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Research paper

A Novel Compact Ultra-Wideband Antenna with Hybrid IE3D/GA Optimization

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Abstract

A novel compact Ultra-wideband antenna is fabricated and measured. The antenna has a size of 31 mm x 34 mm. The antenna is excited by coplanar wave guide and it provides band width from 3.1 GHz to 10.6 GHz with dual notched bands of 3.3-4.2 GHz and 5.1-6 GHz to avoid interference from worldwide interoperability for microwave access and wireless local area network bands respectively in ultra-wideband. These dual notched band characteristics are obtained by etching a co-directional complementary split ring resonator on radiating patch of the antenna. The antenna dimensions and dual notched bands are optimized by hybrid Genetic Algorithm and IE3D electromagnetic solver. The measured antenna has Omni directional radiation pattern and consistent gain in operating frequency range. The time domain group delay of antenna is also measured, which indicates that the antenna has good pulse handling capacity. This antenna can be easily integrated with portable UWB systems.

Keywords: *Ultra-wideband; wireless local area network; dual band notch; genetic algorithm; gain;*

1. Introduction

Since Federal Communication Commission [1] assigned a bandwidth of 3.1-10 GHz for Ultra-Wide Band (UWB) technology, UWB has become popular for fast transfer of data in wireless communications as it offers high capacity under low power consumption when compared to conventional wireless systems [2, 3]. Planar slot antennas have wider bandwidth [4] and compact size and hence they are effective in the design of UWB antennas. Among feed lines, the Coplanar Wave Guide (CPW) feed has become popular because it is easy to fabricate and is cost effective. The CPW feed line has single metallic layer on one side of dielectric [5] and hence active, passive components can be easily integrated on it.

Over the bandwidth of UWB, there are interfering narrowband communication systems such as IEEE802.16 Worldwide interoperability for Microwave Access (Wi-MAX) operating in 3.3-3.6 GHz band and IEEE 802.11a Wireless Local Area Network (WLAN) system in 5.15-5.825 GHz band. Electromagnetic interference from these bands should be avoided for efficient performance of the UWB antenna. For this purpose, band-notched filters can be used. However, they increase the system complexity [6]. Hence, several UWB antennas have been proposed in literature with band-notched characteristics obtained by embedding arc-slot [7], π-slot [8], slits [9] and attaching parasitic elements near patch [10-11]. However, most of these are capable of rejecting a single band only. Therefore, design of UWB antenna with multi band-notched characteristics along with smaller size has become a challenging task.

In this paper, the design and implementation of a compact UWB slot antenna is presented with dual notched bands of 3.3-4.2 GHz and 5.1-6 GHz to avoid interference from Wi-MAX and WLAN bands. A co-directional CSRR is etched on the symmetrical center of the UWB antenna's radiating patch for this purpose. The antenna is 34% smaller in size than the UWB antenna [5] present in literature for band rejection and consistent group delay. The return loss characteristics in the notched bands are obtained by genetically optimizing the length L and width W of the antenna along with IE3D electromagnetic solver.

Genetic Algorithm (GA) is an optimization technique [12] based on natural combination of genes in living creatures to attain fitter values with every new generation. The width W and length L parameters of proposed antenna are optimized. Hence, these parameters are converted to binary encoded sequences and these sequences are taken to form a chromosome. Population is obtained by obtaining a number of such chromosomes. The population is then ranked using the cost function and the best few chromosomes are reserved for next generation. This procedure is repeated to obtain the best solution.

2. Design and Configuration of UWB Slot Antenna

The complementary split ring resonator (CSRR) is shown in Fig. 1 (a) and is the negative image of the Splint Ring Resonator [13]. A Co-directional CSRR [5], as shown in Fig. 1(b) is similar to CSRR, except that the splits lie on the same side of both the rings. These structures are basic components of met materials.

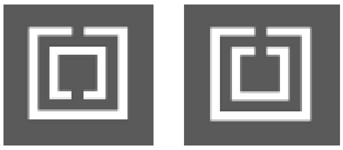

Fig. 1 (a) Rectangular CSRR (b) Co-directional CSRR

The CSRR behave as small LC resonator and its geometry and split orientation affect resonant frequencies [15] .Conventional CSRR can be used to reject narrow band since there exists strong coupling between inner and outer rings. In this paper, a co-directional CSRR is used to reject two bands. A co-directional CSRR could simplify the design process of the notched bands. Due to the greater suitability of mounting a CSRR on planar structures over an SRR [16], the co-directional CSRR is used for the rejection of dual bands in this work. The use of co-directional CSRRs to reject multiple bands in an UWB antenna is relatively new in literature. In this paper, the co-directional CSRR is etched at the centre of the patch of UWB antenna and hybrid IE3D and GA is used for optimization of antenna dimensions and dual notched bands.

A co-directional CSRR is etched in the symmetrical center of the UWB antenna as shown in Fig. 2 to obtain dual band-notched characteristics. The total length of the outer CSRR ring is about half of the guided wavelength λ_{g1} corresponding to the centre frequency f_1 of first notched band. The λ_{g1} is obtained by equation (2) where f_1 is 3.7 GHz. This rejects the band 3.3- 4.2 GHz to avoid interference from Wi-MAX band.

$$\lambda_{g1} = \frac{c}{f_1\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{2}$$

where ε_r is relative dielectric permittivity of dielectric substrate and c is velocity of light in free space.

The total length of the inner CSRR ring is half of the guided wavelength λ_{g2} , which corresponds to second notched band's centre frequency, i.e. f_2 = 5.7 GHz. λ_{g2} is obtained by equation (3). This rejects the band 5.1-6 GHz to avoid interference from WLAN band.

$$\lambda_{g2} = \frac{c}{f_2\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{3}$$

The dimensions of the co-directional CSRR shown in Fig. 2 are such that they can be varied as per equations (4) and (5) to obtain notched bands at different frequencies.

$$4L_8 - s = \frac{\lambda_{g1}}{2} \tag{4}$$

$$4(L_8 - 2d - 2W_8) - s = \frac{\lambda_{g2}}{2} \tag{5}$$

2.1 Geometry and Mathematical Analysis of UWB antenna

The proposed UWB antenna is fabricated on RT Duroid substrate with relative dielectric permittivity ε_r=2.2, thickness h = 0.8 mm. The antenna has compact size of 34 mm × 31 mm and it is fed by a CPW with characteristic impedance Z_o = 50 Ω, strip width W_4 = 3 mm and slot width g = 0.4 mm as shown in Fig. 2. A wide rectangular slot in antenna is used to obtain good impedance matching in operating band. A sub-miniature version A (SMA) connector is connected to the antenna and a radio frequency cable connects the SMA connector to vector network analyzer for obtaining measurements. The antenna is optimized using Method of Moments (MOM) based IE3D electromagnetic simulator [17] and Genetic Algorithm. The optimized geometrical parameters of antenna are W = 34 mm and L = 31 mm. The other dimensions of antenna are S = 0.4 mm. G= 0.4 mm, H = 0.8 mm, W_1 = 15.1 mm, W_2 = 1.5 mm, W_3 = 2 mm, W_4 = 3 mm, W_5 = 2.5 mm, W_6 = 4 mm, W_7 = 4 mm, W_8 = 0.5 mm, L_1 = 8.5 mm, L_2 = 3 mm, L_3 = 2 mm, L_4 = 0.6 mm, L_5 = 3 mm, L_5 = 3 mm, L_6 = 8 mm, L_7 = 3 mm, L_8 = 8.6 mm, L_9 = 3.5 mm. The parameters W and L are obtained from GA Optimization and details are explained in section III.

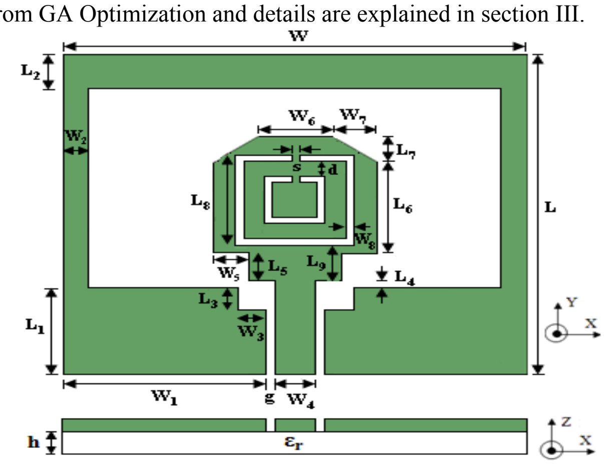

Fig. 2. Geometry of the proposed UWB slot antenna with co-directional CSRR

The slot width g of the CPW feed is limited [18] by equation (6).

$$G \le \frac{10h}{[3(1+\ln\varepsilon_r)]} \tag{6}$$

$$W \approx L \approx \frac{c}{2f_l}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{7}$$

As per this work, W ≈ L ≈ 38.2 mm when f_l is 3.1 GHz. But, it is found that the theoretical values of W and L do not always exhibit the best performance, especially in cases when notched bands are desired. For such cases, GA is employed with IE3D to estimate the optimum valus for W and L.

3. Genetic Algorithm Optimization of Uwb Antenna with Ie3d

The UWB antenna was simulated using IE3D electromagnetic simulator between 2 GHz and 12 GHz by taking 40 intermediate frequency points. The width W and length L are the parameters considered for optimization within ranges of 30-40 mm and 30-40 mm respectively.

It was mentioned in [19] that in case of an internal optimization, overlapping problems arise in the IE3D simulation for certain variation in optimization parameters, which terminate the iteration abruptly. This can be avoided by employing powerful external optimization tools with IE3D. External optimizer such as the Particle Swarm Optimizer (PSO) is available in literature [19-21]. Genetic Algorithm with IE3D is used for the optimization of structure of antenna and also notched bands in this research work.

In notched band of the proposed antenna, the return loss in the notched bands should be higher than -10 dB, and the return loss in the pass bands should be lower than -10 dB. To ensure this, GA is used. A cost function *C* is used and is defined as the sum of the weighted products of the return loss and expressed as

$$C = \sum_{i=1}^{N} \mathcal{W}_i \times \mathcal{R}_i \qquad (8)$$

where R_i is the return loss in dB, N is the total number of frequency points in the IE3D simulation, and W_i is the weight at the i^{th} frequency point. In this work, negative weights are assigned in the notched band and positive weights are assigned in the pass band. The purpose of GA is to minimize the cost function to obtain fitter chromosomes with successive generations.

3.1 Implementation of GA and IE3D Optimization

MATLAB based GA optimization was initiated with the IE3D electromagnetic simulator [17] and the following algorithmic is executed to obtain appreciable chromosome convergence of W and L

Step 1: IE3D electromagnetic is initiated with simulation engine.
Step 2 :(a) The basic geometry of the UWB antenna is designed using IE3D and *.geo file* is generated
(b) The design within the specified frequency range is simulated with in a number of distinct frequency points and *.sim file* is generated.
Step 3: The return loss characteristics are obtained from the S-parameter file (*.sp file*)
Step 4: (a) The MATLAB based GA optimization is plugged in with IE3D
(b) The *.sim file* is modified as specified by the values of chromosomes
(c) 'System Call' function is executed to simulate the new *.sim file* using IE3D engine.
(d) The new *.sp file* is read and populated it in MATLAB workspace
(e) The cost function is computed for every chromosome and these chromosomes are ranked.
(f) The best chromosomes are extracted and saved.
Step 5: Is the Generation Limit reached?

- If *yes* ⇒ *Go to Step 6*
- If *no* ⇒ *Go to Step 4 (b)*

Step 6 :(a) the chromosome population swarm are plotted for *W* and *L* within bounds.
(b) The best values for *W* and *L* are obtained.

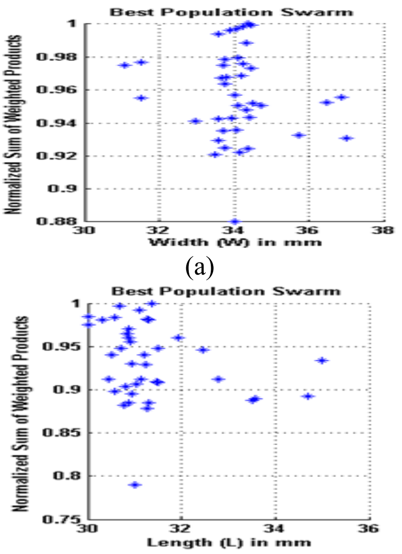

Fig. 3. (a) Best population swarm for W (b) Best population swarm for L

The GA converges the chromosome clusters of the two parameters W and L from the specified range to an optimum value. Fig. 3(a) and Fig. 3(b) show the best population swarms and the fittest chromosomes of the two parameters W and L. From the population swarm of W and L, the obtained optimized values of the two parameters are W = 34 mm and L = 31 mm.

4. Measured Results and Discussion

The fabricated antenna is shown in Fig. 5. The fabricated antenna is measured using Agilent Network Analyzer E8363B. Fig. 5 compares the simulated and measured return losses of the fabricated antenna, which shows very good agreement between them. The slight difference between them is due to the soldering effect at the SMA connector and manufacturing tolerance of the patch. The first two measured resonant frequencies 3.2 GHz and 4.7 GHz are obtained due to the rectangular slot on the antenna whereas the patch provides third measured resonant frequency 8.3 GHz. The ground plane and radiating patch are responsible for one resonant mode to another and provide good impedance matching.

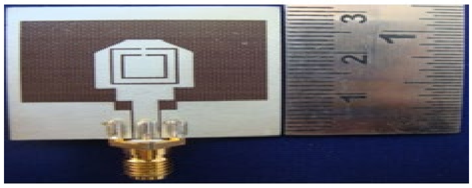

Fig. 4. Photograph of fabricated antenna

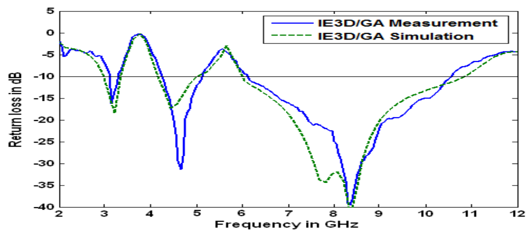

Fig.5. Return loss plots from IE3D/GA simulation and measurement

Parametric analysis is performed with IE3D to study the effects of different geometrical parameters on characteristics of the antenna by varying one parameter while keeping all others constant.

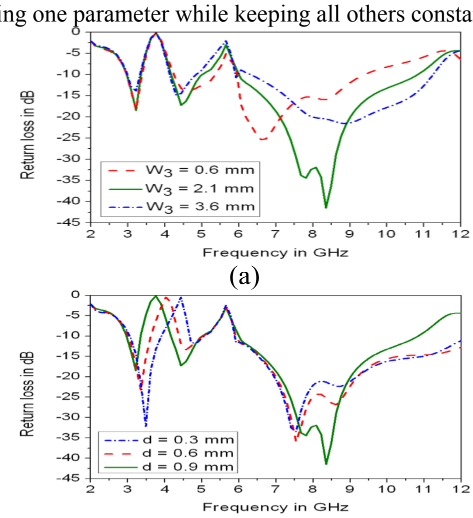

Fig. 6. Simulated return losses of proposed antenna for different (a) slot widths W_3 (b) distance'd'

4.1 Effect of Variation of Width W_3 of Square Slot in Ground Plane near Feeding

Fig. 6(a) shows the effect of width W_3 of square slot in the ground plane on bandwidth of antenna. When the width W_3 decreases from 3.6 mm to 0.6 mm, the total operating bandwidth decreases due to change in electromagnetic coupling between grounds and radiating patch. The first and second simulated notch frequencies 3.25 GHz and 4.7 GHz remain constant whereas the second notched bandwidth decreases from 1.49 GHz to 0.59 GHz. The WLAN band is not fully avoided at W_3 = 0.6 mm. Hence, this parameter has significant effect on operating bandwidth and second notched band. The WLAN band is fully rejected at an optimized value of W_3 = 2.1mm.

4.2 Effect of Distance'd' Between the Rings of the Co-directional CSRR

Fig. 6(b) presents the effects of 'd' between the inner rings of the co-directional CSRR on antenna by keeping the total length of outer ring constant. As 'd' is changed from from 0.3 mm to 0.9 mm, the length of inner ring deceases and the first notch frequency decreases from 4.4 GHz to 3.7 GHz. This is mainly due to inductive and capacitive effects produced by inner ring. However, the second notch frequency remains constant. The operating bandwidth is also changed. The necessary first notched frequency of 3.7 GHz is obtained for d = 0.9 mm with good impedance matching over operating band. Hence, first notch frequency is affected by'd' and this parameter also plays important role in obtaining first notched band of 3.3 to 4.2 GHz.

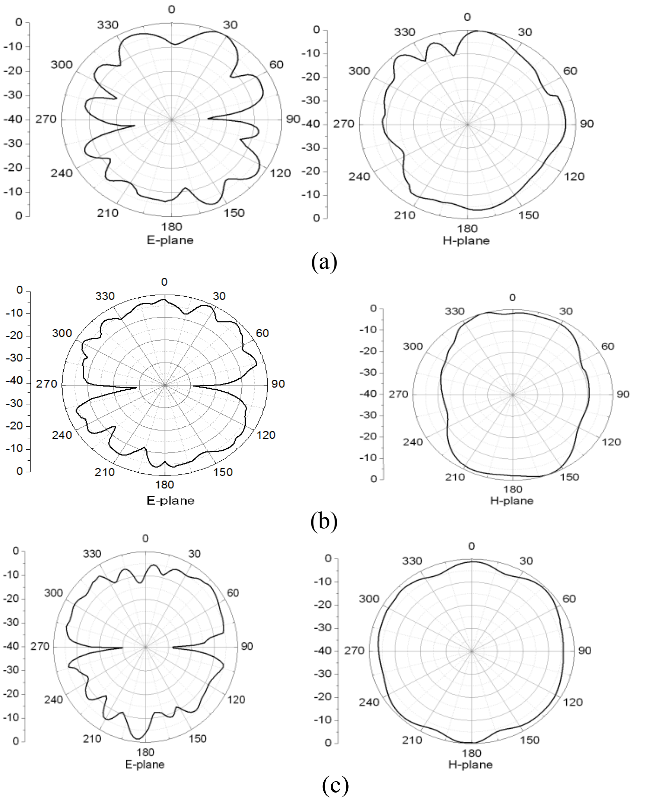

Fig. 7. Measured E and H-plane radiation pattern at (a) 3.2 GHz, (b) 4.7 GHz, (c) 8.3 GHz

4.3 Radiation patterns and Gain

The radiation patterns are measured for the proposed antenna in anechoic chamber in far field. The measured radiation patterns are shown in Fig. 7 at resonant frequencies 3.2 GHz, 4.7 GHz and 8.3 GHz in both E and H planes. The radiation patterns are omni-directional in H-plane and they are relatively stable. The radiation patterns in E-plane are of dipole shape. The measured gain is almost flat with sharp fall in the notched bands as shown in Fig. 8. The gain falls to -9.4 dB in Wi-MAX band and -5 dB in WLAN band. This shows good signal rejection capability in these bands.

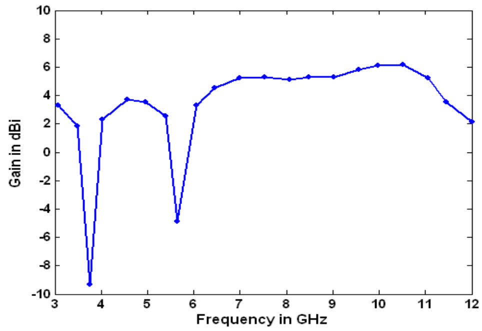

Fig. 8. Measured gain for the band notched antenna

4.4 Group Delay Characteristics

The group delay τ_g indicates a degree of pulse distortion and phase linearity and is an important characteristic in time domain. It is expressed as

$$\tau_g = \frac{1}{2\pi}\left(-\frac{\partial\phi}{\partial f}\right) \tag{15}$$

where ϕ is the phase in far field and f is the frequency and. The group delay is obtained by keeping the two antennas in face to face orientation in far field. τ_g is less than 1 ns in operating band except in the two notched bands as shown in Fig. 9. This indicates good pulse handling capability with linear phase response. In notched bands, τ_g is more than 1 ns, which indicates good rejection of Wi-MAX and WLAN bands.

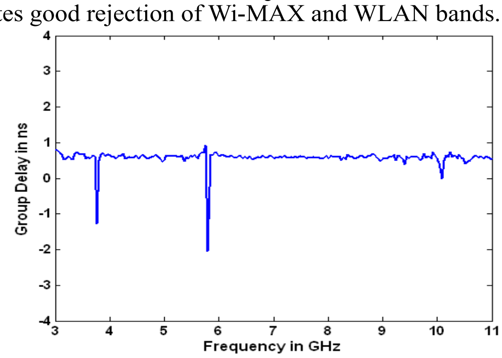

Fig. 9. Measured group delay response of the UWB antenna in the time domain

When compared with other antennas [4, 5], it was found that the proposed antennas has compact size and reasonable band with dual notched bands of 3.3-4.2 GHz and 5.1-6 GHz to avoid interference from Wi-Max and WLAN respectively in the operating UWB band of 3.1-10.6 GHz.

5. Conclusions

A novel compact CPW-fed UWB slot antenna with dual band-notched characteristics is implemented. Genetic Algorithm with IE3D is used to obtain the optimum length and width of the antenna for operation in UWB band along with optimized dual notched bands. The antenna has a compact size. A co-directional CSRR is etched in the center of patch to avoid interference from Wi-MAX and WLAN bands. The dimensions of the inner and outer rings of the co-directional CSRR are engineered to obtain notched bands at different frequencies. The measured antenna has stable radiation patterns in E and H planes. The antenna exhibits consistent gain with sharp decrease in dual notched bands. The group delay of antenna is less than 1 n which represents good linear phase response. The compact size and ultra-wide bandwidth make the antenna suitable for emerging UWB applications.

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