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A Low-Profile, Wideband, Dual-Polarized Patch Dipole with Unidirectional Radiation Patterns

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Abstract—A low-profile, wideband dual-polarized antenna with unidirectional radiation patterns is the design goal of this paper. To obtain such antenna characteristics, the design is divided into two steps. First, a coax-feed wideband antenna element with a simple geometry is proposed. The antenna element consists mainly of a quasi-square patch-dipole, a coupling E-shaped feeding structure and a shorting pin. The electromagnetic coupling between the feeding structure and the non-contact quasi-square patch can be flexibly controlled by a pair of fan-shaped stubs. Secondly, two pairs of the proposed antenna elements are selected to construct a dual-polarized antenna. To further reduce the profile of the antenna, two techniques are utilized. One is the mutual coupling distributing among the elements while the other is to add four rectangular stubs within the inner region. A prototype of the dual-polarized antenna is fabricated and measured. Measurement results demonstrate that the prototype antenna obtains an overlapped fractional bandwidth of 38.9% from 1.7 to 2.52 GHz with a good isolation higher than 32 dB. Both unidirectional radiation patterns with front-to-back ratios better than 20 dB across the whole frequency band and cross polarization levels lower than −22 dB in most operating frequency band are obtained. Additionally, the dual-polarized antenna achieves average gains about 9.9 dBi and 10.1 dBi for Port 1 and Port 2, respectively.

1. INTRODUCTION

Antennas are key components of wireless communication systems as they play important roles in transmitting and receiving signals. With rapidly developed wireless technology, amounts of wireless services emerge which result in a huge challenge on system capacity. Many researchers focus on expanding the system capacity by using techniques such as frequency reuse, radiation patterns diversity and polarization diversity. Among them, antennas with polarization diversity receive extensive attention since they are capable of suppressing multi-path effect and potentially double the transmission channels. In order to meet the requirements of some wireless services simultaneously, antennas are highly demanded to have characteristics of wide bandwidth, low profile and unidirectional radiation patterns.

In recent decades, numerous dual-polarized antennas are proposed. Patch antennas and dipole antennas are two dominating types among them. To expand the bandwidth of a patch antenna, some feeding techniques are proposed for lowering the high Q value. In [1], a hybrid feeding structure consisting of electric probe and magnetic loop feeds is used to feed a patch antenna for dual polarizations. The overlapped fractional bandwidth is improved to 11.5%. In [2–5], feeding methods such as meandering/T-type probe, aperture coupling and probe & aperture hybrid feeds are proposed to excite patch antennas for a wide bandwidth up to 26%. However, it is still far from enough to cover PCS, UMTS and WLAN applications at the same time. As another popular candidate of dual-polarized antenna, dipoles have good characteristics in terms of bandwidth, isolation and cross polarization except the

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profile [6, 7]. In general, dipole antennas have a relatively high profile of about a quarter free-space wavelength for unidirectional radiation patterns. To reduce the high profile of dipole antennas, AMC (Artificial Magnetic Conductor) reflectors are presented to replace the ground plane [8, 9]. However, the AMC-based antennas are not capable of operating in a wide frequency band since the in-phase characteristics of AMC structures can only be sustained in a narrow frequency band.

In this paper, a low-profile wideband dual-polarized antenna with unidirectional radiation patterns is proposed. Firstly, a quasi-square patch dipole is presented. The low profile is realized by enhancing the coupling between the patch and the ground plane. Secondly, a dual-polarized antenna composed of two pairs of differentially-fed antenna elements is constructed. By further utilizing the mutual coupling and designing four small rectangular stubs, the low edge of the frequency band is shifted downward to 1.7 GHz, thus reducing the profile to $0.147\lambda_C$, where λ_C is the free-space wavelength at the center frequency of operation (2.11 GHz). The dual-polarized antenna prototype has been fabricated and measured. Measured results demonstrate that good characteristics including wide bandwidth, high isolation, low cross polarization and high front-to-back ratio are obtained.

2. LOW-PROFILE QUASI-SQUARE PATCH-DIPOLE

2.1. Configuration and Simulation Results of the Quasi-Square Patch Dipole

The configuration of a quasi-square patch dipole is shown in Figure 1. The proposed antenna is mainly composed of a pair of quasi-square patches, an E-shaped coupling feeding structure with two fan-shaped stubs at its two ends, a shorting pin and a metal reflector. In the design, a 1 mm-thick FR4 substrate with dielectric constant of $\epsilon_r = 4.4$ and loss tangent of 0.02 is used. The two quasi-square patches separated by a gap of g are printed on the bottom of the substrate while the E-shaped feedline is etched on the top of the same substrate. To excite the dipole antenna, the inner conductor of the coaxial cable is connected to the E-shaped microstrip line, and the outer conductor is soldered to one of the quasi-square

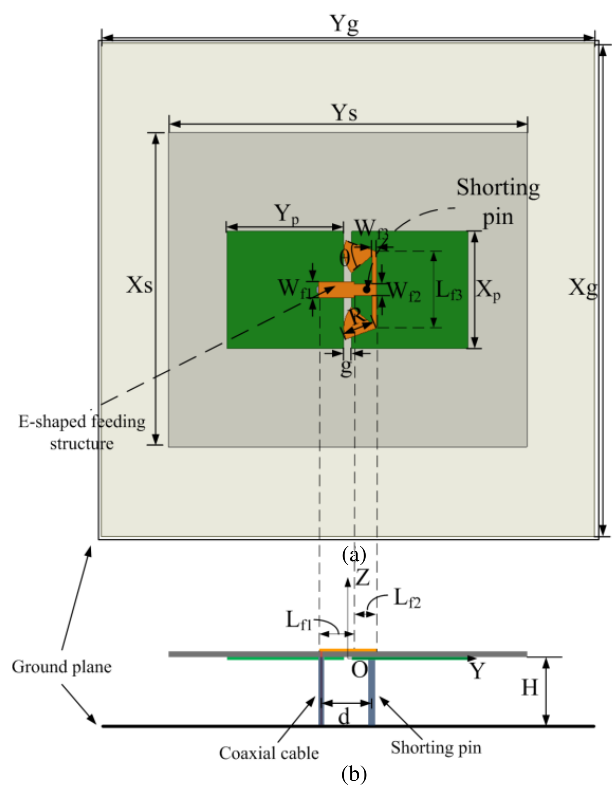

Figure 1. Geometry of the proposed quasi-square patch dipole antenna, (a) top view, (b) side view.

patches, the other patch being coupling fed by the E-shaped microstrip feedline. Symmetrical to the coaxial cable, a shorting pin is designed which connects the radiating patch and the metal ground. The detailed geometry parameters shown in Figure 1 are listed as follows: $Xg = Yg = 130\,\text{mm}$, $Xs = 70\,\text{mm}$, $Ys = 80\,\text{mm}$, $Xp = 27\,\text{mm}$, $Yp = 26.5\,\text{mm}$, $W_{f1} = 3.5\,\text{mm}$, $W_{f2} = 3\,\text{mm}$, $W_{f3} = 1\,\text{mm}$, $g = 1.8\,\text{mm}$, $R = 7.3\,\text{mm}$, $H = 19\,\text{mm}$, $\theta = 60°$, $Lf1 = 8\,\text{mm}$, $Lf2 = 5.75\,\text{mm}$, $L_{f3} = 17\,\text{mm}$, $d = 12.8\,\text{mm}$.

The simulated $|S_{11}|$ of the proposed dipole antenna is plotted in Figure 2. It can be seen that the antenna covers a frequency band from 1.94 to 2.76 GHz. The normalized radiation patterns in both XOZ and YOZ planes at 2.4 GHz is illustrated in Figure 3. Clearly, the main radiations in both planes are towards $+Z$-axis without any tilt while the cross polarizations maintain below -40 dB due to the introduction of the shorting pin.

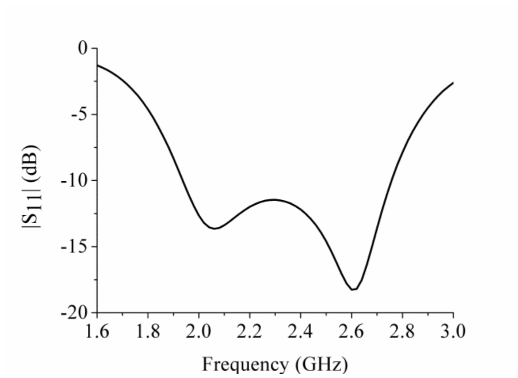

Figure 2. Simulated $|S_{11}|$ of the proposed patch dipole.

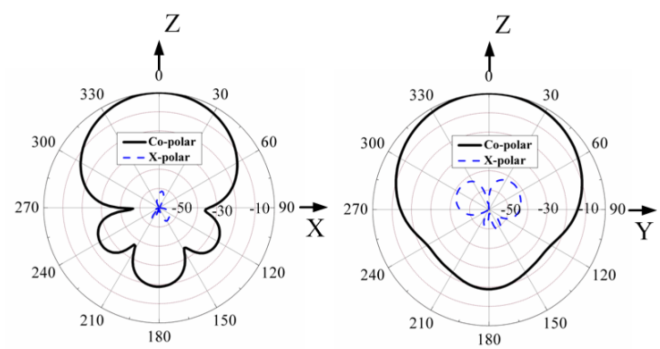

Figure 3. Simulated radiation patterns at 2.4 GHz of the patch dipole.

2.2. Design Process of the Quasi-Square Patch Dipole and Parameter Discussions

Inspired by a previous folded dipole antenna (called as antenna #1) in [10], a low-profile quasi-square patch dipole antenna is developed. To have a better understanding of the design process, the geometry of antenna #1 is given in Figure 4. It should be emphasized that our motivation is to design a low-profile antenna. However, when the distance of the dipole antenna #1 from the ground plane is set at 19 mm (a very low profile compared with conventional dipole antenna), the impedance matching goes worse. While keeping the distance unchanged, we try to find a method to solve the problem. Through some simulations, it is found that the width W plays a crucial role in adjusting impedance matching. Figure 5 illustrates the impedance curves on Smith chart with different W. It can be seen that the impedance curve is pulled almost along the real axis towards the matching point as the width W of antenna #1 increases. Moreover, the impedance circle is gradually shrunk and enclosed by the SWR = 2 : 1 circle. A conclusion is attained that both the real and imaginary parts of the antenna #1's impedance can be improved by enlarging the coupling size with the metal ground. To obtain a stronger coupling, we directly modify the folded dipole antenna into a quasi-square patch dipole (one state when W is wide enough), which is the first step of our design. For a comparison, the impedance curve of the proposed antenna is also added in Figure 5. Clearly, an impedance circle is created, which is located near the matching point. Then, an E-shaped coupling feeding structure with two fan-shaped stubs is designed to replace the L-shaped feedline for better performance. Figure 6 shows the simulated $|S_{11}|$ curves when the antenna is excited with these two different feeding structures. It can be seen that there is no significant difference between the simulated results. However, when the antenna is fed by an L-shaped feeding structure, the antenna cannot operate with $|S_{11}| < -10$ dB in the frequency band from 2.2 to 2.4 GHz after amounts of optimization. It is not flexible for L-shaped feeding structure to adjust f_2 to obtain a wide frequency band with good impedance matching. Furthermore, Figure 7 shows how the E-shaped feedline with two stubs affects f_2. It can be seen that radius (R) can be utilized to adjust the second resonant frequency. As R increases, the second resonant frequency shifts towards the first one. In other words, we can achieve a tradeoff between bandwidth and impedance matching by simply altering the radius of the fan-shaped stubs. Finally, we find that the cross polarization in H-plane is not satisfactory, which is mainly caused by the current distributed on the outer conductor of the coaxial cable. To offset the negative effect, a shorting pin located symmetrically is adopted to generate current with same magnitude and out of phase, improving the cross polarization.

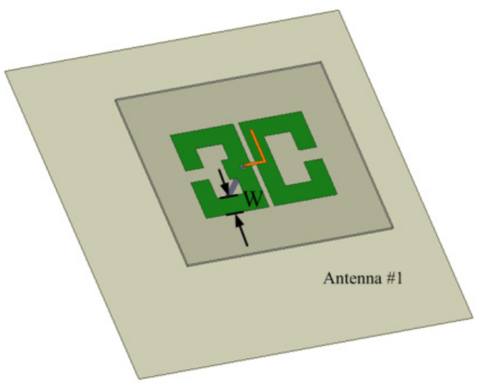

Figure 4. Geometry of antenna #1.

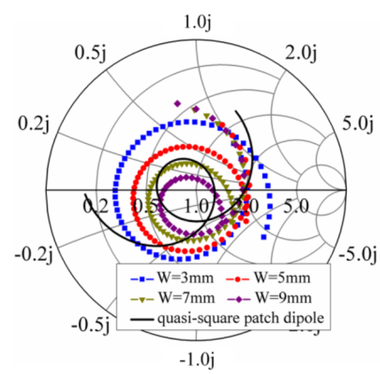

Figure 5. Impedance curves on Smith chart with different W (normalized impedance value equals 50 Ω).

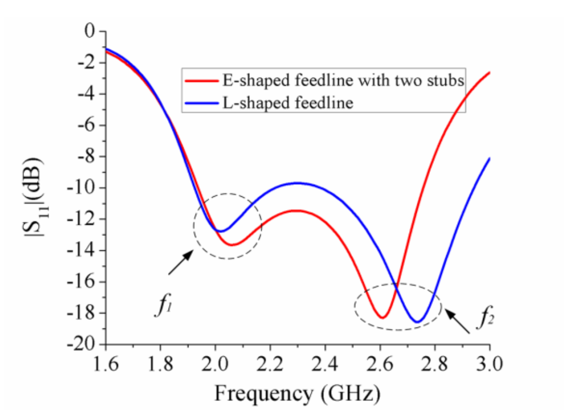

Figure 6. Simulated $|S_{11}|$ of the antenna with different feeding structures.

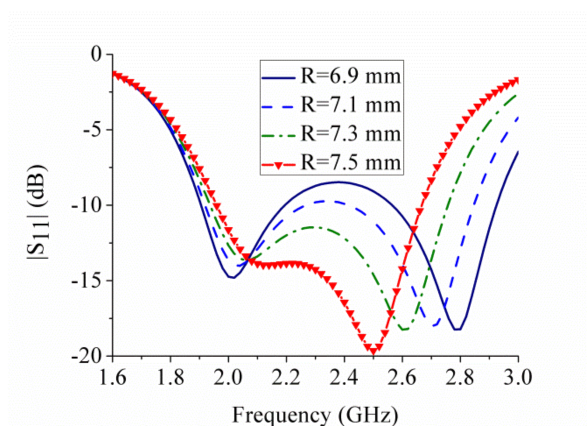

Figure 7. Simulated $|S_{11}|$ with different radii (R).

3. DESIGN OF LOW-PROFILE DUAL-POLARIZED ANTENNA

Based on the designed quasi-square patch dipole, a dual-polarized antenna fed by two similar feeding networks is constructed. The configuration of the dual-polarized antenna is shown in Figure 8. For brevity, the feeding networks [11] printed on the bottom of 1 mm-thick Substrate B (F4B with dielectric constant of $\epsilon_r = 2.2$) are not given in Figures 8(a) and (b). Figure 8(d) shows the detailed geometry of the dividers. In the design, the opposing pairs of antenna elements are 180° differentially excited for low cross polarization. To be specific, four points marked with "A, B, C, D" in Figures 8(a) and (d) are correspondingly connected by coaxial cables, respectively. The simulated S-parameters and phase difference of the feeding network (port 1 is input port, and ports 2 & 3 are output ports) are illustrated in Figure 9. As can be seen, it functions well across the frequency band from 1.7 to 3 GHz.

At the very beginning, four antenna elements without the rectangular stubs are studied. As illustrated in Figure 10, compared with the single antenna element (without any mutual coupling), four antenna elements are capable of working in a lower frequency band with a better impedance matching,

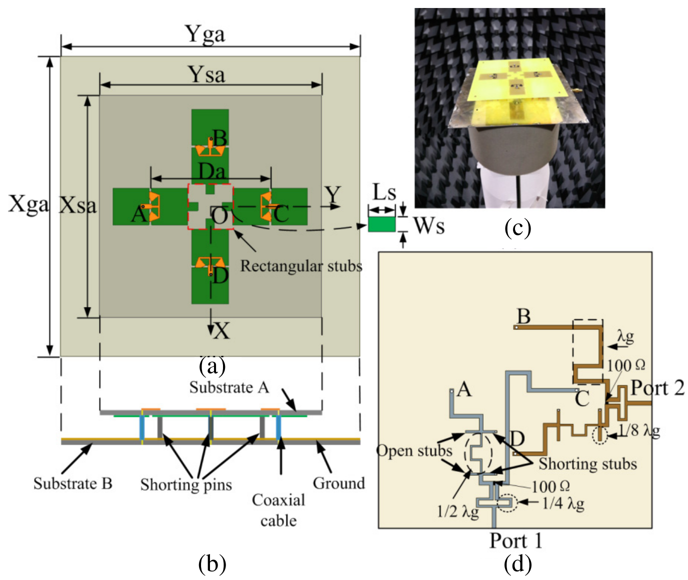

Figure 8. Configuration and picture of the proposed dual-polarized antenna (a) top view (b) side view (c) antenna prototype (d) geometry of the two wideband feeding network along with their deployments. The values of the parameters are listed as follows (unit: mm): $Xsa = Ysa = 163(1.148\lambda_C)$, $Xga = Yga = 220(1.547\lambda_C)$, $Da = 88$, $Ls = 7.6$, $Ws = 6$.

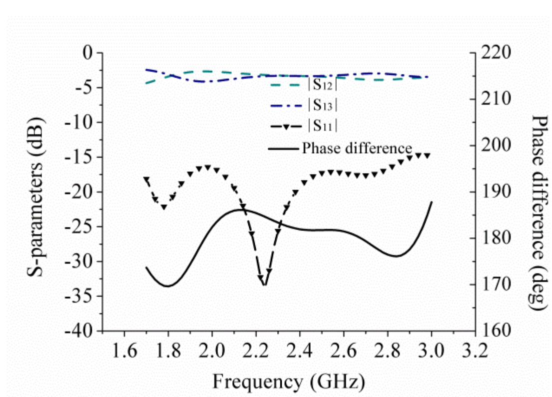

Figure 9. Simulated S-parameters and phase difference for feeding network.

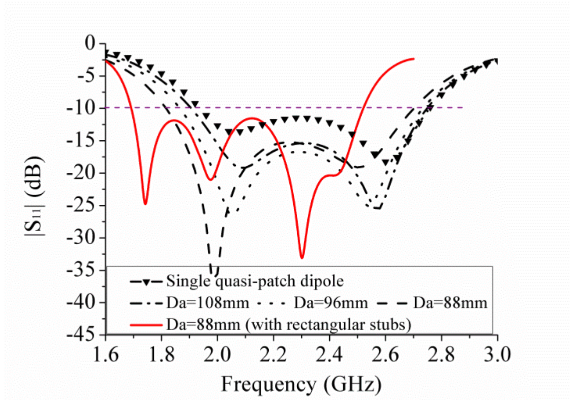

Figure 10. Simulated $|S_{11}|$ results with different mutual coupling.

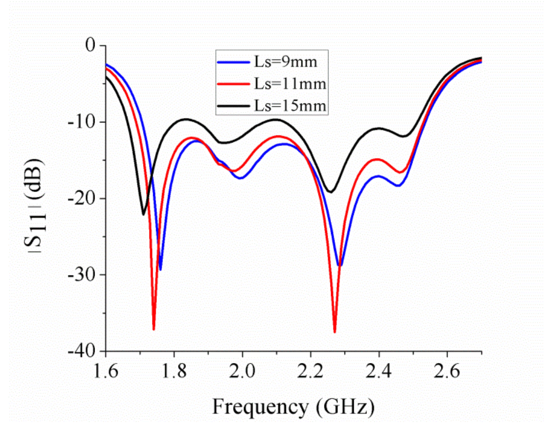

Figure 11. Simulated $|S_{11}|$ results with different stub lengths (Ls).

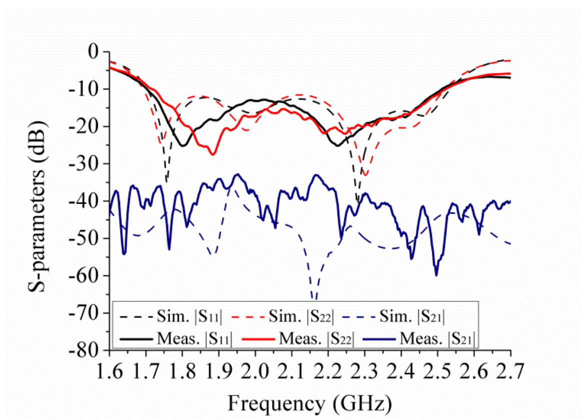

Figure 12. Measured and simulated S-parameters of the dual-polarized antenna.

thus leading to a lower profile. It is also worth noting that the low edge of the working band can shift from 1.91 GHz to 1.82 GHz by reducing the element spacing (Da). In other words, if we can reasonably utilize the mutual coupling between the antenna elements, a low-profile dual-polarized antenna with a wide bandwidth can be achieved. However, if the element spacing becomes too small, the four antenna elements will touch with each other. In this case, the antenna cannot work well. In order to cover PCS (1710–1880 GHz), four rectangular stubs are added which are marked in Figure 8(a). As expected, a further shift (see Figure 10) of the low frequency from 1.82 GHz to 1.69 GHz is obtained, which is mainly caused by two reasons. The first one is that the mutual coupling is further enhanced. The second one is that the length of one arm of the quasi-square dipole which lies close to the center is extended. Also, some parametric analyses on the different stub lengths (Ls) are made as shown in Figure 11. It is clear that the stub length affects the frequency band. When the stub length is increased, the dual-polarized antenna operates in a lower frequency band while the impedance matching goes worse. In this design, $Ls = 11$ mm is selected for good performance. Since the mutual coupling and introduction of the stubs usually change the input impedance of the antenna, we have adjusted radius R of the fan-shaped stub from 7.3 mm to 7.8 mm and the width $Wf2$ of the stepped feedline from 3 mm to 1.5 mm for a good impedance matching in the design of the dual-polarized antenna.

To verify the design, a prototype of the dual-polarized antenna with a low profile of $0.147\lambda_C$ has been fabricated, and its picture is shown in Figure 8(c). In the design process, the antenna is simulated using Ansys HFSS v15.0 software. The S-parameters of the proposed dual-polarized antenna are measured by WILTRON 37269A network analyzer. The measured S-parameters along with the simulated ones are plotted in Figure 12. It can be seen that the dual-polarized antenna achieves an overlapped bandwidth of 820 MHz operating from 1.7 GHz to 2.52 GHz which can simultaneously cover several wireless services such as PCS, UMTS and WLAN. Across the whole frequency band, the measured isolation between the two polarizations is better than 32 dB while the simulated one is higher than 36 dB. The measured results agree well with the simulated ones, and the reasonable difference is mainly due to the inaccurate fabrication and soldering errors. The radiation patterns of the proposed dual-polarized antenna are measured with Satimo's multi-probe antenna measurement system in anechoic chamber. Since the dual-polarized antenna has a symmetrical structure, the radiation patterns for both polarizations are very similar. For brevity, the radiation patterns for Port 1 are given. Figure 13 presents the radiation patterns of the proposed dual-polarized antenna measured and simulated at 1.7, 2.1 and 2.5 GHz. As can be seen, the main radiation patterns are towards $+z$-axis. The cross-polarization levels in both XOZ and YOZ planes maintain lower than -22 dB in most frequency band while the front-to-back ratios are higher than 20 dB across the whole operating frequency band. The measured and simulated gains for both polarizations are depicted in Figure 14. The average measured gains are about 9.9 dBi and 10.1 dBi for Port 1 and Port 2, respectively, slightly lower than the simulated ones.

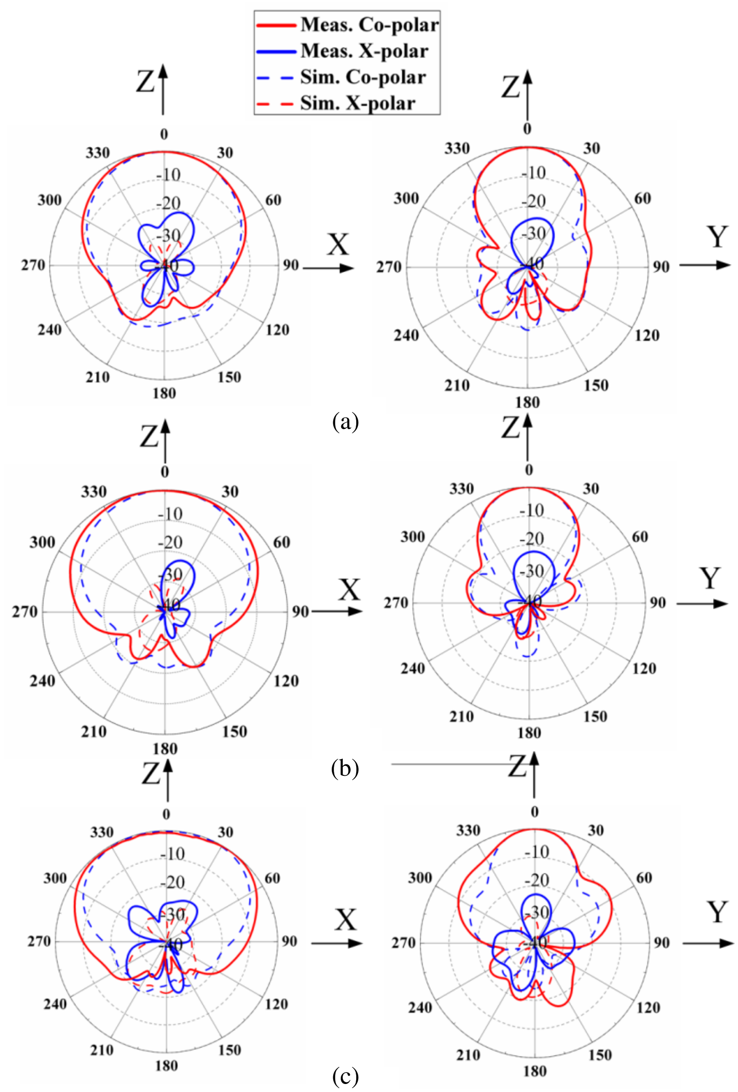

Figure 13. Measured and simulated radiation patterns for Port 1 at (a) 1.7 GHz, (b) 2.1 GHz, and (c) 2.5 GHz.

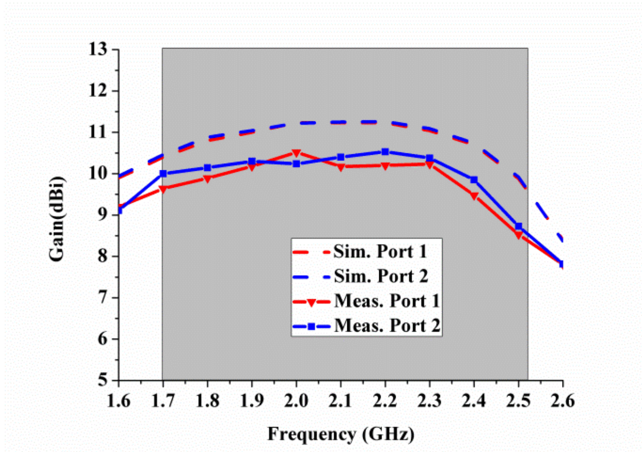

Figure 14. Measured and simulated gains for both polarizations.

Some comparisons between antennas published in [10, 12–16], and the proposed one is made as shown in Table 1. It can be seen that the proposed dual-polarized antenna has some advantages such as lower profile and wider operating frequency band than the works in [12–15]. Although the proposed antenna has a similar profile to the one in [16], it still demonstrates higher isolation and wider bandwidth. Compared with antenna #1 in [10], the proposed dual-polarized antenna has lower profile but narrower bandwidth. It is like a tradeoff version of antenna #1. However, when the profile of antenna #1 is lowered the same as the proposed one, the impedance of the antenna #1 cannot be matched well.

Table 1. Comparisons between some published works with the proposed one.

Ant.	Profile	Overlapped Bandwidth	Isolation (dB)	Cross Polarization (dB)
Ant. in [12]	$0.440\lambda_C$	14%	> 20	< -18
Ant. in [13]	$0.289\lambda_C$	17.3%	> 30	< -10
Ant. in [14]	$0.186\lambda_C$	29%	> 23	< -25
Ant. in [15]	$0.160\lambda_C$	24.9%	> 29	< -15
Ant. in [16]	$0.141\lambda_C$	29%	> 22	< -18
Ant. #1 in [10]	$0.316\lambda_C$	53% (< 15 dB)	> 30	< -20
Proposed Ant.	$0.147\lambda_C$	38.9%	> 32	< -20

4. CONCLUSION

A quasi-square dipole antenna with a simple structure is proposed. Based upon the quasi-square dipole antenna, a dual-polarized antenna with a low profile of $0.147\lambda_C$ is developed by utilizing proper mutual coupling and adding four rectangular stubs. The dual-polarized antenna prototype achieves a wide bandwidth of 38.9% from 1.7 to 2.52 GHz for both ports with a high isolation better than 32 dB, which can be used for PCS, UMTS and WLAN applications. Throughout the entire operating band, the proposed dual-polarized antenna exhibits good unidirectional radiation patterns and low cross-polarization levels. In addition, stable and high gains for both polarizations are obtained.

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