A Tri-band-notched UWB Antenna with Low Mutual Coupling between the Band-notched Structures

Chao-ming LUO, Jing-song HONG, Han XIONG

School of Physical Electronics, University of Electronic Science and Technology of China,
No. 4, Section 2, Chengdu 610054, China

461339852@163.com , cemlab@uestc.edu.cn , xiong1226han@126.com

Abstract. *A compact printed U-shape ultra-wideband (UWB) antenna with triple band-notched characteristics is presented. The proposed antenna, with compact size of 24×33 mm^2, yields an impedance bandwidth of 2.8-12 GHz for VSWR < 2, except the notched bands. The notched bands are realized by introducing two different types of slots. Two C-shape half-wavelength slots are etched on the radiating patch to obtain two notched bands in 3.3-3.7 GHz for WiMAX and 7.25-7.75 GHz for downlink of X-band satellite communication systems. In order to minimize the mutual coupling between the band-notched structures, the middle notched band in 5-6 GHz for WLAN is achieved by using a U-slot defected ground structure. The parametric study is carried out to understand the mutual coupling. Surface current distributions and equivalent circuit are used to illustrate the notched mechanism. The performance of this antenna both by simulation and by experiment indicates that the proposed antenna is suitable and a good candidate for UWB applications.*

Keywords

Band-notched structures, low mutual coupling, triple notched bands, UWB antenna.

1. Introduction

Since the commercial operation of UWB within the range 3.1-10.6 GHz was authorized by the Federal Communication Commission (FCC) in 2002, UWB technology has been rapidly advancing as a high data rate wireless communication technology for various applications [1]. As an essential part of the UWB system, the UWB antenna has received increasing attentions. However, it also faces many challenges including its impedance matching, radiation stability, compact size, low manufacturing cost and electromagnetic interference (EMI) problems. The EMI problems are quite serious for UWB systems since there are some narrow bands for other communications systems within the designated UWB bandwidth. Therefore, it is desirable to design the UWB antenna with band-notched characteristics in order to avoid interference with the existing wireless networking technologies such as WiMAX (3.3-3.7 GH) and WLAN (5-6 GHz), downlink of X-band satellite communication systems (7.25-7.75 GHz).

There are various methods to achieve the band-notched function. A way is using several band stop filters connected to the UWB antenna. But this is bound to increase the complexity of the system. A simpler way to solve this problem is to design the UWB antenna with band-notched characteristics. Some UWB antennas with band-notched characteristics have been proposed, which is usually accomplished by cutting slots on the patch plane [2-5], using a resonator at the center of the antenna [6-8], and putting parasitic elements close to the radiator [9], [10]. However, most UWB antennas have been designed with only one or two notched-frequency bands [11-16]. This reveals that potential interference from other narrow bands may still exist with such antennas. Then, antennas with triple or multiple notched bands have been proposed [17-19] recently. Nevertheless, most of these antennas have the common deficiency of large size, which may lead to increased fabrication costs and difficulty in the integration with microwave integrated circuits. Moreover, the mutual couplings among each slot or each parasitic strip lead to a more complicated design procedure and requiring tedious time for achieving antenna design goals, especially when two notched frequencies are located closely to each other.

In this paper, a compact printed U-shape UWB antenna with triple band-notched characteristics is proposed. By two C-shape half-wavelength slots etched on the radiation patch and a U-slot defected ground structure (DGS), triple band-notched characteristics are created. Note that by introducing DGS to generate the middle notched band, the distances between the band-notched structures of adjacent frequencies are increased. As a result, the mutual coupling between the resonators is very weak and therefore can be neglected.

2. Antenna Design and Analysis

The geometry of proposed UWB band-notched antenna is shown in Fig. 1. Simulation was performed using the commercial software Ansoft HFSS. This antenna is printed on the FR4 substrate with compact size of 24×33 mm^2, thickness of 1 mm, and relative dielectric constant of 4.4. It is composed of a microstrip feed line, a U-shape radiating patch, a simple rectangular ground plane, and three slots. This antenna is more compact in size than previously reported antennas with a similar goal in functionality, such as a 150×150 mm^2 antenna in [17], a 30×39.3 mm^2 antenna in [18], and 27×34 mm^2 antenna in [19].

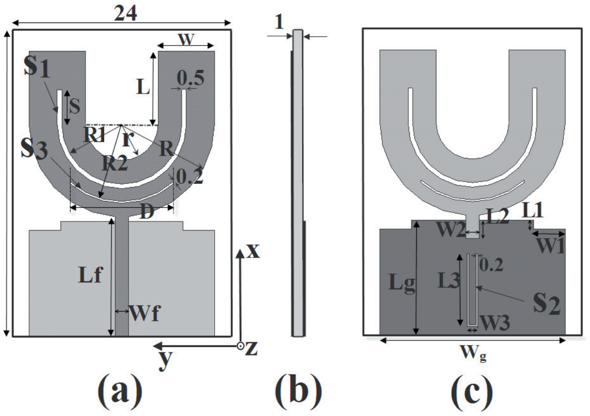

Fig. 1. Geometry of the antenna (units in millimeters). (a) Top view. (b) Side view. (c) Bottom view.

The UWB antenna structure is a variation of a circular monopole antenna. Antenna design is based on the fact that the current is mainly concentrated along the periphery of the circular monopole antenna. Therefore, the central portion of the circular monopole can be removed with negligible effect on impedance bandwidth or radiation characteristics. Initially a circular monopole antenna of radius R is designed and optimized to achieve the desired UWB response. A circular slot of radius r is cut at the centre of the circular monopole resulting in annular ring monopole antenna. Thereafter, a semi annular ring is designed, and a rectangular strip is placed on both sides at the top of semi annular ring monopole, resulting in a U-shape antenna. By adopting the U-shape patch, broadband impedance bandwidth can be easily achieved, which is due to the gradual change structure.

To achieve the desired UWB antenna with triple band-notched characteristics, two C-shape half-wavelength slots (S1 and S3) etched on the radiation patch and a U-slot S2 defected ground structure are adopted to generate notched bands with central frequencies of 3.5, 7.5, and 5.5 GHz, respectively. Here, each slot is responsible for creating a frequency band notch. Theoretically, the notched function is chiefly determined by the lengths of the slots. In the design, the band-notched frequency is given approximately by the expression:

$$f_{notch} = \frac{c}{2L_{slot}\sqrt{\varepsilon_{eff}}},$$

$$\varepsilon_{eff} = \left(\varepsilon_r + 1\right)/2$$

where L_{slot} is the total length of the slot, ε_r is dielectric constant of the substrate, and c is the speed of the light. Hence, the initial length of the slot should be theoretically calculated at notched frequency at the beginning of the design. Fig. 2 exhibits the comparison of the notched bandwidth via the width G of the slot S1. It is observed that, as the width of the slot increases, its peak rejection goes higher and notched band goes wider. In addition, achieving distinct controllability of each notched band, and minimizing the mutual coupling among the three slots are also quite important matters to be considered. As our simulation finds, when the distance between the slots increases, its mutual coupling is reduced and notched characteristic is deteriorated.

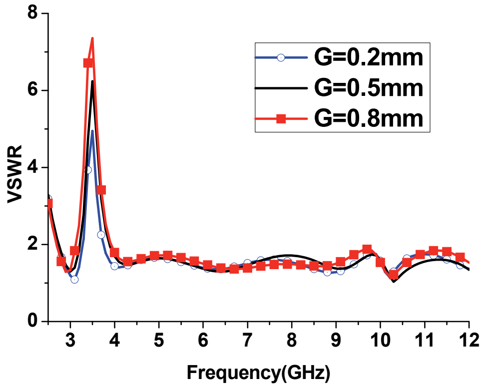

Fig. 2. Effects of G (the width of slot S1).

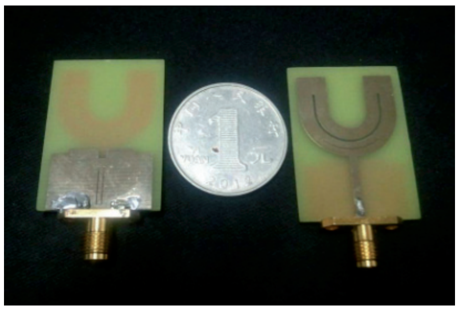

Fig. 3. Photograph of the fabricated antenna.

The design parameters optimized for the antenna were eventually determined with R = 10.2 mm, r = 4 mm, $R1$ = 6.6 mm, $R2$ = 8.5 mm, Wf = 1.5 mm, Lf = 13.2 mm, W = 6.2 mm, L = 8 mm, S = 3.8 mm, D = 11.4 mm, Wg = 20.4 mm, Lg = 12.7 mm, $W1$ = 3.5 mm , $L1$ = 1 mm, $W2$ = 1.5 mm, $L2$ = 2 mm, $W3$ = 1.2 mm, $L3$ = 8 mm. A photograph of the implemented prototype of the proposed antenna is also shown in Fig. 3.

The simulated VSWR of the antenna is shown in Fig. 4, where VSWR of the original antenna (without any slot) is compared to VSWRs of the antenna having either slot S1, S2, or S3, respectively. It can be clearly seen that each slot creates a corresponding notched band. By uniting them together, we get the tri-band-notched UWB antenna as proposed in this paper. To understand the mutual coupling between the band-notched structures, the parametric study is carried out by changing one parameter at a time and fixing the others. For simplicity, only the parameters *S*, *L3*, and *D* are changed. As shown in Fig. 5, 6, and 7, the first, the second and the third notched bands shift to lower frequency as the *S*, *L3*, and *D* increase, respectively, because the length of the corresponding slots increases. The variation of one notched band almost has no effect to the others due to the fact that the band-notched structures of adjacent frequencies are etched in different place and the coupling between them is very weak. From the results, we can also conclude that the notch frequency is controllable by changing the length of the slot.

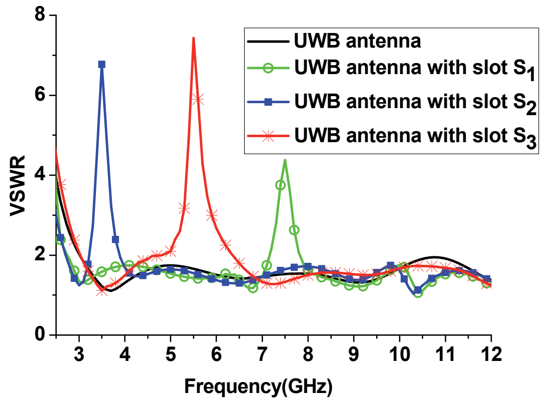

Fig. 4. Influence of the slots on VSWR of the antenna.

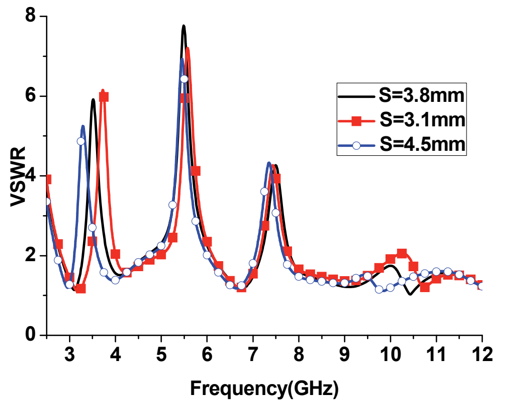

Fig. 5. Simulated band-notched characteristics of the proposed antenna for various S.

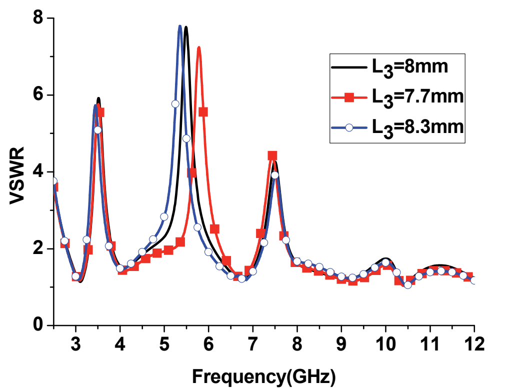

Fig. 6. Simulated band-notched characteristics of the proposed antenna for various *L3*.

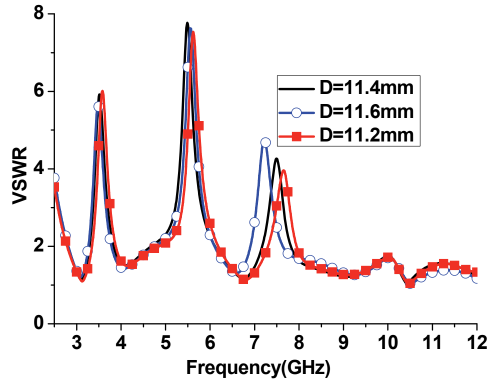

Fig. 7. Simulated band-notched characteristics of the proposed antenna for various *D*.

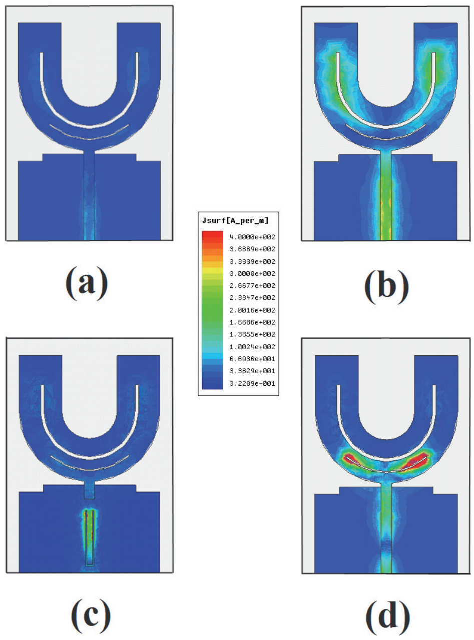

Fig. 8. Surface current distributions of the antenna. (a) A pass-band at 6.8 GHz. (b) The first notched band at 3.5 GHz. (c) The second notched band at 5.5 GHz. (d) The third notched band at 7.5 GHz.

To further analyze the band-notched property, the surface current distributions of the proposed antenna at four different frequencies have been simulated in Fig. 8. At a pass-band frequency of 6.8 GHz, the current distributions near the slots (S1, S2, and S3) are weak as shown in Fig. 8(a). This indicates that the existence of these slots has little effect on the UWB antenna at pass-band frequencies. On the other hand, it can be observed in Fig. 8(b) that the stronger current distribution concentrated near the edge of slot S1 at the center frequency (3.5 GHz) of the corresponding notched band , and there are more current distributions near the top edge of the slot. This phenomenon implies its resonating near 3.5 GHz, thus energy cannot be radiated effectively and form a notched band at 3.5 GHz. The cases at 5.5 and 7.5 GHz can be similarly analyzed.

The distributed element equivalent circuits are shown in Fig. 9 to analyze of band-notched mechanism. As mentioned earlier, the slots resonate at the corresponding

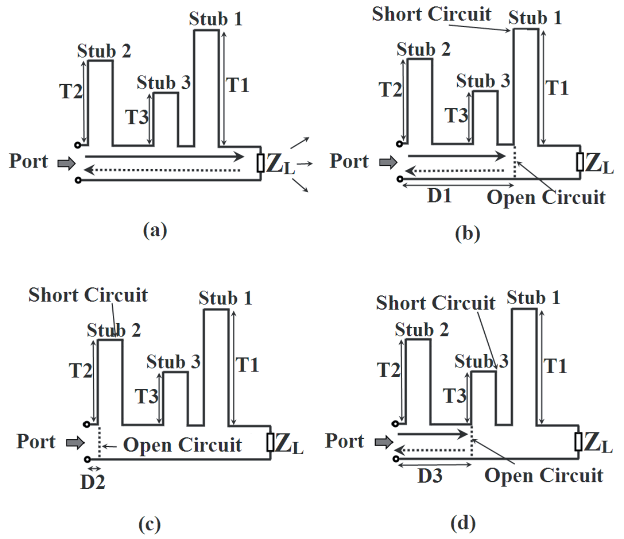

Fig. 9. The distributed element equivalent circuit. (a) At the pass-band. (b) The first notched band at 3.5 GHz. (c) The second notched band at 5.5 GHz. (d) The third notched band at 7.5 GHz.

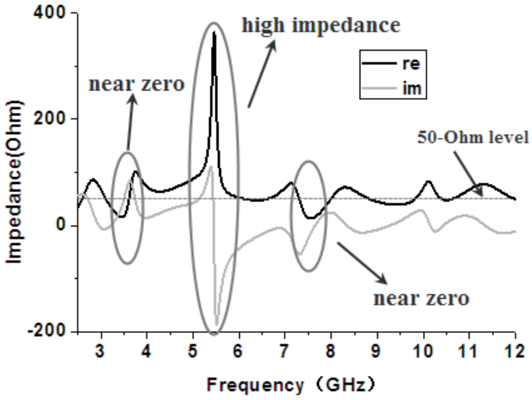

Fig. 10. Input impedance of proposed antenna.

notched band and current is concentrated around the top edges of slots. Consequently, the top edge of the slot is modeled as a transmission-line short-circuited mode. The resultant equivalent load at the bottom of the slot is high impedance due to the length from the top to the bottom along the slot is approximately $\lambda/4$ at the corresponding frequency. This open-circuited is transferred along the antenna structure and the final input impedance value Z_{in} is then determined by distance between the corresponding bottom of the slot and the feed port. By adjusting the position of the slot, the distance is multiples of quarter-wavelengths, so that impedance of the antenna is mismatched at the notched band.

Therefore the proposed antenna can be modeled as three short-circuited stubs connected with antenna resistance Z_L in series. The lengths of the stubs *T1*, *T2*, and *T3* are the lengths from the top of the slots to the bottom, which are half length of the slots. The lengths between the stubs and the feed port *D1*, *D2*, and *D3* are approximately the distances between the corresponding bottom of slots and the feed port. These parameters were calculated by the geometric parameters of the antenna as shown in Fig. 1, which are $T1 = 14.5$ mm, $T2 = 8.6$ mm, $T3 = 6.3$ mm, $D1 = 16.4$ mm, $D2 = 1$ mm, and $D3 = 14.8$ mm. The input impedance Z_L of the original antenna (without any slot) is approximately 50 Ω. At the pass-band frequencies, none of the three stubs has any effects in generating notched bands as shown in Fig. 9(a). In Fig. 9(b), at the first notched band, when $T1 = \lambda/4$ at 3.5 GHz, the stub1 works as a quarter-wavelength long transmission line terminated in an open circuit. Similarly, at the second and third notched bands, the stub 2 and stub 3 work similarly to stub 1 as in Fig. 9(c) and (d). This open-circuited is transferred along the distributed element equivalent circuit. The length $D1 = 16.4$ mm is approximately $\lambda/4$ at 3.5 GHz, $D2 = 1$ mm is short enough to be ignored at 5.5 GHz, and $D3 = 14.8$ mm is approximately $3\lambda/4$ at 7.5 GHz. Therefore the antenna appears near zero impedance at 3.5 and 7.5 GHz, and nearly high impedance at 5.5 GHz. The input impedance is shown in Fig. 10, the agreement of the results is apparent. This means the impedance of the proposed antenna is mismatched, so the triple band-notched characteristics are achieved.

3. Results and Discussions

The proposed antenna has been successfully simulated, fabricated, and measured. A microwave network analyzer (Agilent 8719A) was utilized to measure and verify the antenna performance. Fig. 11 illustrates the simulated and measured VSWR against frequency of the antenna. As observed, the measured impedance bandwidth of the proposed antenna for VSWR < 2 is from 2.8 to 12 GHz, covering the entire UWB frequency band with triple notched bands of 3.3-3.7, 5-6, and 7.25-7.75 GHz. Fairly good agreements between the simulations and measurements have been achieved. Thus, the effects due to the frequency interference can be avoided well.

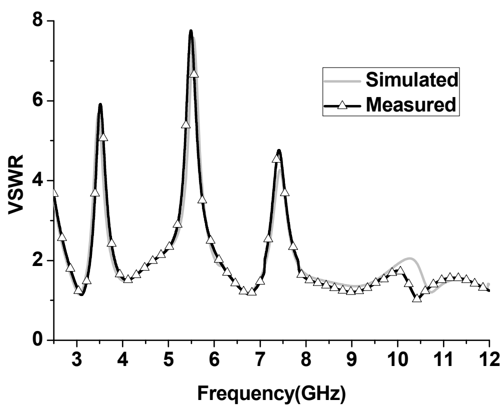

Fig. 11. Measured and simulated VSWR for antenna.

The radiation patterns and gain of the antenna were measured in an anechoic chamber at UESTC with SATIMO Antenna Measurement System as shown in Fig. 12. The measured radiation patterns of the proposed antenna at different frequencies are shown in Fig. 13.

Nearly good omnidirectional patterns have been observed in the H-plane (YZ-plane), and the patterns in the E-plane (XZ-plane) are close to bidirectional. At higher frequency, there are a lot ripples because of the frequency noise caused by the radiation of microstrip line and the edge of the slots.

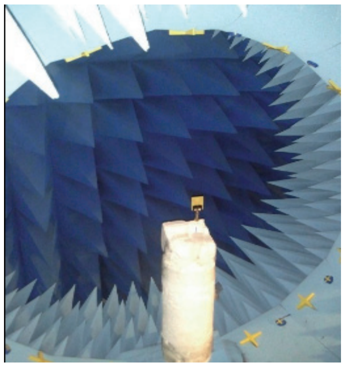

Fig. 12. Photograph of the proposed antenna in an anechoic chamber.

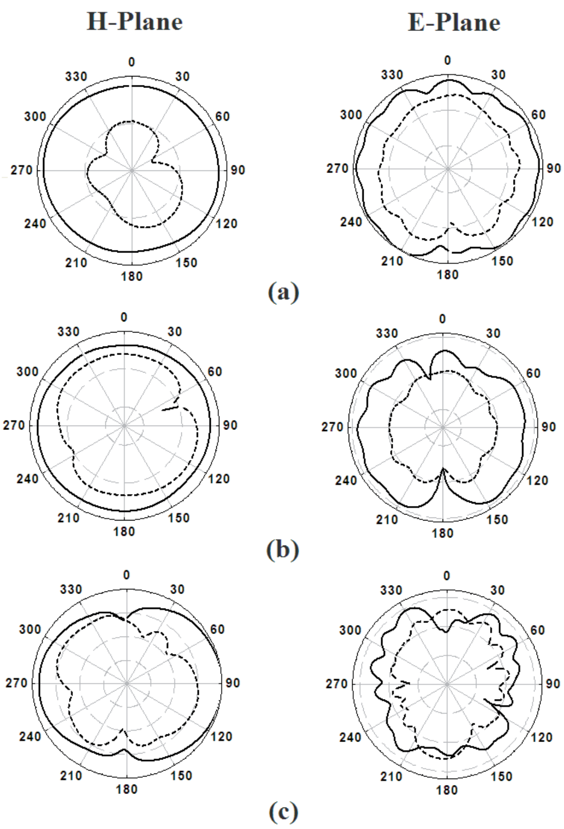

Fig. 13. Measured co-polarized (solid line) and cross-polarized (dashed line) patterns of the antenna: (a) 3.1 GHz, (b) 6.8 GHz, (c) 9 GHz.

The measured antenna gain versus the frequency is plotted in Fig. 14. As can be seen, significant gain reduction has been received at three designed notched bands of 3.5, 5.5, and 7.5 GHz. Outside the notched bands, appropriate gain of the antenna also can be achieved. It clearly indicates the effect of notched bands.

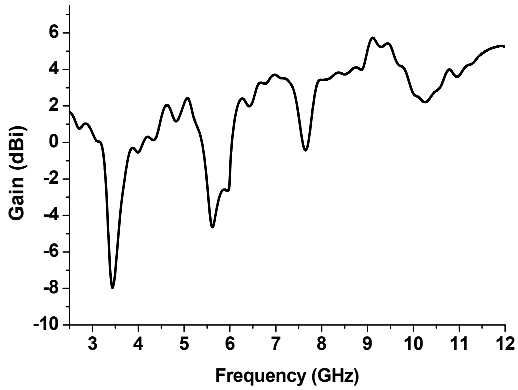

Fig. 14. Measured gain of the proposed antenna with triple band-notched characteristics.

4. Conclusion

To solve the interference problem for UWB communications, a compact microstrip line fed printed U-shape UWB antenna with triple band-notched characteristics is proposed and analyzed. Triple notched bands are achieved by using a U-slot DGS in the ground as well as two C-shape slots in the radiating patch. The mutual coupling between the slots, surface current distributions, and equivalent circuit have been studied and discussed. The measured results show that the designed antenna has appropriate gain and stable radiation pattern, indicating that the antenna is a good candidate for various UWB applications.

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About Authors ...

Chao-ming LUO was born in Jingdezhen, China. He received his B.S. degree from ChengDu University of Information Technology in 2009. He is now working towards his Ph. D. degree in Radio Physics at the University of Electronic Science and Technology of China (UESTC). His interests include antenna technology and wireless communication technology.

Jing-song HONG received the B.S. degree in Electromagnetic from LanZhou University, China, in 1991, and the M.S. and Ph. D. degrees in Electrical Engineering from the University of Electronic Science and Technology of China (UESTC), in 2000 and 2005, respectively. He is now a professor with UESTC. His research interests include the use of numerical techniques in electromagnetic and the use of microwave methods for materials characterization and processing.

Han XIONG was born in HuBei. He received his M.Sc. from Yunnan Normal University in 2010. Now, he is a doctor in Radio Physics in the University of Electronic Science and Technology of China now. His research interests include antenna technology and metamaterials.