry *et al.* [26], SRRs are small resonant elements with a high quality factor at microwave frequency and have been used as a metamaterial periodic structure. In recent years, more attention has been paid on them [27]–[34], because they are able to provide the magnetic field polarized along the axis of the rings and restrain signal propagation in a narrow band in the vicinity of their resonant frequency, and so on. A miniaturized CPW stop band filter based on SRRs has been designed by Ferran [33]. It has been found that single pair of SRRs are able to produce significant rejection property in [34].

The new type of filter with multiple notched bands has been designed in microstrip technology by cascading several pairs of SRRs with different size as shown in Fig. 4. Rectangular SRRs (with detailed parameters shown in Fig. 5) are symmetrically disposed in pairs beside the microstrip to obtain capacitive coupling at resonance frequencies. Since the SRRs are parallel and very close to the microstrip, strong capacitive coupling will be achieved which results in narrow and sharp notched bands. The dimensions of filters are electrically small due to SRRs are sub-wavelength resonant structures; therefore, high level of compactness will achieved in these antennas by using such a structure. According to [32], SRR can be intrinsically described by simple LC circuits with a resonant frequency

$$\omega_0 = \sqrt{\frac{2}{\pi R L C_0}} \tag{5}$$

where C_0 is the per unit length capacitance between the rings, L is the total inductance of the SRR, and R is the average radius of the SRR. Through (5), the rough size of the desired SRR can be estimate generally as an initial point for further design, and tuning procedures need to be implemented by full-wave EM simulation software to determine the optimal size of SRRs. It is convenient to adjust the resonant frequencies through tuning the dimension of SRRs. Moreover, tuning the distance between each pair of SRRs can eliminate the spurious notched bands in undesired frequencies. The filter shown in Fig. 4(a) has triple notched bands in the vicinity of 2.4, 3.5, and 5.8 GHz and the filter shown in Fig. 4(b) has two notched bands in the vicinity of 3.5 and 5.8 GHz.

Combining these notched bands filters with UWB antenna, as shown in Fig. 4(a) and (b) and noted as Type-II and III, can achieve multiple notched bands in ultra wideband. In particular, the antenna in Fig. 4(b)

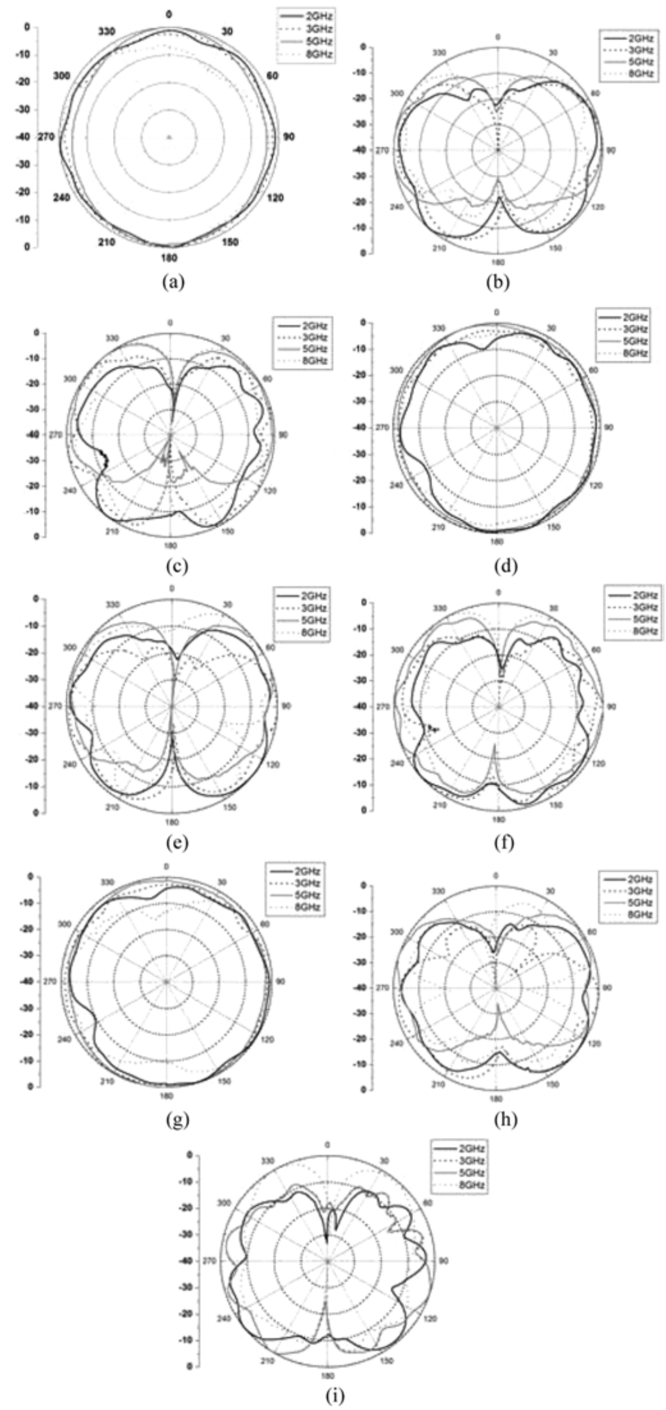


Fig. 10. Measured radiation patterns. (a) x-z plane of Type-I, (b) y-z plane of Type-I, (c) x-y plane of Type-I, (d) x-z plane of Type-II, (e) y-z plane of Type-II, (f) x-y plane of Type-II, (g) x-z plane of Type-III, (h) y-z plane of Type-III, (i) x-y plane of Type-III.

has a slot etched on the patch to generate notched band in the vicinity of 2.4 GHz. As a result, both antennas shown in Fig. 4 can generate triple notched bands. A microstrip with 50-Ω characteristic impedance is used as the feed line in both types.

III. Simulation and Experimental Results

A. Antenna With Etched Slots on the Patch

The proposed antenna with etched slots on the patch (Fig. 1), is fabricated on a rectangular microwave substrate with relative permittivity of 3.0 and thickness of 1 mm with length and width of 54 mm and 47 mm, respectively, as shown in Fig. 6(a). Both simulated and measured VSWR of the antenna are shown in Fig. 7, and footprints are optimal antenna dimensions. The result clearly indicates that the proposed antenna covers an ultra wide frequency band of 2.1–10.5 GHz (defined by $\mathrm{VSWR} < 2$) with triple sharp, notched bands (defined by $\mathrm{VSWR} > 2$) of 2.23–2.45, 3.26–3.48 and 5.54–5.88 GHz, respectively. A little frequency shift is happened in notched band of 3.26-3.48 GHz due to the substrate's relative permittivity has a fluctuation. A distortion $(\mathrm{VSWR} > 2)$ emerged in frequency around 11 GHz can be expected owing to the feed cable placed in the near field of the antenna as in [14] and a further study should be carried out to eliminate the affection.

B. Antenna Witch Band-Notched Filter

The proposed antennas of Type-II and III with notched bands filters (Fig. 4) are also fabricated on a rectangular microwave substrate with relative permittivity of 3.0 and thickness of 1 mm and with length by width of 78 mm $*$ 47 mm and 68 mm $*$ 47 mm, respectively, as shown in Fig. 6(b) and (c). The measured VSWR compared with simulation ones of two antennas are shown in Figs. 8 and 9, respectively, and the optimal antenna dimensions are also presented underneath the figures.

The result of antenna Type-II indicates that the proposed antenna also works on an ultra wide frequency band of 1.89–9.8 GHz $(\mathrm{VSWR} < 2)$ with triple narrow, notched bands $(\mathrm{VSWR} > 2)$ of 2.24–2.62, 3.78–4.03 and 5.94–6.4 GHz, respectively. In contrast, the antenna Type-III covers an ultra wide frequency band of 1.85–10.4 GHz $(\mathrm{VSWR} < 2)$ with triple narrower, notched bands $(\mathrm{VSWR} > 2)$ of 2.25–2.52, 3.53–3.77 and 5.96–6.3 GHz, respectively. Another point worth mentioning is that in the simulation result of antenna Type-III, there exits a spurious notched band around 10 GHz which is cause by the spurious resonance of SRR_1 [shown in Fig. 4(b)]. However, in the measurement, a sharp decrease of VSWR appears instead of this notched band. This phenomenon can be expected to the mutual coupling of SRR_1 and SRR_3 [shown in Fig. 4(b)], between whom the distance is extreme small, i.e., 0.2 mm.

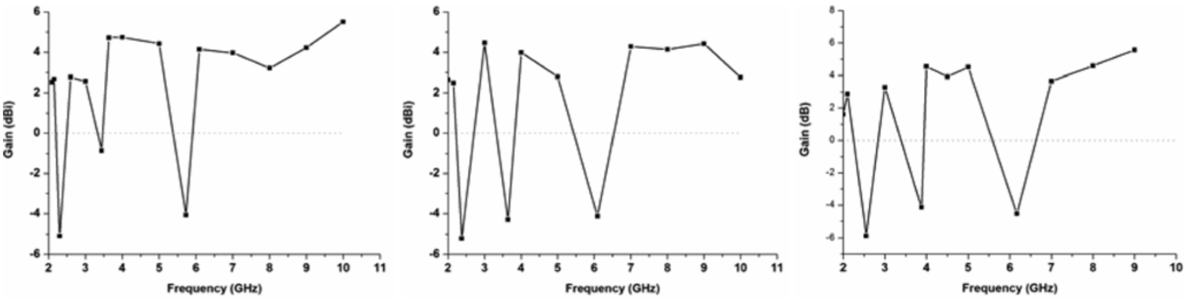
Frequency shifts caused by fluctuations of the substrate's relative permittivity are also happened in measurement of antennas Type-II and III, especially on the notched bands of higher frequencies. It is obvious that higher frequency is more sensitive to the fluctuation of substrate's relative permittivity.

Very sharp selectivity has been observed in VSWR of each type of antenna. Type-I with the smallest size shows narrower notched bands than that of other two types. In contrast, Type-II and III have stronger notches and the bandwidths of notched bands are a little wider. According to the measured VSWR, Type-II exhibits a better band-notched characteristic than other two types, whereas it has the largest size.

C. Antennas Radiation Pattern and Gains

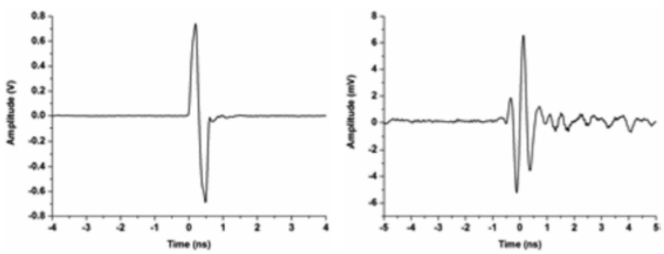
The radiation characteristics of all these proposed antennas have been also studied. The measured radiation patterns of three main cut planes of each antenna at the pass band (among triple notch bands) frequencies of 2, 3, 5 and 9 GHz are illustrated in Fig. 10. In x-z plane the patterns are close to omnidirectional, while dipole-like radiation patterns come out in y-z and x-y planes.

Fig. 11 presents the measured antennas maximum gain. In Fig. 11, gain decreases drastically at the each notched frequency band as expected, and the gain is the lowest at each notched band central frequency. In this section, Type-II also exhibits a better band-notched characteristic.



(a) (b) (c)

Fig. 11. Measured maximum gain of the proposed antennas: (a) Type-I, (b) Type-II, and (c) Type-III.



(a) (b)

Fig. 12. Time domain characteristic of the proposed antenna Type-II: (a) Measured transmitted pulse; (b) measured received pulse.

D. Antennas Time Domain Characteristics

To examine time-domain performance, antenna Type-II was connected as the receive antenna while a UWB antenna without notches was connected as the transmit antenna. The two antennas were placed face to face with a distance of 1 meter. Fig. 12 illustrates the received pulse with a little distortions and ringing effects is similar to the first order differentiated transmitted pulse.

IV. Conclusion

In this paper, three types of new UWB antennas with triple notched bands have been proposed and discussed. These antennas have been carefully investigated and fabricated. The measured results demonstrate the proposed antennas using etched slots on the patch or/and SRRs coupled to feed line can both generate triple tunable narrow notch bands. Antennas' radiation characteristics and gains have also been examined. It indicates that all these antennas consistent radiation properties over the whole band and notable band-notched properties. Accordingly, these antennas are expected to find applications in various UWB systems.

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Application of Hybrid FETD-FDTD Method in the Modeling and Analysis of Antennas

Neelakantam V. Venkatarayalu, Yeow-Beng Gan, Robert Lee, and Le-Wei Li

***Abstract*—The stable hybrid finite-element time-domain–finite-difference time-domain (FETD–FDTD) method is applied for the numerical modeling and simulation of radiation from antennas. Use of unstructured tetrahedral elements in the modeling of antenna structure enables the application of the hybrid method to accurately model geometrically complex radiators. Traditional FDTD method with anisotropic perfectly matched layer (PML) is used to simulate unbounded media. Pyramidal elements are used in the transition from unstructured tetrahedral elements to structured hexahedral elements of the FDTD grid. The hybrid method is extended by using hierarchical mixed order basis functions in the unstructured region. The finite element formulation incorporates the excitation of antennas using coaxial line or stripline feed with transverse electromagnetic mode (TEM). Application of this method in the modeling of typical wideband antennas along with the results of input reflection coefficient and radiation pattern is presented.**

***Index Terms*—Antenna modeling, finite-difference time-domain (FDTD) method, finite-element time-domain (FETD) method, hybrid methods.**

I. Introduction

With requirements on antenna characteristics becoming more complex due to the pervasive use of wireless communication devices, numerical modeling of antennas is becoming an integral and vital step in antenna design. The hybrid finite-element time-domain–finite-difference time-domain (FETD–FDTD) method[4], [5] is a powerful numerical technique that retains the inherent advantage of FETD [1], [2] method in modeling arbitrarily shaped structures along with the efficiency of FDTD method in modeling simple shapes and the unbounded medium using perfectly matched layer (PML). The objective of this communication is to demonstrate the potential use of the hybrid FETD–FDTD technique for analysis of broadband antennas. The hybrid method proposed in [4] is extended by incorporating hierarchical higher order basis functions in the FETD region. Modeling of an antenna feed structure which support the transverse electromagnetic (TEM) mode and the extraction of input impedance is presented. Finally, the method is applied to compute the reflection coefficient and radiation pattern of some typical real-world antennas.

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N. V. Venkatarayalu is with Temasek Laboratories and also with the Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117508, Singapore. (e-mail: tslnv@nus.edu.sg).
Y.-B. Gan was with Temasek Laboratories, National University of Singapore, Singapore 117508, Singapore. He is currently with the European Aeronautic Defence and Space Company, Singapore Research and Technology Centre (EADS SRTC), Singapore 117610, Singapore.
R. Lee is with the ElectroScience Laboratory, The Ohio State University, Columbus, OH 43212 USA.
L.-W. Li is with the Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117508, Singapore.

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