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Wideband Patch Antenna With Ground Radiation Mode and Patch Radiation Mode

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ABSTRACT In this paper, patch antenna structures are studied to simultaneously excite the ground radiation mode and patch radiation mode. Based on the analysis of characteristic current distribution on the ground plane of patch antenna, an exciting method of the ground radiation mode is proposed. Then a dual-mode patch antenna of patch radiation and ground radiation is designed, which can achieve a wideband radiation using two modes resonating at two adjacent frequencies. To improve the radiation efficiency of the ground mode, the electric field distribution of the dual-mode antenna is investigated in detail and the electric field models for two modes are constructed. It is suggested that the additional notches introduced on the ground plane can enhance the resonance component of the ground mode. By this way, the modified patch antenna presents better radiation efficiency over the operating band. The measurement results show that the relative bandwidth of the patch antenna prototype with the notches is about 16.2%, defined by the reflection coefficient less than –10 dB. The proposed dual-mode antennas have the inherent characteristics of weak directivity, for that the antenna application scenarios also are indicated.

INDEX TERMS Patch antenna, wideband antenna, ground radiation, characteristic currents.

I. INTRODUCTION

Generally, traditional self-resonant antenna elements are larger in size, which are not suitable to be built within mobile terminals for multi-band or lower-frequency operations. To deal with this problem, Vainikaine *et al.* switched to use pony-size non-resonant coupling elements to excite the dominating characteristic wavemodes of the metallic chassis [1], [2]. In this way, the utility rate of the terminal space is dramatically enhanced and this kind of antennas is named as the capacitive coupling element based antennas [3]. Because the radiation waves are excited by the grounding chassis current, they are also referred as the ground radiation mode antennas [4] and the corresponding chassis as the ground radiation element. The radiating behavior of ground wavemodes can be discussed using the characteristic current distributions of the chassis. Theoretically, characteristic wavemodes are current modes obtained numerically for arbitrarily shaped conducting bodies. However, only the characteristic currents with eigenvalues close to zero or characteristic angles to 180° can effectively radiate electromagnetic waves, while other modes present stored energy [5]–[7]. So the design of feeding structures, such as capacitive coupling elements, to excite the chassis characteristic current of zero eigenvalue is a key point for ground radiation mode antennas [8].

Though the dual-band antennas utilizing ground element radiation and antenna element radiation, respectively, have been proposed, the frequency point of ground mode usually is far away from that of antenna element mode [9]. The wideband antennas simultaneously using these two modes have little been considered, especially for microstrip patch antennas. On the other hand, the chassis antennas mainly emphasize on the implementation of antenna miniaturization in mobile terminals. The coupling to the ground mode normally is weak and the radiating resonance of the characteristics current is poor [10]. For these reasons, the radiation

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efficiency usually is lower and the radiation patterns always appear approximately omnidirectional feature.

As is well known, a classical patch antenna only works based on the patch element mode and presents narrow band feature. Considering the possibility of ground radiation, we put forward dual-mode patch antennas which work in the ground wavemode and patch wavemode simultaneously. As an example, a wideband dual-mode patch antenna is designed and improved in this paper. To employ the ground mode of a patch antenna, a new exciting technology is introduced. Based on the adjacent dual-frequency effect of ground element mode and antenna element mode, a primary wideband with directivity radiation is implemented. To enhance the coupling strength to the ground mode from the patch element and enlarge the resonant component of the ground characteristic currents, a pair of notches is introduced into the ground plane for the improved wideband antenna. The proposed patch antennas can be applied to the scenario of weak-directivity requirement, such as indoor base-station systems.

The paper is organized as follows. In Section II, the characteristic current distribution on the ground plate of a patch antenna is discussed and the primary dual-mode antenna structure is proposed. Then in Section III, the performances of the primary antenna prototype are validated with both simulation and measurement and the physical reasons for them are investigated. Based on the electric field distribution features of the proposed antenna, an improvement measure for the primary antenna is introduced and the performances of the improved antenna prototype are provided in Section IV. The radiation performances of the primary and improved antennas are compared in Section V. Finally, the conclusions are drawn in Section VI.

II. DESIGN CONSIDERATIONS

A. FUNDAMENTAL MODE CURRENTS

According to the theory of characteristic modes, the surface currents of a conducting body can be decomposed into a weighted orthogonal set of resonant current modes that depend on its shape and size, and are independent of the feed point [11]. However, there are only a few characteristic modes that contribute to the radiation of the ground mode antenna. The most common case is that the ground radiation is only excited by the fundamental mode current along longitudinal distribution of the rectangular chassis as shown in Fig. 1(a) [12], [13]. In fact, there are the similar resonant current distributions on the patch element of a patch antenna and both longitudinal end sides of the patch element work as the radiation edges.

B. GROUND MODE EXCITATIONS

Because the current antinodes locate at midline positions of the ground conductor as shown in Fig. 1(a), the ground mode can be excited with the direct current feed at the midline [9]. However, considering the patch element radiation of a patch antenna, this direct feed method is not a good way since the impedance matching for patch mode is difficult and the patch radiation polarization will be changed in this case.

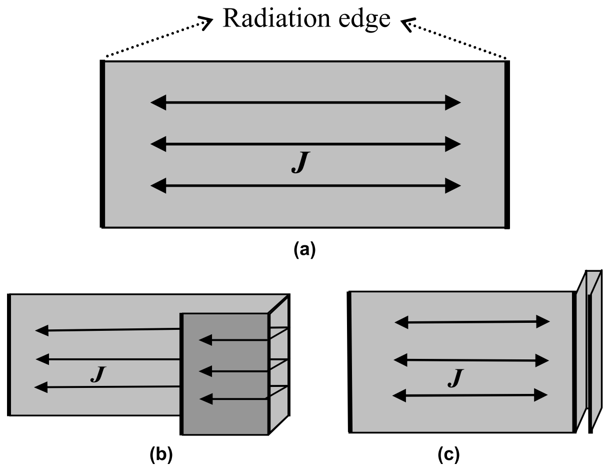

FIGURE 1. Fundamental mode resonant currents (*J*) and the corresponding radiation edges on (a) rectangular conductor plate, (b) bended rectangular conductor plate, and (c) equivalent of (b) when the spacing between the bended plane and the original plane is small.

Though the direct microstrip feed technology at the patch side edges is a common method to excite the patch mode radiation of a patch antenna, it can not be applied to excite the ground mode. For the traditional patch antennas, the fed side edges of the ground plane are at zero potentials in the circuit point of view. However, for the excitation of ground mode radiation, high electric potentials at the side edges are necessary. It is just for this reason that a classical patch antenna only has the patch mode and can not effectively excite the ground mode.

In fact, the fundamental ground current wavemode for a patch antenna would be parallel to the patch element surface and there should be the strongest electric fields at both end edges, which also act as the radiating edges as shown in Fig. 1(a). This indicates that the excitation of the ground mode may be carried out via the capacitive coupling to both ground edges using the electric fields at patch edges. However, for the wideband antenna, the working frequency point in the ground mode should be somewhat different from that in the patch mode. Thus the currents on the patch element present the guided wave feature when the patch antenna works based on the ground mode, and then strong electric fields cannot be kept on the patch edges. Furthermore, most of the coupling electric fields are vertical to the ground plane. It means that the ground mode also cannot be excited directly using the patch edge electric fields.

To implement the edge capacitive coupling of the ground mode and simultaneously stabilize the patch mode, the ground metallic plate is prolonged and turned upwards to the patch plane for the proposed patch antenna as shown in Fig. 1(b). In this way, a part of the ground plate is coplanar with the patch element and then the patch edge electric fields will be coupled to the ground part on the upper surface to excite the ground mode. In this case, it should be known that

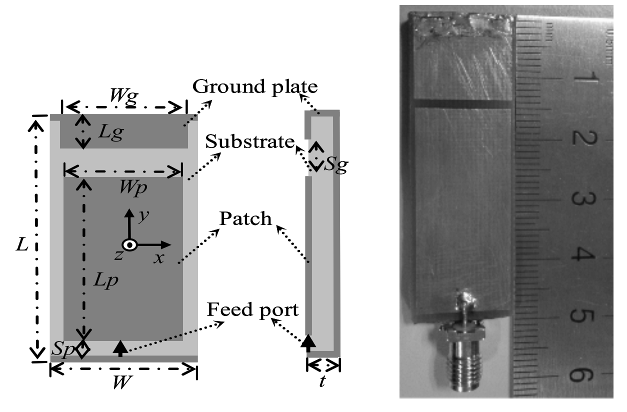

FIGURE 2. Geometry and structure parameters of the proposed primary patch antenna (Ant A) of ground mode. (a) Front view and (b) side view of the antenna model. (c) Prototype photograph in front view.

the bending of the conductor plate only change the current direction of fundamental mode but has little effect on the current distribution and the radiation edge positions, when the spacing between the upper and lower surfaces of the bending segment is large [6].

However, as the spacing of the bending segment is small enough, an equivalent LC circuit can be introduced to characterize the bending ground function. Due to the reactance of LC circuit, or to say the current anti-phase, the fundamental mode resonant current cannot distribute on the bending segment which in turn only has the function of a transmission line. The initial position of the bending segment becomes the current wave node and the resonant current of the fundamental ground mode only covers the straight portion of ground plate, as shown in Fig. 1(c), in which the bending segment is turned back with 90° to display it more clearly. Thus, the bending segment becomes just the feed structure for the resonant current and does not affect the resonant frequency of the fundamental ground mode.

C. PATCH ANTENNA STRUCTURE

Utilizing the above ground mode excitation technology, a primary patch antenna (Ant A) with both ground mode and patch mode is proposed as shown in Fig. 2. There is a narrow slit, which works as the coupling slot of the ground mode, between the patch element and upper ground plate. The physical feed point of the proposed Ant A is located at the other side end of the patch element plane. By adjusting the length of the ground plate and patch element, the operating frequency of patch mode can be tuned close to that of the ground mode for the feature of wide band.

As to the patch element of Ant A, it meets the distribution condition of the self-resonance current to excite patch mode wave on one hand, it is an exciting structure for the ground mode through its edge electric field coupling on the other hand. In this regard, the patch element is not only a radiator for the patch mode wave but also an excitation source for the ground mode wave.

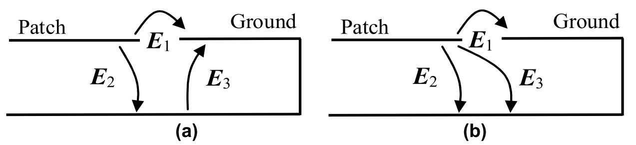

FIGURE 3. Distributions of electric fields (*E*) near the coupling slot for (a) ground mode and (b) patch mode.

D. ELECTRIC FIELD MODELS

Fig. 3 shows the electric field distribution models of both patch mode and ground mode near the coupling slot zone of Ant A. For the ground mode, due to the feed function of the bending ground part, there are two electric field maximums in anti-phase on the ground section under the slot. They are coupled from the patch element edge and the upper ground plate edge, respectively, as shown in Fig. 3(a). So an electric field minimum appears between both maximums on the ground position just under the slot, which indicates that the excitation of the ground mode is similar to that of the non-resonant capacitive coupling element.

For the patch mode as shown in Fig. 3(b), the electric fields through the patch edge coupling to the upper ground edge and the lower ground position are in phase and only one electric field maximum appears on the lower ground section. It indicates that the current on the bending ground segment can only be distributed in common mode. Thus, the patch current mode is the excitation source of electromagnetic radiation as what the traditional patch antenna does and the bending of the ground plate has little effect on the patch mode.

E. COUPLING SLOT

According to the slot antenna theory, it is the electric field distributing on the slot that contributes to the antenna radiation. So the upper-surface coupling slot of the proposed Ant A also can be regarded as the radiation slot. Whether for the patch mode or the ground mode, the electric fields on the slot corresponding to the radiation source mainly are the tangential components, whose function is equivalent to the radiation of a magnetic current. Due to the positive mirror effect of the ground plane on the magnetic current, both radiation modes of the proposed Ant A will present directivity patterns, even though using a low profile substrate.

For the ground mode, from the current point of view, the actual radiation source is the tangential electric fields near the lower ground plane within the substrate. These components are contributed by the characteristic currents on the lower ground plate and reflected to the slot by the lower ground. In this sense, the lower ground plate is not only a radiator but also a reflector for the ground wave mode.

F. FEED SLOT

As shown in Fig. 2, the slot near the feed port, named as feed slot here, also has the function of radiation aperture. Structurally, there also is an upturned part of the ground plate on one side of the slot but not extending on the upper antenna surface. This bending part can make the electric fields on

TABLE 1. Dimensions of the primary prototype antenna. All dimensions are in millimeters.

L	W	Lp	Wp	Sp	Lg	Wg	Sg	t
47.8	17.2	32.4	16.1	1.3	12.9	16.3	1.4	3.0

the feed slot be more easily parallel to the antenna surface. However, if the bending ground part extends into the upper surface, more reactance component will be introduced and the stored energy be enhanced so as to reduce the antenna radiation efficiency. In fact, this negative influence indeed emerges in the case of the ground mode radiation, due to the ground bending on the other end. It is one of the reasons that the ground mode efficiency is relative lower.

If the radiation function is not considered, the feed slot can be taken as an excitation source for the patch mode while the coupling slot as one for the ground mode.

III. PRIMARY DUAL-MODE ANTENNA

A. PROTOTYPE ANTENNA

To demonstrate the antenna performance, a prototype of the primary patch antenna is manufactured based on a 3-mm-thick microwave substrate ($\varepsilon_r = 4.4$, tan$\delta = 0.002$). According to the structure shown in Fig. 2, the initial lengths of the patch element and the lower ground plate are estimated at 2.4-GHz of the patch mode and at 2.2 GHz of the ground mode, respectively. Considering the quasi-ring structure of the primary antenna, about λg/5 (λg, the guided wavelength of the central frequency) is taken as the initial width of the substrate. The optimized antenna structure parameters are listed in Table 1 and the antenna photograph is shown in Fig. 2(c).

For the patch element of the optimized prototype antenna, it is known that the actual length ($Lp = 32.4$ mm) is shorter than the estimated value (38.3 mm) of half wavelength at 2.4 GHz. The main reason is the shortening effect caused by the patch edge capacitance, which is especially strong when an upturned ground plate is adhered to the end face of the substrate on the side of feed slot [14]. It can be verified that for the traditional patch antenna with the same structure and size as the prototype and only without the upper ground plate on the side of radiation slot, there is a 100-MHz frequency upshift when the upturned plate at the end face on the feed slot side is removed (for simplicity, the result is not shown here).

However, for the ground plate of the prototype antenna, its total length ($L + Lg + 2t = 66$ mm) is much larger than the estimated half wavelength (42 mm). The reason is that the bending segment of the ground plate only works as the feed structure of the ground mode, and cannot work as the resonant radiator. If the bending part is subtracted from the whole ground plate length, the remainder approximates to the half wavelength, which also manifests that the resonant current path of the ground mode is only decided by part of the ground plate under the patch element.

It is true that the length is much larger than the width for the prototype antenna. However, the largest distance between the patch edge and the substrate edge only is about 7.7 mm if the patch element is moved to the center position of the antenna structure. Considering the effect of the substrate permittivity, this distance is about $0.09\lambda_0$ (λ_0, the wavelength in free space), which is much smaller than the margin distance of traditional patch antennas (usual larger than $0.25\lambda_0$ [15]). It is to say, considering from the overall structure, the primary antenna has the characteristics of miniaturization.

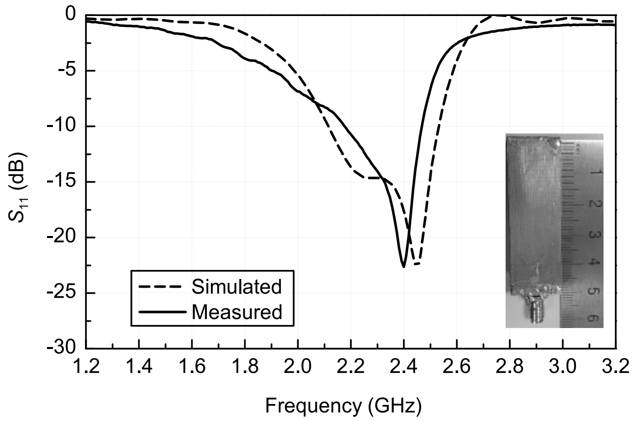

FIGURE 4. Simulated (dashed line) and measured (solid line) frequency responses of the reflection coefficients for the primary prototype antenna. The inset photography is the primary antenna in back view with its front view as shown in Fig. 2(c).

B. IMPEDANCE CHARACTERISTICS

Fig. 4 presents the simulated and measured impedance bandwidths of the primary prototype antenna. The simulation results indicate the operating band defined by S_{11} less than – 10 dB is from 2.12 GHz to 2.52 GHz, which corresponds to the relative bandwidth of 17.2%. However, the measured band is from 2.18 GHz to 2.48 GHz, with the relative bandwidth of 13.0%. Though the bandwidth of the measurement is a bit less than that of the simulation, their variation trends are similar.

Considering the permittivity influence, the substrate thickness is about $0.037\lambda_0$. For the traditional patch antenna with the same substrate and patch size as the proposed antenna, the measured relative bandwidth is only about 4.8%. (To the contrast, the traditional patch antenna is manufactured only by removing the ground plate on the upper surface of the proposed Ant A. The result also is not shown for the sake of simplicity.) The bandwidth increase of the proposed primary antenna is just based on the dual-mode resonance at adjacent frequencies. The simulation curve in Fig. 4 clearly indicates that these two resonant frequency points are lower frequency of 2.25 GHz and higher frequency of 2.45 GHz, respectively.

C. SURFACE CURRENTS

From Fig. 4, it can also be clear that the S_{11} value at lower resonant frequency point is a bit larger than that at higher one and the variation trend over the lower frequency band becomes flat. So it is revealed that the corresponding resonant radiation strength of the ground mode is weaker than that of the patch mode at higher frequency. To discuss this question,

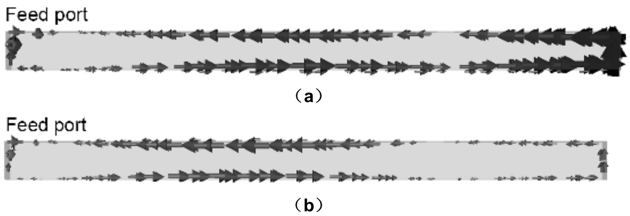

FIGURE 5. Surface currents in side view of the prototype ANT A at (a) lower frequency of 2.25 GHz (maximum current: 8 A/m) and (b) high frequency of 2.45 GHz (maximum current: 10 A/m).

both surface currents at 2.25 GHz and 2.45 GHz are displayed in Fig. 5. It can be seen that at higher frequency, as shown in Fig. 5(b), the current distribution on the patch element presents remarkable resonance feature but that on the bending ground segment is weak. This result verifies that the antenna works as the patch mode at higher frequency.

For the lower frequency, however, there is a position of the current minimum just under the coupling slot on the lower ground plate as shown in Fig. 5(a). This means there are fundamental characteristic currents of the ground mode, which distribute on the lower ground plate part just under the patch element and make antenna present the feature of ground mode radiation over lower frequency band.

Compared with the case at higher frequency, there are strong currents distributing on the bending ground segment at lower frequency. The reason is that at lower frequency, the bending ground also works as the feed structure of the ground mode in directly connecting style. Thus, besides the standing wave mode, there are some currents of travelling wave mode on the ground plate, which make the antenna present some travelling-wave radiation and simultaneously weaken the resonance radiation. Certainly, in this case the bandwidth is increased. With the operating frequency stepping down, the travelling mode components increase. Comparatively speaking, the radiation ability of the guided mode is weaker than that of the resonant mode. So we can observe from Fig. 4 that the lower frequency bandwidth is relatively large and its S_{11} variation is slow.

D. ELECTRIC FIELDS

To further demonstrate the working principle of the proposed antenna and provide some suggestion for the improvement of antenna resonant radiation, the electric field distributions at lower frequency of 2.25 GHz and higher frequency of 2.45 GHz are displayed in Fig. 6. It can be seen that the electric fields on the coupling slot present the maximum over the whole operating band, which means this slot also has the function of radiation aperture.

At 2.25 GHz as shown in Fig. 6(a), there is a position of minimum field closely between two maximum fields on the lower ground just under the coupling slot, which also corresponds to the resonant current wavenode. This implies that there are anti-phase vectors for the electric fields in this zone at the lower frequency, ensuring the guided mode currents can distribute on the bending segment in differential mode style. And the minimum field position, which can be equivalent to an open end, ensures the resonance current of the ground mode only happens on the lower ground segment just under the patch element.

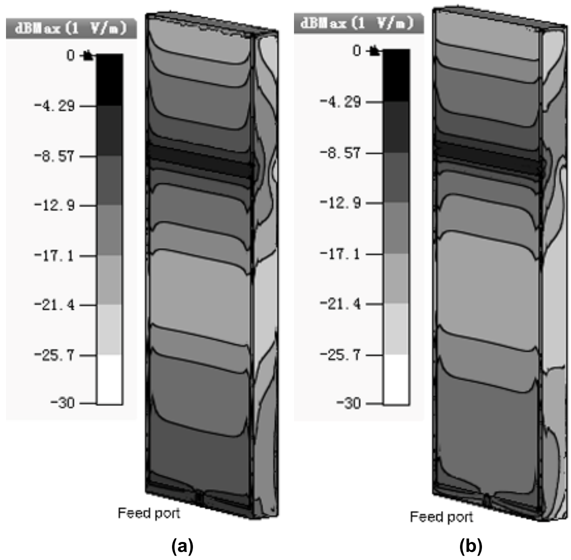

FIGURE 6. Electric field distributions of the primary antenna at (a) lower frequency of 2.25 GHz and (b) higher frequency of 2.45 GHz.

After all, the minimum field position is not an actual break of the ground plate. So some of the guided mode currents across this position can distribute on the whole ground plate and provide the travelling wave mode. For the prototype antenna, the whole length of ground plate is 66 mm, which corresponds to half wavelength of 1.38 GHz. According to Fig. 4, the decline position of S_{11} values just starts at this frequency.

For the ground mode of the primary patch antenna, the more the components of travelling wave are, the wider the bandwidth is and the weaker the resonant radiation is. Due to the minimum field zone of the lower ground being equivalent to an open end, it can be assumed that introducing cuts into this position on the lower ground plate will have little effect on the antenna operating frequency while the travelling wave mode can be rejected in some extent. On the other hand, with the help of the introduced cuts, the anti-phase electric fields on both sides at the minimum field position will become intensive. The electric field in the coupling slot, which can reflect the feed ability of the ground mode, will be enhanced. Thus the resonant radiation of the ground mode can be improved by this way.

For the patch mode at 2.45 GHz as shown in Fig. 6(b), the edge electric field near the coupling slot side of the patch element is in-phase coupled to the lower ground plate and the upper ground edge as the traditional patch antenna does. The travelling wave current cannot exist on the bending ground segment. It is to say, at the higher frequency, only the patch element radiates electromagnetic waves and little stored energy is produced in the bending ground segment. The electric field distribution in this case also indicates that

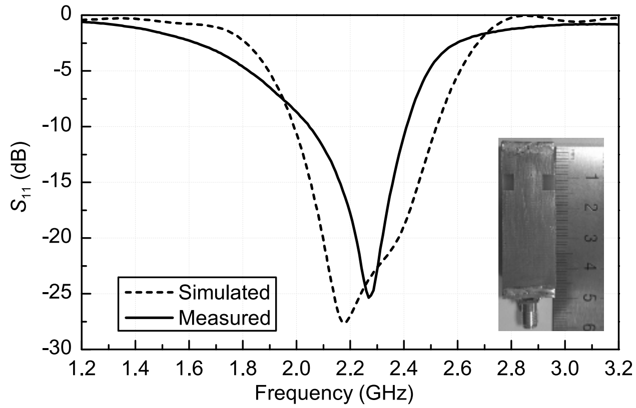

FIGURE 7. Simulated (dashed line) and measured (solid line) frequency responses of the reflection coefficients for the improved antenna (Ant B). The inset is the photography of the Ant B prototype in back view.

the cuts in the lower ground plate will have little effect on the patch mode.

IV. IMPROVED DUAL-MODE ANTENNA

A. ANTENNA STRUCTURE

As analyzed in Section III-D, the weak resonance of the ground mode may be improved by cutting slits in the lower ground plate just under the coupling slot. Because stronger currents mainly distribute on the edges of the conductor plate, it will be better if the lower ground plate is cut open starting from the ground edges to form two notches. The inset in Fig. 7 provides the photography of the improved antenna prototype (Ant B) in back view. Except the additional rectangular notches, the improved Ant B has the same structure and size as the primary Ant A. For the introduced notches, the distance between the upper ground boundary and the top end face of the substrate is 10 mm, while the notch depth and width are 4 mm and 5 mm separately.

B. IMPEDANCE CHARACTERISTICS

Fig. 7 shows the simulated and measured impedance bandwidths of the improved Ant B. The simulation results indicate that there are also the dual-resonance characteristics of 2.16-GHz lower frequency and 2.38-GHz higher frequency. Both of the resonant frequency points appear about 80-MHz frequency downshift, compared with the primary Ant A. The operating band range defined by S_{11} less than – 10 dB is from 1.98 GHz to 2.52 GHz, which has a bit increase compared with that of the primary Ant A. The measured band range is 2.05 – 2.41 GHz and its relative bandwidth is 16.2%, which present a larger increase compared with that of the primary Ant A.

The introduced notches can expand the distribution paths of the ground mode, which is the reason for that the resonant frequency point of the ground mode shifts down. Considering the patch mode in view of the equivalent circuit, the notches have the effect of inductive reactance, which will compensate the capacitive reactance of the antenna own structure and also can drop the resonant frequency of the patch mode.

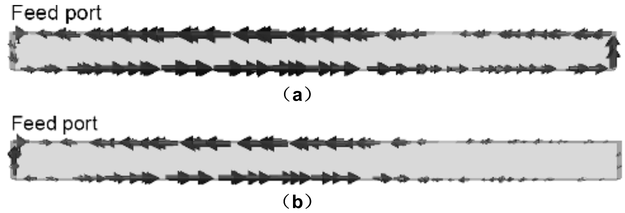

FIGURE 8. Surface currents in side view of the improved Ant B at (a) lower frequency of 2.16 GHz (maximum current: 8 A/m) and (b) high frequency of 2.38 GHz (maximum current: 10 A/m).

For the resonance feature of the ground mode at the lower frequency, the simulation results show that the minimum S_{11} value of the improved antenna (Ant B) is – 27 dB, whereas the corresponding value of the primary antenna (Ant A) is – 14 dB. This implies that the notches can effectively enhance the resonance components of the ground mode. At the higher frequency, the simulated minimum S_{11} value of the improved Ant B is – 20 dB, which has little variation compared with that of – 22 dB for the primary Ant A. It indicates the notches have little influence on the patch mode. Even though both resonant frequency points cannot be identified clearly in the measured curves, it is obviously shown that the resonant performance of the improved Ant B at the lower frequency has remarkably been enhanced.

C. SURFACE CURRENTS

To further demonstrate the cut function, the surface currents of the improved Ant B at lower resonant frequency of 2.16 GHz and higher resonant frequency of 2.38 GHz are depicted in Fig. 8. Comparing the current distributions in Fig. 8(a) with those in Fig. 5(a), it is clear that the current on the bending ground segment for the improved Ant B becomes small at the lower frequency. This means that at lower frequency, the characteristic resonant current of the ground mode strengthens and the travelling wave component on the ground plate is suppressed in some extent, due to two introduced notches. However, for higher frequency as shown in Fig. 8(b), the notches in the ground plate have little influence on the surface current.

V. RADIATION PERFORMANCE

A. DIRECTIVITY

Though the width is far less than the length for the whole antenna structure, the width of the lower ground plate is a bit larger than that of the patch element and the upper ground plate for both proposed antennas, i.e., Ant A and Ant B. For the patch mode, the radiation mechanism is equivalent to that of ground-backed slot antennas. As far as the ground mode is considered, the lower ground plate not only works as the radiator but also as the reflector so that certain directivity should be presented. Thus, ground mode radiation is also equivalent to a ground-backed slot radiation. The radiation patterns for ground mode and patch mode should be similar. According to the coordinate system shown in Fig. 2, the radiation main lobes should be in the positive direction alone the z axis and

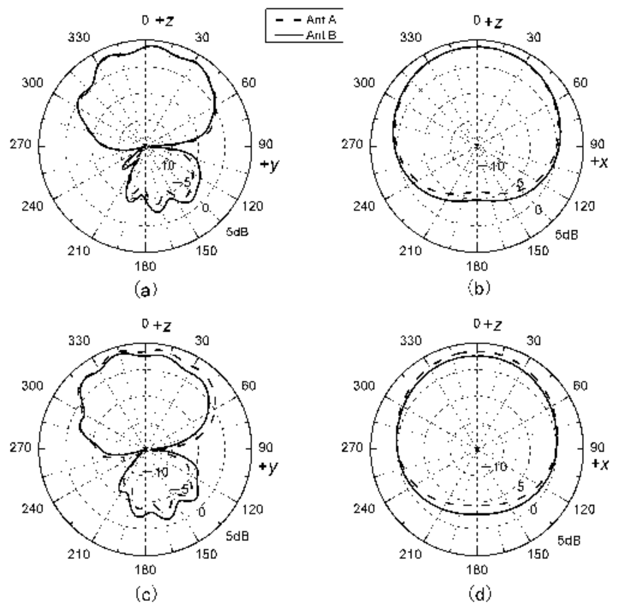

FIGURE 9. Measured radiation patterns of the primary antenna (Ant A, dashed lines) and the improved antenna (Ant B, solid lines) at (a) and (b) lower frequency of 2.2 GHz, and (c) and (d) higher frequency of 2.4 GHz.

the polarization should be in the y-axis direction. Certainly, the proposed antennas cannot reach highly directional feature due to the small ground width and the ground mode excited by the lower ground plate currents.

The radiation performances of both prototype Ant A and Ant B are measured using SATIMO Starlab antenna measurement system, with the measured radiation patterns in different cut planes at 2.2 GHz and 2.4 GHz respectively as shown in Fig. 9. Though the patterns of Ant A are similar to that of Ant B, the directivity of the former is a bit higher than that of the latter since the introduced notches somewhat enhance the back radiation ability. Meanwhile, for both Ant A and Ant B, the directivity of higher frequency patch mode is a bit better than that for lower frequency ground mode.

In H-cut plane (xoz plane), as shown in Fig. 9(b) and 9(d), the patterns of Ant A and Ant B all present the perfect symmetry. However, in E-cut plane (yoz plane) as shown in Fig. 9(a) and 9(c), the main lobes exhibit a bit incline to the negative y-axis direction from the right positive z-axis direction due to the reflection effect of the upper ground plate in the bending segment. Comparatively, the reflection of ground plate is stronger at higher frequency than at lower frequency.

The gains of Ant A at 2.2 GHz and 2.4 GHz are 3.9 dBi and 4.1 dBi, respectively, while those of Ant B are 3.6 dBi and 3.7 dBi. Anyway, both proposed antennas have the similar patterns which can be kept stable over the whole operating band.

B. RADIATION EFFICIENCY

For the Ant A prototype, the measured radiation efficiency is 79% at 2.2 GHz and 93% at 2.4 GHz. It indicates that the efficiency at the lower frequency, where larger travelling wave current components in the ground mode can weaken the resonant radiation, is far smaller than that at the higher frequency. At higher frequency, this antenna works based on the patch mode to present effectively resonant radiation as the traditional patch antennas.

The radiation efficiency of 89% can be obtained at 2.2 GHz for Ant B, 10% larger than that of Ant A. Nevertheless, the radiation efficiency is 91% at 2.4 GHz, which almost keeps the same as that of Ant A. In turn, these results confirm that the introduction of notches in the ground plate can improve the resonance strength of the ground current mode while maintaining the patch mode radiation.

C. APPLICATION CONSIDERATIONS

As discussed above, both the proposed dual-mode patch antennas present lower directivity of about 4-dBi gain. For a traditional patch antenna, the radiation gain can be somewhat enhanced by increasing the size of its ground plane. Reducing the diffraction effect of the ground plate edges, e.g., adding metallic side walls on the borders of the ground plane, is another way to reject the back lobe and enhance the directivity [16].

For the proposed antennas, however, the lower ground plate is not only the reflection plane but also the actual radiator of the ground mode. Its size has to be restrained to carry out the ground mode radiation, which implies that the directivity cannot be enhanced by widening the ground width or using other ground-adjusting measure. In all, both the proposed dual-mode patch antennas have the inherent characteristics of lower directivity that should be considered on putting them into use. Compared with other broadband patch antennas [17], [18], the proposed antennas have compact structures.

VI. CONCLUSION

For a patch antenna, the ground mode can be excited by bending the ground plate to the patch element plane. Utilizing the dual-resonance feature of ground mode and patch mode, the improved patch antenna can easily achieve the wideband performance. The weak resonant currents of the ground mode can be enhanced by adjusting the feed structure, such as adding the notches in the lower ground plate. It also can be desired that the bandwidth of the dual-mode antenna can be further increased by changing the shape of the ground plate or patch element. The low directivity is the inherent characteristic of the proposed dual-mode patch antenna, suitable for the application scenarios of low directivity requirements, e.g., in mobile terminals or indoor base-station systems. When working as an indoor base-station antenna, the dual-mode antenna should be in wall-mounted type to meet the nearly half-omnidirectional requirement for the indoor waves.

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