the average, the highest, and the lowest, respectively, over the 10-dB impedance bandwidth corresponding to each resonant mode. The simulation shows that the total efficiency of the fundamental slot mode can be slightly improved by about 0.4 dB when e is increased from 1.5 to 5.5 mm, while that of the third-harmonic of the strip monopole mode is decreased by about 0.8 dB.

This slot antenna can be embedded on PCB of a notebook PC or a tablet, or on the metal casing of a handheld device.

VI. Conclusion

A multi-band H-shaped slot antenna has been designed, with a complete analysis on its geometrical parameters. Its 10-dB impedance bandwidth covers the bands of 1.555–1.5775 GHz, 2.395–2.695 GHz and 4.975–5.935 GHz, making it ready for GPS and Wi-Fi applications. Four different operating resonant modes are identified, and the effects of different parameters on these modes have also been analyzed for consistency. Radiation patterns and total radiation efficiency are also presented, and the measurements confirm the simulation results reasonably well.

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A Compact Dual-Polarized Double E-Shaped Patch Antenna With High Isolation

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***Abstract*—A compact dual-polarized double E-shaped patch antenna with high isolation for pico base station applications is presented in this communication. The proposed antenna employs a stacked configuration composed of two layers of substrate. Two modified E-shaped patches are printed orthogonally on both sides of the upper substrate. Two probes are used to excite the E-shaped patches, and each probe is connected to one patch separately. A circular patch is printed on the lower substrate to broaden the impedance bandwidth. Both simulated and measured results show that the proposed antenna has a port isolation higher than 30 dB over the frequency band of 2.5 GHz – 2.7 GHz, while the return loss is less than -15 dB within the band. Moreover, stable radiation pattern with a peak gain of 6.8 dBi – 7.4 dBi is obtained within the band.**

***Index Terms*—Dual-polarization, E-shaped patch, high isolation, microstrip antenna.**

I. Introduction

With the development of base station for next generation mobile communication, compact microstrip antennas have received much attention for their attractive features, such as light weight, low profile, low cost, and ease to integrate with circuits. These features of microstrip antenna attracted amounts of researchers to study and a series of literatures have been reported [1]–[5]. Dual-polarized antenna is commonly used to improve the system performance by polarization diversity in base station. In a dual-polarized antenna with both transmitting and receiving channels for a frequency-reuse communica-

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Digital Object Identifier 10.1109/TAP.2013.2262664

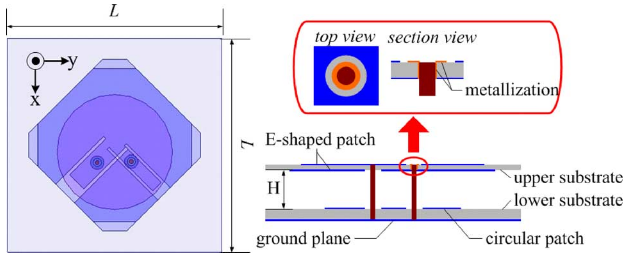

Fig. 1. Geometry of the proposed antenna.

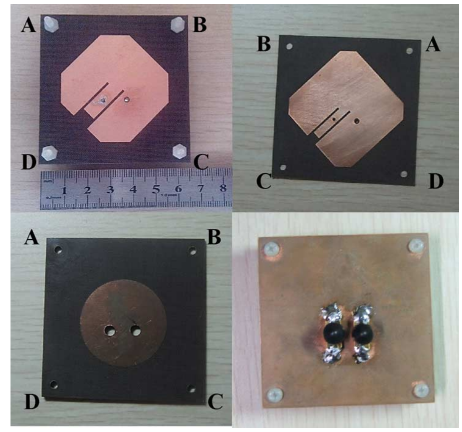

Fig. 2. Photos for the prototype of the proposed antenna, showing the upper face (upper left) and lower face (upper right) of the upper substrate, the upper face (lower left) and lower face (lower right) of the lower substrate.

tion system, good port isolation within each operation range is necessary. Various designs have been proposed to realize dual-polarized antenna with good port isolations. Many previous works focus on the feed method and new network layout to obtain high isolation. The port isolation can be up to about 30 dB by using an H-slot coupled feed [6] and 28 dB by using C-slot coupled feed [7]. Anti-phase feeding technique can also be used to achieve very high port isolation and low cross-polarization [8], [9]. However, the feed network seems more complicated and the power divider also affects the radiation performance. Other techniques by modifying antenna structure to improve port isolation were also reported. In [10], a slot loaded lower patch is introduced to improve isolation between the two polarization ports, which maintains a port isolation of 30 dB within the band 2.5–2.7 GHz. However, this antenna needs an air thickness of about $0.092\lambda_0$ (λ_0 is the free-space wavelength at the central operating frequency). By etching out a symmetric portion of crossed slots from the surface of a square probe-fed patch, a compact, probe-fed microstrip patch antenna with a high isolation of 38 dB between the two ports is achieved in [11]. A coax-feed wide-band dual-polarized patch antenna with high port isolation is designed in [12]. By introducing two short pins, the isolation between the two ports remains more than 38 dB within the frequency band 1.7–2.73 GHz. However, the performance may be degenerated in array environment due to the large ground plane.

On the other hand, for pico base station application, the antenna with compact size is usually of more importance than high port isolation. Yet the compact size always leads to narrow bandwidth, thus the design trade-off among different antenna configurations or parameters has to be made. Generally speaking, the techniques presented in [6]–[12] are not suitable if compact size, wide bandwidth and high port isolation are required simultaneously. Technique of slot cutting on the radiating patch is usually used to enhance the bandwidth of a compact patch antenna. Recently, a series of E-shaped patch antennas (ESPAs) have been presented in [13]–[18]. ESPAs proposed in [13]–[16] have wide bandwidth, but the air gap thickness of these antennas are all over $0.06\lambda_0$. In [17], by introducing a distributed LC circuit to the ESPA, the air thickness is reduced to $0.0344\lambda_0$. ESPA attracted much attention for its wide impedance bandwidth and good radiation characteristic, but it is mostly used in unipolar antennas and rarely employed in dual-polarized antennas. To our knowledge, there is still no open literature report to show that E-slot structure has ever been applied to dual-polarized antenna. In [18], a diversity antenna composed of two orthogonal ESPAs is used for space and polarization diversity, but the two antennas work independently, one for transmitting and the other for receiving. Moreover, the maximum edge length of the antenna is approximately $1.174\lambda_0$, and the port isolation is only about 20 dB. Some other types of slot-loaded patch antennas, such as the U-shaped patch [19] and the Wang-shaped patch [20], are also rarely employed in dual-polarized antennas.

In this communication, two E-slot structures mounted orthogonally are introduced to form dual-polarization antenna with high port isolation. The maximum edge length L (Fig. 1) of the antenna is only about $0.574\lambda_0$, which is 49% smaller than that of the design in [17]. The air thickness H (Fig. 1) of the proposed antenna is only about $0.043\lambda_0$, which is 47% thinner than that of the design in [10] and also much thinner than those of the ESPAs in [13]–[17]. Simulated and measured results show that the proposed antenna achieves a very good antenna performance with low return loss and high port isolation over the LTE (Long Term Evolution) frequency band 2.5–2.7 GHz, and is thus suitable for pico base station antennas in the LTE wireless communication system.

II. Antenna Design and Discussion

A. Two E-Shaped Patches for Dual-Polarization

The general theory of the ESPA has been well studied that the antenna width controls the higher resonant frequency while the slots control the lower resonant frequency. Because of the dual resonant character, this kind of microstrip antenna can achieve a wide bandwidth. In this communication, two orthogonal E-slot structures are combined together to achieve dual-polarization. Fig. 1 shows the configuration of the proposed antenna. The antenna is composed of two layers of substrate, with a thickness of 0.508 mm and 1.575 mm, respectively. Both of the substrates have a permittivity of 2.55 (Taconic TLX-8). The two E-shaped patches are printed orthogonally on both sides of the upper substrate, while a circular patch and a metallized ground plane are printed on both sides of the lower substrate. A prototype of the antenna is illustrated in Fig. 2.

As shown in Fig. 1, two probes are used to feed the E-shaped patches. On each patch, there is an isolating hole for the probe to go through, and each probe connects to one patch and is isolated to the other. For each E-shaped radiating patch, the other one is equivalent to a parasitic patch, while the small circular patch is used to enhance the capacitance effect. Moreover, there is a trick as shown in Fig. 1, that the probe connected to the lower E-shaped patch is jointed on the upper surface of the upper substrate through a metallized via, which is helpful for the ease of antenna fabrication.

B. Design of the E-Shaped Patches and Parameter Discussion

Design steps of the two radiating E-shaped patches are shown in Fig. 3. The proposed antenna employs square E-shaped patch, different from the rectangular shaped ESPAs in [13]–[18], and here the two patches have the same edge length (L_1). It has been demonstrated that the length of E-slot affects the bandwidth of an ESPA distinctively.

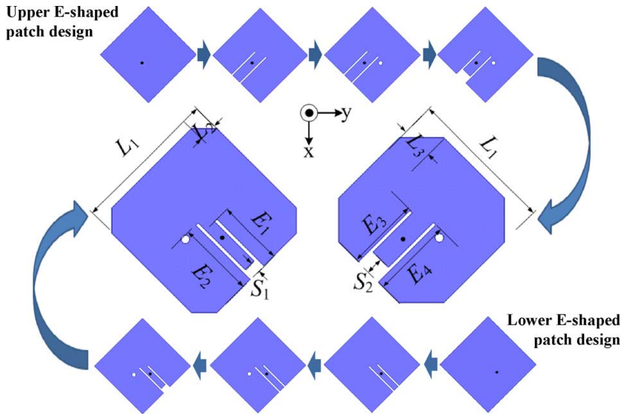

Fig. 3. Design steps of the two E-shaped patches. Some of the optimized key parameters are listed as follows: $L_1 = 42$ mm, $L_2 = 5.2$ mm, $L_3 = 9$ mm, $E_1 = 21.7$ mm, $E_2 = 18.8$ mm, $E_3 = 20.5$ mm, $E_4 = 22.9$ mm, $S_1 = 3.1$ mm, $S_2 = 5$ mm.

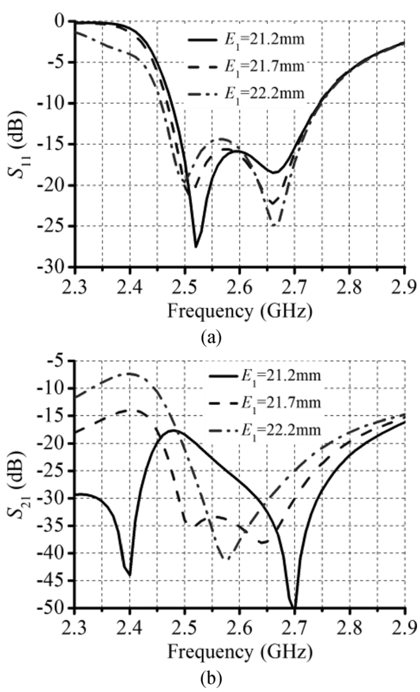

Fig. 4. (a) Simulated S_{11} for port1 versus different slot lengths, (b) Simulated S_{21} versus different slot lengths.

In the proposed antenna, however, the slot lengths (E_1–E_4) play important roles in controlling not only the bandwidth but also the port isolation. Fig. 4(a) shows the effect of the slot length (E_1) on the bandwidth of antenna. It can be seen that when the slot length decreases, the lower resonant frequency increases and leads to bandwidth deterioration, due to the fact that the inductance of the slot is reduced as the slot length decreases. Fig. 4(b) shows the effect of the slot length (E_1) on the port isolation of antenna. It can be observed that when the slot length decreases, the port isolation decreases in the operating band. Similarly, the other slot lengths (E_2–E_4) have similar influence on the bandwidth and the port isolation.

Nevertheless, the above E-slot structure cannot achieve good bandwidth and high port isolation simultaneously. To solve this problem, a small portion with length S_1 is cut from the central wing of the E-shaped patch tentatively. In order to understand the effect of the cut

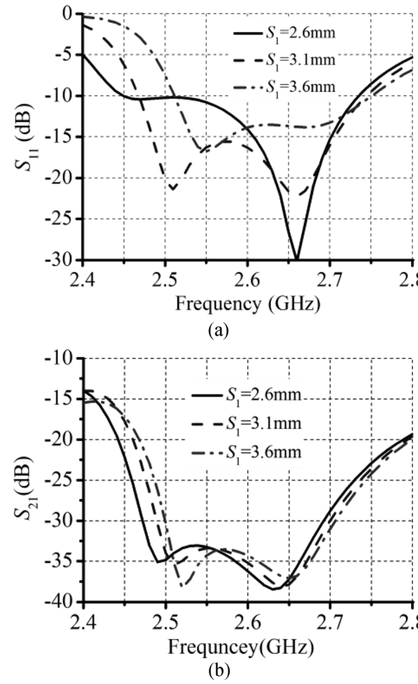

Fig. 5. (a) Simulated S_{11} for port1 versus different portion, (b) Simulated S_{21} versus different portion.

portion, Fig. 5 shows the variation of S_{11} and S_{21} versus frequency for different S_1. It can be seen from Fig. 5(a) that the lower resonant frequency increases evidently with the increasing of S_1. This is because the portion reduces the length of the central wing so that the current path around the central wing is reduced. The inductance introduced by the central wing is also reduced, causing the lower resonant frequency increased. However, as can be observed from Fig. 5(b), there is no obvious change of the port isolation while S_1 varies. Thus, it can be concluded that S_1 mainly affects the bandwidth of the antenna. Consequently, a suitable S_1 can be used to solve the problem of bandwidth deterioration due to the changed slot length.

Moreover, four corners of each patch were properly cut to reduce the dimensions of the patches. The sizes of the corners in the two patches are different for the purpose of making the antenna operate in the same band for the two polarizations.

Fig. 6 depicts the current distributions of the two E-shaped patches at 2.6 GHz for the two ports. It can be observed that the current mainly flows along the slots. Thus, the two E-slot structures are successfully applied in dual- polarization antenna and behave good polarization purity, namely, a $+45^\circ$ linear polarization from the lower E-shaped patch and a -45° linear polarization from the upper E-shaped patch.

C. A Circular Patch Added to the Proposed Antenna

For each E-shaped radiating patch, the other E-shaped patch forms a loaded distributed circuit, introducing the capacitance and inductance effects. Due to the two slots and the two probes, a large inductance is introduced, and the capacitance among the two E-shaped patches and the ground plane is relatively small, making the antenna difficult to match. Inspired by the basic principle of distributed LC circuit mentioned in [18], a small circular patch (CP) is introduced to the proposed antenna. Suitable capacitance introduced by the circular patch and E-shaped patches as well as the ground plane can be obtained to compensate for the inductance. Fig. 7 shows the geometry of the circular patch. Different from the circular patch in [18], two circular holes are etched on the patch to isolate the two feeding probes from the patch.

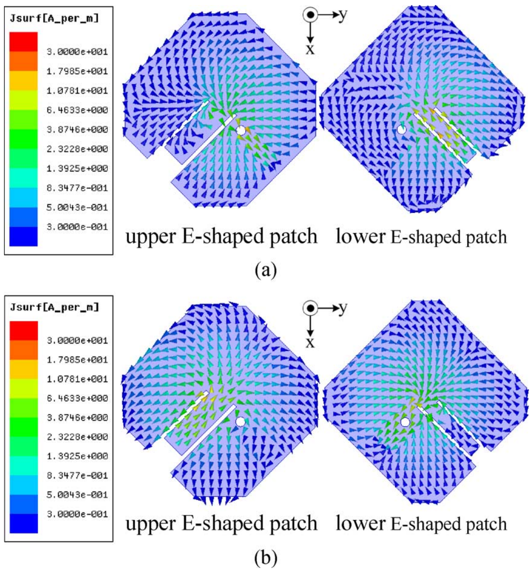

Fig. 6. Current distribution of the two E-shaped patches at 2.6 GHz. (a) port1 ($+45^\circ$, lower patch is excited); (b) port 2 (-45°, upper patch is excited).

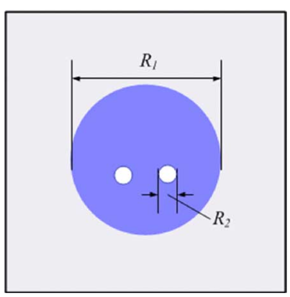

Fig. 7. Geometry of the circular patch, $R_1 = 35$ mm, $R_2 = 4.1$ mm.

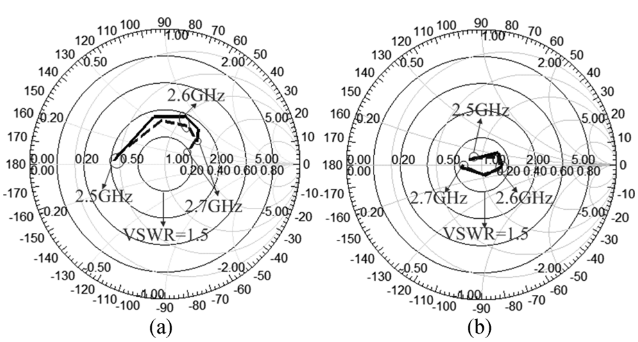

Fig. 8. Comparison of the input impedance of port1 (solid line) and port2 (dashed line) for the antenna (a) without circular patch and (b) with circular patch.

Fig. 8 presents the Smith Chart comparison for the antenna without circular patch and with circular patch. It can be seen from Fig. 8(a) that large inductance is obtained around the band 2.5–2.7 GHz. While the circular patch is introduced, a large capacitance around the band is obtained to match the large inductance, shown as Fig. 8(b). Fig. 9 shows the S_{11} and S_{22} comparison of the antennas without circular patch and with circular patch. As can be seen, the operating frequency band moves toward lower frequency without increasing the size of the antenna. In other words, the loaded circular patch makes the antenna miniaturized.

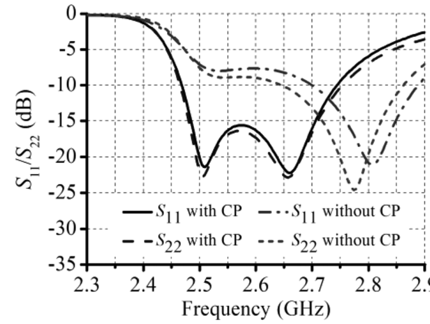

Fig. 9. Simulated S_{11}/S_{22} for the two ports with/without circular patch (CP).

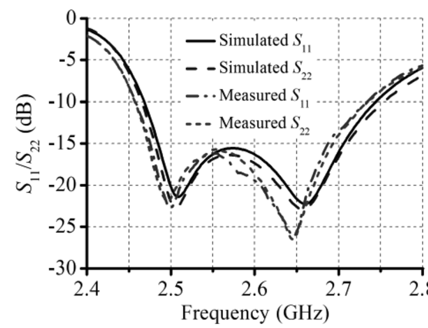

Fig. 10. Simulated and measured S_{11}/S_{22} of the proposed antenna.

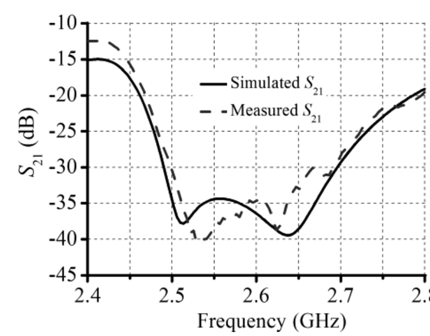

Fig. 11. Simulated and measured S_{21} of the proposed antenna.

Eventually, by properly adjusting the key parameters, the designed antenna achieve both good bandwidth characteristics and high port isolation with a low air thickness of $0.043\lambda_0$ (H $= 5$ mm, shown in Fig. 1). The proposed antenna is designed and simulated by using commercial software HFSS.

III. Simulated and Measured Results

Fig. 10 shows the simulated and measured reflection coefficient of each port of the proposed antenna. It can be seen that the simulated return loss for both two ports is better than 15 dB from 2.48 GHz to 2.7 GHz. The measured results are in good agreement with the simulated results.

The simulated and measured S_{21} between the two ports are shown in Fig. 11. It is observed that the simulated port isolation is better than 30 dB over the frequency band from 2.49 GHz to 2.7 GHz, while the measured result behaves similarly ranging from 2.5 GHz to 2.69 GHz.

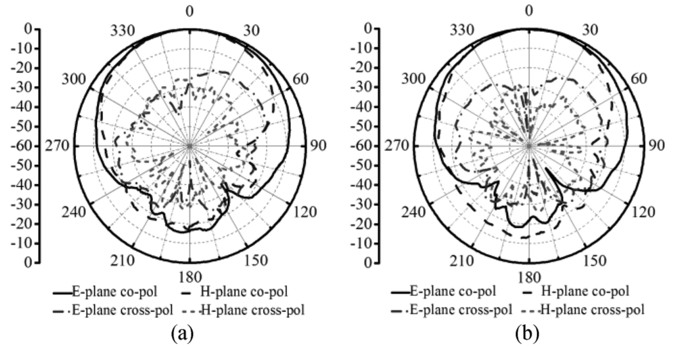

Fig. 12. Radiation patterns of the antenna at 2.6 GHz for (a) port1 and (b) port2.

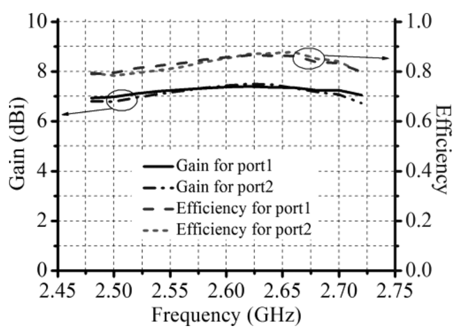

Fig. 13. Measured gain and efficiency versus frequency for port 1 and port 2.

Measured radiation patterns in both of E- and H-plane at 2.6 GHz for port1 ($+45^\circ$-pol) and port2 (-45°-pol) are illustrated in Fig. 12. It can be seen that the measured cross-polarization levels within the main lobe are about -25 dB in both E- and H-plane for the two ports while the front-to-back ratio remains over 14 dB due to small metallized ground plane. In addition, the 3 dB beamwidth is about 70° in the E-plane and 60° in the H-plane, respectively, for both two ports.

The measured gain and radiation efficiency of the antenna for both two ports are shown in Fig. 13. The gain for the two ports ranges from 6.8 dBi to 7.4 dBi within the operation frequency band, and the radiation efficiency is also stable across the frequency band.

IV. Conclusion

A novel compact dual-polarized E-shaped patch antenna with high isolation is proposed. The double E-slot structure is employed and extended to achieve dual polarized antenna. A prototype antenna with an impedance bandwidth of 7.7% ($S_{11}/S_{22} < -15$ dB) for both ports has been designed and experimentally verified. The measured port isolation remains better than 30 dB within the LTE bandwidth of 2.5 GHz–2.7 GHz. The proposed antenna achieves a much lower profile with a thickness of only about $0.062\lambda_0$, and is especially suitable for pico base station applications.

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