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Wideband Omnidirectional Slotted Patch Antenna With Filtering Response

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ABSTRACT A wideband omnidirectional patch antenna with filtering response is investigated in this paper. The circular patch antenna is centrally fed by a probe, with its TM_{01}, TM_{02}, and TM_{03} modes simultaneously excited. Two ring slots are meticulously introduced into the patch and ground plane to merge the three modes of a kind, realizing a wide omnidirectionally radiating passband. The introduction of the slots also generates two radiation minimums at the lower and upper band-edges, leading to an enhanced suppression level in the stopbands. Hence, a compact wideband filtering patch antenna with quasi-elliptic bandpass response is obtained, without using any extra circuit. The proposed antenna has a low profile of 0.027 λ_0, a 10-dB impedance bandwidth of 19.5%, an average gain of 7.5 dBi within passband, and an out-of-band suppression level of over 23 dB within stopband.

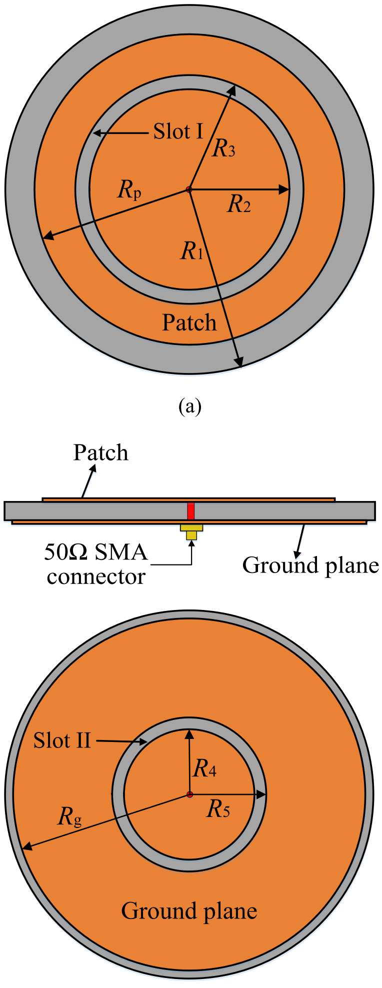
INDEX TERMS Omnidirectional antenna, filtering antenna, wideband antenna.

I. INTRODUCTION

Omnidirectional antenna with uniform radiation pattern in the horizontal plane is desirable for certain wireless communication systems owing to its large signal coverage. On the other hand, it is increasingly popular to integrate the bandpass filter and antenna into a single module to reduce the system size as well as insertion loss. As a result, varieties of omnidirectional filtering antennas with filter-like frequency response for both the reflection coefficient and realized gain were developed [1]–[5]. For instance, a printed planar filtering antenna was obtained by integrating a stepped-impedance dipole, a stepped-impedance resonator, and a low-pass filter [1], and another printed planar filtering antenna was realized by combining an inverted-L dipole and a series of parallel coupled microstrip lines [2]. Also, a filtering fan-shaped patch antenna with defected ground structure was realized by using it as the second resonator of a two-pole Butterworth bandpass filter [3]. Obviously, these designs are based on the filter synthesis approach. Bandpass filter is developed first, and then the integration is realized by taking the antenna radiator as the last stage resonator of the filter. This method can generally provide satisfying filtering performance, but often with radiation efficiency and antenna gain degraded due to the inevitable insertion loss of the filter.

Recently, an alternative antenna fusion design concept was proposed [6]–[11]. This approach focuses on the design of antenna, and the filtering function is realized by introducing simple parasitic elements or resonators into the radiator or its feeding circuit. Since no specific filtering circuits are involved, the resultant designs have more compact size and lower insertion loss. This method has been successfully utilized to design a variety of filtering patch antennas [8], [9] and dielectric resonator antennas [10], [11]. However, most of them are unidirectional antennas with broadside radiation patterns. Thus far, only one omnidirectional filtering patch antenna was designed using this concept [12]. Eighteen shorting vias together with a small ring slot were added to an equilateral triangular patch. The equilateral triangular patch provides a radiation null near the upper band-edge, whereas the ring slot and vias produce another radiation null close to the lower band-edge. Filtering response with good selectivity is thus obtained. However, the fractional bandwidth of this filtering antenna is only 8.9%, and the average gain is 6.0 dBi.

Due to the rapid development of high speed wireless communication, there is an increasing demand for broadband operation. In this paper, a wideband (19.5%) and high gain (7.5 dBi) omnidirectional filtering patch antenna which simply consists of a slotted circular patch and a slotted



(a)

(b)

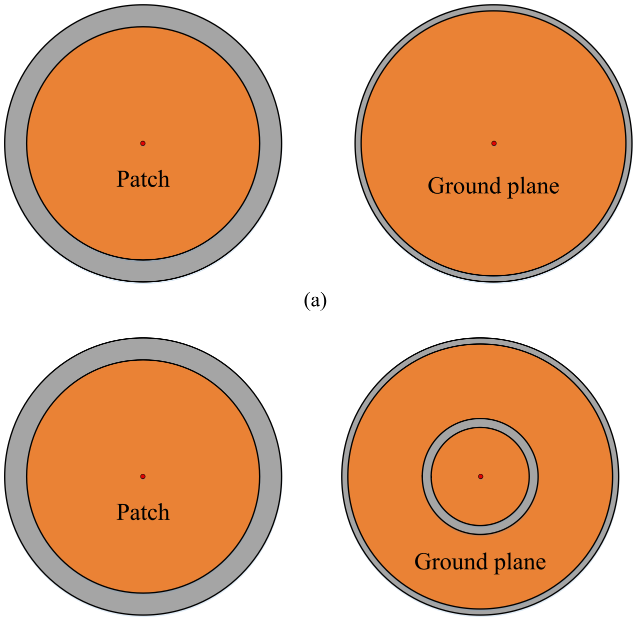
FIGURE 1. **Configuration of the proposed filtering omnidirectional patch antenna. (a) Top-view. (b) Bottom-view. ($R_1 = 80.7$ mm, $R_2 = 48$ mm, $R_3 = 49.9$ mm, $R_4 = 28.1$ mm, $R_5 = 29$ mm, $R_p = 68.2$ mm, and $R_g = 79.8$ mm.)**

circular ground plane is investigated. The detailed generation mechanisms of the wide radiating passband and the filtering response are discussed. For demonstration, a filtering antenna operating at 4 GHz was designed and measured. Its return loss, radiation pattern and antenna gain were simulated using ANSYS HFSS. Measurements were carried out, and reasonable agreement between the measured and simulated results is observed.

II. ANTENNA DESIGN

A. ANTENNA CONFIGURATION

Fig. 1 shows configuration of the proposed omnidirectional filtering patch antenna. The antenna is designed on a single layer printed circuit board (PCB) with relative permittivity $\varepsilon_r = 2.65$, thickness $h = 2$ mm, and loss tangent tan $\delta < 0.001$. It simply consists of a slotted circular patch and a slotted circular ground plane, which are fabricated on the top and bottom surfaces of the PCB respectively. With reference to Fig. 1(a), the circular patch has a radius of R_p, and a ring slot (slot I) with inner radius R_2 and outer radius R_3 is etched on the patch. With reference to Fig. 1(b), the circular ground plane has a radius of R_g, and a smaller ring slot (slot II) with inner radius R_4 and outer radius R_5 is etched on it. It will be shown in the following subsection that the use of the two slots is very essential for improving the antenna bandwidth and realizing the filtering characteristic. A coaxial probe is used to feed the antenna, and it is located at the center to realize omnidirectional radiation.



(a)

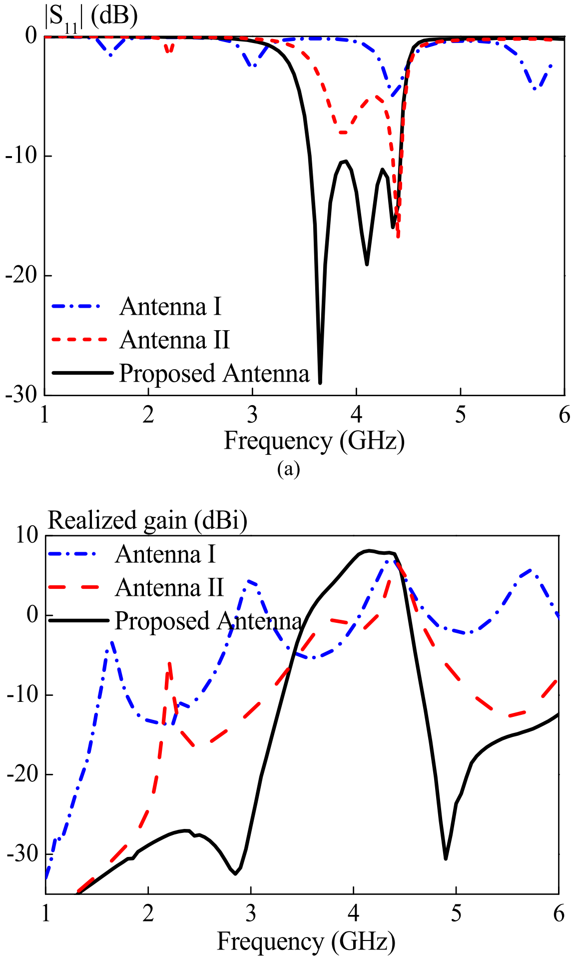
(b)

FIGURE 2. **Configurations of the reference antennas. (a) Reference Antenna I: traditional circular patch antenna without any slot. (b) Reference Antenna II: circular patch antenna with only slot II on the ground plane.**

B. ANTENNA MECHANISM

In this section, the operating mechanism of the proposed filtering patch antenna is explained by comparing it with two other reference antennas, which are (I) traditional circular patch antenna without any slot, and (II) circular patch antenna with only slot II on the ground plane. Fig. 2 shows configurations of the reference antennas, and Fig. 3 shows their simulated reflection coefficients and realized gains as a function of frequency. For ease of comparison, the results of the proposed antenna which has both slot I on the patch and slot II on the ground plane are also included in Fig. 3. Same dimensions are used for each antenna, as listed in the caption of Fig. 1.

With reference to Fig.3 (a), four resonant modes are excited at 1.65 GHz, 3.0 GHz, 4.35 GHz, and 5.75 GHz in Antenna I. To characterize these modes, the surface current distributions on the patch are simulated and shown in Fig. 4. It can be deduced from the patterns (Fig. 4(a), (b) and (c)) that the first three modes correspond respectively to the TM_{01}, TM_{02}, and TM_{03} modes of circular patch, where the first and second



(b)

FIGURE 3. **Simulated reflection coefficients and realized gains of the reference and proposed antennas. (a) Reflection coefficient. (b) Realized gain at $\theta = 20°$, $\phi = 0°$.**

subscripts refer to the field variations along the azimuth (ϕ) and radial (r) directions, respectively. The fourth resonant mode in Fig. 3 (a) was also studied. It was found that it is the higher-order TM_{04} mode, but it does not contribute to the proposed design. As the fields of all the three modes are independent of the azimuth angle ϕ, omnidirectional radiation pattern will be generated in the azimuth plane for each mode. A wide omnidirectionally radiating passband is therefore expected if the three patch modes can be merged together. As can be seen from Fig. 4(c), the current direction of TM_{03} mode changes twice along the radial direction and the current intensity is close to zero at the change zones, i.e., $R = R_2$ and $R = R_4$. Based on the microwave theory, any small change that introduced at these regions should not affect this mode. Instead, it will affect significantly the two lower-order TM_{01} and TM_{02} modes which have strong current distribution there. Ring slot II is therefore added to the ground plane at $R = R_4$ to obtain reference Antenna II (It will be discussed in detail below that adding the slot to the ground plane rather than the patch is beneficial to the filtering response). With reference to the red dash line, it can be observed that the third TM_{03} mode remains almost unchanged, but the resonance frequencies of both the TM_{01} and TM_{02} modes shift upwards significantly, with TM_{02} and TM_{03} modes adjacent to each other. This is as expected, since the slot cuts the current lines of the two lower-order modes and decreases the effective radiating area of the patch, as shown in Fig. 4(d) and (e). The introduction of the slot also shifts up (suppresses) the TM_{04} mode at 5.75 GHz, enhancing significantly the suppression level of the upper stopband. Next, to further combine the TM_{01} mode, ring slot I is introduced on the patch at $R = R_2$ to obtain the proposed antenna. With reference to Fig. 4(e) and (f), the current intensities of the TM_{02} and TM_{03} modes are rather weak at this place. Therefore, the resonance frequencies of the two modes are slightly affected although the impedance matching has been greatly improved due to the loading effect of the slot. Again, the TM_{01} mode shifts significantly from 2.2 to 3.7 GHz. It combines with the two higher-order TM_{02} and TM_{03} modes, generating a wide bandwidth of 21.4%. In this case, there is no resonant mode below 3 GHz, and the suppression level in the lower stopband is thereby substantially enhanced, as shown in Fig. 3(b). Consequently, good filtering response is achieved without involving complex filtering circuits.

It is worth mentioning that although the slots have been used in omnidirectional patch antennas to enhance the impedance bandwidth [13], [14], but their effects on the filtering response have not been investigated yet. Also, it is notable that in the previous designs, the slots were mostly introduced to the patch. To demonstrate the advantages of the proposed design that has a slot on the ground plane, a reference antenna with both slots on the patch is investigated and compared. Fig. 5 shows configuration of the reference slotted patch antenna (Antenna III). All its dimensions are the same as for the proposed design, and the only difference is that slot II is now also added to the circular patch. The comparison of the simulated reflection coefficients and realized gains between the two antennas is shown in Fig. 6. With reference to Fig. 6(a), the conventional slotted patch antenna has a 10-dB impedance bandwidth of 17.3% (3.7–4.4 GHz), comparable with that (21.4%) of the proposed antenna. Only two resonances can be found within its passband, this is because the lower-order TM_{01} and TM_{02} modes are merged together. For both antennas, flat stopbands with $|S_{11}|$ close to 0 dB can be observed on the left and right sides of the passband. The biggest difference is that the lower band-edge of the reference antenna is not as sharp as that of the proposed one, indicating a poorer filtering selectivity. Similar results can be observed from the realized gain. As shown in Fig. 6(b), the two antennas have comparable gains in the passband. However, two additional radiation minimums at 2.9 GHz and 4.9 GHz are generated near the passband edges of the proposed antenna, leading to an enhanced selectivity and suppression level in the stopbands, especially in the left one. These results indicate that although both slotted antennas possess similar radiating performances, the proposed one provides better filtering response.

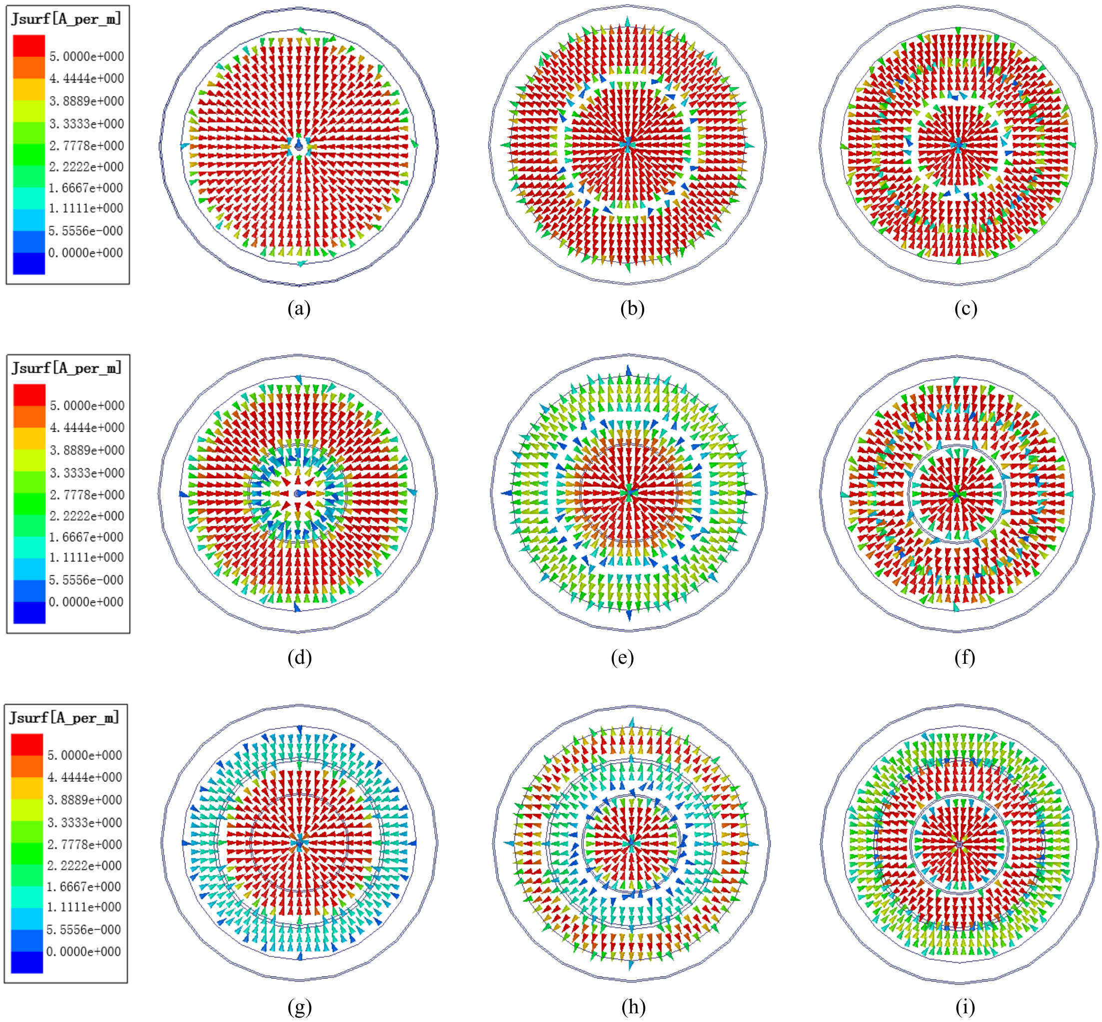


FIGURE 4. **Simulated surface current distributions on patch of the reference and proposed antennas. (a) Reference Antenna I at 1.7 GHz. (b) Reference Antenna I at 3 GHz. (c) Reference Antenna I at 4.4 GHz. (d) Reference Antenna II at 2.2 GHz. (e) Reference Antenna II at 3.9 GHz. (f) Reference Antenna II at 4.4 GHz. (g) The proposed antenna at 3.7 GHz. (h) The proposed antenna at 4.1 GHz. (i) The proposed antenna at 4.4 GHz.**

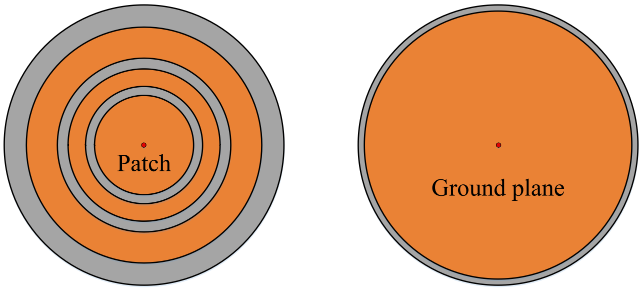
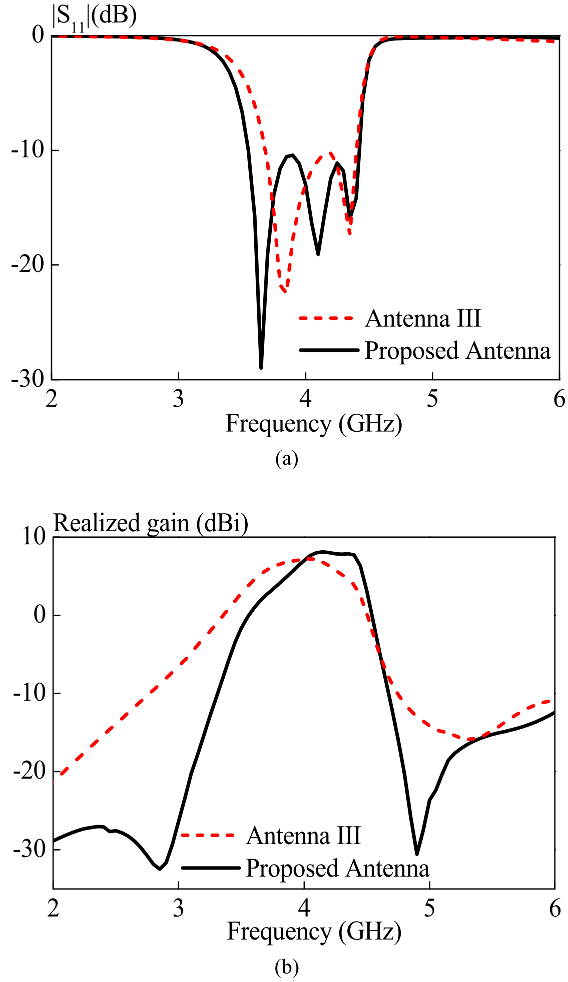


FIGURE 5. **Configuration of reference Antenna III which has two slots on the circular patch.**

To further investigate the physical mechanism, the elevation radiation patterns of the two antennas at 2.9 GHz, 4 GHz and 4.9 GHz are simulated and compared in Fig. 7. It can be observed that the patterns of the conventional slotted antenna are relatively stable, and the maximum radiation beam in either the passband or stopbands is always found near $\theta = 20^\circ$. The maximum radiation of the proposed antenna in the passband also directs to $\sim 20^\circ$, but it shifts to $\sim 140^\circ$ in its stopbands due to the slot that introduced on the ground plane, leading to a negligible radiation at the target angle ($\theta = 20^\circ$). It is worth mentioning that the radiation within the stopband is generally weak in any direction, since the reflection coefficient is about 0 dB at stopband frequencies which indicates a nearly total reflection of signal.

III. SIMULATED AND MEASURED RESULTS

To validate the design, a prototype operating at 4-GHz was fabricated and tested. It is worth mentioning that the working frequency is arbitrarily selected, and the presented design can be rescaled and tuned straightforwardly to other frequencies of interest. Fig. 8 shows two photographs of the prototype. In the measurement, a quarter-wavelength choke [2] is added to the outer conductor of the cable to suppress its stray radiation. The reflection coefficient is measured using an



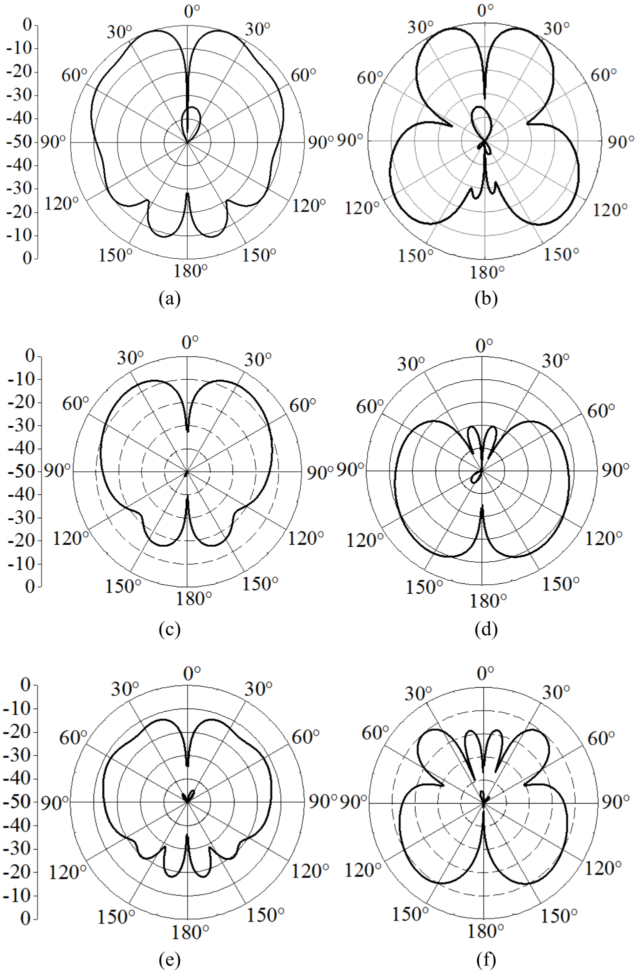
(a)

(b)

FIGURE 6. **Simulated reflection coefficients and realized gains of the reference and proposed antennas. (a) Reflection coefficient. (b) Realized Gain at $\theta = 20°$, $\phi = 0°$.**

Agilent N5230A network analyzer, whereas the antenna gain and radiation patterns are obtained by a Satimo Starlab System.

Fig. 9 shows measured and simulated reflection coefficients of the prototype, and reasonable agreement between them can be observed except for a small frequency shift. This small deviation is mainly caused by the error of PCB's permittivity. Three resonant modes (TM_{01}, TM_{02} and TM_{03} modes) are simultaneously excited in the passband, with the measured and simulated 10-dB impedance bandwidths given by 19.5% (3.7 GHz to 4.5 GHz) and 21.4% (3.55 GHz to 4.4 GHz) respectively. Stopbands with $|S_{11}| \approx 0$ dB can be found on both the left and right sides of the passband, showing good selectivity and bandpass filtering response. Fig. 10 shows measured and simulated realized gains of the prototype at $\theta = 20°$, $\phi = 0°$. Obviously, a quasi-elliptic bandpass filtering response can be observed. The measured average gain is 7.5 dBi across the passband, agreeing well with the simulated value of 7.8 dBi. Beside the passband, two radiation minimums appear at ~3.1 GHz and 4.9 GHz, leading to a high roll-off rate at band-edges.

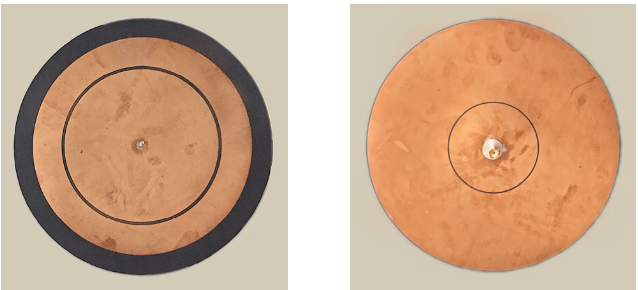


(a) (b)

(c) (d)

(e) (f)

FIGURE 7. **Simulated radiation patterns of the reference and proposed antennas. (a) Reference Antenna III at 4 GHz. (b) The proposed antenna at 4 GHz. (c) Reference Antenna III at 2.9 GHz. (d) The proposed antenna at 2.9 GHz. (e) Reference Antenna III at 4.9 GHz. (f) The proposed antenna at 4.9 GHz.**



(a) (b)

FIGURE 8. **Photographs of the proposed omnidirectional filtering patch antenna. (a) Top-view. (b) Bottom-view.**

Also, a suppression level of more than 23 dB is obtained in both the lower and upper stopbands. The antenna efficiency shows a similar filtering trend, with the in-band and out-band efficiencies given by >90% and <5% respectively.

The measured and simulated radiation patterns in the elevation ($\phi = 0°$) and azimuth ($\theta = 20°$) planes at 4 GHz are plotted in Fig. 11. As shown in the figure, the elevation pattern has a null in the boresight direction ($\theta = 0°$), with

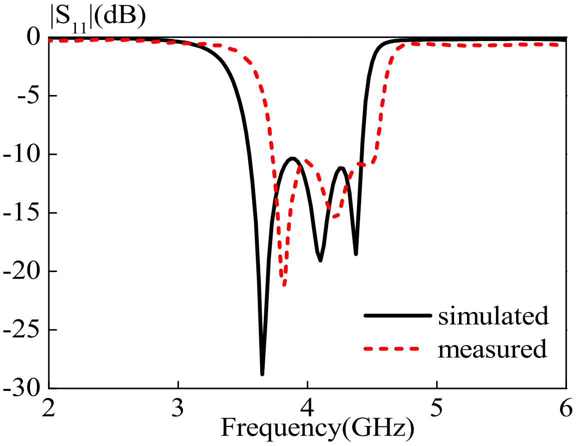


FIGURE 9. Simulated and measured reflection coefficients of the prototype.

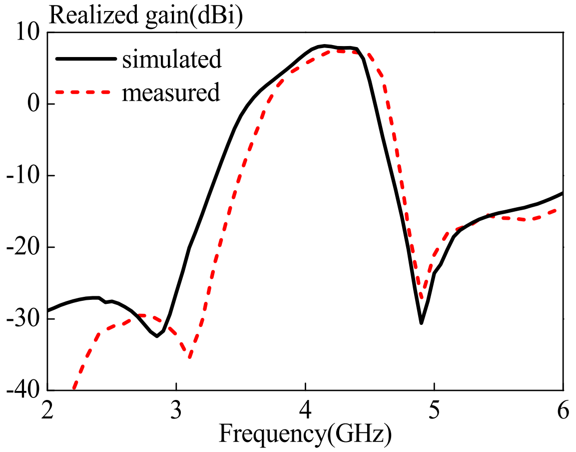


FIGURE 10. Simulated and measured realized gains of the prototype at $\theta = 20°$, $\phi = 0°$.

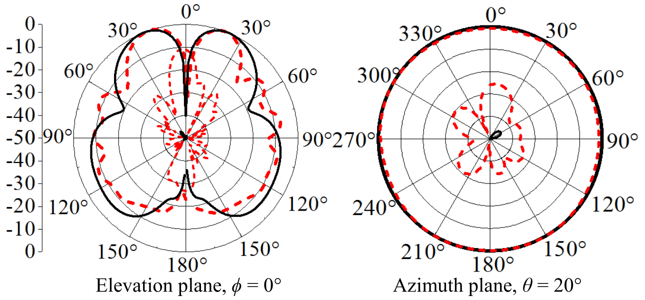


FIGURE 11. Simulated and measured radiation patterns of the prototype at 4 GHz. —— Simulated ------ Measured.

the strongest radiation found near $\theta = 20°$. Good omnidirectional radiation pattern is obtained in the azimuth plane, and the co-polarized field is stronger than the cross-polarized conterpart by more than 25 dB. Similar patterns are obtained for the *yz*-plane ($\phi = 90°$) due to the symmetry of structure, and therefore are not shown here for brevity.

IV. CONCLUSION

A wideband omnidirectional filtering patch antenna is realized using the fusion design concept. The antenna consists of a slotted circular patch and a slotted ground plane. It has been shown that when located at appropriate places, the slots can not only merge the three omnidirectional patch modes, i.e., TM_{01}, TM_{02} and TM_{03} modes, to obtain a wide radiating passband, but also can generate two radiation minimums at the lower/upper band-edges to realize filtering function. A wide omnidirectionally radiating passband with filtering response is thus achieved without using extra filtering circuit. It has been shown that the proposed filtering antenna has a 10-dB impedance bandwidth of 19.5%, an average gain of 7.5 dBi within passband, and an out-of-band suppression level of more than 23 dB within the stopband from 0 to 6 GHz.

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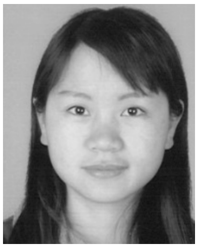

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