Progress In Electromagnetics Research C, Vol. 35, 253–267, 2013

A PLANAR SELF-COMPLEMENTARY BOW-TIE ANTENNA FOR UWB APPLICATIONS

Khalil H. Sayidmarie[1, *] and Yasser A. Fadhel[2]

[1]College of Electronic Engineering, University of Mosul, Iraq

[2]Department of Electronic Techniques, Mosul Institute of Technology, Iraq

Abstract—A new planar bow-tie antenna is proposed here for UWB applications. The self-complementary principle has been applied to a planar triangular monopole antenna along with bending the microstrip feed line. The antenna has a wider frequency band compared to the traditional bow-tie antenna, complies with the UWB requirements and it is directly matched to the (SMA) connector via $50\,\Omega$ microstrip feed line. This antenna has a simple shape which overcomes the complicated matching techniques using baluns or impedance matching sections that are commonly used in bow-tie antennas for widening their limited bandwidths. Another improvement on this new bow-tie antenna is achieved through fractal self-similarity repetition of the triangular shape on each of the patch and its complimentary slot. The simulation results obtained from the CST and HFSS software packages are verified by experimental measurements.

1. INTRODUCTION

Much attention has been given to commercial UWB systems, since the Federal Communications Commission "FCC" permitted the new radio transmission technology in February 2002 [1]. Considerable research efforts have been put into UWB radio technology worldwide, while the non-digital part of UWB system, i.e., transmitting and receiving antennas, remains a particularly challenging topic. Patch antennas are used in wireless communication systems because of the following features; light weight, low cost and ease of fabrication. As a drawback, it is well known that the bandwidth of the patch antenna is narrow. Thus many techniques have been used to increase and

Received 31 October 2012, Accepted 21 December 2012, Scheduled 28 December 2012
* Corresponding author: Khalil Hassan Sayidmarie (kh.sayidmarie@gmail.com).

improve the bandwidth of printed antennas to comply with the UWB requirements [2–6]. Among the proposed broadband antenna shapes; there were the planar volcano-smoke slot antenna [2, 3], triangular monopole [4], circular and elliptical disc monopoles [6, 7]. The dipole configuration has also been investigated for the UWB required characteristics, where circular, square, triangular, and other shapes for the two arms have been used [8, 9]. In a recent publication a class of printed antipodal drop-shaped dipole antennas for wideband wireless communication systems was presented. A suitable shaping of the feeding lines and radiating arms was used to achieve an operating bandwidth larger than 10 GHz [10].

Most of the presented design methodologies were trial and error methods with the help of simulation packages to get the desired UWB operation by tailoring corners, tips, slots, or parasitic parts. Nevertheless, there are some other efficient methods that can be exploited to design UWB antennas, but unfortunately, these methods were rarely used. One of these methods depends on the idea, introduced by Yasuto Mushiake in the 1940's, which accounts for the so-called self-complementary principle, to produce frequency independent antennas. That work was then updated by inventing another type of this antenna [11].

One of the important types of antennas, used in many broadband applications, is the Bow-Tie antenna which has undergone various attempts to enhance its performance. Some of these attempts were to resistively load the antenna to obtain higher radiation efficiency with small late-time ringing and reduced antenna dimensions [12]. Another improvement was by applying the Sierpinski fractal on the bow-tie arms to produce multi-resonant narrow bands of operation frequencies [13].

Due to multiple complicated design parameters, many bow-tie antennas have been designed with adequate impedance bandwidth, not more than 2 GHz [14–17], while some of them have been designed for a dual band of operation [18, 19]. Another bow-tie antenna has been tuned for just a certain frequency [20]. Other researchers tried to increase the impedance bandwidth to (8.2∼12.5 GHz), but it is still less than the UWB requirements [21]. An array has been formed by using four bow-tie elements fed by electromagnetic coupling microstrip patch antenna (ECMSA), but the achieved bandwidth was limited to the range (2.7∼3.3 GHz) [22].

After deep examination of bow-tie antenna literature, one can conclude that there is a problem of matching each side of the bow-tie antenna to a suitable practical feeding port (usually the 50 Ω (SMA) connector). The bow-tie antenna, like the biconical antenna, requires to be fed via 300 Ω balanced transmission line [23]. Therefore, in order to feed the dipole by 50 Ω (SMA) connector, the designer has to follow one of two ways. The first way is to use a balun transformer, which is somewhat difficult to be implemented, due to its limited bandwidth and sometimes it requires a complicated shape, as well as an extra size [24, 25]. The second way uses a multi-section microstrip line of different widths or a gradually-widened microstrip line, to work as an impedance transformer for matching the bow-tie to the (SMA) connector [9, 26].

In the efforts of improving the bow-tie antenna, some researchers preferred resorting to form this antenna inside a slot which also needs the above mentioned matching techniques, or at least the first one. Some of such trials have succeeded to achieve matching over the entire UWB bandwidth, but on the account of a long list of design parameters [27, 28]. Such solutions have added complexity on the design procedure. Other researchers have formed the bow-tie slot antenna in the ground plane of a certain monopole antenna and achieved a limited bandwidth of about 2 GHz [29].

To overcome all of the above mentioned difficulties, a new self-complementary bow-tie planar antenna (SCBT-Antenna) is introduced here. The antenna is easier in design and implementation, smaller in size, wider in bandwidth, neither it needs baluns nor impedance matching sections because it is fed directly via a (50 Ω) right-angle bended rectangular microstrip line. Further improvement has been done on this new bow-tie by implementing a fractal repetition of the triangular shape, which has been introduced in a previous work [30]. The modification has been applied on both arms of the bow-tie (patch and its complementary slot), producing a fractal self-complementary Bow-Tie antenna (FSCBT-Antenna), which gives better return loss performance.

The proposed design is analyzed and assessed by two computer simulation software packages; the CST Microwave Studio^{TM} package which utilizes the Finite Integration Technique for electromagnetic computation, and the commercial computer software package, Ansoft HFSS, which is based on the Finite Element Method. The simulation results are then verified by experimental measurements.

2. DESIGN METHODOLOGY

Traditional Bow-Tie TBT-antenna, can be designed by choosing suitable dimensions, keeping in mind that the antenna needs to be fed via the 300 Ω line source. If it is desired to be fed via a 50 Ω SMA connector, then microstrip line must be designed to work as an impedance transformer with slanted width or stepped sections. The aim of this work is mainly to design new types of Bow-Tie antenna which do not need impedance transformer frontend, and they are very convenient for coupling to SMA-connectors. The designed antennas are discussed in the following sections.

2.1. The Traditional Bow-tie Antenna (TBT-antenna)

A TBT-antenna has been designed to cover the entire UWB range, using CST simulation tool, with shape and optimized dimensions as shown in Fig. 1. By feeding this antenna with a discrete port having an impedance of 300 Ω, simulation results show that this antenna has

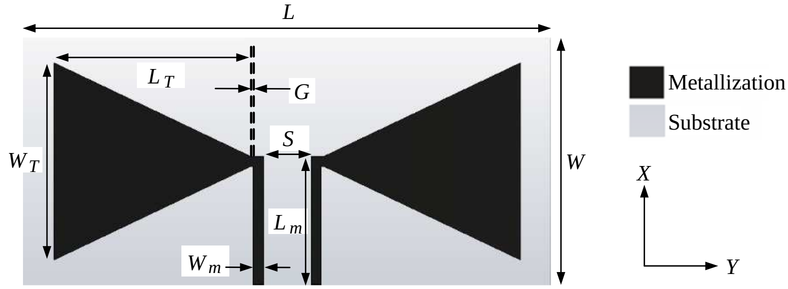


Figure 1. Geometry of the traditional bow-tie antenna (TBT-antenna). The design parameters are: $L = 65\,\mathrm{mm}$, $L_T = 23.6\,\mathrm{mm}$, $L_m = 15.65\,\mathrm{mm}$, $W = 30\,\mathrm{mm}$, $W_T = 24\,\mathrm{mm}$, $W_m = 1.3\,\mathrm{mm}$, $S = 5.8\,\mathrm{mm}$, $G = 0.4\,\mathrm{mm}$, dielectric FR4 substrate of 1.6 mm thickness, relative permittivity (ε_r) of 4.3, and dielectric loss tangent of 0.025.

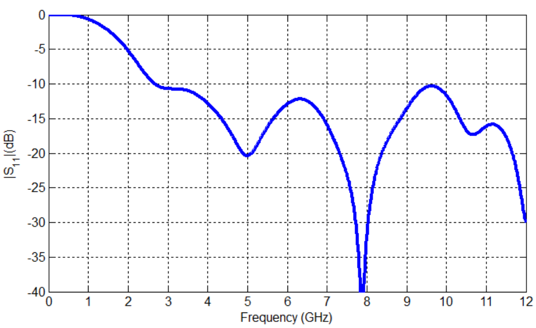


Figure 2. Simulated return loss versus frequency for the TBT-antenna shown in Fig. 1.

a -10 dB return loss response covering more than the UWB range (2.688 GHz, up to more than 12 GHz), as depicted in Fig. 2. Although this antenna has achieved the required UWB range, it needs a matching section if it is desired to be fed via SMA-connector.

2.2. The Self-complementary Bow-tie Antenna (SCBT-antenna)

The proposed Self Complementary Bow-Tie (SCBT)-antenna has been designed through applying the self-complementary principle [11]. The design idea stems from a modification on the triangular monopole antenna by adding an opposite triangular slot on its ground plane, and bending its microstrip feed line, as can be seen in Fig. 3.

To estimate the lower frequency of operation f_L, one can apply the relations proposed in [31, 32]. These relations were derived by considering the patch monopole as a cylindrical monopole. The length of the equivalent cylinder is set equal to that of the patch monopole, and the radius of the cylinder is found by equating its surface area to the surface area of the monopole. The most closer shape to the proposed SCBT antenna is the triangular monopole antenna, and the corresponding relations in [31] are as follows:

$$f_L = \frac{7.2}{(L_T + r + p) * k}\,\text{GHz} \tag{1}$$

$$r = \frac{W_T}{4\pi} \tag{2}$$

$$L_T = \frac{\sqrt{3}W_T}{2} \tag{3}$$

$$k = \sqrt{\varepsilon_{eff}} \tag{4}$$

where:

p = feed probe length, neck height or gap between the radiating structure and the ground plane (in cm).

r = the radius of the equivalent cylindrical monopole (in cm).

L_T = the height of the equivalent cylinder which is taken equal to that of the triangular monopole (patch) (in cm).

W_T = the base of the triangular patch (in cm).

ε_{eff} = effective dielectric constant, which can be calculated from the relative dielectric constant of the substrate (ε_r) using the following relation:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} \tag{5}$$

The SCBT antenna introduced here has been designed using triangular shape and dimensions as shown in Figure 3. The values

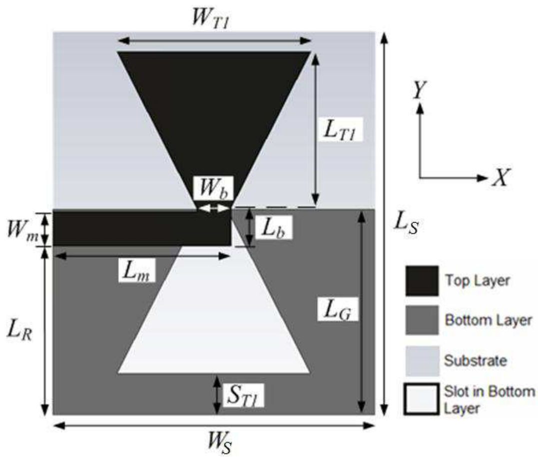


Figure 3. Geometry of the self-complementary bow-tie antenna (SCBT-antenna). The design parameters are: $L_S = 36\,\text{mm}$, $L_{T1} = 14.6\,\text{mm}$, $L_m = 16.6\,\text{mm}$, $L_b = 3.6\,\text{mm}$, $L_G = 19.2\,\text{mm}$, $L_R = 15.8\,\text{mm}$, $W_S = 30\,\text{mm}$, $W_{T1} = 18\,\text{mm}$, $W_m = W_b = 3.2\,\text{mm}$, $S_{T1} = 3.9\,\text{mm}$, $p = L_b - W_m = 0.4\,\text{mm}$, dielectric FR4 substrate of 1.6 mm thickness, relative permittivity (ε_r) of 4.3, and dielectric loss tangent of 0.025.

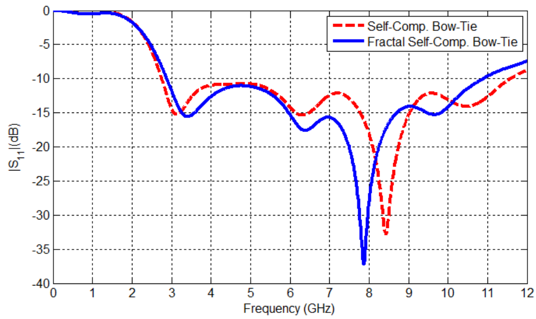


Figure 4. Simulated return loss versus frequency for: SCBT-antenna, and FSCBT-antenna.

of various parameters computed from the above equations, using FR4 substrate of $\varepsilon_r = 4.3$, are listed below:

$$W_T = W_{T2} = 18\,\text{mm}, \quad r = 1.43\,\text{mm}, \quad L_T = L_{T1} = 15.56\,\text{mm}.$$

Substituting the above values into Eqs. (1)–(5), f_L was found to be equal to 2.539 GHz. However, L_T was chosen as 14.6 mm to increase the value of the lower frequency f_L by a small value. The other dimensions for this antenna have been optimized using the CST software package. The return loss curve obtained from simulation is shown in Fig. 4 (the red dashed curve), which indicates the simulation value of f_L at (2.75 GHz). The results of simulation show that SCBT-antenna has a wide range of frequency (2.75∼11.58 GHz) which exceeds the UWB requirements.

2.3. The Fractal Self-complementary Bow-tie Antenna (FSCBT-antenna)

The benefits obtained from the fractal repetition in monopole antennas having two patch shapes; rectangular and triangular, have been demonstrated in our previous work [30]. That method has been applied to the SCBT-antenna to achieve an improved version named fractal self-complementary bow-tie antenna (FSCBT-antenna). Fig. 5 shows the proposed antenna and its design parameters. The fractal repetition has been applied on the triangular radiating patch and its complementary slot as well. As depicted in Fig. 4 (the blue solid curve), the simulation results obtained from the CST software showed

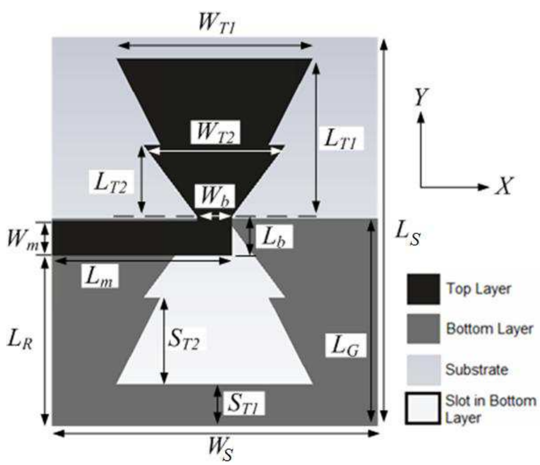
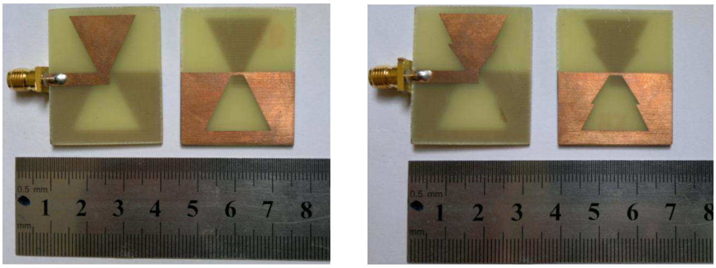


Figure 5. Geometry of the fractal self-complementary bow-tie antenna (FSCBT-antenna). The design parameters are: $L_S = 36\,\text{mm}$, $L_{T1} = 14.6\,\text{mm}$, $L_{T2} = 6.6\,\text{mm}$, $L_m = 16.6\,\text{mm}$, $L_b = 3.6\,\text{mm}$, $L_G = 19.2\,\text{mm}$, $L_R = 15.8\,\text{mm}$, $W_S = 30\,\text{mm}$, $W_{T1} = 18\,\text{mm}$, $W_{T2} = 13\,\text{mm}$, $W_m = W_b = 3.2\,\text{mm}$, $S_{T1} = 3.9\,\text{mm}$, $S_{T2} = 8\,\text{mm}$, $p = L_b - W_m = 0.4\,\text{mm}$, dielectric FR4 substrate of 1.6 mm thickness, relative permittivity (ε_r) of 4.3, and dielectric loss tangent of 0.025.



(a) (b)

Figure 6. Fabricated (a) SCBT and (b) FSCBT antennas.

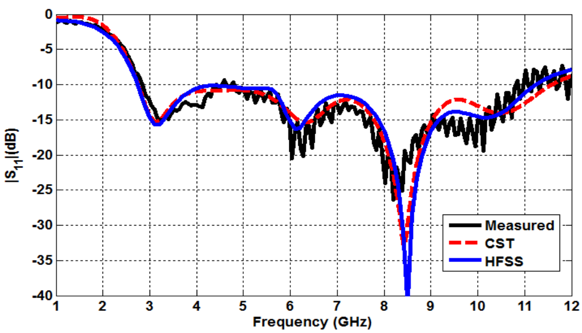


Figure 7. Measured return loss versus frequency for SCBT-antenna, compared to simulated one using: (a) CST, and (b) HFSS software packages.

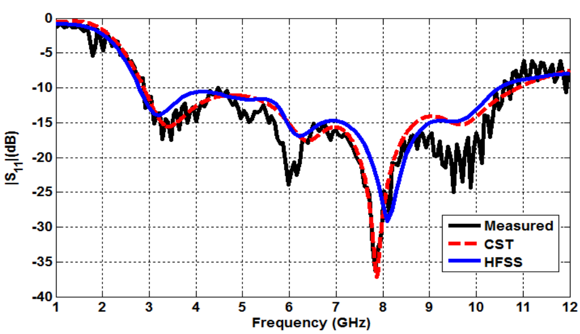


Figure 8. Measured return loss versus frequency for FSCBT-antenna, compared to simulated one using: (a) CST, and (b) HFSS software packages.

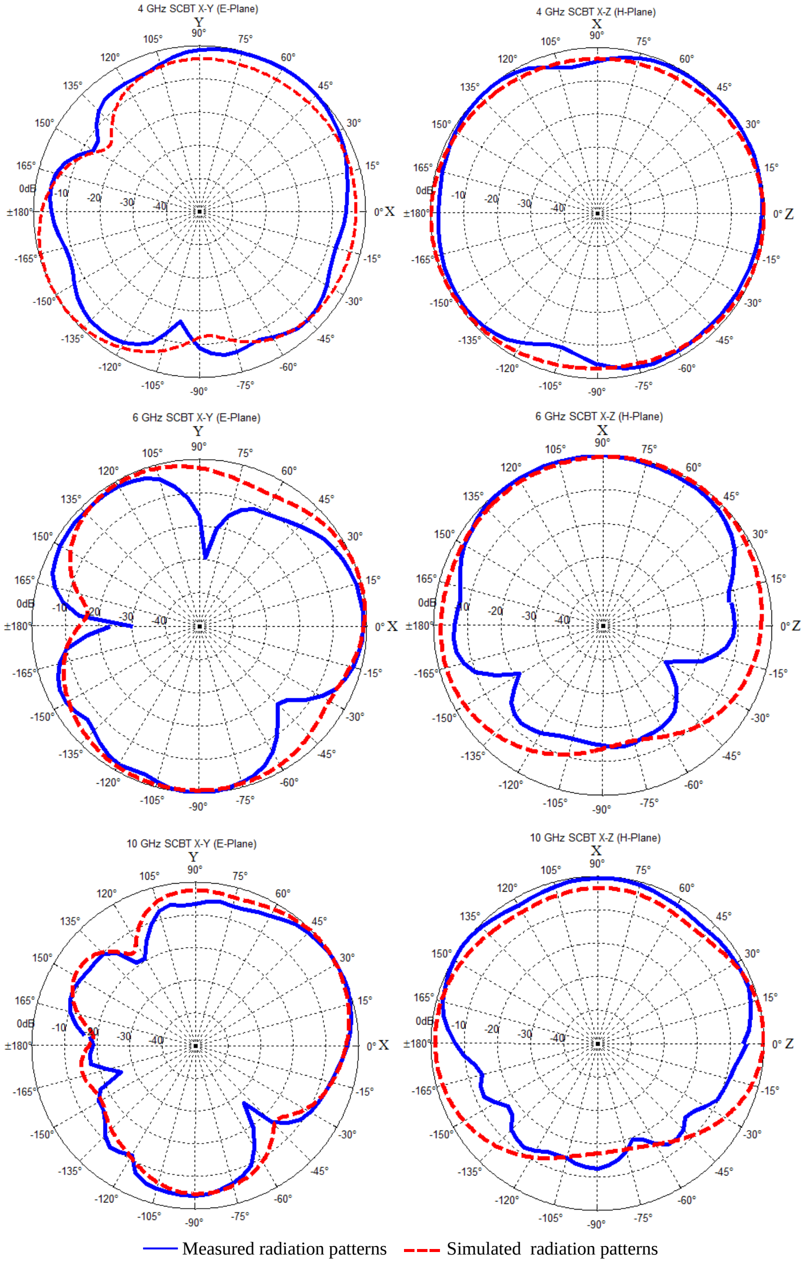


Figure 9. Measured and simulated radiation patterns of the SCBT-antenna in E and H planes, for the three frequencies 4, 6 and 10 GHz.

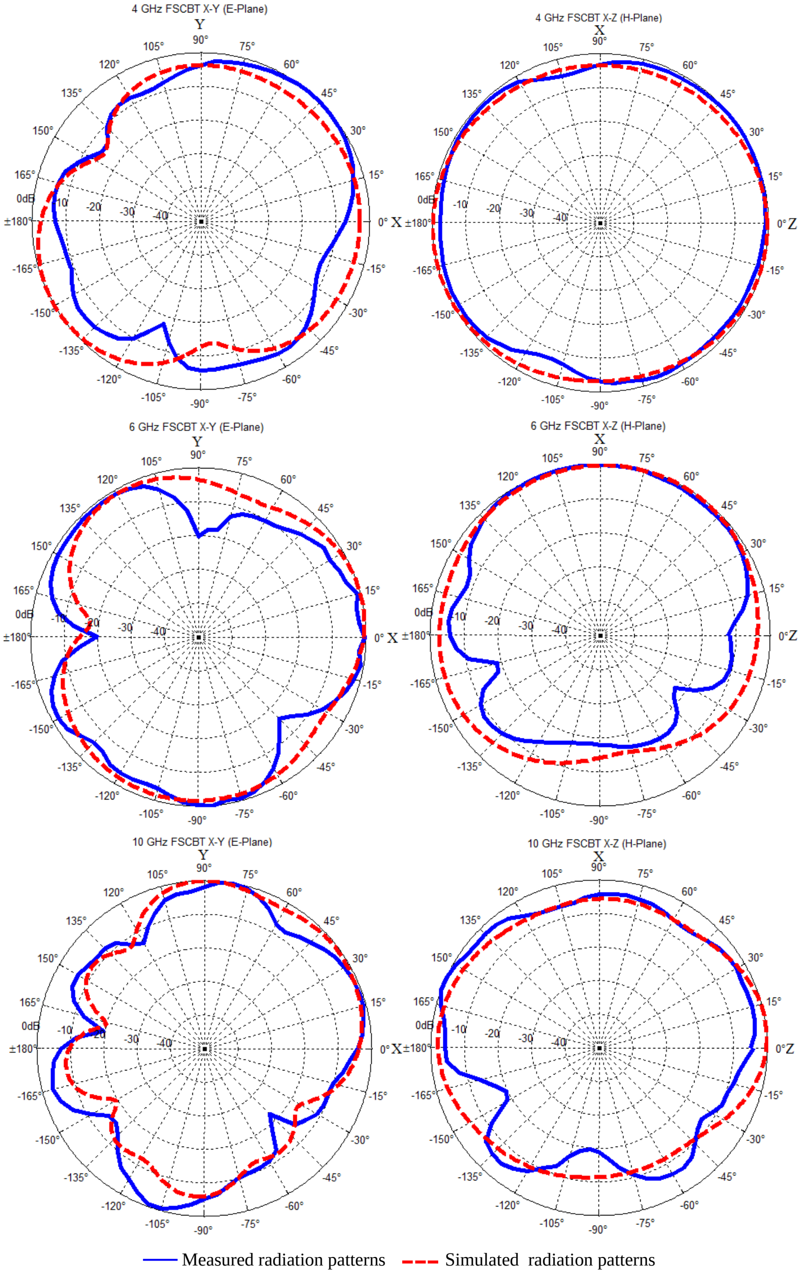


Figure 10. Measured and simulated radiation patterns of the FSCBT-antenna in E and H planes, for the three frequencies 4, 6 and 10 GHz.

a −10 dB return loss bandwidth of (2.88 to about 10.89 GHz) which is within the UWB requirements. In comparison with the results of the SCBT antenna, both antennas comply with the UWB requirements, but the FSCBT-antenna has lower return loss values over most of the band.

To verify the simulation results, both of SCBT and FSCBT antennas were fabricated on FR4 substrate as shown in Fig. 6. The Rode and Schwarz ZVL13 vector network analyzer (VNA) was used to measure the return loss of the two antennas. Figs. 7 and 8 show the measured return loss responses of the SCBT-antenna and FSCBT-antenna, respectively. Simulation results obtained with CST and HFSS software packages are also displayed for comparison. A very good agreement between the results obtained from the two software packages is noticed, also the experimental responses show very good agreement with those of the simulations.

The measurements of the radiation patterns were performed inside an anechoic chamber, and the radiation patterns have been measured for E and H planes at frequencies of 4, 6 and 10 GHz, using Anritsu MS2665C spectrum analyzer of frequency range of (9 kHz∼21.2 GHz). Figs. 9 and 10 show the measured radiation patterns compared to the simulation results, for SCBT and FSCBT antennas, respectively. The results show almost omnidirectional radiation patterns especially in the H-plane.

The realized gain of the simulation results and measured maximum gain for the FSCBT-antenna are plotted in Fig. 11, which shows the general trend of increasing gain with frequency. Examining Figs. 4 and 11 with more insight, it can be seen that in the range (6∼10 GHz), the gain of the FSCBT-antenna increases because of the good reduction in the return loss (down to about −15 dB). In Fig. 11,

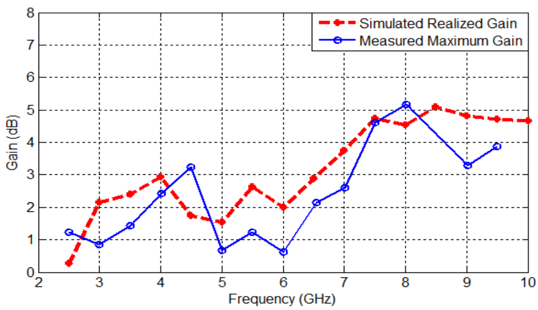


Figure 11. Simulated realized gain and measured maximum gain for the FSCBT-antenna.

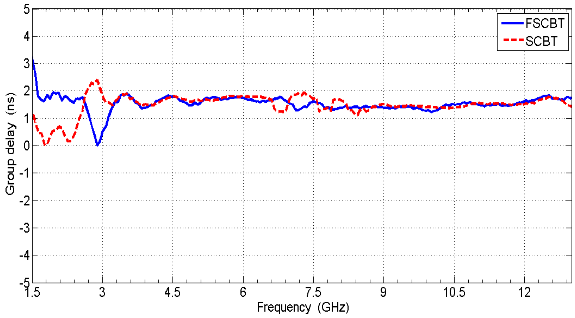


Figure 12. Measured group delay for SCBT-antenna, and FSCBT-antenna.

the measured maximum gain curve for the FSCBT-antenna can be noticed comparable to that of the simulated realized gain in overall shape, with some deviations less than 1.5 dB. The difference can be attributed to the fact that the direction of maximum radiated field was noticed to change slightly, while the frequency was varied.

To examine the time response of the proposed antennas, the group delay for each of the two fabricated antennas was measured. The transmitting and receiving antenna-pair were placed side-by-side, at separation of 30 cm, and the obtained group delay results are shown in Fig. 12. The two responses are almost constant over the UWB frequency range indicating practically linear phase change with frequency. The FSCBT antenna shows smoother response indicating closer to linear phase variation and hence better time response.

3. CONCLUSIONS

A new self complementary bowtie SCBT-antenna and fractal self complementary bowtie FSCBT-antenna have been demonstrated. Both antennas deploy the self complementary principle, while the FSCBT-antenna utilizes the self similarity feature of the fractal geometry as well. A simple technique has been applied to relate the lower frequency of the operation band to the antenna dimensions. These antennas overcome the problem of limited band of the traditional bow-tie TBT-antenna, which needs complicated matching sections to widen its bandwidth to the UWB requirements. Unlike the conventional bow-tie antennas the proposed antennas are of simple structure, easier design, suitable for the simple 50 Ω port feeder, and comply with UWB requirements. Ansoft HFSS package has been used as a validation tool for the simulation results obtained from the CST software. The FSCBT-antenna showed better return loss curve as compared to that of SCBT-antenna. Experimental validations for the return loss and radiation patterns showed good agreement with simulation results. The measurement of the maximum gain of FSCBT-antenna validated its relatively high gain. The measured group delay results showed almost constant response for SCBT and FSCBT antennas over the UWB frequency range.

REFERENCES

1. First Report and Order (FCC 02-48), "New public safety applications and broadband internet access among uses envisioned by FCC authorization of ultra-wideband technology," Action by the Commission, Feb. 14, 2002.
2. Yeo, J., Y. Lee, and R. Mittra, "Wideband slot antennas for wireless communications," *IEE Proc. Microwaves Antennas and Propagation*, Vol. 151, 351–355, 2004.
3. Ying, C., G. Li, and Y. Zhang, "An LTCC planar ultra-wideband antenna," *Microwave and Optical Technology Letters*, Vol. 42, 220–222, 2004.
4. Lin, C., Y. Kan, L. Kuo, and H. Chuang, "A planar triangular monopole antenna for UWB communication," *IEEE Microwave and Wireless Components Letters*, Vol. 15, No. 10, 624–626, 2005.
5. Lee, S., J. Park, and J. Lee, "A novel CPW-fed ultra-wideband antenna design," *Microwave and Optical Technology Letters*, Vol. 44, 393–396, 2005.
6. Liang, J., C. Chiau, X. Chen, and C. Parini, "Study of a printed circular disc monopole antenna for UWB systems," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 11, 3500–3504, 2005.
7. Wang, L., W. Wu, X.-W. Shi, F. Wei, and Q.-L. Huang, "Design of a novel monopole UWB antenna with a notched ground," *Progress In Electromagnetics Research C*, Vol. 5, 13–20, 2008.
8. Low, X. N., Z. N. Chen, and T. S. P. See, "A UWB dipole antenna with enhanced impedance and gain performance," *IEEE Transactions on Antennas and Propagation*, Vol. 57, No. 10, 2959–2966, Oct. 2009.
9. Karakolak, T. and E. Topsakal, "A double-sided rounded bow-tie antenna (DSRBA) for UWB communication," *IEEE Antennas and Wireless Propagation Letters*, Vol. 5, 2006.
10. Cappelletti, G., D. Caratelli, R. Cicchetti, and M. Simeoni, "A low-profile printed drop-shaped dipole antenna for wide-

band wireless applications," *IEEE Transactions on Antennas and Propagation*, Vol. 59, No. 10, 3526–3535, Oct. 2011.
11. Mushiake, Y., "Self-complementary antennas," *IEEE Antennas and Propagation Magazine*, Vol. 34, No. 6, 23–29, Dec. 1992.
12. Lestari, A. A., A. B. Suksmono, A. Kurniawan, E. Bharata, A. G. Yarovoy, and L. P. Ligthart, "Modified bow-tie antenna for efficient transmission of UWB pulses," *Proceedings of ISAP' 04*, 521–524, Sendai, Japan, 2004.
13. Yamini, A. H. and M. Soleimani, "Multiband behavior of wideband sierpinski fractal bow-tie antenna," *The European Conference on Wireless Technology*, 503–506, Paris, France, Oct. 2005.
14. Ng, C. H., S. Uysal, and M. S. Leong, "Microstrip bowtie patch antenna for wireless indoor communications," *Radio and Wireless Conference, RAWCON' 98*, 205–207, Colorado Springs, CO, Aug. 1998.
15. Rufus, E., Z. C. Alex, and P. V. Chaitanya, "A modified bow-tie antenna for microwave imaging applications," *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, Vol. 7, No. 2, 115–122, Dec. 2008.
16. Gomaa, A. M., D. A.-E. Mohamed, and M. A. Mangoud, "Double-sided printed triangular bow-tie antenna for UWB communications," *Proceeding of the 17th International Conference on Computer Theory and Applications*, Alexandria, Egypt, Aug. 2007.
17. Zheng, G., A. Z. Elsherbeni, and C. E. Smith, "A coplanar waveguide bow-tie aperture antenna," *Antennas and Propagation Society International Symposium*, 564–567, San Antonio, Texas, Aug. 2002.
18. Mehdipour, A., C. W. Trueman, A. R. Sebak, and S. V. Hoa, "Carbon-fiber composite T-match folded bow-tie antenna for RFID applications," *Antennas and Propagation Society International Symposium*, Charleston, SC, 2009.
19. Joshi, R. K. and A. R. Harish, "A modified bow-tie antenna for dual band applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 6, 468–471, 2007.
20. Mahmoud, K. R., "Design optimization of a bow-tie antenna for 2.45 GHz RFID readers using a hybrid BSO-NM algorithm," *Progress In Electromagnetics Research*, Vol. 100, 105–117, 2010.
21. Eldek, A. A., A. Z. Elsherbeni, and C. E. Smith, "Wideband microstrip-fed printed bow-tie antenna for phased-array systems," *Microwave and Optical Technology Letters*, Vol. 43, No. 2, 123–

126, Oct. 2004.

22. Zhang, F., F.-S. Zhang, Y.-B. Yang, and Z. Zhang, "Wide band antenna array using bowtie-shaped microstrip patch antenna," *ICMMT 2010 Proceedings*, 424–427, Chengdu, China, May 2010.
23. Kraus, J. D., *Antennas*, 2nd Edition, 67, McGraw-Hill, New York, 1988.
24. Persico, R., "Design of a balun for a bow tie antenna in reconfigurable ground penetrating radar systems," *Progress In Electromagnetics Research C*, Vol. 18, 123–135, 2011.
25. Kubota, S., X. Xiao, N. Sasaki, K. Kimoto, and T. Kikkawa, "Characteristics of UWB bow-tie antenna integrated with balun for breast cancer detection," *Antennas and Propagation Society International Symposium*, Charleston, SC, 2009.
26. Eldek, A. A., A. Z. Elsherbeni, and C. E. Smith, "Wide-band modified printed bow-tie antenna with single and dual polarization for C- and X-band applications," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 9, 3067–3072, Oct. 2009.
27. Liu, J., D. Zhao, and B.-Z. Wang, "A beveled and slot-loaded planar bow-tie antenna for UWB application," *Progress In Electromagnetics Research M*, Vol. 2, 37–46, 2008.
28. Sadek, S. and Z. Katabay, "Ultra wideband CPW bow-tie antenna," *International Conference on Electromagnetics in Advanced Applications*, 261–263, Torino, 2009.
29. Wu, S.-J. and T.-G. Ma, "A slotted bow-tie antenna with reconfigurable CPW-to-slotline transition for pattern diversity," *Proceedings of ISAP2007*, 720–723, Niigata, Japan, Aug. 2007.
30. Sayidmarie, K. H. and Y. A. Fadhel, "UWB fractal monopoles of rectangular and triangular shapes," *Proceedings of MAPE2011*, 709–712, Beijing, China, 2011.
31. Ray, K. P., "Design aspects of printed monopole antennas for ultra-wide band applications," *International Journal of Antennas and Propagation*, Vol. 2008, 1–8, 2008.
32. Ray, K. P., S. S. Thakur, and R. A. Deshmukh, "Broadbanding a printed rectangular monopole antenna," *Applied Electromagnetics Conference (AEMC)*, 1–4, Kolkata, India, Dec. 2009.