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DESIGN AND MANUFACTURE OF THE WIDE-BAND APERTURE-COUPLED STACKED MICROSTRIP ANTENNA

F. Zhao, K. Xiao, W.-J. Feng, S.-L. Chai, and J.-J. Mao

College of Electronic Science and Engineering
National University of Defense Technology
47 Yanwachi Street, Changsha 410073, China

Abstract—The X-band wide band aperture-coupled stacked microstrip antenna is studied and manufactured. Based on the finite-difference time-domain method, a parametric study of the input impedance of the antenna is presented, and the effects of some parameters which are not easy to control in manufacture of the antenna impedance are illustrated. The structure of screw-plane-support is used for the manufacture of this kind of antenna. And several notes for manufacture are considered based on the parameter analysis. The measured bandwidth in which VSWR ≤ 2 is greater than 50%. The measured results are basically accordant to numerical simulated results. It testifies the capability of the model in expanding bandwidth and validity of this structure. The radiation patterns within operation bandwidth are presented and discussed.

1. INTRODUCTION

The microstrip antenna has been widely applied in mobile communication systems and various radar systems [1–6]. But the most serious limitation of this technology is the narrow bandwidth of its basic element, which is normally about a few percent. Therefore, much work has been devoted to increasing the bandwidth of microstrip antennas, such as adding an impedance matching network, stacked patches, using edge-coupled parasitic patches, or lossy materials [1–3].

Compared with other classical edge- or probe-fed microstrip antennas, the aperture-coupled microstrip antenna, first proposed by Pozar [7], has many advantages, including the isolation between the

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Corresponding author: F. Zhao (feizhao1983@hotmail.com).

antenna and the feed circuit, the elimination of probe reactance, easy integration of arrays and active circuits [7]. It is shown in [8] that using two stacked patches can improve the bandwidth by 1∼2 times. The resonant aperture with stacked patches is also presented in [8]. In this structure, the big aperture and thick substrate is used, with bandwidth nearly doubled that of the single patch antenna. The aperture coupled stacked square patches with the H-shaped aperture is proposed in [9]. The front-to-back ratio of the antenna radiation pattern is improved by using this kind of aperture, and the bandwidth of the antenna with the thick foam air layer is increased. The structure presented in [9, 10] uses the foam layer, and it could not form a strong support, and this fixed structure is not easy to optimize antenna performances after the manufacture.

In this paper, we present an X-band wide-band microstrip antenna which utilizes a H-aperture with stacked patches. The antenna uses four screws and several nuts to separate the radiating patch from the parasitic patch, which is different from the antenna in [7–10]. The metal plane is under the back of the aperture in order to enhance the gain. From this configuration, bandwidths (VSWR ≤ 2) greater than 50% have been realized. This compact structure ensures stable antenna performances. Section 2 provides antenna configuration and researches on input impedance with different parameters. Some details and considerations of manufacture are presented in Section 3. Finally, the experimental results are presented and discussed in Section 4.

2. ONFIGURATION AND METHOD OF ANALYSIS

The configuration of the wide-band aperture coupled stacked microstrip antenna is shown in Fig. 1. The antenna consists of three dielectric substrate layers and two air layers. The radiating patch which has a length of a_1 and width of w_1 is on the back of substrate1. Substrate1 has a permittivity of ε_{r1} and a thickness of h_1. The patch is inversed, so the substrate acts as the radome for environmental protection [9]. The parasitic patch having a length of a_2 and width of w_2 is put upon substrate2. Substrate2 has a permittivity of ε_{r2} and a thickness of h_2.

The air layer1 of thickness h_0 is between the radiating and parasitic patches. The configuration of inversed patch makes air layer act as a special substrate between the two patches. The performance of antenna could be easily controlled accordingly. The ground is between subtrate2 and substrate3 having a permittivity of ε_{r1} and a thickness of h_1. The H aperture which is defined by parameters w_h, l_h, w_a, and l_a is on this ground. Especially, the aperture is under the parasitic

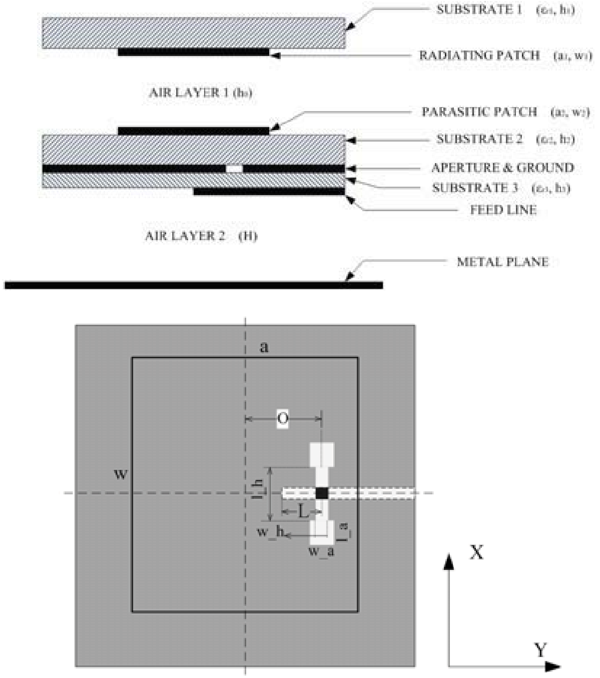


Figure 1. The configuration of the antenna.

patch and at the center of direction X, and the offset of aperture from the centre of the patch is o in direction Y (polarization direction). We use the H-shaped aperture, since it can couple more electromagnetic energy compared with the other shape aperture. Furthermore, a good performance of the wide-band resonance may be gained by this type of aperture. The microstrip line is on the bottom of the substrate3. And the length of the microstrip feed line, which exceeds the centre of the aperture, is L in direction Y.

This kind of bandwidth enhancement techniques uses a common trait of the wide-band characteristics resulting from coupled resonances. The operation of this configuration makes the two coupled resonances: one of them is a lower frequency resonance which is over coupled to the microstrip feed line, and the other is a low-Q resonance between the two patches which is a higher frequency resonance.

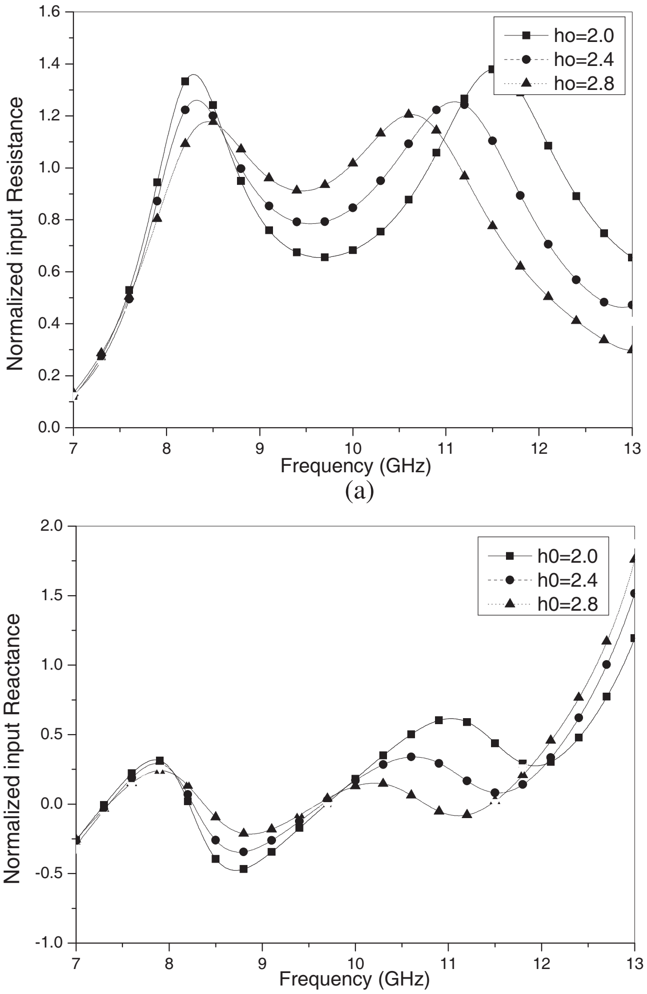
It would be helpful to practical antenna designs, if we could understand the resonant characteristics of the antenna with the variation of each design parameter. Most of the parameters of the similar antenna, such as a_1, w_1 ,a_2 ,w_2, w_h, l_w, w_a, and l_a are studied in [8–10]. The conclusions are very important to design the microstrip antenna which has a similar structure. But, some parameters that describe the tiny figure of the configuration are not paid enough attention, and some of these parameters have such a great effect on antenna performances, that we cannot neglect them when manufacturing the antenna. The sensitivity of the geometric parameters h_0, o and L will be studied as the three most critical parameters in the manufacture of aperture coupled stacked patch.

A parameter study of impedance of the antenna is performed. It is very helpful to study the effects of each parameter with one parameter being varied and the others being fixed. The theoretical analysis is based on the finite-difference time-domain (FDTD) method.

Figure 2 shows the input impedance of the antenna as a function of h_0. The results of the normalized input reactance are also shown in the figure. Two resonances are clearly observed, due to the use of stacked patches. For brevity, the resonant frequencies and normalized (to 50) resonant resistances are denoted by f_{01} and R_{01} for the lower resonance f_{02} and R_{02} for the upper resonance, respectively. f_{01} is increased by 1.7%, and f_{02} is decreased by 8.4%, when h_0 is increased by 40%. The results show that the air thickness of h_0 has more effect on the higher resonance f_{02}. That is because the resonance between the two patches is weakened and the resonance frequency is decreased when the upper patch goes away form the lower patch. It is found that the space between two resonance frequency points is increased as soon as h_0 is increased. This result is very useful to optimize the wide-band characteristic of the antenna.

Figure 3 gives the input impedance of the antenna as a function of o. f_{01} and f_{02} are increased by 3.6% and 2.1% respectively, when o is increased by 60%. Meanwhile R_{01} is reduced by 18.9%, and R_{02} is increased by 17.6%. The results mean that the increase in o will increase both f_{01} and f_{02} slightly. The lower resistance is strengthened, but the higher resistance is weakened, when o is increased. Fig. 4 shows the effects of L on the input impedance. From the results, the variation of L has nearly no effects on the input resistance. The increase in L has some effect on the input reactance only. So, the feed line which exceeds the centre of the aperture can be equivalent to an inductance functionally.

Compared with Fig. 3 and Fig. 4, it is obvious that the variation of o has more effect on the input impedance of antenna than L. This conclusion is significant to the manufacture of this aperture-coupled stacked microstrip antenna.



(a)

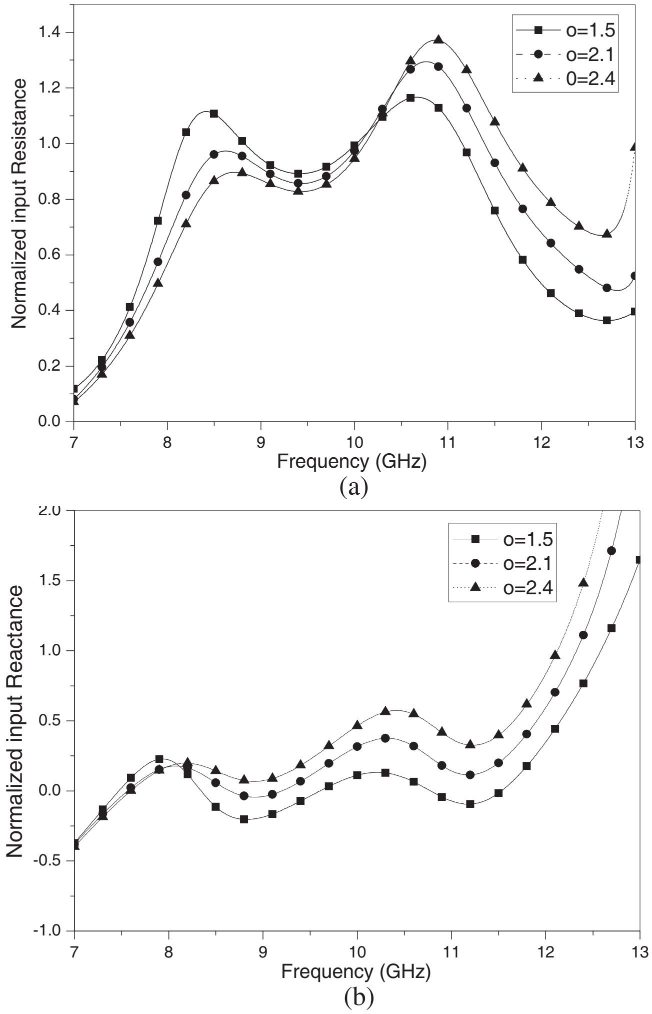
(b)

Figure 2. Normalized input impedance as a function of h_0. Other parameters: $h_1 = h_2 = 1.43\,\text{mm}$, $h_3 = 0.43\,\text{mm}$, $\varepsilon_{r1} = \varepsilon_{r2} = 2.35$, $a_1 = 8.2\,\text{mm}$, $w_1 = 12\,\text{mm}$, $a_2 = 8.1\,\text{mm}$, $w_1 = 11\,\text{mm}$, $w\_h = 0.6\,\text{mm}$, $l\_h = 4.3\,\text{mm}$, $w\_a = 1.5\,\text{mm}$, $l\_a = 1.1\,\text{mm}$, $o = 1.65\,\text{mm}$, $L = 2.5\,\text{mm}$.

3. CONSIDERATION AND MANUFACTURE

A similar kind of the aperture coupled stacked antenna has been proposed in [7–10]. But there is not enough description to illustrate how to manufacture this structure. Turning the ideal configuration to the real structure and maintaining its good performance are very important. In this section, the antenna is manufactured and several notes are considered.

The three dielectric layers are manufactured respectively. The top

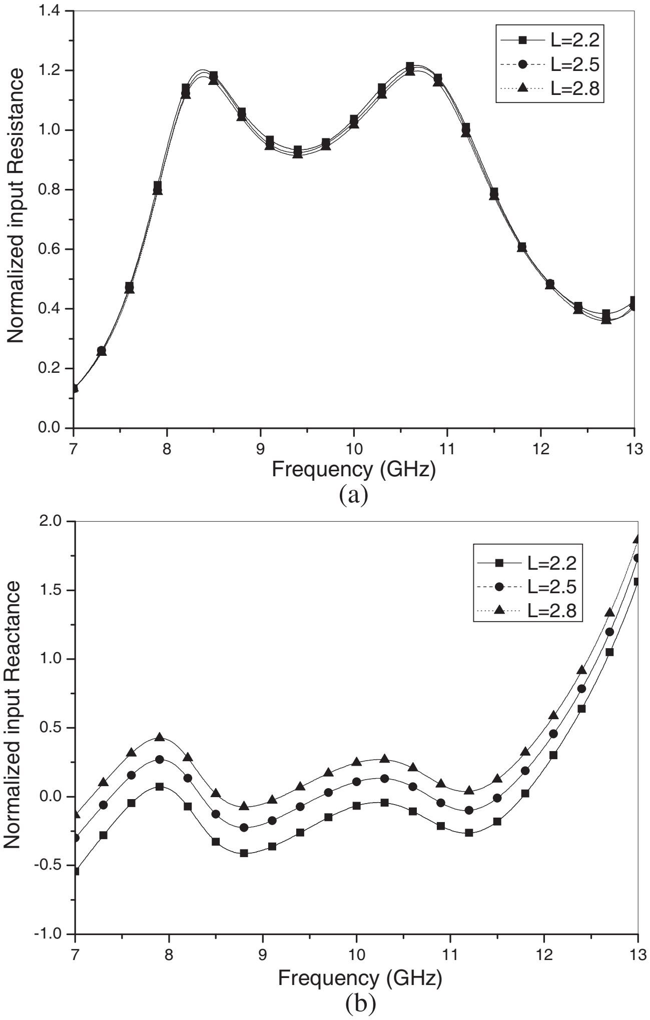


(a)

(b)

Figure 3. Normalized input impedance as a function of o. Other parameters: $h_0 = 2.6\,\text{mm}$, $h_1 = h_2 = 1.43\,\text{mm}$, $h_3 = 0.43\,\text{mm}$, $\varepsilon_{r1} = \varepsilon_{r2} = 2.36$, $a_1 = 8.2\,\text{mm}$, $w_1 = 12\,\text{mm}$, $a_2 = 8.1\,\text{mm}$, $w_1 = 11\,\text{mm}$, $w\_h = 0.6\,\text{mm}$, $l\_h = 4.3\,\text{mm}$, $w\_a = 1.5\,\text{mm}$, $l\_a = 1.1\,\text{mm}$, $L = 2.5\,\text{mm}$.

patch is printed directly on the bottom of the substrite1. Fig. 5(a) gives the structure of substrate2. It is shown that the lower patch is printed on the top of the structrue2. Meanwhile the metal ground is printed on the back of the structre2, and H-aperture is placed on the ground.



(a)

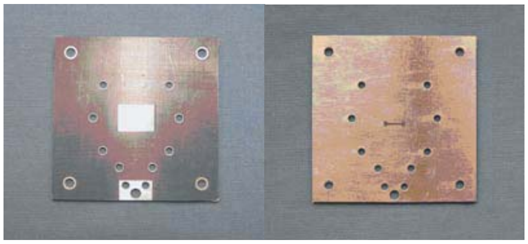
(b)

Figure 4. Normalized input impedance as a function of L. Other parameters: $h_0 = 2.6\,\text{mm}$, $h_1 = h_2 = 1.43\,\text{mm}$, $h_3 = 0.43\,\text{mm}$, $\varepsilon_{r1} = \varepsilon_{r2} = 2.35$, $a_1 = 8.2\,\text{mm}$, $w_1 = 12\,\text{mm}$, $a_2 = 8.1\,\text{mm}$, $w_1 = 11\,\text{mm}$, $w\_h = 0.6\,\text{mm}$, $l\_h = 4.3\,\text{mm}$, $w\_a = 1.5\,\text{mm}$, $l\_a = 1.1\,\text{mm}$, $o = 1.65\,\text{mm}$.

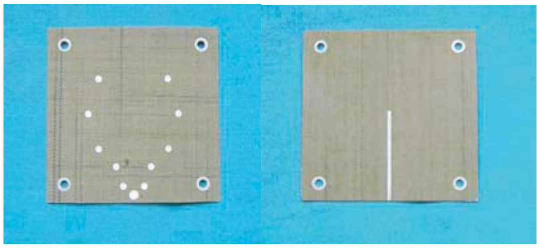
This structure ensures that the location of the lower parasitical patch relative to H-aperture is fixed. We would rather tolerate the small motion of the feed line than the aperture. From Section 2, we have the conclusion that the variation of o has more effect on the input impedance of antenna than L. So, the patch and aperture are both printed on the same substrate in this structure.

There are some via-holes on substrate2. They are distributed close to the nonradiation side of the lower patch. Fig. 5(b) shows the structure of the substrate3. The feed line is placed on the back face of this substrate, besides several circle metal pads are printed on the top of it. The pads of substrate3 and the via-holes of substrate2 are in the same location. Nevertheless, the diameter of the pads is little less (almost 0.1 mm) than the via-holes. There are two advantages for this structure. On the one hand, subtrate2 and stustrate3 can be touched compactly, by jointing the via-holes and the pads. On the other hand, the pads being placed in the via-holes can fix the location of the two substrates. Therefore, the precision of the length of the feed line which exceeds the centre of the H-aperture is improved efficiently.

Fig. 5(b) shows that there are small patch and three bigger via-holes on the verge of substrate2, corresponding to the three bigger pads on the top of substrate3. This configuration offers good grounding performance for the SMA feed port.



(a) Subtrate2



(b) Subtrate3

Figure 5. The structure of the antenna.

Figure 6. The manufactured aperture coupled stacked microstrip antenna.

Finally, four screws are fixed on the metal plane. And the three substrates are dug through by these screws. Four nuts which are under subtrate3 are used for supporting substrate3 and substrate2. These two substrates are pressed compactly by another four nuts which are on the top of subtrate2. The subtrate1 is supported in the same way. In particular, there is the air between subtrate1 and subtrate2. The antenna is fabricated as Fig. 6 shows. After the manufacture, the structure could be adjusted all the same. Tuning the nuts could change the distance between the toper patch and the lower patch, so as to optimize the impedance bandwidth of the antenna, based on the analysis in Section 2. The distance between the subtrate3 and the metal plane could also be adjusted to optimize the radiation patterns.

4. EXPERIMENT AND RESULTS

Using the data provided in Section 2 and the manufacture method in Section 3 as a guide, the antenna was designed, fabricated, and tested. Referring to the geometry shown in Fig. 6, the dimensions of the antenna are as follows.

Substrate1: $h_1 = 1.43\,\text{mm}$, $a_1 = 8.2\,\text{mm}$, $w_1 = 12\,\text{mm}$;

Air layer: $h_0 = 2.4\text{mm}$;

Substrate2: $h_2{=}1.43\,\text{mm}$, $a_2{=}8.1\,\text{mm}$, $w_1{=}11\,\text{mm}$, $w\_h{=}0.6\,\text{mm}$, $w\_a{=}1.5\,\text{mm}$;

Substrate3: $h_3{=}0.43\,\text{mm}$, $l\_h{=}4.3\,\text{mm}$, $l\_a{=}1.1\,\text{mm}$, $o{=}1.65\,\text{mm}$, $L{=}2.5\,\text{mm}$;

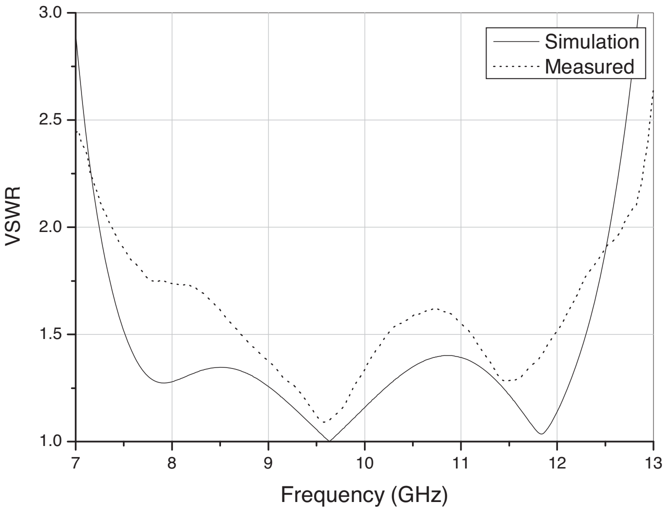


Figure 7. Simulated and measured VSWR for antenna.

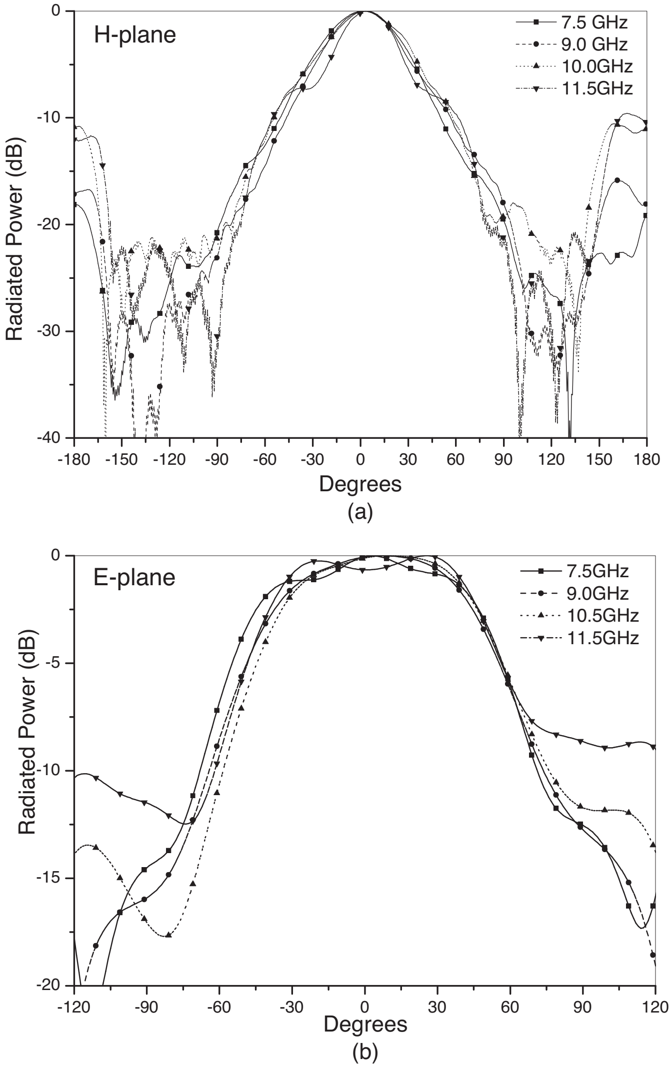
The distance between the aperture and the metal plane which is used as a reflector is 7.5 mm.

The simulated and measured VSWR for the antenna is shown in Fig. 7. The measured input impedance bandwidth (VSWR ≤ 2) from 7.4 to 12.7 GHz (52.7%) is well consistent with numerical simulated bandwidth from 7.3 to 12.5 GHz (52.5%). Fig. 8 shows the both *H*- and *E*-plane radiation patterns for the antenna at 7.5 GHz, 9.0 GHz, 10.0 GHz, and 11.5 GHz. The radiation patterns in lower band (7.5∼10 GHz) are almost the same, but the radiation performance at the 11.5 GHz is degraded.

Table 1. The characteristics of gain and front-to-back ratio vs frequency.

Frequency (GHz)	7.5	9.0	10	11.5
Gain (dB)	10.5	11.2	10.2	8.6
Front-to-back ratio (dB)	18.1	15.8	10.8	9.6
Main radiation direction Cross-polar (dB)	-29	-27	-25	-22

The measured gain, front-to-back ratio and the main radiation direction cross-polar for the above frequencies are shown in the Table 1. The gain between 7.5 and 12.5 GHz (42%) is from 8.0 dB to 11.2 dB. The metal plane makes the antenna achieve a higher gain than normal

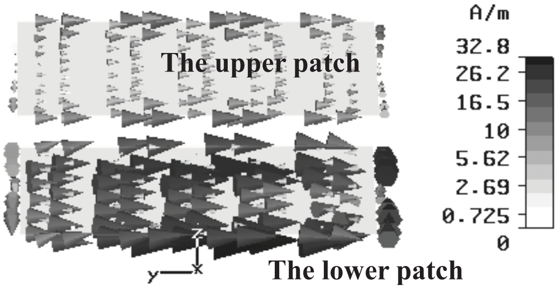


(a)

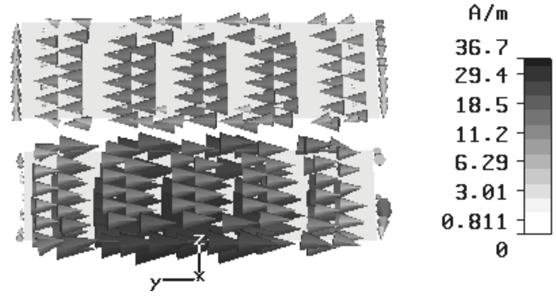
(b)

Figure 8. Radiation patterns at 7.5 GHz, 9.0 GHz, 10GHz, and 11.5 GHz.

microstrip antenna. However, there is only 8.0 dB at 12.5 GHz. And the front-to-back ratio ranges from 9.6 to 18.1 dB over most of the band and drops to 7.8 dB at the upper band edge. The main radiation cross-polar is form -29 dB to -22 dB. The performance of the radiation pattern is degraded quite rapidly near the upper input impedance band edge. It is due to an increased phase difference between the currents



(a) 7.5 GHz



(b) 12.5 GHz

Figure 9. The surface currents on the two patches.

of the two patches, which approaches 180° near the top end of the band, as shown in Fig. 9. Fig. 9(a) gives the surface currents on the two patches at the 7.5 GHz; the directions of the currents on the both patches are almost the same. However the currents at the 12.5 GHz are nearly in the opposite direction (Fig. 9(b)). So the patches do not radiate efficiently.

In similar configurations [9, 10], the thick substrate or the foam is used between the two patches to expand the bandwidth of the antenna. An amount of power can be lost to surface waves due to the thick substrates. And using foam to support the toper patch is not solid. The screw-plane-support is the solid structure which can improve the efficiency of the radiation. The metal plane reduces radiation bandwidth in a certain extent due to the fixed $\lambda_0/4$ distance for certain frequency. But it obviously enhances the gain of antenna.

5. CONCLUSION

In this paper, the wide-band aperture coupled stacked patches micorstrip antenna at X-band is studied. The effects of several key physical parameters which are not easy to control in manufacture are examined. Results of this parameter study provide a good design and fabrication guide for antenna. The structure of the screw-plane-support is proposed. By etching the toper patch and the H-aperture on the same substrate and using the via-holes and pads to fix the location of the feed and aperture, the manufacture errors are reduced effectively. The screws and nuts reinforce the stacked structure. And the reflection plan enhances the gain. Based on the analysis, the antenna is designed, manufactured and measured. Good agreement between theory analysis and experiment result demonstrates the capability of the model in expanding bandwidth and the validity of the structure.

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