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Triple-Band, Dual-Mode and Dual-Polarization Antenna

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Abstract—A low-profile triple-band, dual-mode and dual-polarization antenna is proposed in this paper. An annular interdigital slot etched on the top conductor layer of the antenna is employed as a radiator. Through adjusting the location of coaxial probe, three operating modes TM_{11}, TM_{02}, and TM_{12} of the antenna are excited simultaneously. Two patch-like radiation patterns and one monopolar radiation pattern at three different frequencies are obtained. In addition, circularly polarized (CP) property for TM_{11} and TM_{12} modes is achieved by employing a 45° inclined rectangular slot at the center of the antenna. To validate the properties, a prototype is fabricated and measured. The results illustrate that this antenna is attractive in wireless communication systems for its simple structure and multifunction.

1. INTRODUCTION

In modern wireless communication, antennas with different radiation characteristics have different functions. For example, antennas with unidirectional radiation patterns are in demand for satellite communication or point-to-point communication systems while antennas with omnidirectionality property are useful in Global Position Systems (GPSs) or personal mobile systems. With the development of multiband wireless systems and multifunctional devices, one single antenna with multiple functions such as multi-frequency and pattern selectivity is attractive in wireless communication [1]. For example, in vehicular communications, aircraft communications or wireless body communications, one antenna that has radiation patterns in both azimuth plane and elevation plane with different bands is required.

A number of multifunctional antennas have been presented in the literature [2–7]. Printed inverted-F antennas (PIFAs) with multiband characteristic have been applied in vehicle communication [2, 3]. In [4], compact multimode patch antennas were proposed at a single frequency. However, there are few antennas which can realize multi-band and dual-mode simultaneously. A substrate integrated waveguide (SIW) cavity-backed annular ring slot antenna with multi-band multi-mode characteristics was proposed in [5]. Two patch-like radiation patterns and one monopolar radiation pattern at three different frequencies were achieved in this single fed antenna. However, because high-order modes were used, the antenna size was large. Resonant-type CRLH antennas offer an alternative solution of multi-band multi-mode operation for miniaturization [6, 7]. Using negative order, zeroth-order and positive order resonances in CRLH structure, these antennas could be designed with very compact sizes. However, these antennas also have drawbacks such as low gain and low radiation efficiency.

In this paper, multi-band, dual-mode and dual-polarization characteristics are achieved in a simple single-fed and single-layer microstrip antenna. Three operating modes of the antenna are excited to realize two patch-like radiation patterns and one monopolar radiation pattern at three different frequencies. Moreover, an interdigital structure slot is introduced to reduce the whole antenna size, and

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circularly polarized (CP) property is obtained for the resonances of TM_{11} and TM_{12} modes. Therefore, compared with other multi-band and dual-mode antennas, the proposed antenna has advantages of compact size, high efficiency and dual-polarization characteristics.

2. ANTENNA DESIGN AND ANALYSIS

The geometry of the proposed antenna is shown in Fig. 1. The antenna is fabricated on a single-layer circular Rogers-Duroid 5880 substrate with radius $R = 27\,\text{mm}$, thickness $h = 1.5\,\text{mm}$, $\varepsilon_r = 2.2$, and $\tan\delta = 0.0009$. It consists of an annular interdigital slot on top of the substrate as the radiator. The external and internal radii of the slot are R_1 and R_2, and the slot width is w. The signal excitation is accomplished by using a coaxial probe. It is placed offsetting from the centre of the substrate to excite TM_{11}, TM_{02}, and TM_{12} simultaneously. A 45° inclined rectangular slot (size: $L_s \times W_s$) is employed at the centre of the antenna to achieve circularly polarized (CP) property for the TM_{11} and TM_{12} modes.

The fundamental mode of annular ring slot antenna is TM_{11} mode, and other higher modes can also be excited by tuning the location of coaxial probe [5]. The resonant frequencies of different modes are:

$$f_{mn} = \frac{k_{mn} c}{2\pi R\sqrt{\varepsilon_r}} \tag{1}$$

where f is the resonant frequency, k_{mn} the eigen value, mn the order of modes, c the velocity of the light in vacuum, R the slot radius, and ε_r the relative dielectric constant. In terms of the empirical equation, the antenna size can be reduced efficiently by using an interdigital structure slot. In this work, we use the lowest three operating modes TM_{11}, TM_{02}, and TM_{12} to design a multi-functional antenna. According to the multimode theory of microstrip antenna, the fundamental TM_{11} and the higher order TM_{12} mode can radiate boresight beams, while the TM_{02} mode can be used to generate a vertically polarized and conical radiation pattern, similar to a conventional monopole antenna. The

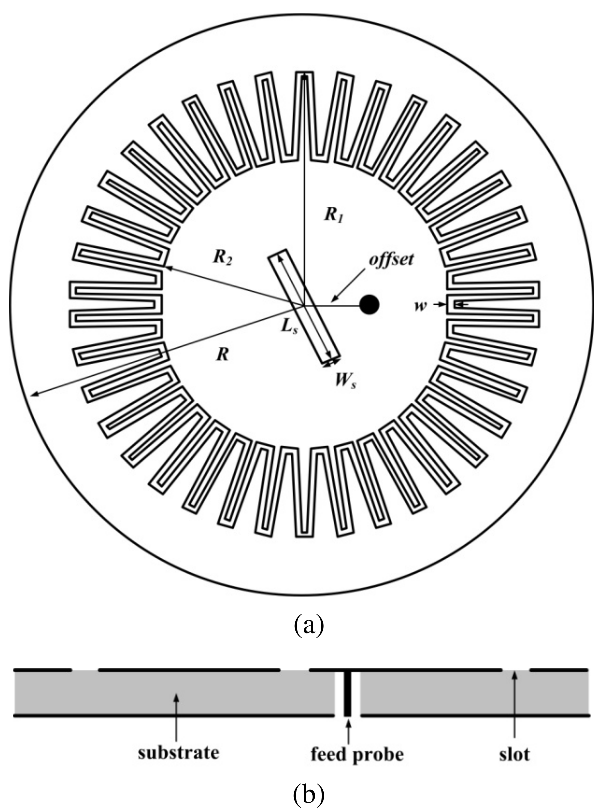

Figure 1. Geometry of the proposed antenna: (a) top view; (b) side view.

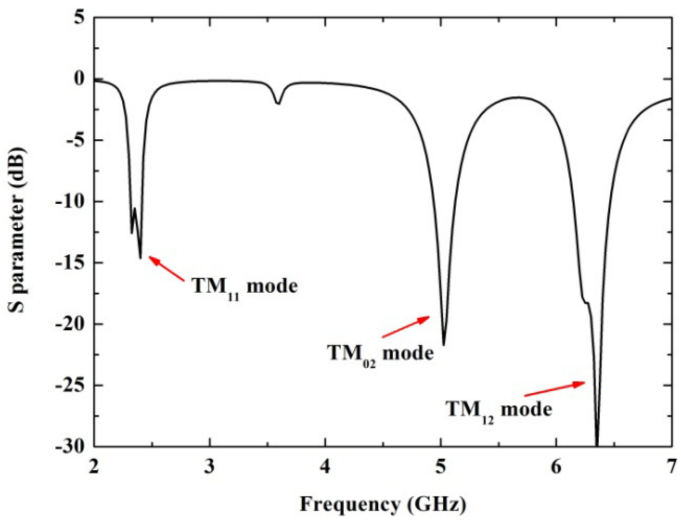

Figure 2. Simulated reflection coefficient of the antenna.

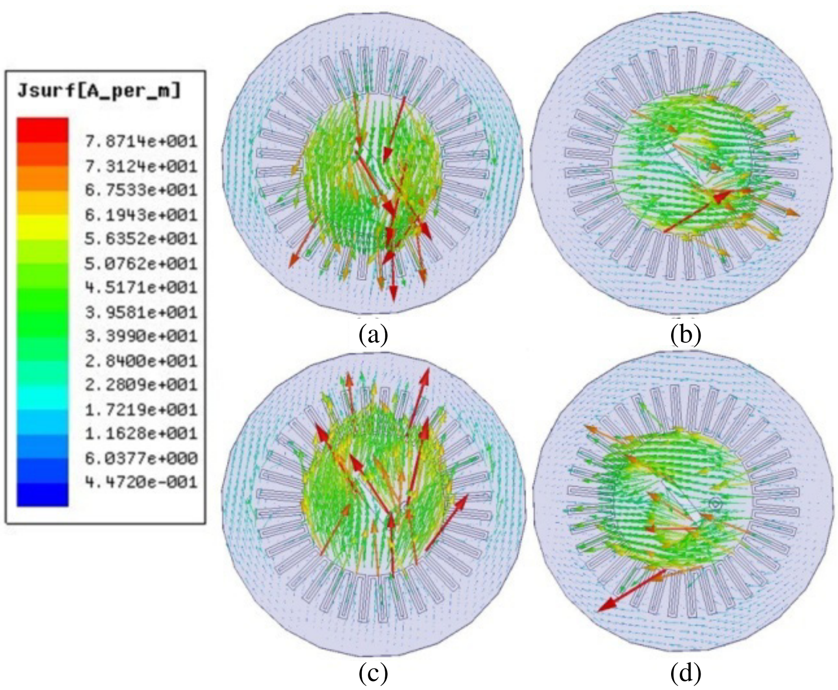

Figure 3. Current distributions of the antenna at TM_{11} mode: (a) $t = 0$; (b) $t = T/4$; (c) $t = T/2$; (d) $t = 3T/4$.

feed probe position *offset* is the main factor to excite three modes. Only one resonance (TM_{02}mode) can be excited when *offset* is zero. When *offset* becomes nonzero, a lower frequency resonance (TM_{11} mode) and a higher frequency resonance (TM_{12} mode) appear. With *offset* increasing, the impedance match for TM_{11} and TM_{12} modes gets better while that for TM_{02} mode gets worse. Fig. 2 shows the simulated reflection coefficient of the antenna. Through tuning the parameter *offset*, three resonant points are excited, and reflection coefficient in these three frequency bands are lower than -10 dB.

Figures 3 to 5 describe the current distributions of the antenna at three modes, respectively. We can

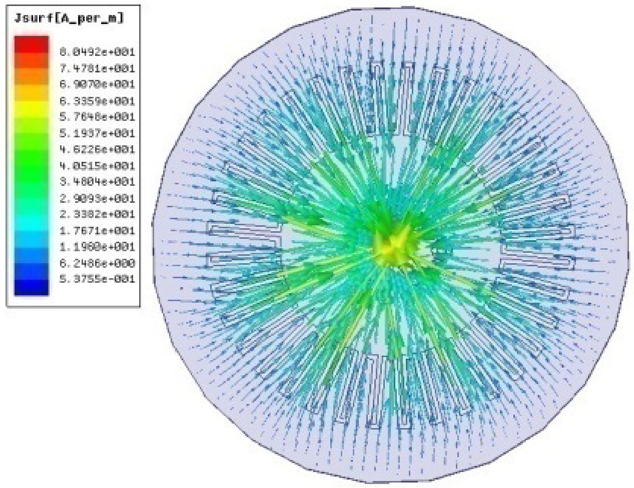

Figure 4. Current distribution of the antenna at TM_{02} mode.

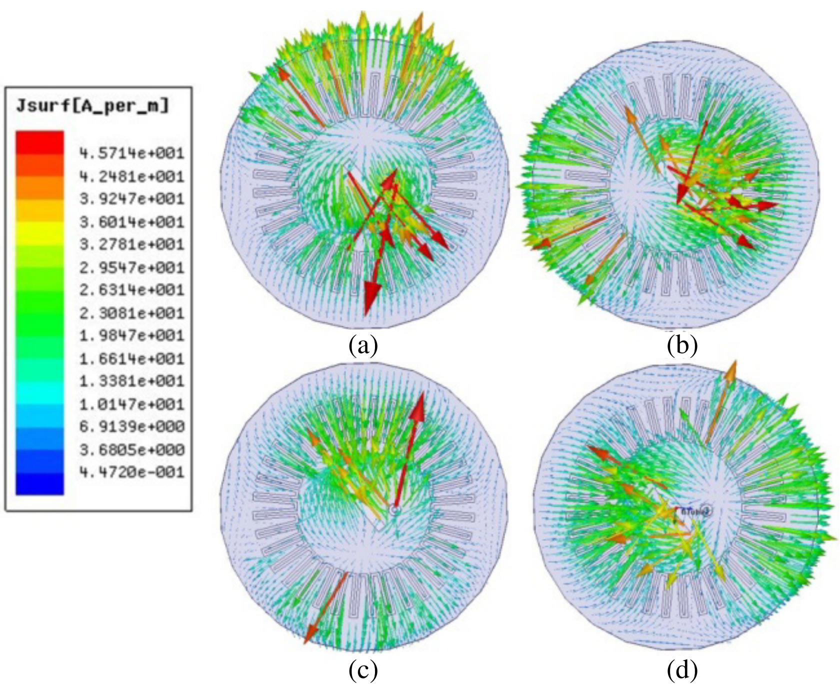

Figure 5. Current distributions of the antenna at TM_{12} mode: (a) $t = 0$; (b) $t = T/4$; (c) $t = T/2$; (d) $t = 3T/4$.

see that the currents have the same direction in Fig. 3, thus at this situation antenna operates at TM_{11} mode, contributing a maximum of radiation in the broadside. In Fig. 5, there exist opposite currents, which means that the antenna operates at TM_{12}. The high-order TM_{12} mode can also radiate boresight beams, and the rigorous analysis has been done in [8]. The current distribution has radial symmetry as shown in Fig. 4. It is illustrated that the antenna operates at TM_{02} mode, and the radiation pattern for this mode will be similar to that of the monopolar antenna, giving a null radiation in the broadside.

Moreover, through adjusting the size of the 45° inclined rectangular slot, circularly polarized (CP) property for the TM_{11} and TM_{12} modes can be achieved. As shown in Fig. 2, two near-degenerate resonant modes are separated at TM_{11} and TM_{12} modes. Fig. 3 and Fig. 5 describe the current distributions of the antenna for the TM_{11} and TM_{12} modes at $t = 0$, $t = T/4$, $t = T/2$ and $t = 3T/4$. It can be found that the direction of currents rotates in the counterclockwise direction with a period of time T. So TM_{11} and TM_{12} own right-hand circularly polarized (RHCP) characteristic.

3. SIMULATED AND EXPERIMENT RESULTS

After optimization with Ansoft HFSS, geometry parameters for the antenna are fixed as $offset = 5.8$ mm, $w = 0.5$ mm, $R_1 = 20.8$ mm, $R_2 = 12.5$ mm, $L_s = 10.6$ mm, $W_s = 1.7$ mm. A prototype antenna is fabricated to validate the predictions, and its picture is shown in Fig. 6. The simulated and measured reflection coefficients are depicted Fig. 7. It is demonstrated that there is good agreement between simulation and measurement expect for a frequency shift, which may be caused by the fabrication tolerance. The measured impedance bandwidths with reflection coefficients below −10 dB are around 130 MHz at 2.4 GHz, 125 MHz at 5.2 GHz, and 330 MHz at 6.35 GHz. The relative bandwidths are 5.2%, 2.4%, 5.1%, respectively. The simulated and measured axial ratios (ARs) at TM_{11} and TM_{12} modes are

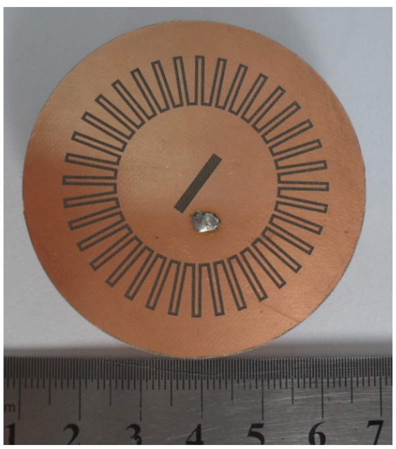

Figure 6. Photograph of the antenna prototype.

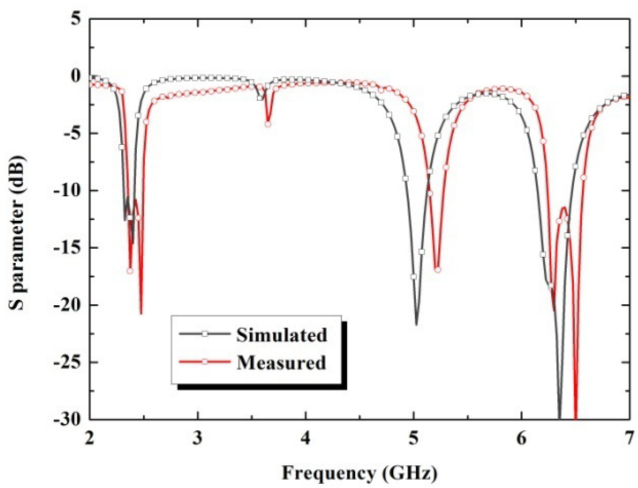

Figure 7. Simulated and measured reflection coefficients of the antenna.

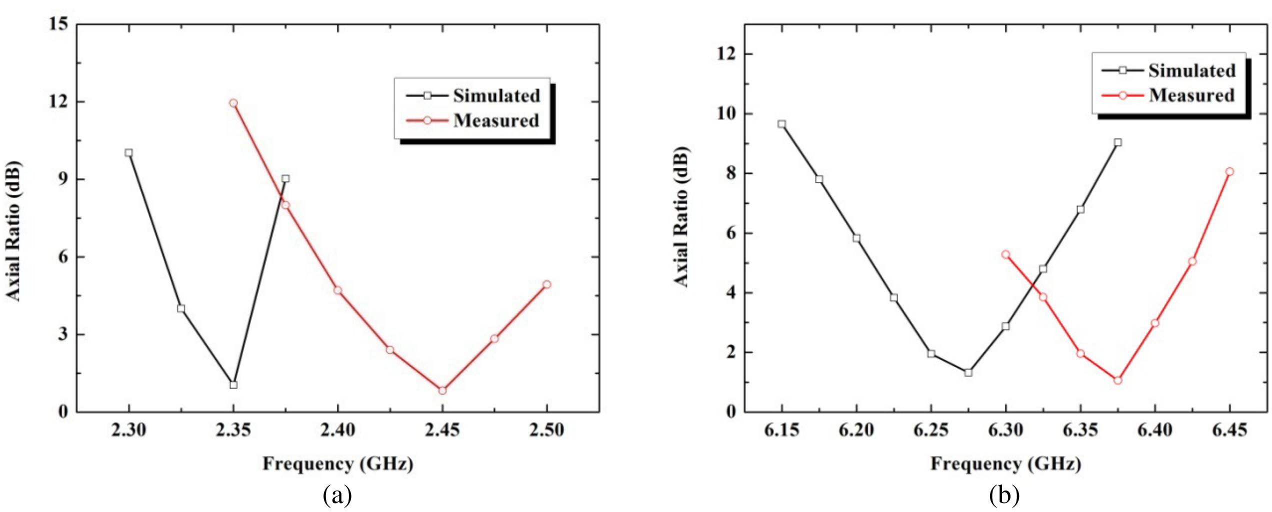

Figure 8. Simulated and measured axial ratios: (a) TM_{11} mode; (b) TM_{12} mode.

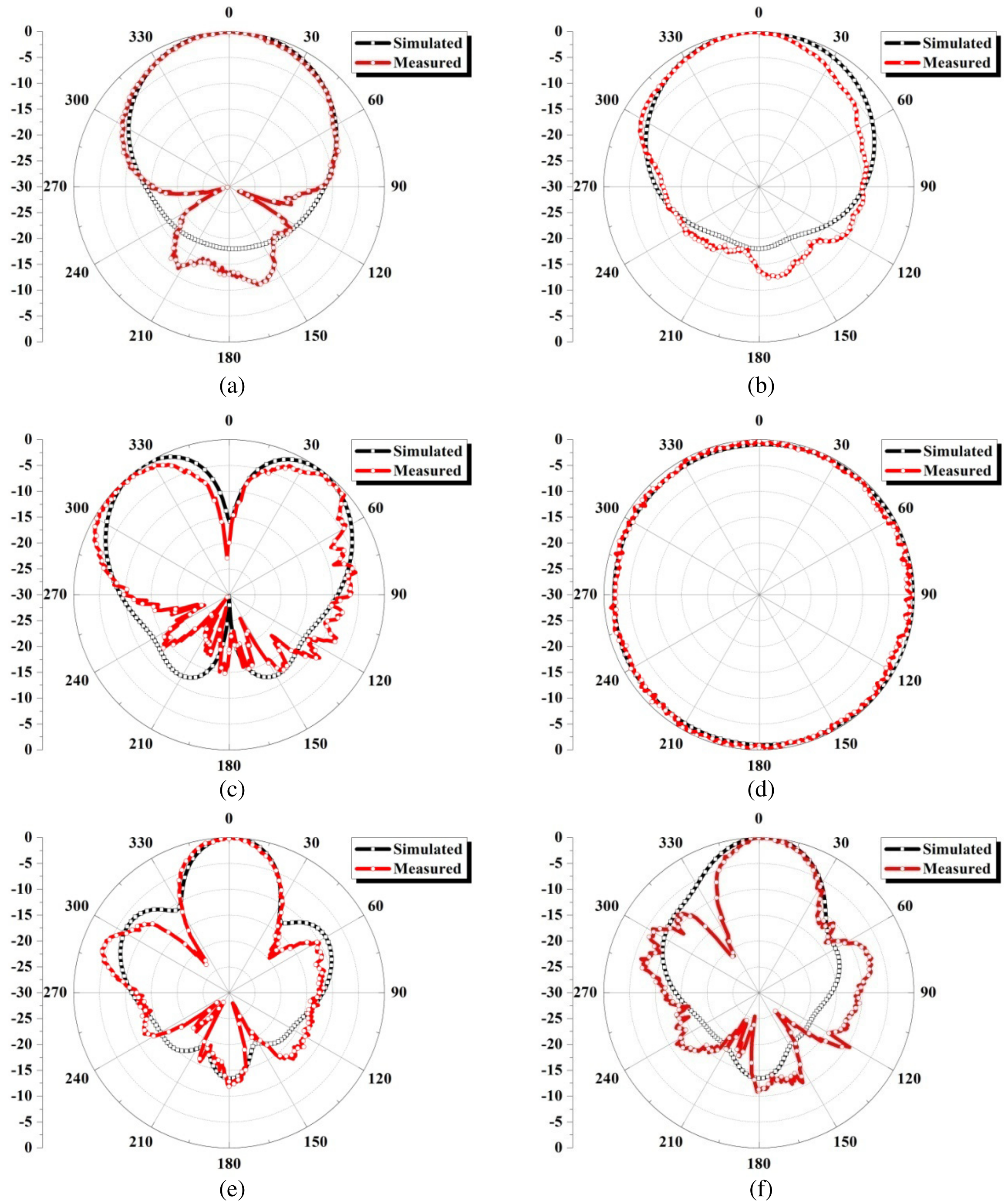

Figure 9. Simulated and measured radiation patterns: (a) E plane at 2.4 GHz; (b) H plane at 2.4 GHz; (c) E plane (simulated at 5 GHz, measured at 5.2 GHz); (d) H plane (simulated at 5 GHz, measured at 5.2 GHz); (e) E plane at 6.35 GHz; (f) H plane at 6.35 GHz.

shown in Fig. 8. The measured 3-dB AR bandwidths are approximately 2.5% and 1.1%, respectively.

The normalized simulated and measured radiation patterns of the antenna are plotted in Fig. 9. Measured radiation patterns are compared with simulated ones in E-plane and H-plane at three resonant frequencies. All the measured radiation patterns are in good agreement with the simulated ones. As analyzed above, the patch-like radiation for TM_{11} and TM_{12} modes and the monopole-like radiation for TM_{02} mode are obtained. The measured peak gains are 4.8 dBi at 2.4 GHz, 4.7 dBi at 5.2 GHz and 8.1 dBi at 6.35 GHz. At the frequency of 5.2 GHz, the measured E-plane pattern has a null of -23 dB in broadside, and the peak gain is obtained with an up obliquitous angle of 45° from the azimuthal plane. In H-plane, the omni-direction with gain variation less than 2.5 dB is achieved. At the frequency of 6.35 GHz, the radiation patterns have side lobes, and the maximum side lobe is nearly -5 dB in the measured E-plane pattern, which is caused by the opposite currents in TM_{12} mode as shown in Fig. 5.

4. CONCLUSION

In this paper, a multifunction microstrip slot antenna is developed. Based on a simple single-layer and single-feed structure, this antenna can work at three bands with two patch-like radiation patterns and one monopolar radiation pattern. Besides, circularly polarization is realized at TM_{11} and TM_{12} modes while linearly polarization is realized at TM_{02} mode. The simulated and measured results show that this antenna is promising for applications in vehicle communication for its merits of simple structure, high gain, multi-frequency, polarization diversity and radiation pattern selectivity.

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