Research Article

Novel Wideband Metallic Patch Antennas with Low Profile

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Two planar metallic patch (MP) antennas with low profiles are investigated and compared in this paper. The MP of each antenna consists of metallic patch cells and it is centrally fed by a rectangular slot. Two modes with close resonance frequencies are excited, providing a quite wide bandwidth. The antenna principle is explained clearly through a parametric study. Simulated and measured results show that the MP antennas with profile of $0.06\lambda_0$ can obtain a 10 dB impedance bandwidth of $\sim 32\%$ and an average gain of ~ 10 dBi.

1. Introduction

Microstrip patch antenna attracts increasing interest in the wireless communication systems with low profile, low cost, and ease of fabrication and installation. Nevertheless, it is repulsive for the narrow impedance bandwidth. In fact, the bandwidth has been enhanced to about 10% with thick substrate [1], about 30% with U-slot on the patch [2, 3], about 35% with L-shaped feeding probe [4–6], and about 40% with stacked patches [7]. In the past few decades, metamaterials have been attractive to a wide range of electromagnetic applications due to their very unique properties. Various metasurfaces based antennas have been proposed and investigated for performance enhancement and size miniaturization [8–11]. The attempt of designing a broadband and directive metamaterial-inspired antenna has been reported [12]. It has demonstrated a bandwidth of 36% with a 2×2 mushroom structure and with an elliptical ring slot on the surface.

Recently, a metamaterial-based broadband 4×4 mushroom antenna has been presented in [13]. The mushroom unit cell consists of a square patch and a shorting via. The shorting via is positioned at the center of the square patch and it connects the patch to the ground plane. Fed by a microstrip-coupled slot, two resonant modes on the right-handed region of the metasurface mushroom structure can be excited and the antenna with a thickness of $0.06\lambda_0$

achieves an impedance bandwidth of 25% and an average gain of 9.9-dBi. In this paper, the shorting vias are removed and MPs consisting of simple rectangular patch cells are used instead above a rectangular slot. It is found that the antenna performances are comparable to those of the antenna having vias [13]. A 32% impedance bandwidth and a 10-dBi average gain can be obtained. This is very desirable since the fabrication process is greatly simplified and the cost reduces accordingly. To demonstrate the idea, two wideband MP antennas operating at 5 GHz were designed. For each antenna, the reflection coefficient, radiation pattern, and antenna gain were simulated and measured, with reasonable agreement obtained.

2. Antenna Configuration

Three antennas using different MPs are studied and compared in this section. Figure 1(a) shows configuration of the reference 4×4 mushroom MP I [13], which is fabricated on a substrate having thickness $h_1 = 3$ mm and relative permittivity $\epsilon_{r1} = 2.2$. Each mushroom cell consists of a rectangular patch and a shorting via. The via is located at the center of the patch, connecting the patch to the background plane. The diameter of the shorting via, the length, and width of the patch are d , l , and w , respectively. The 4×4 mushroom cells are evenly distributed along x - and y -axes,

FIGURE 1: Three slot-fed antennas with different MPs. (a) MP I composed of 4×4 rectangular patch cells which are shorted to the ground plane with vias. (b) MP II composed of 4×4 rectangular patch cells. (c) MP III composed of 1×4 rectangular patch cells. (d) Microstrip-coupled slot.

with the gap width between two adjacent units given by g . Figure 1(b) shows a new MP of antenna II, which has similar configuration with MP I except that all shorting vias are removed. Based on MP II, another simpler MP III is proposed and shown in Figure 1(c). In this case, the gaps between the patch cells along x -axis are eliminated and the MP turns into a 1×4 rectangular patch array. All three MPs are fed at the center by a microstrip-coupled slot, which is fabricated on a substrate with thickness $h_2 = 0.813$ mm and relative permittivity $\epsilon_{r2} = 3.38$. As shown in Figure 1(d), the slot having length l_s and width w_s was cut at the top surface, and a 50Ω microstrip feed-line with a width of w_m and a stub length of l_m was fabricated on the other side of the substrate.

For comparison, three antennas using different MPs were designed to operate at the same frequency of 5 GHz. In each case, the slot length l_s and microstrip stub length l_m were tuned to optimize the impedance match. Figures 2(a) and 2(b) show the simulated reflection coefficients and antenna gains, respectively. It can be seen from Figure 2(a) that reference antenna I has a -10 dB impedance bandwidth ($|S_{11}| < -10$ dB) of 22.1% (4.42–5.52 GHz), comparable to 25% of the

design in [13]. The TM_{10} and antiphase TM_{20} modes of the mushroom structure are simultaneously excited to provide such a broadband operation. As for antennas II and III, also two modes exist in the passbands, but their resonance frequencies move farther away from each other, leading to even wider bandwidths of 29.9% (4.21–5.69 GHz) and 32.1% (4.16–5.75 GHz).

With reference to Figure 2(b), the three antennas have almost the same gain level. An average gain of near 11 dBi is obtained for each antenna in its corresponding impedance passband. Table 1 summarizes the antenna dimensions, bandwidths, and gains for the three cases. It was found that antenna I has the largest area of $0.88\lambda_0^2$, which is 10.1% larger than antenna III and 26.8% larger than antenna II. Figure 3 depicts the simulated surface current distributions on the three MPs at 5 GHz. As can be observed from the figure, the distribution patterns of the three cases are very similar with each other, especially for MP II and III.

Based on the comparison, it can be concluded that instead of increasing the complexity of structure, the introduction of shorting vias shows no advantage in improving antenna

FIGURE 2: Simulated reflection coefficients and gains of the three slot-fed antennas with different MPs. (a) Reflection coefficients. (b) Antenna gains.

TABLE 1: Antenna dimensions, bandwidths, and average gains of antennas.

Antenna	Cell size $w \times l \times g$ (mm)	Slot size $l_s \times w_s$ (mm)	Stub length l_m (mm)	Impedance bandwidth	Average gain (dBi)
I	$13.3 \times 13.3 \times 1$	33×2	10	22.1%	11.4
II	$12.1 \times 12.1 \times 0.5$	30×2	10	29.9%	10.6
III	$12.1 \times 56 \times 0.5$	32×2	10	32.1%	10.9

FIGURE 3: Simulated surface current distributions on MPs at 5 GHz. (a) MP I. (b) MP II. (c) MP III.

FIGURE 4: Simulated reflection coefficients of antenna III as a function of frequency for different cell widths. (a) $w_1 = w_4 = 12.1$ mm, $w_2 = w_3 = w$. (b) $w_2 = w_3 = 12.1$ mm, $w_1 = w_4 = w$.

performance. Therefore, MPs II and III are superior to MP I in the design of a wideband antenna. On the other hand, the similar performances and current distributions of MPs II and III verify that their operating principles should be the same, and the gaps along x -axis can be eliminated without affecting antenna performances at all.

3. Simulated and Measured Results

3.1. Parametric Study. The geometry of the slot-fed MP antennas is illustrated in Figure 1. The MP unit cell consists of a square patch with a side width w , and the MP cells are two-dimensionally distributed with a gap width g in between on the center of the dielectric substrate. When the height of the substrate h is very small compared with the wavelength λ_0 , a transmission-line model can be utilized to analyze the proposed MP antenna. Due to the fringing field at the open edges of the MP array, the MP array cavity is assumed to have an additional extended length at each end. Since the gap width g is much smaller than the MP cells period, the extended length ΔL can be approximated to that of the corresponding entire rectangular patch with the same width of W_p , and it is given by [14]

$$\frac{\Delta L}{h} = 0.412 \frac{(\epsilon_{\text{reff}} + 0.3) (W_p/h + 0.262)}{(\epsilon_{\text{reff}} - 0.258) (W_p/h + 0.813)}, \quad (1)$$

$$\epsilon_{\text{reff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W_p} \right)^{-1/2},$$

$$W_p = 4w + 3g.$$

To characterize the designs, parametric studies of antennas II and III have been carried out using HFSS. Similar phenomena have been observed, and therefore only the results of simpler MP antenna III are shown here for brevity.

Figure 4 shows the reflection coefficients as a function of frequency for different patch cell widths. Two different cases have been studied: (a) the widths of w_1 and w_4 are fixed at 12.1 mm, but $w_2 = w_3 = w$ varies from 10.1 to 14.1 mm; (b) the widths of w_2 and w_3 are fixed at 12.1 mm, but $w_1 = w_4 = w$ varies from 10.1 to 14.1 mm. In each case, w_1 and w_4 , w_2 and w_3 are set equal to each other to provide a symmetrical antenna structure and thus symmetrical radiation patterns. With reference to Figure 4(a), when only w_2 and w_3 increase from 10.1 to 14.1 mm, the upper resonance frequency at ~ 5.5 GHz remains unchanged, but the lower resonance frequency decreases from 4.8 to 4.16 GHz, showing that the lower mode is generated by the pair of patches 2, 3 which are right above the feeding slot. The situation is reversed in case (b). As shown in Figure 4(b), the resonance frequency is more sensitive to w_1 and w_4 in the upper band than for the lower band, indicating that the upper band is associated with the pair of patches 1, 4.

The surface current distribution of MP III at the two resonance frequencies 4.5 and 5.5 GHz is shown in Figure 5. It can be seen that the currents are concentrated mainly on patches 2 and 3 at lower 4.5 GHz whereas they are concentrated mainly on patches 1 and 4 at upper 5.5 GHz, verifying the above conclusion. These results demonstrate that MP III behaves like a gap-coupled parasitic patch antenna, which consists of several patch resonators coupled together by capacitive radiating-edge gaps [15, 16]. At one frequency, one of the patch resonators is resonant and at nearby frequency other resonators become resonant. The multiple resonances yield a wide bandwidth. The difference is that in probe-fed parasitic patch antenna [15, 16], driven patch and parasitic elements should have slightly different resonant lengths to provide close resonance frequencies. However, for the slot-fed MP III, identical patch cells can be used and the two close resonance frequencies are obtained by the different loading effects of the feeding slot on the patches. Also, it is worth

FIGURE 5: Simulated surface current distribution on MP III at resonance frequencies. (a) 4.5 GHz. (b) 5.5 GHz.

FIGURE 6: Simulated E -field distribution on $y = 0$ mm planes of MP II at resonance frequencies. (a) 4.5 GHz. (b) 5.5 GHz.

mentioning that compared with the probe-fed parasitic patch antennas, the proposed slot-fed MP III provides much wider bandwidth, higher gain, and more stable and symmetrical radiation patterns.

The simulated field distribution of MP II at the two resonance frequencies 4.5 and 5.5 GHz is shown in Figure 6. It can be seen that the E -field distribution of the 4×4 MP cell array at 4.5 GHz is similar to the TM_{10} mode of a conventional patch antenna except the radiation from the gaps between MP cells shown in Figure 6(a). And the E -field distribution of the 4×4 MP cell array at 5.5 GHz is similar to the antiphase TM_{20} mode shown in Figure 6(b). In the MP structure, the ratio of the antiphase TM_{20} mode resonant frequency to the TM_{10} mode resonant frequency can be much less than two. Therefore, the smaller ratio of the antiphase TM_{20} mode resonant frequency to the TM_{10} mode, together with the reduced quality factor with the cell gaps, leads to broadband operation of the MP antenna.

Figure 7 shows the reflection coefficients for different cell lengths l . As can be seen from the figure, the reflection coefficient varies very slightly when l is increased significantly from 46 to 56 mm, and good match is maintained across the impedance passband. This is because l corresponds to the dimension of nonradiating edge of the patch. Also due to this reason, the antenna performances of MP II and III are similar to each other regardless of having gaps along the nonradiating edge or not. However, there is a sharp change point at 4.28 GHz for $l = 51$ mm and 4.75 GHz for $l = 46$ mm in the passband. This should be caused by the weak

FIGURE 7: Simulated reflection coefficients of antenna III as a function of frequency for different cell lengths of $l = 46, 51$ and 56 mm.

resonance along the nonradiating edge, since the length and frequency satisfy the relation of $l = \lambda_e = c/f_o\sqrt{\epsilon_e}$, where λ_e is the guide wavelength, and ϵ_e is the effective dielectric constant of the microstrip line given by $\epsilon_e = (\epsilon_r + 1)/2 + (\epsilon_r - 1)/2\sqrt{1 + 12h/w}$ [17]. Although the weak resonance affects the reflection coefficient insignificantly, it decreases the

FIGURE 8: Photo of two planar MP antennas. (a) MP II composed of 4×4 rectangular patch cells. (b) MP III composed of 1×4 rectangular patch cells.

FIGURE 9: Measured, simulated reflection coefficients and gains of antennas II and III. (a) Antenna II. (b) Antenna III.

antenna gain by ~ 1 dB at that frequency. Therefore, a larger l of 56 mm is preferable to exclude the resonance outside the useable passband. It is worth mentioning that since the length is divided into 4 subsections in MP II, the resonance condition is destroyed; then smaller total length can be used without weak resonance happening. This is the reason why the size of MP II is a bit smaller than that of MP III, as shown in Table 1.

Finally, the effects of feeding slot are investigated. It is found that the variations of parameters w_s , l_s , and l_m mainly affect the match level but not the resonance frequency. Therefore, they can be tuned for a good match. Since the results are similar with those in [13], they are not included in this paper for brevity.

3.2. Measurement Verification. To verify the designs, two prototypes of antenna II and III were fabricated (shown in Figure 8) and tested. In this paper, the reflection coefficient was measured using an HP8510C network analyzer, whereas

other measured results were obtained using a Satimo Starlab System. Figures 9(a) and 9(b) show the measured, simulated reflection coefficients and gains of antennas II and III, respectively. Reasonable agreement between the simulated and measured results is observed, with the discrepancy caused by experimental tolerances and imperfections including the inevitable airgap between the two substrates. With reference to the figure, the measured bandwidths of the two antennas are almost the same, given by 32.2% (4.12–5.70 GHz) and 33.3% (4.11–5.75 GHz) for antennas II and III, respectively. Also, similar gain levels have been observed for the two antennas. Take antenna III for an example, the antenna gain varies between 8.4 and 11.4 dBi across the impedance passband. The average antenna gain is 10.2 dBi, which is close to 9.9 dBi in [13]. Figure 10 shows the measured and simulated field pattern at 5 GHz. Broadside radiation patterns are observed as expected, with maximum radiation pointing to the boresight direction ($\theta = 0^\circ$). The copolarized fields in the boresight direction of both antennas are stronger than

FIGURE 10: Measured and simulated radiation patterns of antennas II and III at 5 GHz. (a) Antenna II. (b) Antenna III.

the cross-polarized fields by more than 25 dB. The radiation patterns were also simulated at other frequencies and very stable results were obtained across the entire passband.

4. Conclusion

Two slot-fed MP antennas which consist of metallic patch cells have been investigated in this paper. Compared with metamaterial-based mushroom antenna, the proposed designs have advantages of simple configuration, ease of fabrication, compact size, and even wider bandwidth. A parametric study of the MP antennas has been done to examine the effects of various parameters, and two prototypes operating at 5 GHz were designed and fabricated. The antennas have a low profile of $0.06\lambda_0$, a wide impedance bandwidth of $\sim 32\%$, and a medium average gain of ~ 10 dBi.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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