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ANALYSIS AND INVESTIGATION OF A CANTOR SET FRACTAL UWB ANTENNA WITH A NOTCH-BAND CHARACTERISTIC

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Abstract—A coplanar waveguide (CPW) fed ultra-wideband (UWB) antenna with a notch band characteristic is presented in the paper. The radiation patch of the proposed UWB antenna is designed using cantor set fractal technology. The bandwidth is broadened by setting two symmetrical triangular tapered corners at the bottom of the wide slot of the proposed UWB antenna. The notched band characteristic is achieved by employing a T-shaped tuning stub at the top of the wide slot. The notched band can be controlled by adjusting the length and the width of the T-shaped tuning stub to give tunable notched band function. The proposed cantor set fractal wide slot UWB antenna has been designed in details and optimized. Experimental and numerical results show that the proposed antenna, with compact size of $26 \times 21\,\mathrm{mm}^2$, has an impedance bandwidth range from 2.8 GHz to 11 GHz for voltage standing-wave ratio (VSWR) less than 2, except the notch band frequency 5.0 GHz–6.3 GHz for HIPERLAN/2 and IEEE 802.11a (5.1 GHz–5.9 GHz).

1. INTRODUCTION

Recently, ultra wideband (UWB) technology has attracted much attention not only in academic but also in industry because of the potential for high data rate and ultra low radiation power for short

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range applications such as wireless personal area network (WPAN). Especially after the protocol of the UWB wireless communications released by the Federal Communications Commission (FCC) in 2002 [1] that covers the frequency range from 3.1 GHz up to 10.6 GHz, the design of UWB systems became a challenging topic and was widely studied all over the world. As an important part of the UWB systems, the antenna plays a key role in transmitting and receiving the signals. Therefore, the design of UWB antenna with small size, wide bandwidth, and good omni-directional radiation pattern is a hot topic. Due to the attractiveness of the high data rate and low cost, printed antenna is a good candidate for UWB communications systems. Recently, a number of planar monopole antennas for this application have been presented [2–6]. However, the size of the antenna is large, and the impedance cannot cover the whole band reported by FCC. To broaden the impedance bandwidth of the planar antennas, tapered slot technology [7, 8] and wide slot antenna [9–11] have been studied and analyzed. But there are several existing narrow systems which have been used for a long time, such as HIPERLAN/2 bands (5.15–5.35 GHz and 5.470–5.725 GHz in Europe) and the IEEE 802.11a bands (5.15–5.35 GHz and 5.725–5.825 GHz in US) for wireless local area network communications. Therefore, the UWB systems may generate potential interference with the narrow systems. In order to avoid or reduce the interference with the existing narrow systems, a band-stop filter should be employed in the ultrawideband systems. So, the system will become larger and more complex. To overcome the potential interference between UWB systems and narrow systems, several UWB antennas with notched band have been studied [12–19]. Generally speaking, the conventional methods to obtain a notched band set proper filters after the UWB antenna cutting proper slots, such as inverted L notched filter [12], U-shaped slot [13, 14], arc-shaped slots [15], V-shaped slot [16], E-shaped slot [17], H-shaped slot [18] and switch PIN diodes [19] in the radiation patch or the ground plane. Another way is to put parasitic elements along the printed radiation patch, which can be considered as a filter to reject the un-required bands [20]. Recently, some antennas using SRRs [21, 22] in the fed structures are utilized to avoid the limited band. All the methods can achieve a good band notch characteristic, but some of the notched band structures are complex and difficult to design. In addition, some fractal antennas have been proposed for UWB antenna and multiband applications, such as sierpinski fractal antenna [23], Koch fractal antenna [24], snowflake antenna [25], Hilbert antenna [26], circular fractal monopole antenna [27], cantor set fractal antenna [28]. However, the proposed antennas have large size and narrow impedance bandwidth which cannot cover the whole UWB band.

Based on the previous researches mentioned above, a CPW-fed wide slot ultra-wideband (UWB) antenna with a notch band characteristic is realized numerically and experimentally. The radiation patch of the proposed antenna is designed by using cantor set technology. To increase the impedance bandwidth of the proposed antenna, two triangular tapered corners are set at the bottom of the wide slot. In addition, a T-shaped tuning stub is suspended at the top of the wide slot to produce a notched band which can be regarded as a filter to reduce the potential interference with WLAN. The proposed antenna can not only cover the whole UWB band, but also have a good notch band characteristic. The proposed antenna consists of a cantor set fractal radiation patch, a T-shaped tuning stub and a $50\,\Omega$ CPW-fed structure. The antenna was successfully optimized by using HFSS, fabricated, and tested. It is found that the designed antenna satisfied all the requirements in the UWB frequency band except 5.0–6.3 GHz for HIPERLAN/2, IEEE 802.11a and C-band applications. Details of the antenna design are presented herein, and the measured voltage standing-wave ratio (VSWR), radiation patterns and gains are also given.

The paper is structured as follows: The geometry of the proposed UWB antenna is illustrated in Section 2. The analysis and the discussions of the key parameters are detailed in Section 3. Section 4 gives the optimized and measured results of the proposed cantor set fractal UWB antenna with a notch band characteristic, such as VSWRs and radiation patterns. At last, we will give a conclusion of the paper.

2. ANTENNA DESIGN

Figure 1(a) illustrates the geometry of the proposed cantor set fractal UWB antenna with a notched band. The antenna is printed on a substrate TLX-6 with relative permittivity 2.65, a loss tangent of 0.002 and a thickness of 1.6 mm. The size of the antenna is $26 \times 21\,\text{mm}^2$ $(L \times W)$. The proposed antenna consists of a cantor set fractal radiation patch, a T-shaped tuning stub, and a $50\,\Omega$ CPW fed structure. The $50\,\Omega$ CPW fed structure consists of a CPW transmission line with a signal strip width $W3 = 3.6$ mm and gap between the CPW ground plane and transmission signal strip with width $s = 0.2$ mm. The $50\,\Omega$ CPW structure of the proposed UWB antenna is designed by using the standard equations [29]. The cantor set fractal radiation patch can be designed using the following procedures which are shown in Figs. 1(b)–(d). The cantor set fractal structure can be calculated using the following Equations (1)–(11). The 0th radiation patch is a

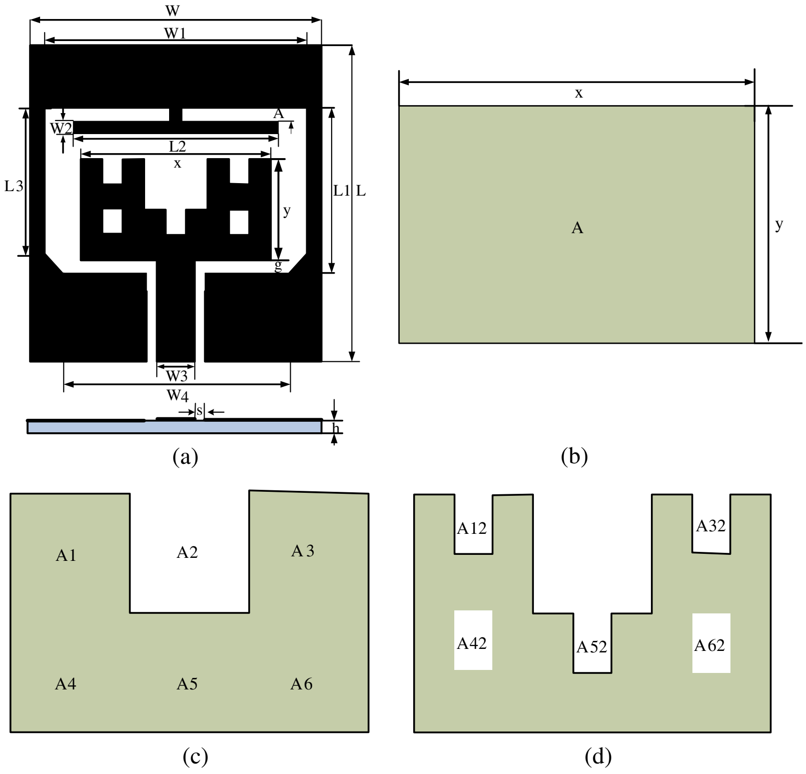

Figure 1. Geometry of the proposed Notched band UWB antenna. (a) The proposed antenna, (b) 0th cantor set fractal radiation patch of the radiation patch, (c) 1st cantor set fractal radiation patch of the radiation patch, (d) 2nd cantor set fractal radiation patch of the radiation patch.

rectangular patch with a width y and length x. The dimension y can be postulated by using Equations (1) and (2).

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

$$y = \frac{c}{2f_h\sqrt{\varepsilon_{eff}}} \tag{2}$$

where ε_{eff} is the effective dielectric constant; ε_r is the relative dielectric constant; y is the width of the 0th cantor set fractal radiation patch; f_h is the higher band the ultra-wideband; c is the speed of light. The 0th, 1st and 2nd cantor set fractal radiation patches of the radiation patch are denoted as A, B and C respectively.

$$W(A) = \bigcup_{i=1}^{6} A_i \tag{3}$$

$$W(B) = \bigcup_{i=1}^{6} A_i - A_2 = W(A) - A_2 \tag{4}$$

$$W(A_1) = \left[(0,0)\left(\frac{x}{3},0\right)\left(\frac{x}{3},\frac{y}{2}\right)\left(0,\frac{y}{2}\right)\right] \tag{5}$$

$$W(A_3) = \left[\left(\frac{2x}{3},0\right)(x,0)\left(x,\frac{y}{2}\right)\left(\frac{2x}{3},\frac{y}{2}\right)\left(0,\frac{y}{2}\right)\right] \tag{6}$$

$$W(A_4) = \left[\left(0,\frac{y}{2}\right)\left(\frac{x}{3},\frac{y}{2}\right)\left(\frac{x}{3},y\right)(0,y)\right] \tag{7}$$

$$W(A_5) = \left[\left(\frac{x}{3},\frac{y}{2}\right)\left(\frac{2x}{3},\frac{y}{2}\right)\left(\frac{2x}{3},y\right)\left(\frac{x}{3},y\right)\right] \tag{8}$$

$$W(A_6) = \left[\left(\frac{2x}{3},\frac{y}{2}\right)\left(x,\frac{y}{2}\right)(x,y)\left(\frac{2x}{3},y\right)\right] \tag{9}$$

$$W(C_i) = \bigcup_{k=1}^{6} A_{i,k} - A_{i,2}\ (i = 1,3,4,5,6) \tag{10}$$

$$W(C) = \bigcup_{i=1}^{6}\left(\bigcup_{k=1}^{6} A_{i,k} - A_{k,2}\right)(i \neq 2) \tag{11}$$

The T-shaped tuning stub determines the notched band which rejects the frequency range from 5 GHz to 6.3 GHz. Generally speaking, the designed central frequency of the notch band function is to adjust the length of the T-shaped tuning stub which is equal to about half wave-length at the required notched band. The notch frequency, given the dimensions of notch band characteristic, can be postulated by Equations (1) and (12).

$$L_{notch} = \frac{\lambda_{notch}}{2\sqrt{\varepsilon_{eff}}} = \frac{c}{2f_{notch}\sqrt{\varepsilon_{eff}}} \tag{12}$$

where L_{notch} is the total length of the T-shaped tuning stub; λ_{notch} is the wavelength of the center frequency of the notched band; f_{notch} is the center frequency of the notched band; c is the speed of light. We take Equations (1)–(12) into consideration in achieving the dimensions of the cantor set fractal radiation patch and the T-shaped tuning stub at the beginning of the design and then adjust the geometry for the final design. In order to obtain wide impedance bandwidth of the proposed antenna, two symmetrical triangular tapered corners are setting at the bottom of the wide slot.

3. PARAMETERS STUDIES

Every geometrical parameter has different effects on the performance of the proposed antenna. In this section, eight parts of the proposed CPW fed cantor set fractal UWB antenna with a notched band will be described and discussed by using HFSS, respectively: the order of the cantor set fractal radiation patch; the length $L2$ and the width $W2$ of the T-shaped tuning stub; the gap between the CPW ground and the T-shaped tuning stub named A; the gap between the CPW ground and the cantor set fractal radiation patch denoted as g; the dimensions of the rectangle wide slot excited by the cantor set fractal radiation patch; the dimension of the two symmetrical triangular tapered corners set at the bottom of the wide slot.

3.1. The Effect of the Length of Wide Slot $L1$

Figure 2(a) shows the simulated VSWRs of the antenna as a function of frequency for the different values of $L1$ with other parameters fixed. It can be seen from Fig. 2(a), the length of the wide slot has an obvious effect on the bandwidth of the proposed ultra wide band antenna. Therefore, the bandwidth of UWB antenna can be improved by optimizing the length of the rectangle wide slot. With the increasing of length $L1$, the impedance bandwidth is getting narrow. But the notched band frequency has a little influence, due to the reduced electromagnetic coupling between the cantor set fractal radiation patch and the CPW ground which changes the distributed capacitive and the inductive effectively.

3.2. The Effect of the Width of Wide Slot $W1$

Figure 2(b) gives the simulated VSWR results for the proposed antenna in terms of $W1$. By varying $W1$ from 17 mm to 19 mm with other parameters fixed, the impedance bandwidth of the proposed antenna is improved, and the characteristic of the notched band is also ameliorated. The bandwidth of the notched band becomes narrow to cover the wireless local area network (WLAN) band. It meets the requirement of the notched band characteristic which can reduce the potential interference between UWB and the WLAN because of the reduced electromagnetic coupling between the cantor set fractal radiation patch and the CPW ground. In addition, the increased width

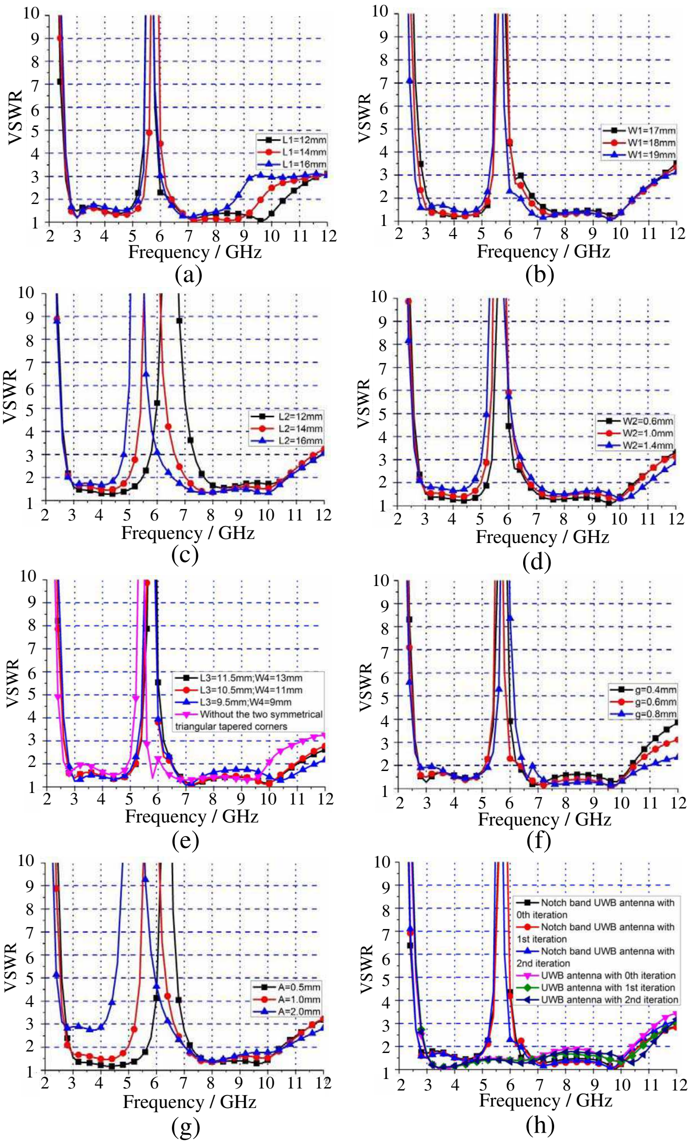

Figure 2. Effects on the VSWR with the various dimensions of the proposed antenna. (a) Various $L1$ with other parameters fixed, (b) various $W1$ with other parameters fixed, (c) various $L2$ with other parameters fixed, (d) various $W2$ with other parameters fixed, (e) effect of the two triangular tapered set at the bottom of the wide slot, (f) the gap g between the cantor set fractal radiation patch and the CPW ground, (g) the gap A between the T-shaped tuning stub and the CPW ground, (h) the order of the cantor set fractal.

of the wide slot also decreases coupling between the T-shaped tuning stub and CPW ground. The couplings alter the current distributions in the CPW ground, the distributed capacitive and the distributed inductive which not only increase the impedance bandwidth of the proposed antenna but also improve the notched band characteristic.

3.3. The Effect of the Length of the T-shaped Tuning Stub $L2$

Figure 2(c) clarifies the simulated VSWRs of the antenna as a function of frequency for the different values of $L2$ with other parameters fixed. It is found that the notched band frequency moves to the lower band with increasing length of the T-shaped tuning stub. This is also can be verified by using Equation (12). But the impedance bandwidth of the notched band UWB antenna changes a little. Therefore, the center of notched frequency can be adjusted by optimizing the length of the T-shaped tuning stub.

3.4. The Effect of the Width of the T-shaped Tuning Stub $W2$

Figure 2(d) describes the simulated VSWR results for the proposed antenna in terms of $W2$. For $W2 = 0.6\,\text{mm}$ to $1.4\,\text{mm}$ with other parameters fixed, the notched band frequency remains almost unchanged. Because the current distributions flowed from the T-shaped tuning stub are stable, the impedance bandwidth of the proposed antenna is almost constant.

3.5. The Effect of the Dimension of the Two Symmetrical Triangular Tapered Corners

The dimension of the two triangular tapered corners set at the bottom of the wide slot has much effect on the higher band and is shown in Fig. 2(e). However, the notched band and impedance bandwidth at lower band keep constant. It also can be seen from Fig. 2(e) that the proposed notched band UWB antenna without symmetrical triangular tapered corners at the bottom of the wide slot cannot cover the whole UWB band range from from 3.1 GHz to 10.6 GHz. And with the increasing of the dimension of the two triangular tapered corners, the impedance bandwidth is getting wider, because the two symmetrical triangular tapered corners set at the bottom of the wide slot not only affect the current distributions along the CPW ground but also change the coupling between the cantor set fractal radiation patch and the

CPW ground, which improve the impedance matching characteristics of the proposed antenna.

3.6. The Effect of the Gap g Between CPW Ground and the Radiation Patch

Figure 2(f) demonstrates the simulated VSWR characteristics with other parameters fixed for different values of g. From Fig. 2(f), one can find that the change of g has an obvious effect on the center frequency of the notched band and the impedance bandwidth of the proposed antenna. Therefore, the region plays an important role in improving the characteristics of the bandwidth of the antenna. With the increasing of the gap g, the impedance characteristic at the lower band deteriorated while at the higher band the impedance improved. At the same time, the center frequency of the notched band moves to the higher band. By adjusting the gap g, the notched band and the overall matching are improved. Therefore, the distance g has an important effect on the characteristics of the proposed UWB antenna, due to the changed capacitive and the inductive effects caused by the electromagnetic coupling between CPW ground and the cantor set fractal radiation patch.

3.7. The Effect of the Gap A Between CPW Ground and T-shaped Tuning Stub

Figure 2(g) elaborates the simulated VSWRs against the frequency with other parameters fixed for different values of A. It can be seen from Fig. 2(g), the gap A has an obvious effect on the center frequency of the notched band and the impedance bandwidth of the proposed antenna. So, the region plays an important role in optimizing the bandwidth characteristics of the antenna. With the increasing of the gap A, the impedance bandwidth of the proposed UWB antenna deteriorated at the lower band. At the same time, the center frequency of the notched band moves to the lower band. By properly adjusting the gap A, the impedance bandwidth and the center frequency of the notched band can be improved to meet the requirement of the UWB applications, due to the various gaps A which change the current length of the T-shaped tuning stub.

3.8. The Effect of the Order of the Cantor Set Fractal

Figure 2(h) illustrates the simulated VSWRs with the different orders of the cantor set fractal radiation patch. It can be seen from Fig. 2(h) that the impedance bandwidth of the antenna and center frequency of the notched band have little influence. The order of the cantor set fractal can improve the notched band characteristic. It is found that the proposed antenna without T-shaped tuning stub broadened the impedance bandwidth of the antenna by increasing the order of the iterations. So, in the paper we choose 2nd iteration cantor set fractal to design the notched band UWB antenna. Generally speaking, the order of the cantor set fractal also broadens the impedance bandwidth of the proposed antenna without the T-shaped tuning stub.

In order to further investigate the proposed cantor set fractal UWB antenna with a notched band. The current distributions of the proposed antenna are investigated by using the Ansoft High Frequency Structure Simulator (HFSS) based on Finite Element Method (FEM). The current distributions of the proposed antenna at 3.5 GHz, 5.5 GHz, 9 GHz are shown in Figs. 3(a)–(c), respectively. And the current distribution of the proposed UWB antenna without T-shaped tuning stub at 5.5 GHz is also shown in Fig. 3(d) for comparison.

Figure 3(a) shows the current distributions at 3.5 GHz of the proposed UWB antenna with a notched band. The current flows along the CPW transmission signal strip and edge of the gap of the CPW fed structure, and the current along the CPW ground is small. Fig. 3(b) gives the current distributions at 5.5 GHz. The current mainly flows along the T-shaped tuning stub and the edge of the gap between the T-shaped tuning stub and CPW ground, which produces a resonance frequency of the notched band. Fig. 3(c) shows the current distributions of the proposed antenna 9 GHz, and they mainly flow along the CPW ground, patch and the edge of the wide slot, while around the T-shaped tuning stub the current is small. Fig. 3(d) reveals the current distribution of the proposed cantor set fractal UWB antenna without the T-shaped tuning stub at 5.5 GHz. It can be seen from Fig. 3(d), the current distribution mainly flows along the CPW

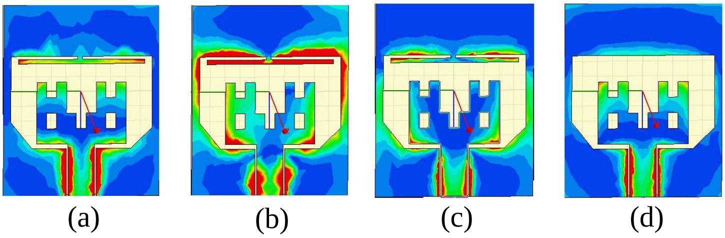

Figure 3. Current distributions of the proposed antenna. (a) Notch band UWB antenna at 3.5 GHz, (b) notched band UWB antenna at 5.5 GHz, (c) notched band UWB antenna at 8.5 GHz, (d) UWB antenna at 5.5 GHz.

fed structure and the edge of the wide slot which prolongs the path of the current distribution. Thereby, the bandwidth of the antenna is broadened.

4. RESULTS AND DISCUSSIONS

According to the study and the discussions of parameters of the proposed antenna, the antenna has been optimized by utilizing HFSS. During the optimizing process, the parameters are adjusted according to the results of the parameters study and the current distributions. The optimized results are as follows: $L = 26$ mm; $W = 21$ mm; $L1 = 12.5$ mm; $W1 = 19$ mm; $L2 = 17$ mm; $W2 = 0.6$ mm; $L3 = 9.7$ mm; $W3 = 3.6$ mm; $W4 = 13.4$ mm; $A = 0.4$ mm; $g = 0.6$ mm; $x = 12$ mm; $y = 8.4$ mm; $s = 0.2$ mm, $h = 1.6$ mm.

To evaluate the performance of the optimized antenna, the proposed antenna is implemented and tested. The VSWRs of the antenna are obtained by using Anritsu 37347D vector network analyzer. In order to compare the simulated and measured results of the antenna, the proposed antenna with T-shaped tuning stub and without T-shaped tuning stub are manufactured and measured. The photograph of the proposed antenna is shown in Fig. 4, and the VSWRs of the antennas are shown in Fig. 5.

From Fig. 5, the simulated result agree well with the measured result, which helps to verify the accuracy of the measurement. The differences between the simulated and measured values may be due to the errors of the manufactured antenna and the SMA connector to CPW-fed transition, which is included in the measurements but not taken into account in the calculated results. It can also be found that the notched band is caused by the T-shaped tuning stub suspended at

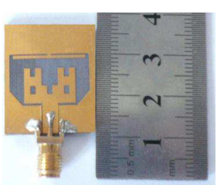

Figure 4. Photograph of the antenna.

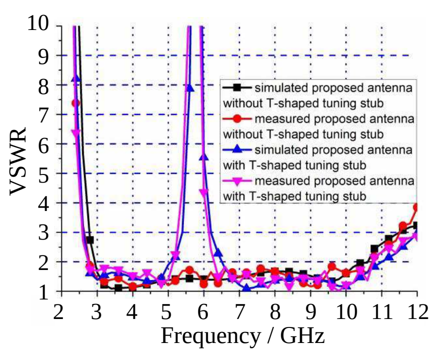

Figure 5. VSWRs of the proposed antenna.

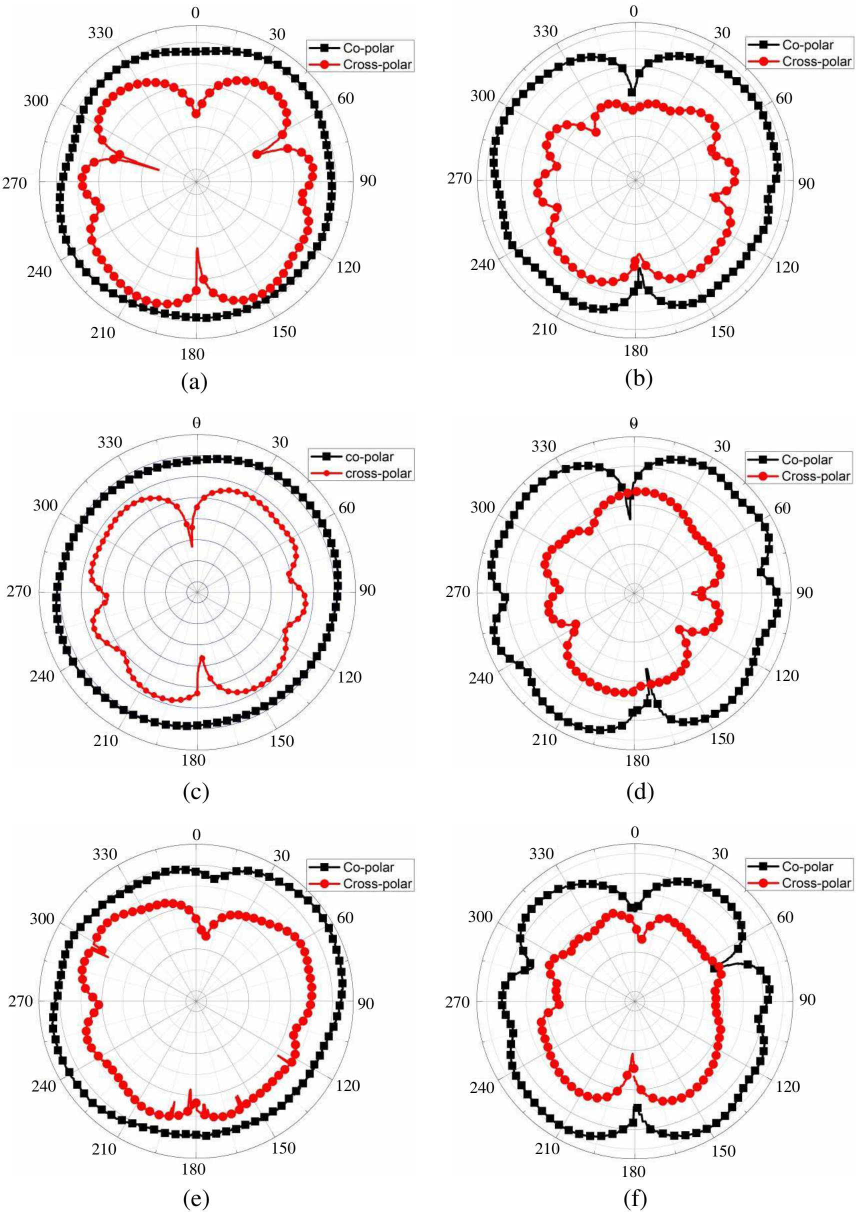

Figure 6. Measured radiation patterns of the proposed antenna. (a) H-plane at 3.5 GHz, (b) E-plane at 3.5 GHz, (c) H-plane at 7 GHz, (d) E-plane at 7 GHz, (e) H-plane at 9.5 GHz, (f) E-plane at 9.5 GHz.

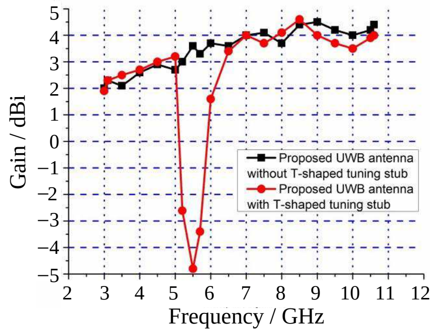

Figure 7. Measured gain of proposed UWB antenna.

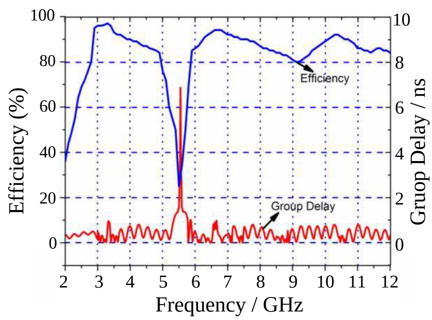

Figure 8. Efficiency and the group delay.

the top of the wide slot.

The measured radiation patterns at 3.5 GHz, 7.0 GHz, 9.5 GHz are shown in Fig. 6. It is shown that the antenna can give a nearly omni-directional characteristic in the H-plane and quasi omni-directional pattern in the E-plane. As can be seen from Fig. 6, the radiation patterns in the E-plane deteriorate more or less with the frequency increasing, but the radiation patterns are still nearly quasi omni-directional. The peak gains of the proposed antenna at these frequencies are achieved by comparing to a double ridged horn antenna. A stable gain can be obtained throughout the operation band except the notched frequency. For comparison, the proposed antenna without T-shaped tuning stub is also measured. The peak gain of the proposed antenna with and without T-shaped tuning stub is shown in Fig. 7. The measured gain of the proposed antenna without T-shaped tuning stub is increased from 2 dBi to nearly 4.5 dBi, which is caused by the deteriorated radiation patterns of the proposed antenna at the high band. In the operation band, the antenna without T-shaped tuning stub has stable gains with fluctuation less than 2.5 dBi. But the gain of the proposed antenna with T-shaped tuning stub drops quickly from 5.0 GHz to 6.3 GHz. As desired, a sharp gain decreases in the vicinity of 5.5 GHz. The gain drops deeply to −4.8 dBi at the notched band.

Figure 8 gives the simulated efficiency and the group delay of the proposed cantor set fractal UWB antenna with a notched band. As can be seen from Fig. 8, the variation of the group delay is within 1.0 ns in the UWB band, except in the notched band where the maximum group delay is nearly 7 ns. And the radiation efficiency in the UWB is above 80% apart from the notched band. The radiation efficiency in the notched band decreases drastically near 5.5 GHz.

5. CONCLUSION

A CPW-fed wide slot antenna with a band-notch characteristic is proposed for UWB applications. The proposed antenna is designed using cantor set fractal technology and has an impedance bandwidth over 8.2 GHz. The antenna has a small size of $26 \times 21 \times 1.6\,\mathrm{mm}^3$. The impedance bandwidth of the proposed notched band UWB antenna is broadened by utilizing wide slot technology, and two symmetrical triangular tapered corners are set at the bottom of the wide slot. The notched band is obtained by suspending a T-shaped tuning stub at the top of the wide slot. The antenna is successfully designed, optimized, fabricated and tested. The results show that the antenna not only has a notch band characteristic but also has a large impedance and good radiation pattern.

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REFERENCES

1. Federal Communications Commission, First report and order, Revision of Part 15 of commission's rule regarding UWB transmission system FCC 02–48, Washington, DC, April 22, 2002.
2. Kim, Y. and D. H. Kwon, "CPW-fed planar wideband antenna having a frequency band notch function," *Electronics Letters*, Vol. 40, No. 7, 403–405, 2004.
3. Lee, S. H., J. K. Park, and J. N. Lee, "A novel CPW-fed ultra-wideband antenna design," *Microwave and Optical Technology Letters*, Vol. 44, No. 5, 393–395, 2005.
4. Zheng, Z. A. and Q. X. Chu, "CPW-fed ultra-wideband antenna with compact size," *Electronics Letters*, Vol. 45, No. 12, 593–594, 2009.
5. Qing, X. and Z. N. Chen, "Compact coplanar waveguide-fed ultra-wideband monopole- like slot antenna," *IET Microwave Antennas & Propagation*, Vol. 3, No. 5, 889–898, 2009.

6. Li, Z., C.-X. Zhang, G.-M. Wang, and W.-R. Su, "Designs on CPW-FED aperture antenna for ultra-wideband applications," *Progress In Electromagnetics Research C*, Vol. 2, 1–6, 2008.
7. Ammann, M. J. and Z. N. Chen, "A wide band shorted planar monopole with bevel," *IEEE Trans. on Anten. and Propag.*, Vol. 51, No. 45, 901–903, 2003.
8. Pu, L. and X.-M. Zhang, "Design of a low-profile dual exponentially tapered slot antenna," *Progress In Electromagnetics Research Letters*, Vol. 6, 67–74, 2009.
9. Kim, H. and C. W. Jung, "Ultra-wideband endfire directional tapered slot antenna using CPW to wide-slot transition," *Electronics Letters*, Vol. 46, No. 17, 1183–1185, 2010.
10. Dastranj, A. and M. Biguesh, "Broadband coplanar waveguide-FED wide-slot antenna," *Progress In Electromagnetics Research C*, Vol. 15, 89–101, 2010.
11. Gao, G. P., J. S. Zhang, and T. Jin, "Printed ultra-wide band microstrip-line fed slot antenna with a band-notched function," *Microwave and Optical Technology Letters*, Vol. 51, No. 6, 1573–1576, 2009.
12. Barbarino, S. and F. Consoli, "UWB circular slot antenna provided with an inverted-L notch filter for the 5 GHz WLAN band," *Progress In Electromagnetics Research*, Vol. 104, 1–13, 2010.
13. Dong, Y. D., W. Hong, Z. Q. Kuai, and J. X. Chen, "Analysis of planar ultrawideband Antennas with on-ground slot band-notched structures," *IEEE Trans. on Anten. and Propag.*, Vol. 57, No. 7, 1886–1893, 2009.
14. Lizzi, L., G. Oliveri, P. Rocca, and A. Massa, "Planar monopole UWB antenna with unii1/unii2 WLAN-band notched characteristics," *Progress In Electromagnetics Research B*, Vol. 25, 277–292, 2010.
15. Eshtiaghi, R., R. Zaker, J. Nouronia, and C. Ghobadi, "UWB semi-elliptical printed monopole antenna with subband rejection filter," *AEÜ - International Journal of Electronics and Communications*, Vol. 64, No. 2, 133–141, 2010.
16. Ahmadi, B. and R. Faraji-Dana, "A miniaturised monopole antenna for ultra-wide band applications with band notch filter," *IET Microwave Antennas & Propagation*, Vol. 3, No. 8, 1224–1231, 2009.
17. Mohd Sobli, N. H. and H. E. Abd-El-Raouf, "Design of a compact printed band-notched antenna for ultrawideband

communications," *Progress In Electromagnetics Research M*, Vol. 3, 57–78, 2008.

18. Li, Y. S., X. D. Yang, C. Y. Liu, and T. Jiang, "Compact CPW-fed ultra-wideband antenna with dual band-notched characteristics," *Electronics Letters*, Vol. 46, No. 14, 967–968, 2010.
19. Sim, C.-Y.-D., W.-T. Chung, and C.-H. Lee, "Planar UWB antenna with 5 GHz band rejection switching function at ground plane," *Progress In Electromagnetics Research*, Vol. 106, 321–333, 2010.
20. Abbosh, A. M. and M. E. Bialkowski, "Design of UWB planar band-notched antenna using parasitic elements," *IEEE Trans. on Anten. and Propag.*, Vol. 57, No. 7, 1886–1893, 2009.
21. Chang, T. N. and M. C. Wu, "Band-notched design for UWB Antennas," *IEEE Antennas and Wireless Propagation Letters*, Vol. 7, 636–640, 2008.
22. Kim, J., C. S. Cho, and J. W. Lee, "5.2 GHz notched ultra-wideband antenna using slot-type SRR," *Electronics Letters*, Vol. 42, No. 6, 315–316, 2006.
23. Puente-Baliarda, C., J. Romeu, R. Pous, and A. Cardama, "On the behavior of the Sierpinski multiband fractal antenna," *IEEE Trans. on Anten. and Propag.*, Vol. 46, No. 4, 517–524, 1998.
24. Baliarda, C. P., J. Romeu, and A. Cardama, "The koch monopole: A small fractal antenna," *IIEEE Trans. on Anten. and Propag.*, Vol. 48, No. 11, 1773–1781, 2000.
25. Werner, D. H. and S. Ganguly, "An overview of fractal antenna engineering research," *IEEE Antennas and Propagation Magazine*, Vol. 45, No. 1, 38–57, 2003.
26. Vinoy, K. J., K. A. Jose, V. K. Varadan, V. V. Varadan, "Resonant frequency of Hilbert curve fractal antenna," *IEEE Antennas and Propagation Society International Symposium*, Vol. 3, 648–651, 2001.
27. Khan, S. N., J. Hu, J. Xiong, and S. He, "Circular fractal monopole antenna for low VSWR UWB applications," *Progress In Electromagnetics Research Letters*, Vol. 1, 19–25, 2008.
28. Manimegalai, B., S. Raju, and V. Abhaikumar, "A multifractal cantor antenna for multiband wireless applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 8, 359–362, 2009.
29. Garg, R., P. Bhartia, I. Bahl, and A. Ittipiboon, *Microstrip Antenna Design Hand Book*, 1st edition, 794–795, Artech House, 2001.