International Journal of Electronics and Communication Engineering (IJECE)
ISSN 2278-9901
Vol. 2, Issue 4, Sep 2013, 139-148

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

A DESIGN AND AN EQUIVALENT CIRCUIT OF A QUAD BAND-NOTCHED ULTRA-WIDE BAND PATCH ANTENNA

AYAD SHOHDY W. GHATTAS[1] & ELSAYED ESAM M. KHALED[2]

[1]Electrical Engineering Department, Sohag University, Sohag, Egypt

[2]Electrical Engineering Department, Assiut University, Assiut, Egypt

ABSTRACT

A proximity feed ultra-wide band (UWB) patch antenna with four notched bands is presented. The proposed antenna introduces UWB performance in the frequency range of 1.9 GHz to 10.3 GHz with omnidirectional radiation pattern. Slots etching techniques are utilized to provide four bands notches at frequencies of 2.3, 2.8, 3.5, and 5.5 GHz to avoid the interference with the existing wireless networks which occupy bands at these frequencies. Furthermore a curve fitting technique is applied to synthesize an equivalent electric circuit model to the proposed antenna. The analysis and design of the proposed antenna were carried out using the commercially available Ansoft high frequency structure simulator (HFSS). The antenna is fabricated and tested. The measured data of the fabricated antenna demonstrate very good agreement with the simulated results and the equivalent circuit results.

KEYWORDS: Circuit Modeling, Four Frequency-Band Notches, Patch Antenna, SPICE Equivalent Circuit, Ultra-Wide Band, Vector Fitting

INTRODUCTION

The ultra-wide band (UWB) antennas have gained high interest in the recent years since 2002 when the unlicensed use of the commercial UWB communications devices is permitted [1–3]. However communications with these antennas need to avoid interference with the existing standard wireless networks such as UMTS2100 (1.92–1.98 GHz, 2.11–2.18 GHz) WiMAX (2.3–2.5 GHz, 2.7–2.9 GHz, and 3.3–3.9 GHz) WLAN in USA (5.15–5.35 GHz, 5.725–5.825 GHz) and HIPERLAN/2 in Europe (5.15–5.35 GHz, 5.47–5.725 GHz). To avoid such interference, frequency band-notches are preferably applied directly to the UWB antennas instead of adding filters. Most of researches in the literature are focused to design an antenna with a single [4], dual [5] or three [6] frequency band-notches. In this paper, a novel planar patch antenna with UWB frequency range with four rejected bands corresponding to the previously mentioned applications is presented. The proposed antenna in this work is adopted with a proximity-feed line technique. The desired four notched bands are achieved by etching different shaped slots in the ground plane of the antenna. The length of each slot can be approximately by [5], [7]:

$$l_{slot} \approx \frac{c_o}{4 f_{notch} \sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{1}$$

where l_{slot} is the length of the slot, f_{notch} is the centre frequency of the notched band, ε_r is the relative permittivity, and c_o is the velocity of light. However, the exact length which corresponds to the required centre frequency of a notched band can be achieved by parametric studies using a software simulator. The proposed antenna is simulated using Ansoft high frequency structure simulator (HFSS). Also the antenna is fabricated and its performance parameters are measured using HP8719 vector network analyzer. An equivalent electric lumped-elements circuit for the proposed antenna is established through the use of the Vector Fitting (VF) and the ready software SPICE techniques. The simulated results, equivalent circuit results and the measured data are presented.

ANTENNA DESIGN

The antenna is etched on FR4 substrate of a relative permittivity $\varepsilon_r = 4.5$, loss tangent tan $\delta = 0.01$, a thickness $h = 1.5$ mm. The total dimension of the substrate and the ground plane is $l_g \times w_g = 30 \times 30$ mm^2. The Geometry of the proposed UWB antenna is shown in Figure 1(a). The antenna is fed by a proximity 50 Ω microstrip line of dimensions $l_f \times w_f = 18.5 \times 3$ mm^2 printed on one surface of the substrate. To achieve UWB range with a band notch at frequency 5.5 GHz, a rectangle slot is etched in the ground plane on the other side of the substrate and of dimensions $l_r \times w_r = 19 \times 28$ mm^2 along with a smaller rectangular slot of dimensions $l_p \times w_p = 4 \times 4.5$ mm^2 . The two rectangular slots are etched with the same symmetric vertical line as shown in the figure. A circular patch of radius $r = 4$ mm is located concentric in the larger rectangle slot. Two more rectangle slots of dimensions $l_s \times w_s = 12.5 \times 2$ mm^2 with length l_s =12.5 mm which approximately corresponds to notched frequency 3.5 GHz according to Eq. (1) are introduced in the lower part of the ground plane to provide a notch centered at this frequency. Also two rectangle slots of dimensions $l_b \times w_b = 18 \times 0.4$ mm^2 with length l_b =18 mm which approximately corresponds to notched frequency 2.8 GHz are etched in the ground plane at both sides of the larger rectangular slot as shown in the figure. Dimensions of each part of the antenna are illustrated in detail in Table 1. The top and bottom views of the antenna are shown in Figure 1(b) and Figure 1(c), respectively. The antenna is fabricated and photographs of the top and bottom views of the antenna are shown in Figure 2.

RESULTS AND DISCUSSIONS

The proposed antenna is simulated using Ansoft HFSS software. The fabricated antenna was tested using the vector network analyzer HP8719. Figure 3 illustrates the simulated results and measured data of the Return Loss (RL) as a function of frequency. The simulation results show a bandwidth from 1.85 GHz to 10.3 GHz whereas the measured data show a bandwidth from 1.9 GHz to 10 GHz. Dimensions of the wide rectangle slot in the ground plane and the small rectangle slot beneath the feeding line, and the radius of the circular patch are the key factors to adjust the notched frequency bands. Figure 4 shows the effect of changing the width of the wide rectangle slot w_r and keeping the length $l_r = 19$ mm. Also the figure shows the effect of changing the length l_r with fixed wr = 28 mm on the values of the RL as a function of frequency, both with $r = 4$ mm, $l_p \times w_p = 4 \times 4.5$ mm2 and without any other slot etching in the ground. It is observed that, the optimum values of the wide rectangle slot are $w_r = 28$ mm and $l_r = 19$ mm.

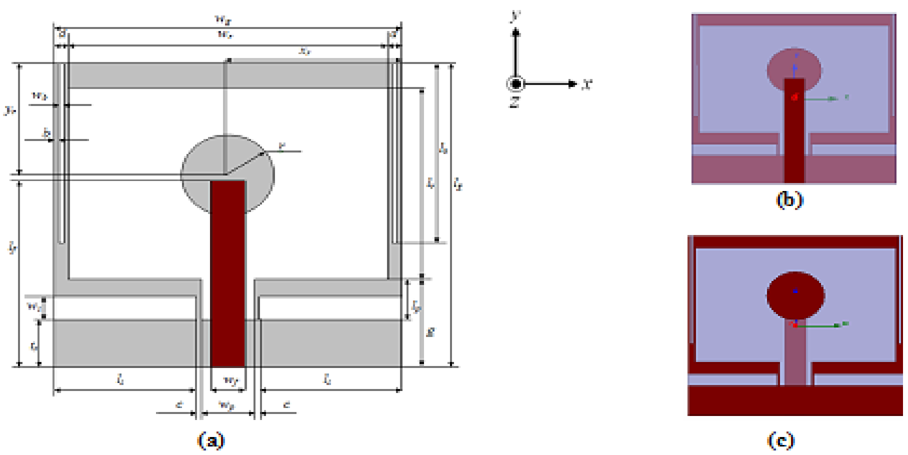
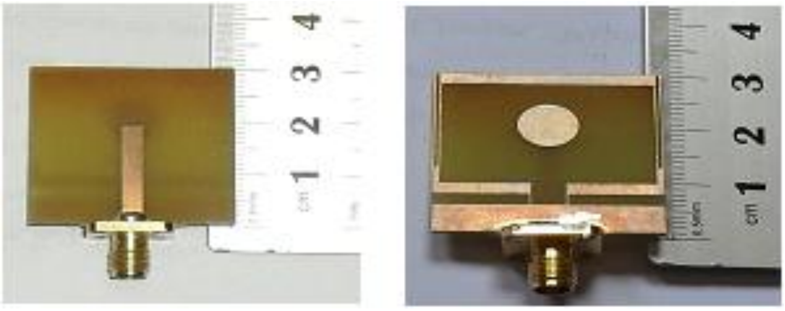


Figure 1: (a) The Geometry of the Proposed UWB Antenna, (b) Top-View of the Antenna, (c) Bottom-View of the Antenna

Table 1: The Elements Dimensions of the Proposed UWB Antenna

Dim.	l_g	w_g	l_r	w_r	l_f	w_f	r	x_r	y_r	l_s	w_s	t_s
Value (mm)	30	30	19	28	18.5	3	4	15	10	12.5	2	5
Dim.	l_p	w_p	g	c	d	l_b	w_b	b	Substrate's height (h)			
Value (mm)	4	4.5	9	0.25	1	18	0.4	0.3	1.5			



(a) (b)

Figure 2: Photograph of the Fabricated Proposed Antenna, (a) Top-View, (b) Bottom-View

When the width or the length of the rectangle slot increases over these optimum values the bandwidth decreases and the center frequency of the notched band 5.5 GHz increases. Figure 5 shows the effect of varying the width of the small rectangle slot w_p with fixed length l_p = 4 mm and the effect of changing the length l_p at fixed width w_p = 4.5 mm, and with r =4 mm, $l_r \times w_r$ = 19 × 28 mm^2 without any other slot etching in the ground. The figure illustrates that the optimum dimensions are w_p = 4.5 mm and l_p = 4 mm. As w_p increases over the optimum value the center frequency of the notched band at 5.5 GHz decreases.

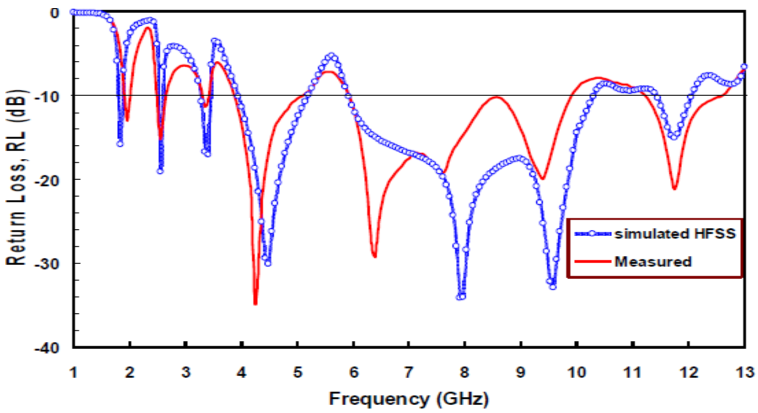
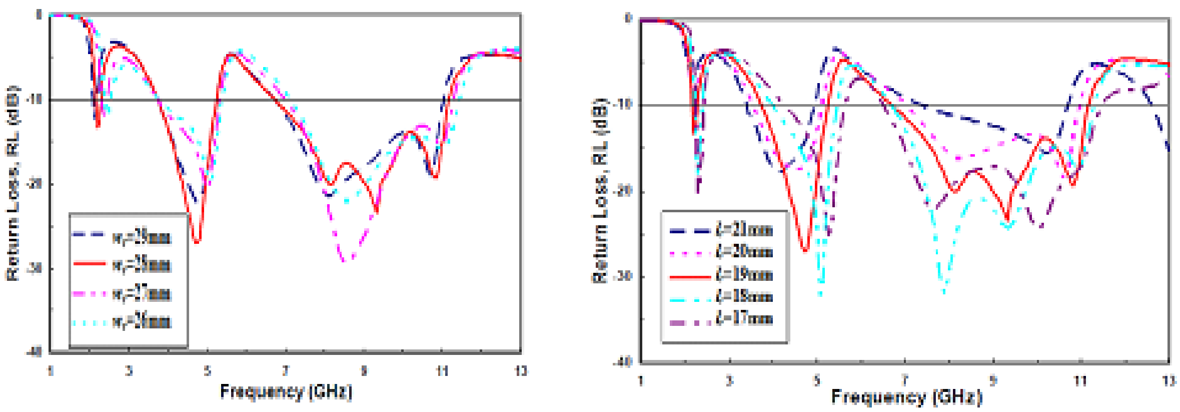
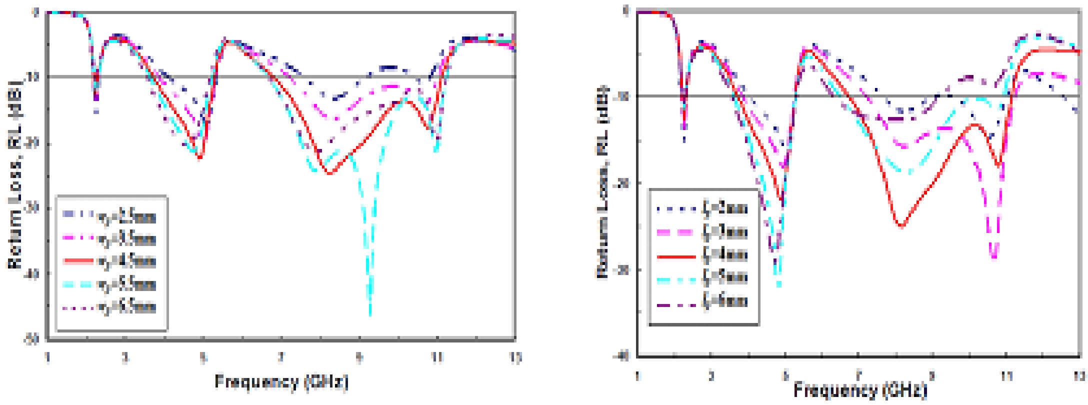


Figure 3: Simulated and Measured Return Loss (RL), versus Frequency of the Proposed UWB Antenna



(a) (b)

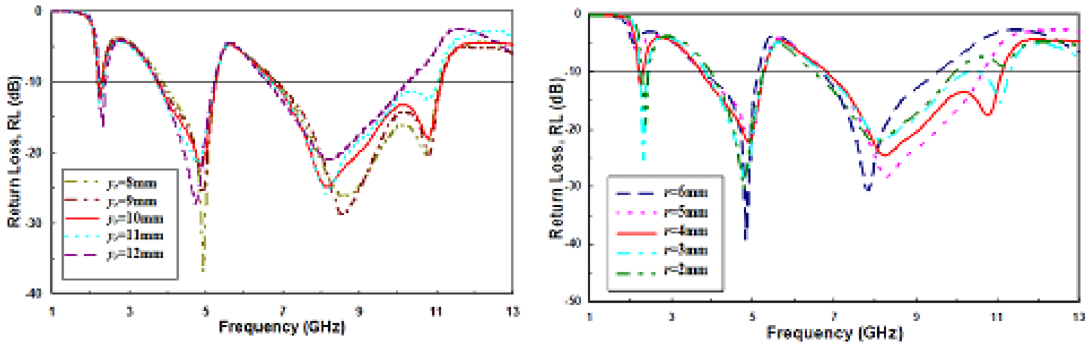
Figure 4: Simulated RL versus Frequency of the Proposed Antenna, (a) with Different Values of w_r at l_r = 19 mm, (b) with Different Values of l_r at w_r = 28 mm



(a) (b)

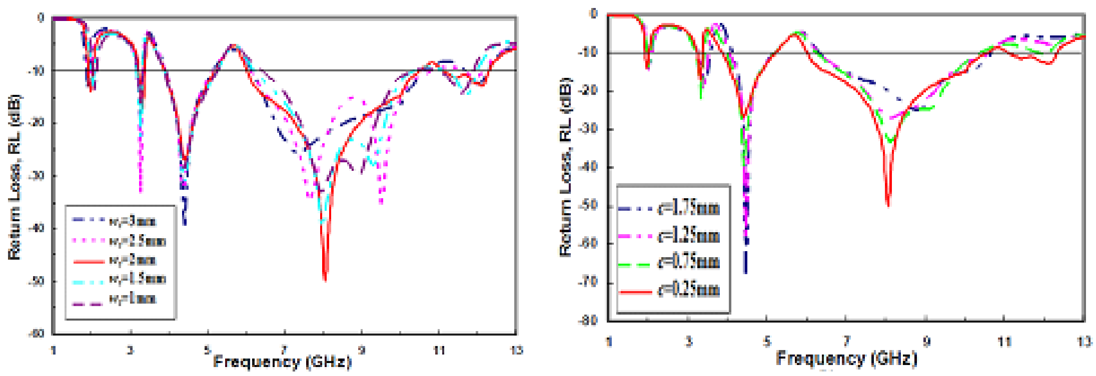
Figure 5: Simulated RL versus Frequency of the Proposed Antenna, (a) with Different Values of w_p at l_p = 4 mm, (b) with Different Values of l_p at w_p = 4.5 mm

Also when l_p increases over the optimum value the bandwidth decreases. As l_p decreases the overall bandwidth of the antenna decreases. Figure 6 shows the effect of changing the vertical distance of the center of the circular patch y_r and keeping its radius r = 4 mm. The figure illustrates also the effect of changing the radius r with fixed y_r = 10 mm, and with $l_r \times w_r$ = 19 × 28 mm^2, $l_p \times w_p$ = 4 × 4.5 mm^2, x_r = 15 mm, and without introducing any other slots. It is clear that the best parameters for the circular patch are y_r = 10 mm and r = 4 mm. To achieve another frequency notch in the response of the antenna two small rectangle slots of dimensions $l_s \times w_s$ are etched in the ground plane underneath and at both sides of the feed line. These etched slots provide a band notch at frequency 3.5 GHz. Figure 7 illustrates the effect of changing the width w_s at l_s = 12.5 mm, c = 0.25 mm. Also the figure shows the effect of changing the length l_s at w_s = 2 mm. Both at t_s = 5 mm. It can be noted that the optimum values are $l_s \times w_s$ = 12.5 × 2 mm^2, c = 0.25 mm.



(a) (b)

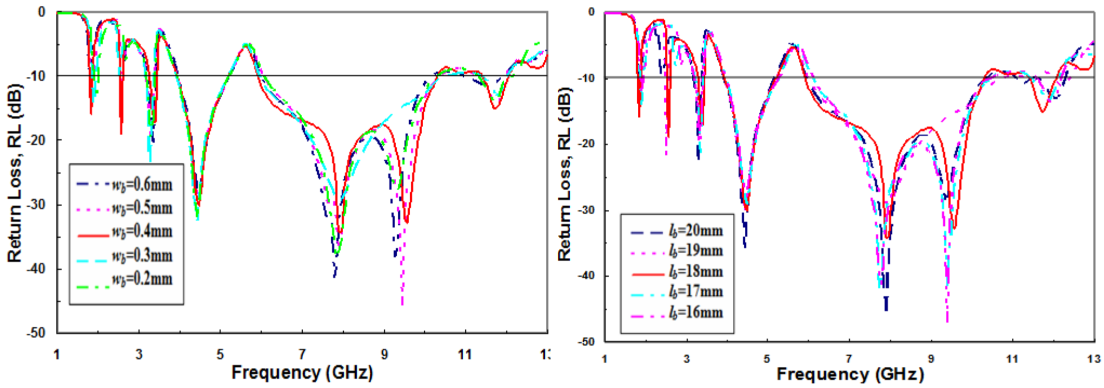
Figure 6: Simulated RL versus Frequency of the Proposed Antenna, (a) at r = 4 mm and Different Values of y_r, (b) at y_r = 10 mm and Different Values of r



(a) (b)

Figure 7: Simulated RL versus Frequency of the Proposed Antenna, (a) with Different Values for w_s at l_s = 12.5 mm, c = 0.25 mm, (b) with Different Values for c at w_s = 2 mm

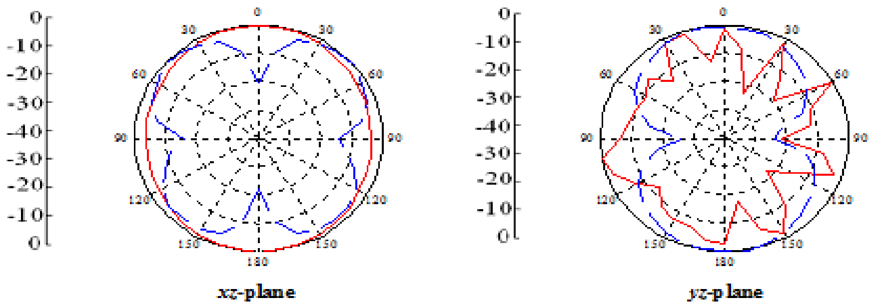
The changing w_s has an effect on the notched bandwidth at 5.5 GHz and has no effect on the notched bandwidth at 3.5 GHz. Furthermore by etching two other small rectangular slots of dimensions $l_b \times w_b$, two band notches at frequency 2.8 GHz and 2.3 GHz can be achieved. Figure 8 shows the effect of varying the width w_b of the two rectangular slots at l_b = 18 mm and the effect of changing the length l_b at w_b =0.4 mm and keeping b=0.3 mm. The figure demonstrates that the optimum values are l_b = 18 mm and w_b =0.4 mm. As w_b or l_b increases the center frequency at 2.3 GHz increases and at certain limit the two band-notches at 2.8 GHz 2.3 GHz can not be obtained. Figure 9 shows the normalized far-field radiation patterns of $E\varphi$ and E_θ in the *yz*- (*E*-plane) and *xz*- (*H*-plane) planes of the proposed antenna at frequencies 4.2 GHz and 6.5 GHz. It is observed that the simulated patterns exhibit a nearly omnidirectional radiation in the *xz*-plane at these frequencies, whereas, in *yz*-plane the radiation pattern is bi-directional and looks like the radiation from a dipole antenna.



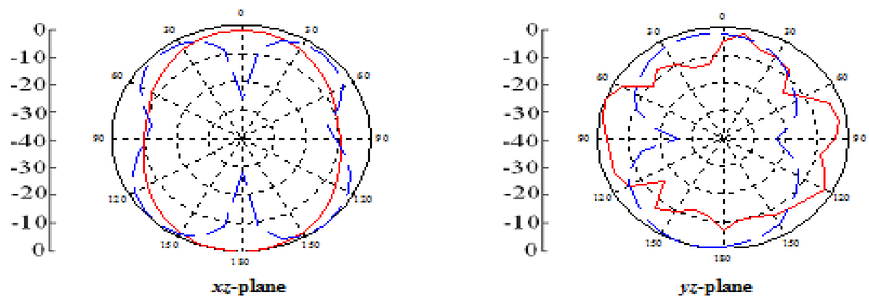
(a) **(b)**

Figure 8: Simulated RL versus Frequency of the Proposed Antenna, (a) with Different Values of w_b at l_b=18 mm, b=0.3 mm, (b) with Different Values of l_b at w_b =2 mm, b=0.3 mm

Figure 10 illustrates the gain and the radiation efficiency of the proposed antenna versus frequency. The figure shows that the proposed antenna has high gain and good radiation efficiency over the entire frequency band except at the four frequency band-notches.

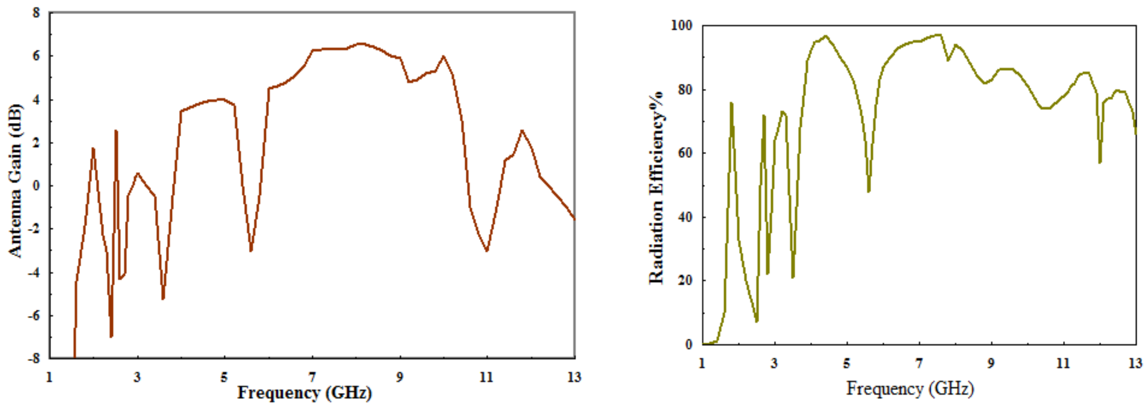


(a)



(b)

Figure 9: Simulated Radiation Patterns of $E\varphi$ (Solid Line) and E_θ (Dashed Line) in the *xz*- and *yz*- Planes of the Proposed Antenna at Frequency (a) 4.2 GHz, (b) 6.5 GHz



(a) (b)

Figure 10: (a) Simulated Antenna Peak Gain, (b) Simulated Radiation Efficency of the Proposed Antenna

EQUIVALENT CIRCUIT MODELING FOR THE PROPOSED ANTENNA

For more performance perception of the antenna with notched bands integrated with an UWB communication system a SPICE-compatible circuit modeling is provided to get a lumped-elements equivalent circuit model for the proposed antenna. This can be achieved by using the VF technique. This method can be applied to the input impedance or admittance of the antenna. The procedures can be found in details in [8] and can be summarized as follow: first the input impedance or admittance of the proposed antenna is obtained by simulation or measurements over the frequency band of the antenna. Second this obtained results or data should be fed to a MATLAB code to obtain a rational function approximation and finally the rational function is converted into a SPICE-compatible equivalent circuit and the synthesized component values are obtained.

The rational function approximation of a certain frequency domain response F(s) can be expressed as:

$$F(s) = \sum_{k=1}^{N} \frac{res_k}{s - p_k} + d + se \qquad (2)$$

where res_k and p_k denote the k-th residues and poles, respectively, which are may be real quantities or come in conjugate pairs of N identical sets of poles, s is a complex frequency = jw, d is a constant term and e is a proportional term. All coefficients of Eq. (2) are extracting by using the VF technique procedures so that an approximation of F(s) is obtained over a given frequency band. In this work the VF technique is applied to the input admittance of the proposed antenna. The constant term d and the proportional term e can be synthesized as a resistance R_o and a capacitor C_o respectively whose values are determine as follow [9]:

$$R_o = \frac{1}{d}\ ,\ C_o = e \qquad (3)$$

The remaining part of $F(s) = \sum_{k=1}^{N} \frac{res_k}{s - p_k}$ (for k=1 to N), where the number of poles N can be determined by setting an order for an acceptable approximation, can be calculated as follow:

Each real pole gives RL-branch

$$L_k = \frac{1}{res_k}, \qquad R_k = -\frac{p_k}{res_k} \qquad (4)$$

Each complex conjugate pair gives *RLC*-branch

$$L = \frac{1}{res_1 + res_2}$$

$$C = \frac{res_1 + res_2}{p_1 p_2 + \left[-(p_1 + p_2) + \frac{res_1 p_2 + res_2 p_1}{res_1 + res_2} \right] \times \left[\frac{res_1 p_2 + res_2 p_1}{res_1 + res_2} \right]} \tag{5}$$

$$R = \frac{1}{res_1 + res_2} \times \left[-(p_1 + p_2) + \frac{res_1 p_2 + res_2 p_1}{res_1 + res_2} \right]$$

$$R' = -\frac{1}{C} \times \frac{res_1 + res_2}{res_1 p_2 + res_2 p_1}$$

The complete equivalent circuit can be established as shown in Figure 11. The process can be started by $N = 2$ which is the minimum order of approximation and it is provide two real poles or one complex conjugate pair. By increasing the order of approximation N, the number of either the resultant real poles or complex pair will increase. For more N the fitted data are more agreeing with the simulated or measured data, but with more computing time and storage, and the relative error will decrease. For the proposed antenna it is found that by setting $N = 28$ a very accurate approximation is achieved and a root-mean square error of magnitude 3.816e–04 is obtained. The resultant poles and residues of the rational function approximation of Y(s) using the VF is listed in Table 2. Figure 12 shows the magnitude and phase of the simulated results of the input admittance and the fitted results using the VF technique procedures, the figure illustrates that the fitted data (magnitude and phase) are coinciding with the simulated data.

Using the SPICE software the values of the electric lumped-elements of the synthesized circuit can be established. Table 3 shows the components values for the equivalent circuit of the proposed antenna. It is noted that, while the VF technique generate stable poles and also enforcing passivity [10], the resulting electrical components may still have unphysical values such as negative resistances, inductors and capcitors. But this technique can be used as a tool to aid engineers in designing an actual passive circuit that can be used to emulate the scattering parameters response of a UWB antenna [11]. The equivalent circuit model for the input admittance of the proposed antenna for $N = 28$ is shown in Figure 13. Comparison of the simulated, measured, and equivalent circuit model results of the proposed antenna are shown in Figure 14. The figure shows a very good agreement between the simulated results, the measured data and the results obtained from the equivalent circuit model. The provided circuit model is useful to consider the effect of the proposed antenna when integrated with the whole communication system. It also helps designers to predict the communication system performance.

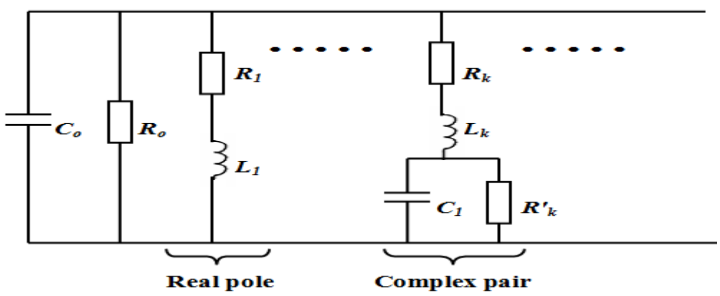


Figure 11: SPICE-Compatible Equivalent Circuit Model for Antenna

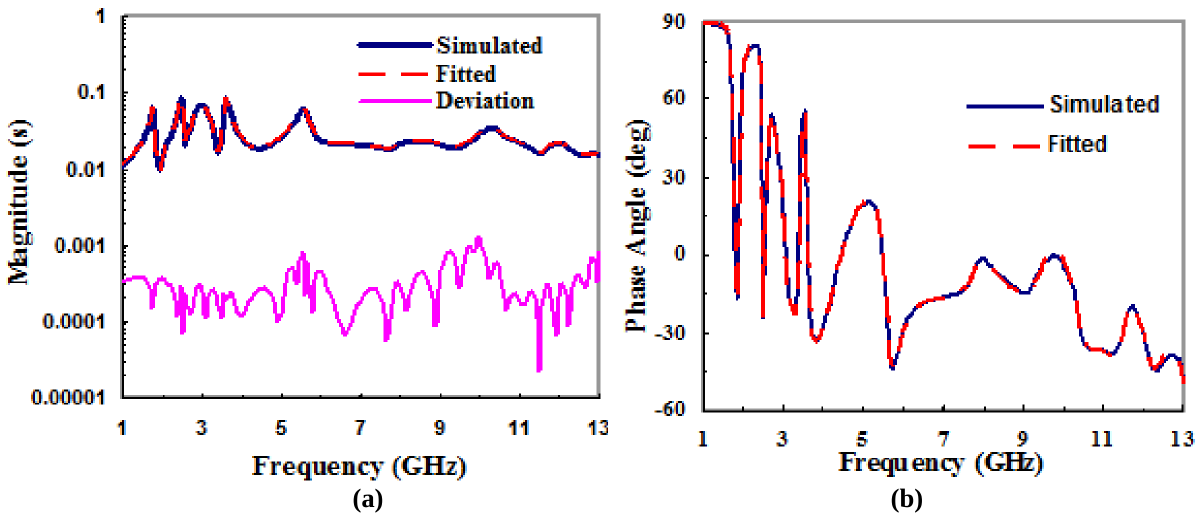


Figure 12: The Magnitude and Phase of the Simulated Results of the Input Admittance and the Fitted Results Using the VF Technique Procedure, (a) Magnitude, (b) Phase Angle

Table 2: The Rational Function Approximation for the Input Admittance Y (s) of the Antenna

Type and No. of Poles	Poles (1e+11)	Residues (1e+09)
Complex 1	–0.0022 ± 0.1105i	0.0161 ± 0.0022i
Complex 2	–0.0011 ± 0.1557i	0.0162 ± 0.0009i
Complex 3	–0.0142 ± 0. 1888i	0.0988 ± 0.0100i
Complex 4	–0.0040 ± 0.2246i	0.0249 ± 0.0207i
Complex 5	–0.1366 ± 0. 3047i	0.0349 ± 0.2478i
Complex 6	–0.0157 ± 0.3403i	0.0133 ± 0.0030i
Complex 7	–0.0075 ± 0.3503i	0.0210 ± 0.0165i
Complex 8	–0.0260 ± 0.4991i	–0.0036 ± 0.0153i
Complex 9	–0.0251 ± 0.5965i	–0.0113 ± 0.0082i
Complex 10	–0.0039 ± 0.6240i	0.0002 ± 0.0004i
Complex 11	–0.0159 ± 0.6511i	0.0173 ± 0.0119i
Complex 12	–0.0217 ± 0.7185i	–0.0164 ± 0.0005i
Complex 13	–0.0196 ± 0.7622i	0.0014 ± 0.0177i
Complex 14	–0.0016 ± 0.8321i	–0.0118 ± 0.0050i
d	**0.01489**	
e	**0**	

Table 3: Synthesized Components Values for the Proposed Antenna

Type and No. of Poles	*L* (H)	*R* (Ω)	*C* (F)	*R′* (Ω)
Complex 1	3.0950e–08	54.1625	2.5921e–13	–2956.8753
Complex 2	3.0765e–08	30.3665	1.3353e–13	–9980.9671
Complex 3	5.0590e–09	16.9607	5.4848e–13	–3623.1879
Complex 4	2.0070e–08	382.7416	5.8403e–14	–937.4891
Complex 5	1.4326e–08	3296.1547	1.4613e–15	–3374.9751
Complex 6	3.7554e–08	350.8529	2.1847e–14	–7393.7630
Complex 7	2.3742e–08	–636.8456	2.1187e–14	1666.0200
Complex 8	–1.3682e–07	28395.5723	–1.5666e–16	–30002.2866
Complex 9	–4.4192e–08	1805.4929	–4.1598e–15	–5237.9806
Complex 10	1.7593e–06	156501.0912	4.8429e–17	–234211.8939
Complex 11	2.8846e–08	–1245.2663	5.5520e–15	3884.9176
Complex 12	–3.0369e–08	1.1181	–6.3722e–15	–35809.5004
Complex 13	3.5396e–07	–338573.5034	3.0559e–18	340716.0162
Complex 14	–4.2345e–08	1505.1426	–2.8799e–15	–9676.4807
Constant *d*	R_o = 67.1681 Ω			

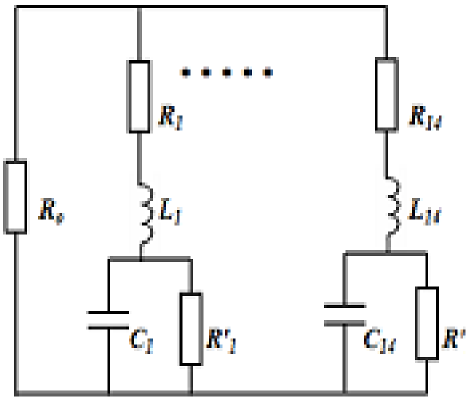


Figure 13: Equivalent Circuit Model of the Proposed Antenna

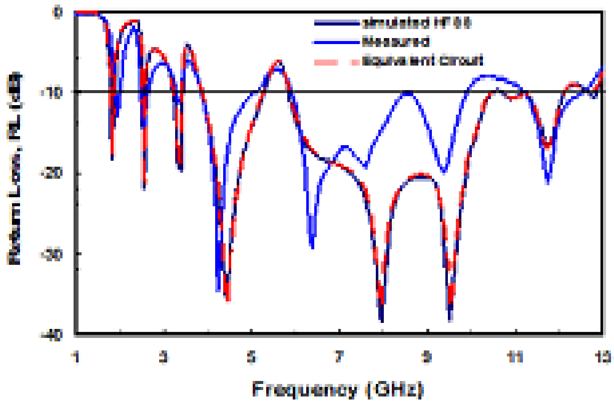


Figure 14: Simulated, Measured and Equivalent Ciruit Return Loss, (RL) versus Frequency of the Antenna

CONCLUSIONS

In this work an UWB antenna with four bands notches is designed. Matching between the UWB antenna and the 50 ohm microstrip line is done through a proximity-feed technique. To obtain the required four band notches, slots etching in the ground plane are implemented. The effects of adding these slots on the performance of the antenna are demonstrated. The proposed antenna provides wideband performance in a frequency band from 1.9 to 10.3 GHz with notching bands at 2.3, 2.8, 3.5 and 5.5 GHz which correspond to UMTS2100, WiMAX, WiMAX, and WLAN respectively. The proposed antenna shows omnidirectional radiation with good radiation efficiency over the frequency band except at the four band notches. Moreover a SPICE-compatible lumped-elements equivalent circuit modeling for the proposed antenna is established with the help of the VF technique. The proposed antenna is fabricated and the measured data of the return loss showed a very good agreement with the simulated results and the equivalent circuit model results for the antenna. The performances of the antenna illustrate that it is good candidate for UWB applications.

REFERENCES

1. Revision of part 15 of the Communication's Rules Regarding Ultra-Wideband Transmission Systems, Federal Communications Commission, ET-Docket 98-153, FCC 02-48, 2002.
2. Danideh, A., R. Sadeghi Fakhr, and H. R. Hassani, "Wideband co-planar microstrip patch antenna," Progress In Electromagnetics Research Letters, Vol. 4, 81–89, 2008.
3. Zhang, Y., W. Hong, C. Yu, Z.-Q. Kuai, Y.-D. Don, and J. Y. Zhou, "Planar ultrawideband antennas with multiple notched bands based on etched slots on the patch and/or split ring resonators on the feed line," IEEE Transactions on Antennas and Propagation, Vol. 56, No. 9, 3063-3068, Sep. 2008.
4. Saad, A. A. R., D. A. Salem, and E. E. M. Khaled, "5.5 GHz notched ultra-wideband printed monopole antenna characterized by electromagnetic band gap structures," International Journal of Electronics and Communication Engineering (IJECE), Vol. 1, No. 1, 1-12, Aug. 2012.
5. Ali, M. M. M., A. A. R. Saad , E. E. M. Khaled "A design of miniaturized ultra–wideband printed slot antenna with 3.5/5.5 GHz dual band–notched characteristics: analysis and implementation," Progress In Electromagnics Research B, Vol. 52, 37–56, 2013.
6. Islam, M. T., R. Azim, and A. T. Mobashsher, "Triple band-notched planar UWB antennaa using parastic strips," Progress In Electromagnetics Research, Vol. 129, 161-79, 2012.

7. Zheng, Z.-A., and Q.-X. Chu, “Compact CPW-fed UWB antenna with dual band-notched characteristics” Progress In Electromagnetics Research Letters, Vol. 11, 83-91, 2009.

8. Gustavsen, B. and A. Semlyen, “Rational approximation of frequency domain responses by vector fitting,” IEEE Trans. Power Delivery, Vol.14, 1052-1061, Jul. 1999.

9. Antonini, G., “SPICE equivalent circuits of frequency-domain responses,”IEEE Trans. Electrom. Compatibility, Vol. 45, No. 3, 502-512, Aug. 2003.

10. Gustavsen, B. and A. Semlyen, “Enforcing passivity for admittance matrices approximated by rational functions,” IEEE Trans. Power System, Vol. 16, 97-104, Feb. 2001.

11. DeJean, G. R. and M. M. Tentzeris, “The application of lumped element equivalent circuits approach to the design of single-port microstrip antennas,” IEEE Trans. Antennas Propag., Vol. 55, No. 9, 2472-2468, Sept. 2007.