International Journal of Applied Electromagnetics and Mechanics 46 (2014) 527–536
DOI 10.3233/JAE-141937
IOS Press

Design of antipodal Vivaldi antenna with better performances for ultra wideband applications

Xiao Qing Yang[a], Ying Ya Zhai[a], Chen Xu[b,*] and Guo Zhu Jia[c]
[a]*College of Electronics and Information Engineering, Sichuan University, Chengdu, Sichuan, China*
[b]*Institute of Nuclear Science and Technology, Key Laboratory of Radiation Physics and Technology, Ministry of Education, Sichuan University, Chengdu, Sichuan, China*
[c]*Sichuan Normal University, Chengdu, Sichuan, China*

Abstract. Two different antipodal Vivaldi antennas design with better performances are proposed. The one is a small antipodal Vivaldi antenna for a 4.1–20 GHz frequency range, and its dimension is only 34 × 50 mm^2. Another proposed high gain antenna can achieve the maximum gain of 15.2 dBi within its operating band. Measured results of the manufactured antipodal Vivaldi antennas are in good agreement with the simulated ones. Besides the $|S_{11}|$, far field radiation pattern, current distribution, phase, gain, and group delay which are important parameters of impulse distortion in ultra-wide band antenna are well analyzed. All results show that the proposed antipodal Vivaldi antennas have better performances and they are well suited for ultra-wide band communications.

Keywords: Ultra-wide band, small antenna, high gain, Vivaldi antenna

1. Introduction

During the last few years, the ultra-wide band (UWB) technology development is getting faster and faster. The antenna is one of the important components in UWB systems. Many kinds of UWB antennas have been proposed in recent years such as monopole, fractal, printed circuit board antennas, and so on [1–6].

Many antennas are studied in order to improve broadband, such as the exponentially tapered slot antenna can provide a broad band (up to a ratio 4.5:1) within an array featuring a scan angle up to 45° [7]. But asymmetric feed structures tend to produce high cross-polarization. Since in 1979, Gibson proposed a tapered slot antenna, also known as a Vivaldi antenna [8]. Various forms of Vivaldi antennas have been developed so far. Furthermore, antipodal Vivaldi antennas have been proposed as a solution for the above problem. It is found that in the design of a printed UWB antenna, the radiator and the ground plane shape as well as the feeding structure can be optimized to achieve a good broad impedance bandwidth [9–11].

*Corresponding author: Chen Xu, Institute of Nuclear Science and Technology, Key Laboratory of Radiation Physics and Technology, Ministry of Education, Sichuan University, Chengdu 610065, Sichuan, China. E-mail: xuchen9269@163.com.

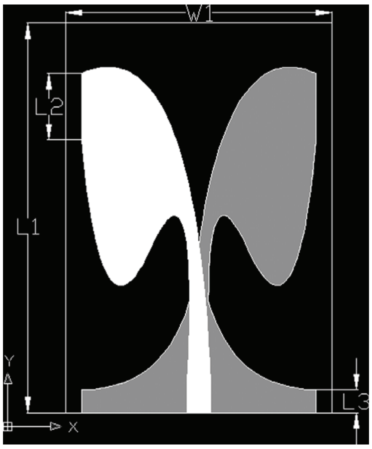
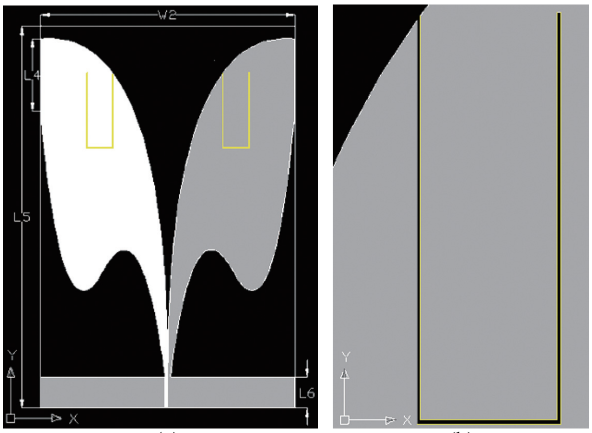


Fig. 1. The model of antenna 1.



(a) (b)

Fig. 2. The model of antenna 2, (a) The total model of antenna 2, (b) The amplifying U shape slot in the antenna 2.

The study of antipodal Vivaldi antennas has attracted the attention of many researchers, and the different characteristics of them are studied. In [12], adding an elliptical strip on the substrate can decrease the lower frequency band while the variation of $|S_{11}|$ remains smaller than -10 dB in the rest of the band. In [13], an ultra broadband direction finding antenna array covering the whole ultra high frequency range from 0.3 to 3 GHz is introduced. In [14], a small antipodal Vivaldi antenna is designed for two substrates, FR4 and Rogers RO3006. The peak gain of antenna achieves 5 dBi.

With the development of communication technology, the characteristics of some conventional antennas cannot meet some communication development requirements, such as broadband, small size, high gain, and so on. As an UWB antenna, small size is advantageous for conformal system, and high gain can enhance the degree of energy radiation in the case of ensuring broadband. On the one hand, in some communication fields such as PDAs, laptop, MP3, 3G wireless phone, videophone, and so on, small size is to pay close attention to the case of keeping other parameters available because the volume of those systems is limited. On the other hand, in those fields such as military communication, satellite communication, microwave radio relay communication, and so on, high gain antenna is taken into account because of high communication quality. In this paper, two antipodal Vivaldi antennas with better performances are studied by numerical calculation finite-difference time-domain (FDTD) method. One is the small antipodal Vivaldi antenna whose ground plate is designed by transition curve. Another is the high gain antenna with U shape structure. Finally, they are fabricated to perform measurements for validation.

2. Modified Vivaldi antenna model

The models of modified antipodal Vivaldi antenna are shown in Figs 1 and 2. There are three basic parts in the antipodal Vivaldi antenna: Transmission line, Radiator, Transition between transmission line and the radiator. The transmission line is a microstrip that is compatible with monolithic microwave integrated circuits. Generally, the transition between transmission line and the radiator has an exponential form. Actually, this is the most important part that affects the impedance matching. In this paper, the xy-plane and yz-plane are referred to as the E and H planes respectively. Two symmetric exponentially

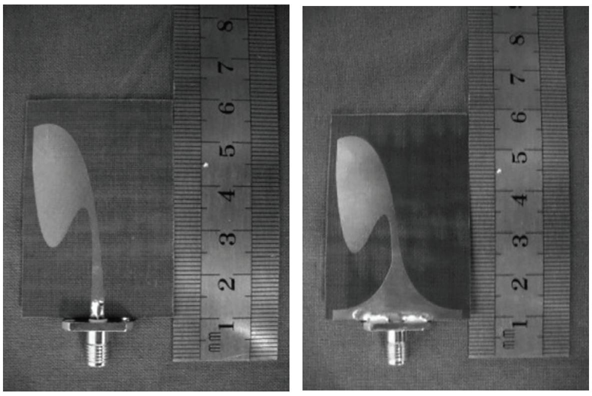


Fig. 3. Top and bottom views of the fabricated antenna 1.

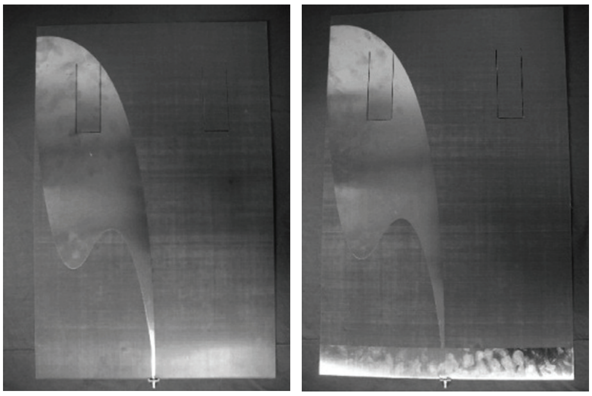


Fig. 4. Top and bottom views of the fabricated antenna 2.

tapered patches lie on opposite sides of the substrate. The exponentially taper patch is defined by the opening rate γ and the two points D_1 (x_1, y_1) and D_2 (x_2, y_2) (the start and the end points of the exponential taper)

$$x = c_1 e^{\gamma y} + c_2 \tag{1}$$

where

$$c_1 = \frac{x_2 - x_1}{e^{\gamma y_2} - e^{\gamma y_1}} \tag{2}$$

$$c_2 = \frac{x_1 e^{\gamma y_2} - x_2 e^{\gamma y_1}}{e^{\gamma y_2} - e^{\gamma y_1}} \tag{3}$$

Given the highest frequency (f_H), the width $W1$ of the antipodal Vivaldi antenna should satisfy Eq. (4) to avoid any grating lobes for the Vivaldi antenna.

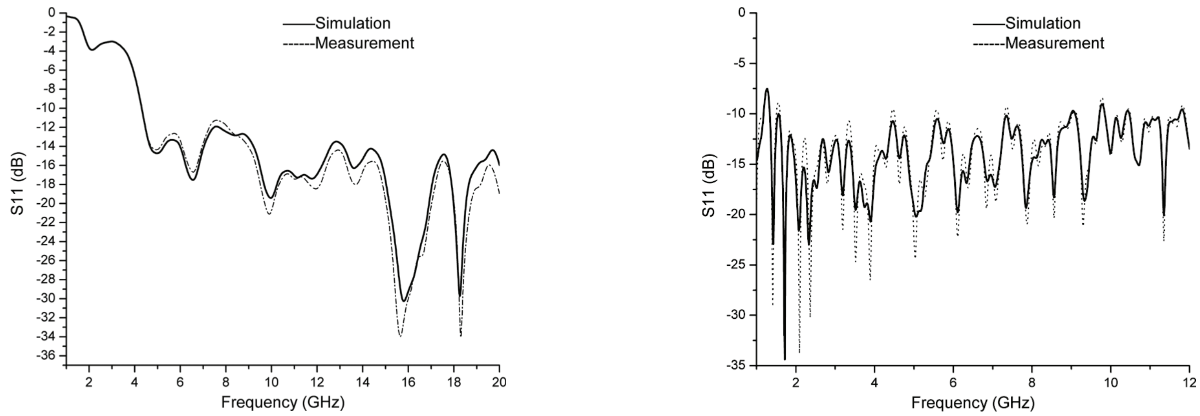
$$W1 < \frac{c}{f_H \sqrt{\varepsilon_e}} \tag{4}$$

where c is the speed of light in vacuum, ε_e is the effective dielectric constant.

The optimization method is based on the genetic algorithm (GA). The GA is a robust, stochastic and global optimization method simulated on the concepts of natural selection and evolution. There are two sets of four structural parameters needed to be optimized. The fitness function plays an important role in the GA optimization because it influences the direction of GA optimization. In this paper, the fitness function should take wide bandwidth and high gain into account, hence it is defined as

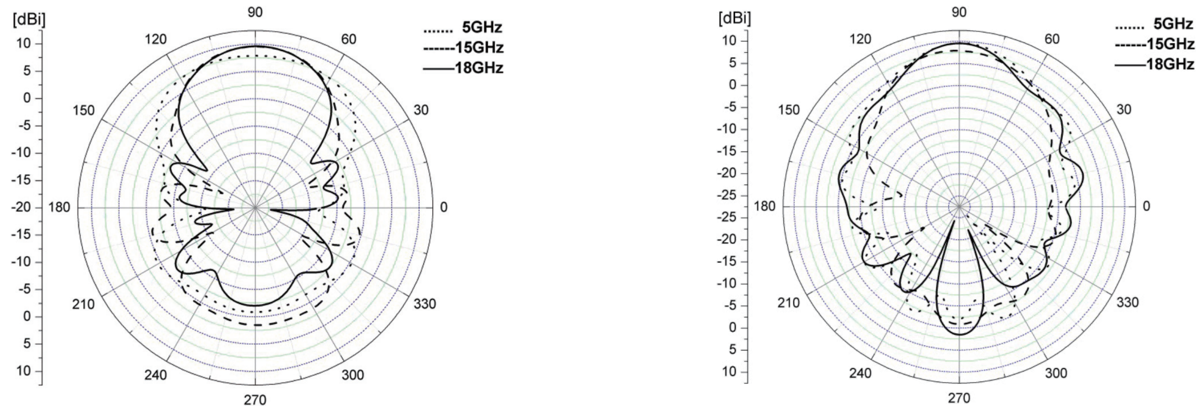
$$\mathit{Fitness} = C_1 * \mathit{Bandwidth} + C_2 * \mathit{Gain} \tag{5}$$

where Fitness is the fitness value, Bandwidth refers the $|S_{11}| < -10$ dB bandwidth, Gain denotes the gain over a measured frequency band, C_1 and C_2 are weight factors. Through repeated applications of selection, crossover and mutation operators, the initial population is transformed into a new population in an iterative way. New population will obtain better chromosomes and will finally converge to an optimal population. In the process of simulation, when the fitness function is bigger than the threshold value or



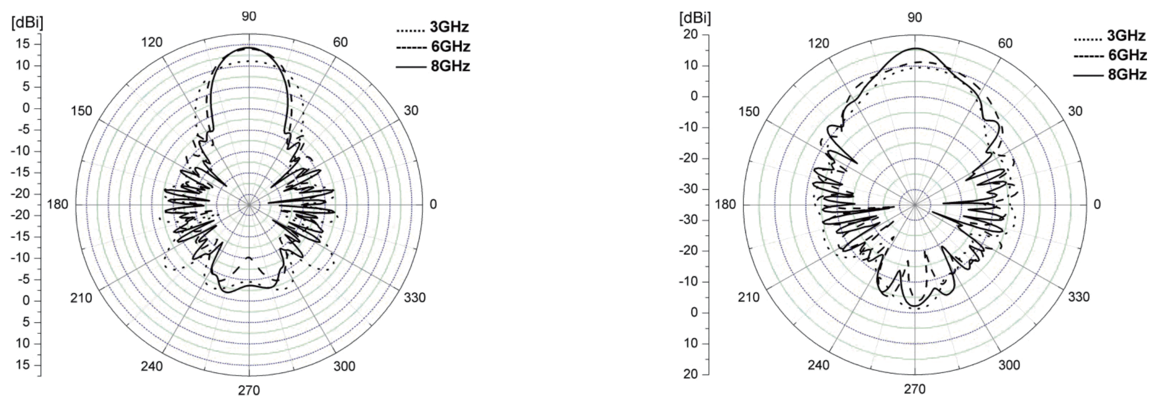
(a) (b)

Fig. 5. The $|S_{11}|$, (a) antenna 1, (b) antenna 2.



(a) (b)

Fig. 6. Measured radiation pattern of antenna 1 at 5, 15, and 18 GHz: (a) H plane, (b) E plane.



(a) (b)

Fig. 7. Measured radiation pattern of antenna 2 at 3, 6, and 8 GHz: (a) H plane, (b) E plane.

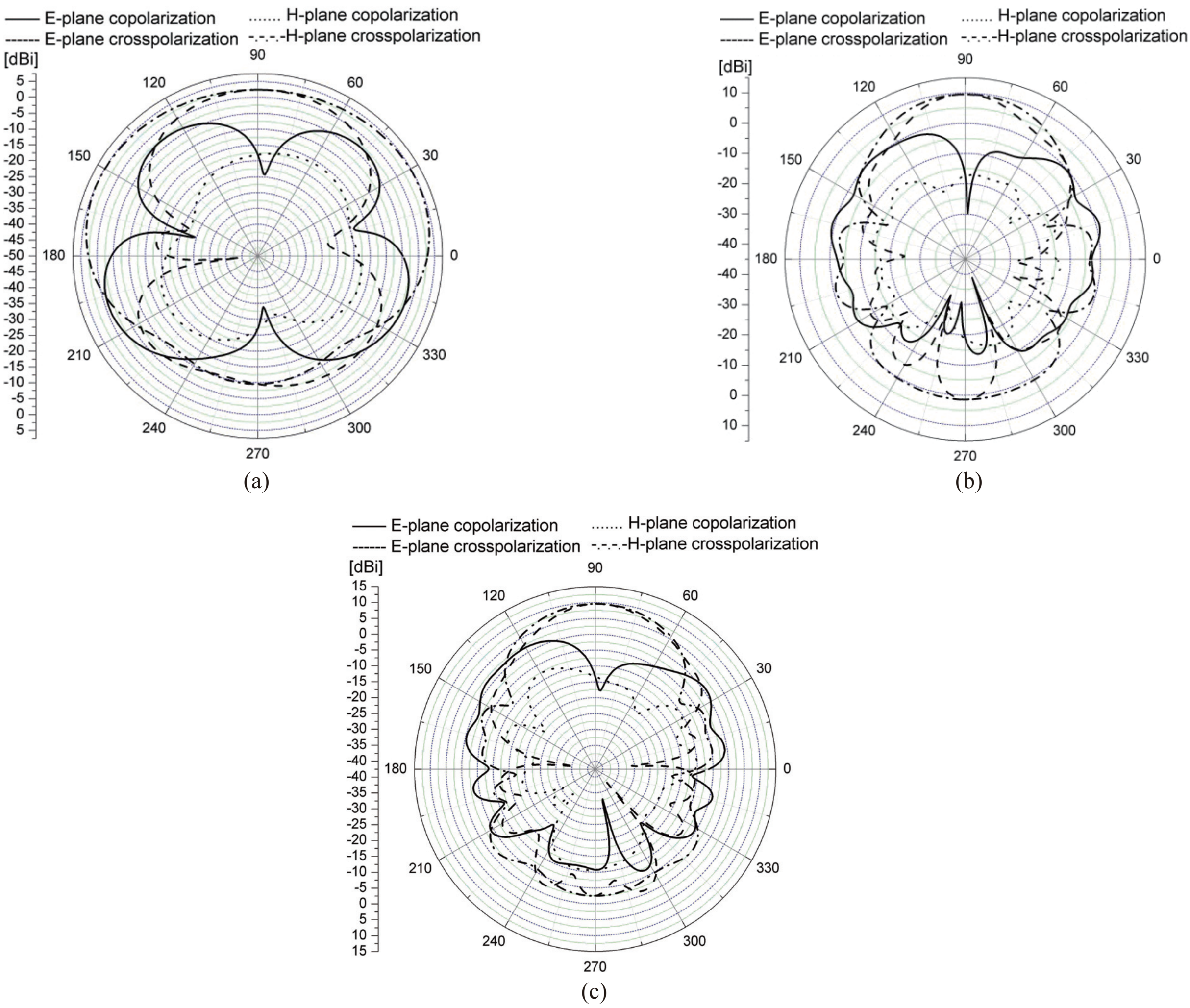


Fig. 8. The copolarization and crosspolarization radiation patterns for antenna 1 at (a) 5 GHz, (b) 15 GHz, (c) 18 GHz.

the GA do not find a better population within 400 successive generations, the GA will be terminated and a solution will be obtained.

The geometry of antenna 1 is shown in Fig. 1, and the U shape slot which can increase gain in antenna 2 is shown in Fig. 2. The two antennas are printed on PTFE ($\varepsilon_r = 2.65$, $\tan\delta = 0.003$) substrate with the thickness of 1 mm respectively. In Fig. 1, the dimensions are optimized as follows: $L1 = 50$ mm, $L2 = 8.5$ mm, $L3 = 3$ mm, $W1 = 34$ mm. It is a small UWB antipodal Vivaldi antenna. In Fig. 2, the dimensions are optimized as follows: $L4 = 85$ mm, $L5 = 450$ mm, $L6 = 36$ mm, $W2 = 300$ mm. The width of U shape in antenna 2 is 0.8 mm. The top and bottom views of the fabricated antennas are shown in Figs 3 and 4, respectively.

The gain reflects the ability of an antenna to radiate the power of a given waveform. In order to improve gain, the U shape slot is proposed in current radiation direction. From the point of view of physical characteristic, it effectively adds the current path.

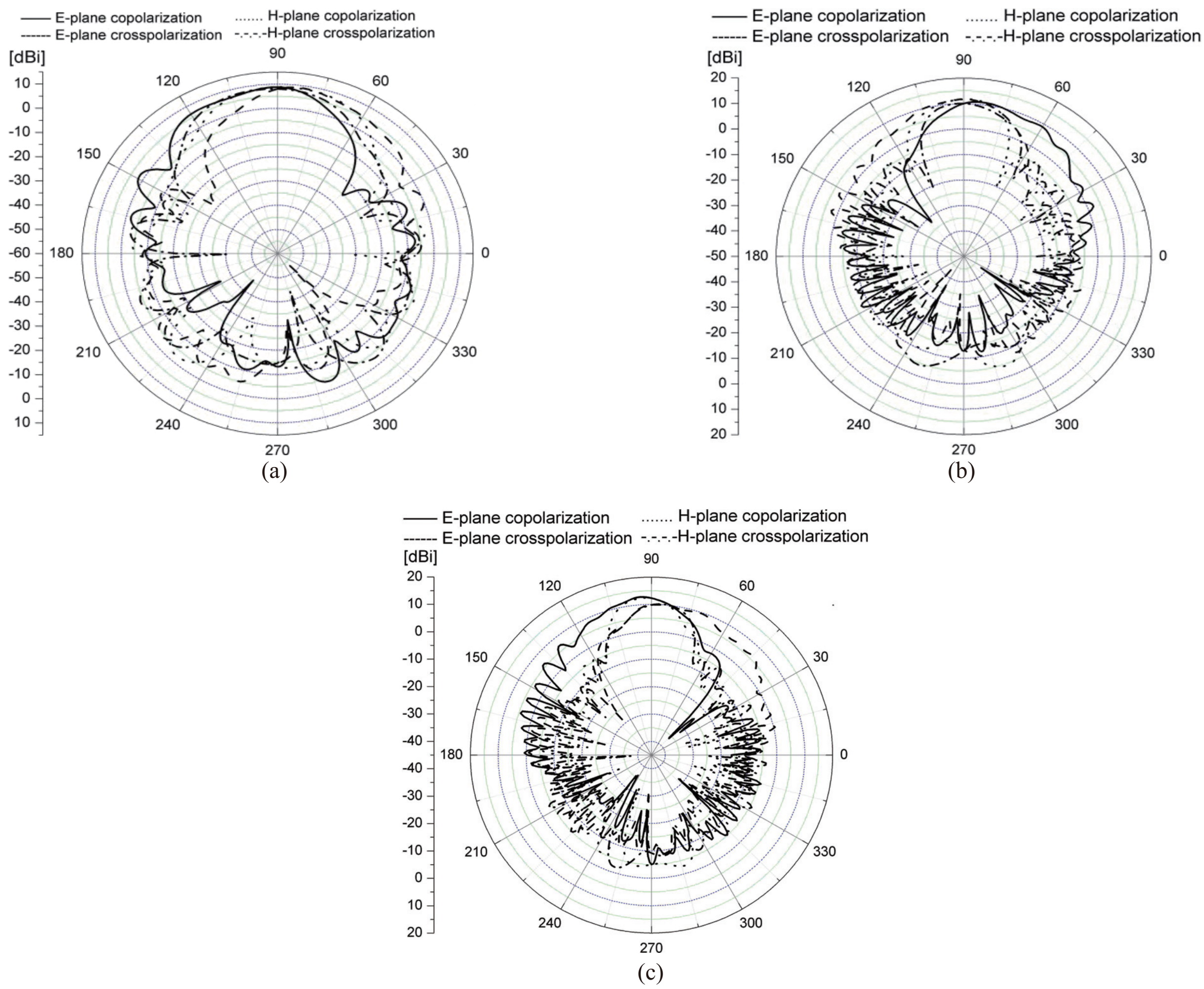


Fig. 9. The copolarization and crosspolarization radiation patterns for antenna 2 at (a) 3 GHz, (b) 6 GHz, (c) 8 GHz.

3. Results and discussion

UWB antipodal Vivaldi antennas are analyzed using FDTD method. By optimizing their parameters, the better characteristics are obtained in the proposed antennas.

In antenna design, $|S_{11}|$ provides an estimate of an antenna's match. And it is important that the $|S_{11}|$ is below -10 dB across the entire UWB spectrum. Measured and simulated $|S_{11}|$ are compared in Fig. 5. Using an Agilent Vector Network Analyzer, the measured $|S_{11}|$ of the proposed antenna 1 is obtained at 4.1–20 GHz and that of antenna 2 is obtained at 1.3–12 GHz, as depicted in Figs 5(a) and (b), respectively. From Fig. 5, it is observed that the measured $|S_{11}|$ reasonably agrees with the simulated results. Measured results indicate that the antenna 1 can operate across the entire UWB spectrum with $|S_{11}|$ of lower than -10 dB, and the $|S_{11}|$ of antenna 2 is below -10 dB within the operating frequency range except for a few points. The frequency shift between measured and simulated $|S_{11}|$ is attributed to the fabrication inaccuracy.

Figure 6 shows the measured radiation pattern of E and H planes at 5, 15, and 18 GHz for the proposed

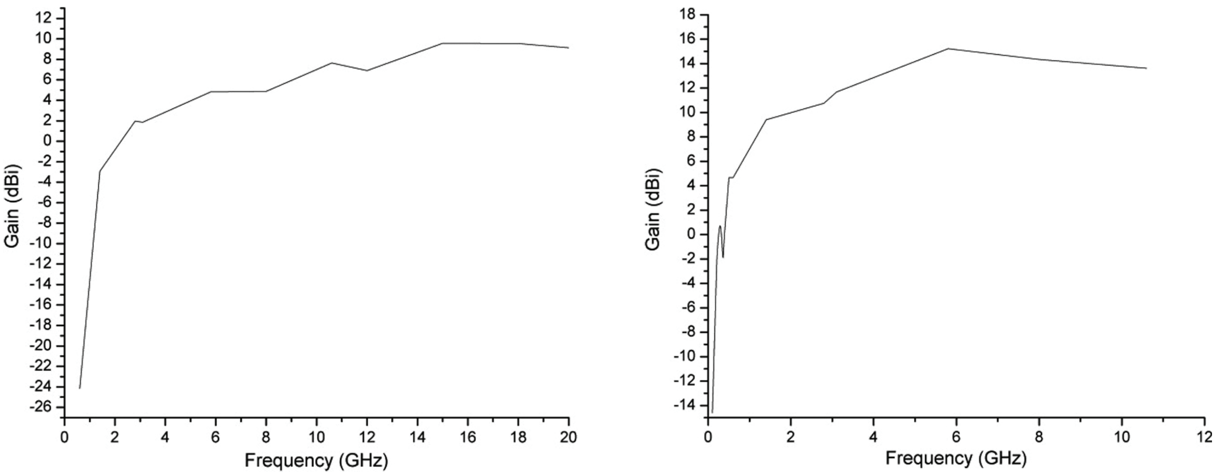


Fig. 10. The peak gain, (a) antenna 1, (b) antenna 2.

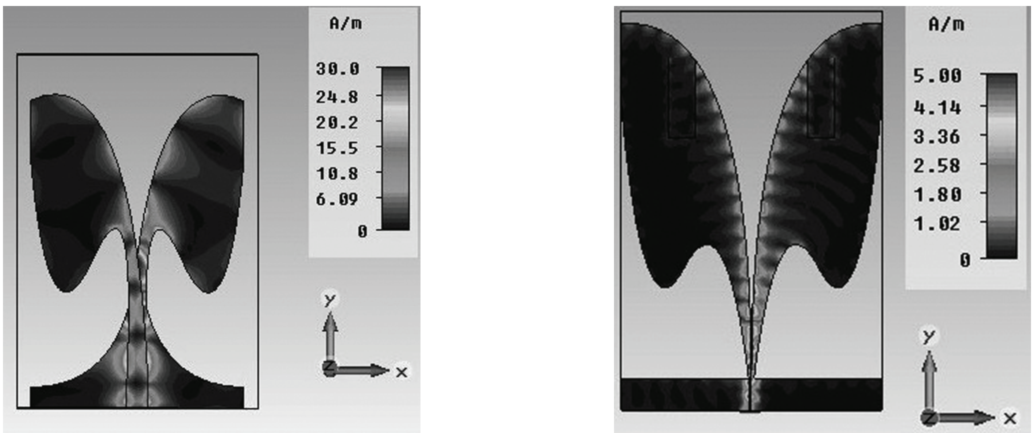


Fig. 11. The current distribution, (a) antenna 1, (b) antenna 2.

antenna 1, and Fig. 7 shows the measured radiation pattern of E and H planes at 3, 6, and 8 GHz for antenna 2. It can be seen from Figs 6 and 7 that the measured radiation patterns of antennas 1 and 2 are symmetrical. Figure 8 shows the copolarization and crosspolarization radiation patterns for antenna 1 at 5, 15, and 18 GHz. Figure 9 shows the copolarization and crosspolarization radiation patterns for antenna 2 at 3, 6, and 8 GHz. The measured radiation patterns are similar and stable across the operating frequency from Figs 6–9. The results clearly show that two proposed antipodal Vivaldi antennas meet the UWB radiation characteristic.

Figures 10(a) and (b) show the gains of the fabricated antennas 1 and 2 respectively. As can be seen from Fig. 10, the gain gradually increases with the increase of frequency. Above a certain frequency, the gain begins to decrease. The decrease can be attributed to the dielectric loss. The maximum gains in Figs 10(a) and (b) approach 9.6 dBi and 15.2 dBi which are increased by 4.6 dBi and 10 dBi than ordinary antenna respectively. At 10 GHz, the gains of antennas 1 and 2 are increased by 2.5 dBi and

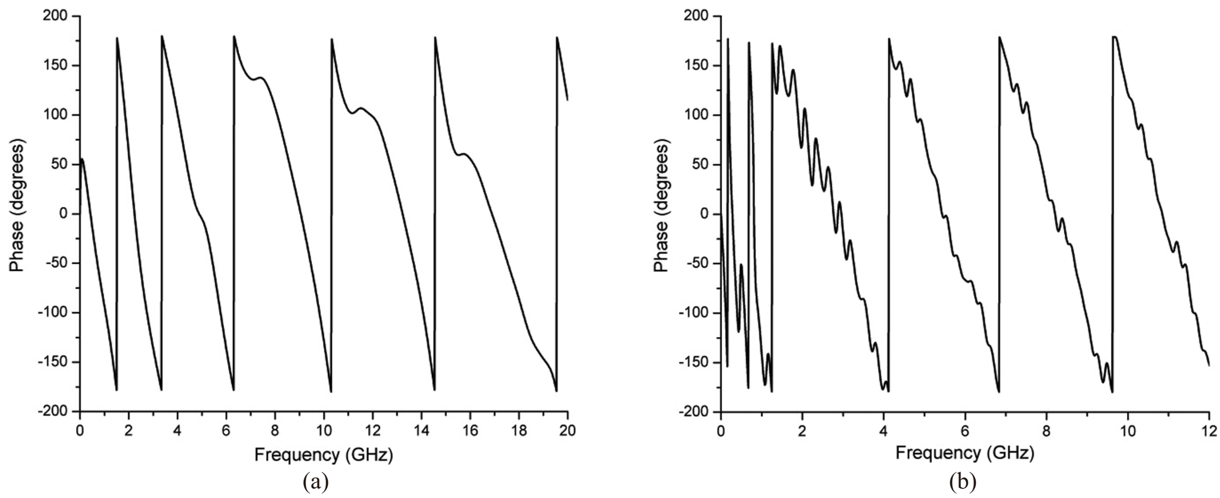


Fig. 12. The phase, (a) antenna 1, (b) antenna 2.

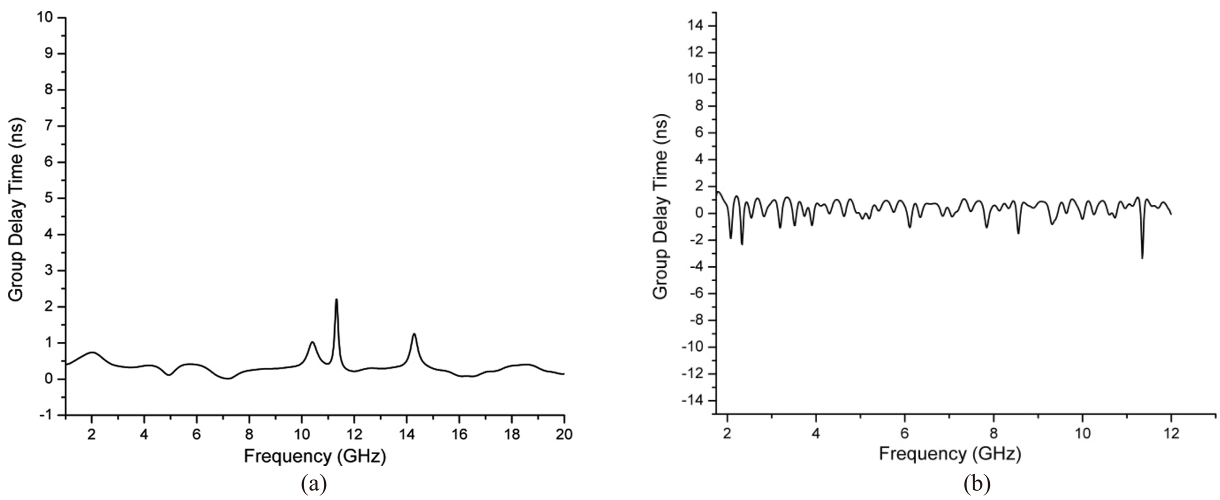


Fig. 13. The group delay, (a) antenna 1, (b) antenna 2.

8.5 dBi than ordinary antenna respectively.

Figures 11 and 12 show the current distribution and phase of the fabricated antennas 1 and 2 respectively. Figure 11 shows current densities on the exponentially tapered patch decrease with the distance from feed point, and the current densities are higher at the edges of the slot.

Besides the parameters already mentioned above, group delay is also an important parameter in UWB antenna design, which represents the degree of distortion of pulse signal.

The group delay of an antenna is the frequency dependence of the time delay [15]. It is defined as follows:

$$\tau(\omega) = -\frac{dj(\omega)}{d\omega} = -\frac{dj(f)}{2\pi df} \tag{6}$$

where $j(f)$ is the frequency-dependent phase of the radiated signal.

The group delay is obtained from the derivative of the phase response. A nondistorted structure is characterized by a constant group delay, i.e., linear phase, in a relevant frequency range. The nonlinearity of a group delay indicates the resonant character of the device, which implicates the ability of the structure to store the energy. It produces ringing and oscillation of the antenna impulse response. Figures 13(a) and (b) show clearly the group delay of the fabricated antennas 1 and 2 respectively.

From Figs 13(a) and (b), it is observed that the variations of group delay on antennas 1 and 2 are only 2.5 ns and 4 ns, respectively. The group delay time is superior to [16] whose group delay time is 58 ns. This guarantees the stability of transmission signal to some extent.

4. Conclusions

In this paper, two designs for antipodal Vivaldi antenna with better performance are presented and analyzed. One is the small Antipodal Vivaldi antenna whose ground plate is designed by transition curve. Another is high gain antenna with U shape slot structure. Finally, they are fabricated to perform measurements for validation. The different types of UWB characteristics such as $|S_{11}|$, far field radiation pattern, gain, current distribution, phase and group delay are well analyzed, especially the group delay as an important parameter of impulse distortion in UWB antenna. UWB antennas with better performances are an essential part of UWB radar and communication systems in relevant fields. The proposed antipodal Vivaldi antennas give good results and they are well suited for UWB communications.

Acknowledgment

This project was supported by 973 programs (No. 2013CB328905), National Natural Science Foundation of China (No. 61372043 and No. 61102044), Sichuan Province Science and Technology Plan (No. 2013GZX0149) and Fund of Chinese Academy of Sciences Laboratory (No. 11H1772).

References

[1] J. Liang, C.C. Chiau, X. Chen and C.G. Parini, Study of a printed circular disc monopole antenna for UWB systems, *IEEE Transaction on Antennas and Propagation* **53** (2005), 3500–3504.

[2] S. Rani and A.P. Singh, Modified koch fractal antenna with asymmetrical ground plane for multi and UWB applications, *International Journal of Applied Electromagnetics and Mechanics* **42** (2013), 259–267.

[3] Z.N. Low, J.H. Cheong and C.L. Law, Low-cost PCB antenna for UWB applications, *IEEE Antennas Wireless Propagation Letters* **4** (2005), 237–239.

[4] S.H. Choi, J.K. Park, S.K. Kim and J.Y. Park, A new ultra-wideband antenna for UWB applications, *Microwave Opt Technol Lett* **40** (2004), 399–401.

[5] C.B. Kim, J.S. Lim, J.S. Jang, Y.H. Jung, H.S. Lee and M.S. Lee, Wideband notched compact UWB antenna, *International Journal of Applied Electromagnetics and Mechanics* **28** (2008), 101–110.

[6] J. Young and L. Peters, A brief history of GPR fundamentals and applications, *Proc* 6^{th} *Int Conf Ground Penetrating Radar* (1996), 5–14.

[7] S. Wang, X.D. Chen and C.G. Parini, Analysis of ultra wideband antipodal vivaldi antenna design, *IEEE Loughborough Antennas and Propagation Conference* Loughborough, UK, (2007), 129–132.

[8] P.J. Gibson, The vivaldi aerial, *Proc 9th Europe Microwave Conference*, Brighton, UK, (1979), 101–105.

[9] X.H. Wu, Z.N. Chen and M.Y.W. Chia, Note on antenna design in UWB wireless communication systems, *IEEE Conference on Ultra Wideband Systems and Technologies* (2003), 503–507.

[10] S.Y. Suh, W.L. Stutzman and W.A. Davis, A new ultrawideband printed monopole antenna: The planar inverted cone antenna (PICA), *IEEE Transactions on Antennas and Propagation* **52** (2003), 1361–1364.

[11] Z.N. Chen, T.S.P. See and X. Qing, Small printed ultrawideband antenna with reduced ground plane effect, *IEEE Transactions on Antennas and Propagation* **55** (2007), 383–388.
[12] M.H.H. Agahi, H. Abiri and F. Mohajeri, Investigation of a new idea for antipodal vivaldi antenna design, *International Journal of Computer and Electrical Engineering* **3** (2011), 277–281.
[13] R. Mueller, S. Lutz, R. Lorch and T. Walter, A UHF ultrabroadband vivaldi-type direction finding antenna, *Antennas and Propagation Society International Symposium (APSURSI), 2010 IEEE*, Toronto, ON, (2010), 1–4.
[14] A.Z. Hood, T. Karacolak and E. Topsakal, A small antipodal vivaldi antenna for ultrawide-band applications, *IEEE Antennas and Wireless Propagation Letters* **7** (2008), 656–660.
[15] B.W. Wiesbeck, G. Adamiuk and C. Sturm, Basic properties and design principles of UWB antennas, *Proceedings of the IEEE* **97** (2009), 372–385.
[16] A. Mehdipour, K.M. Aghdam and R.F. Dana, Complete dispersion analysis of vivaldi antenna for ultra wideband applications, *Progress in Electromagnetics Research* **77** (2007), 85–96.