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COMPACT MULTIBAND FOLDED IFA FOR MOBILE APPLICATION

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Abstract—A compact multiband Inverted-F Antenna (IFA) for the use in a mobile phone is presented. By adopting a novel folded 3-D structure, a quarter-wave resonator and a parasitic strip, the proposed antenna covers eight bands and exhibits reduced electrical size and low profile. S_{11} less than -6 dB is obtained in the GSM900, GSM1800, DCS, Bluetooth, Wi-Fi, WLAN5.2, WLAN5.8 and the WiMAX bands. The dimensions of the proposed antenna with the 3-D structure are only $39.6 \times 4.3 \times 3.4\,\text{mm}^3$, which are very small in respect with other antennas in mobile terminal devices. A prototype of the proposed antenna is fabricated and measured. Measured and simulated results exhibit good bandwidth, radiation patterns and efficiency across all eight bands.

1. INTRODUCTION

With the rapid development of microelectronics technology and the manufacturing process, the wireless communication equipment has led the way toward miniaturization, broadband and multifunction. Nowadays, wireless communication bands including GSM900 (890 MHz–960 MHz)/GSM1800 (1710 MHz–1820 MHz)/DCS (1.71 GHz–1.88 GHz)/WIFI (2.400 MHz–2.484 GHz)/Bluetooth (2.400 GHz–2.500 GHz)/WLAN (5.150 GHz–5.250 GHz, 5.725 GHz–5.825 G-Hz) wavebands are practical in mobile wireless applications. GSM and DCS are essential in communication systems. WLAN is based on the IEEE802.11 standard, including WLAN 2.4 GHz, WLAN 5.2 GHz and WLAN 5.8 GHz. Wi-Fi and Bluetooth have found wide applications in mobile equipments. WiMAX (3.4 GHz–3.6 GHz) can be used

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to connect mobile terminals with the internet. Thus, the requirement of a single compact antenna covering multi-wireless radiation bands is increasing. A number of designs have been reported focusing on multiband small antennas in which various practical techniques were utilized [1–10]. However, as more and more functional blocks are intergraded into mobile phones, the room for antennas is limited and required bands of antenna are increased. Existing antennas for mobile phones can no longer meet the changing requirements.

The PIFA reported in [6] used parasitic patches, slots and quarter-wave resonators to realize the tri-band operation within a volume of $40 \times 20 \times 8\,\mathrm{mm}^3$. Inverted-F antennas and Planar inverted-F antennas [6–9] have been widely applied in the mobile phone as internal antennas because of their reduced specific absorption rate (SAR). A compact printed ultra-wideband (UWB) antenna design using resonators, a parasitic patch and a matching stub was reported in [10] with dimensions of $30 \times 30 \times 1\,\mathrm{mm}^3$. However, designs mentioned above were still a little bulky and too large to be integrated into mobile terminals such as phones. Recently, some three dimension (3D) folded antennas were proposed in reference [11, 12]. Since a three-dimensional structure is more compact in the same electrical length, folding the radiation part of an antenna can reduce the size of the antenna tremendously. In addition, the coupling between folded parts in 3-D structures can also bring more useful bands. For example, the folded monopole antenna in [11] with a folded structure is smaller than other monopole antennas. But there is no one single antenna can operate in all the mobile wireless bands so far.

In this paper, an IFA is folded into 3-D to obtain a compact eight-band design. The proposed novel antenna consists of a parasitic strip and a quarter-wave resonator and a folded IFA. Volume occupied by the proposed IFA is only $39.6 \times 4.3 \times 3.4\,\mathrm{mm}^3$. The antenna operates in GSM900, GSM1800, DCS, Bluetooth, Wi-Fi, WLAN and the WiMAX frequency bands with impedance bandwidth measured at $S_{11} = -6\,\mathrm{dB}$ (VSWR $= 3:1$). The size of proposed antenna is reduced by more than 70% compared with antennas mentioned in reference papers, which allows it to be integrated into mobile phone easily. The measured and simulated results have been presented and discussed in the following sections. Simulation results have been obtained by Ansoft HFSS 13.

2. PHYSICAL DESIGN OF THE PROPOSED ANTENNA

The geometry of the proposed IFA is illustrated in Fig. 1. The details of the folded IFA, parasitic strip and resonator are given in Figs. 1(b), (c), (d) for a better vision. The antenna sits on a $90 \times 60\,\mathrm{mm}^2$ printed

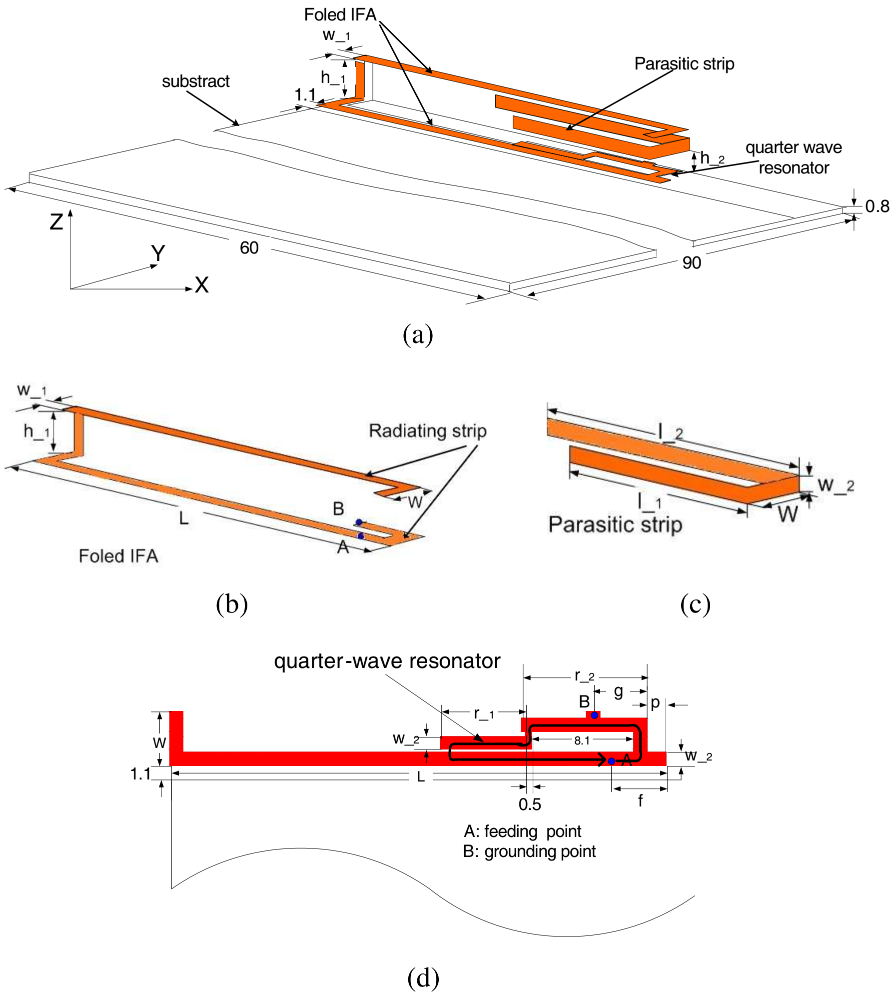


Figure 1. Geometry of the proposed antenna structures, (a) 3-D view, (b) folded IFA, (c) parasitic strip, (d) added resonator.

circuit board (PCB) made of FR4 dielectric material with a thickness of 0.8 mm. The ground plane (GND) is on the other side with a size of $84.6 \times 60\,\text{mm}^2$, and the gap between the grand plane and the antenna is 1.1 mm. As shown in Fig. 1(a), the presented antenna consists of a folded IFA, a parasitic strip, and a quarter-wave resonator. The radiating strip of IFA is folded into 3-D around the supporting plastic foam with the permittivity close to that of air. The parasitic strip is also supported by this foam. The quarter-wave resonator with a part of the radiating strip is printed on the substrate. This folding technique reduces the antenna size significantly, making the proposed structure much more compact than general IFA. The parasitic strip and resonator is used to help the antenna to cover more useful bands. Main dimensions of the proposed antenna are presented in Table 1. To test the antenna in the experiment, a 50-Ohm coaxial line was used, with its central conductor connected to point A, the feeding point, and its outer grounding sheath connected to the ground.

Table 1. Optimized dimensions of the proposed antenna (mm).

L	39.6	r_1	6.8
W	4.3	r_2	10
h_1	$h\_13.4$	f	3.5
h_2	1.7	g	3.7
w_1	1	p_1	16
w_2	1	p_2	23
p	1.5		

The folded IFA was designed to cover GSM900, GSM1800, WLAN5.2 and WLAN5.8. So the radiating strip of IFA should have an electrical length of approximately a quarter of the wavelength at the lowest frequency, i.e., at 0.9 GHz, which means:

$$\text{Length of radiating stripe} \approx \frac{\lambda_0}{4\sqrt{(1+\varepsilon_r)/2}}$$

ε_r is the permittivity of the substrate. The radiating stripe of IFA is folded to produce more resonance modes, so $L + W$ is chosen to be half the length of the radiating strip to guarantee the superposition of electromagnetic fields created by different parts. The resonator, marked by a bolded line in Fig. 1(d), which was supposed to created resonator at 2.45 GHz, has an electrical length of approximately a quarter of the wavelength at 2.45 GHz. That is to say:

$$2(r\_1 + r\_2) \approx \frac{\lambda_0}{2\sqrt{(1+\varepsilon_r)/2}}$$

The parasitic strip was added in order to generate resonator at 3.5 GHz by coupling with the main radiating strip. The length of parasitic strip should be at least a quarter of the wavelength at 3.5 GHz to ensure effective coupling. So we have the following result: $l\_1+l\_2+W \approx \lambda_0/2$. Position of points A and B is tuned to optimize the input impedance matching of the IFA. Finally, the proposed antenna was optimized as a whole through extensive numerical simulations and experimental prototyping. All parameters were tuned and some were changed greatly because different parts could influence each other inevitably. Optimized dimensions of the proposed antenna are given in Table 1.

3. ANALYSIS AND OPTIMIZATION

Vector surface currents on different antenna structures at different frequencies are given in Fig. 2 to reveal the roles of different antenna

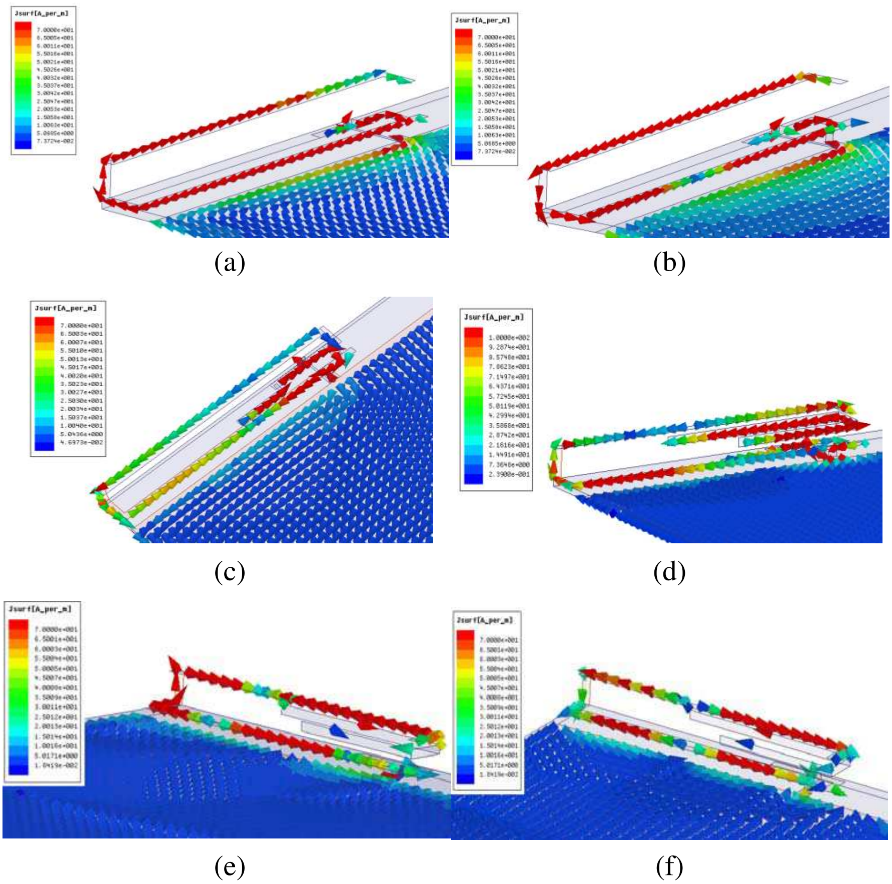


Figure 2. Surface currents on (a) IFA at 900 MHz, (b) IFA at 1.76 GHz, (c) IFA with a resonator at 2.45 GHz, (d) complete antenna at 3.5 GHz, (e) complete antenna at 5.2 GHz and (f) complete antenna at 5.8 GHz.

parts in reaching the final eight-band IFA. The antenna structure controls the current distribution on the surface of the antenna, which controls its radiation properties.

The IFA, without the quarter-wave resonator and the parasitic strip, is basically a four-band antenna operating at 0.9, 1.76 GHz and two other higher resonance modes. The radiating strip of IFA is designed to have an electrical length of approximately a quarter of the wavelength at 0.9 GHz which is 84.4 mm. The higher modes appear because of the folded structure. Position of points A and B is tuned to optimize the input impedance matching of the IFA. Surface currents on the single IFA structure at different frequencies are given in Figs. 2(a), (b). Obviously, currents in IFA at 0.9 GHz are in the same direction, while currents at 1.8 GHz reverse in the middle of the radiating strip because of phase change. S_{11} for the optimized multiband IFA is shown in Fig. 3. The achieved bands are 0.85–1.10 GHz and 1.70–1.89 GHz, covering GSM-900, GSM-1800 and DCS-1800 bands.

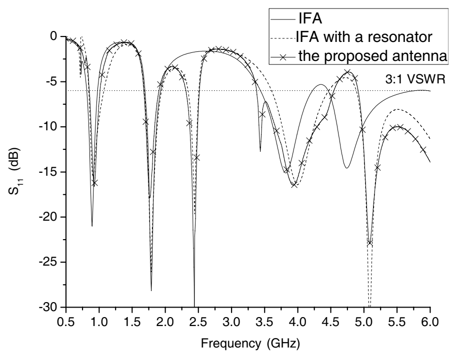


Figure 3. Simulated S_{11} of different antenna structures.

As shown in Fig. 1(a), in order to generate a resonance at 2.45 GHz for the Bluetooth and Wi-Fi operations, an L-shaped strip was added to create a quarter-wave resonator. The resonator, marked by a bolded line in Fig. 1(d), has an electrical length of approximately a quarter of the wavelength at 2.45 GHz which is 32 mm. The quarter-wave resonator is of great importance as it not only creates a broadband operating in the 2.40–2.51 GHz range, but also helps to improve the impedance matching at 5.2 and 5.8 GHz. S_{11} of different antenna structures are given in Fig. 3. The results show that the IFA with a resonator covers Bluetooth and Wi-Fi and performs better at WLAN 5.2 GHz and 5.8 GHz. As shown in Fig. 2(c), strong surface currents have been distributed around the resonator at 2.45 GHz.

The parasitic element creates resonance at 3.5 GHz which is combined with a high resonance mode of the folded IFA to cover the WiMAX frequency band. The parasitic strip, with a volume of $43.3 \times 1\,\mathrm{mm}^2$, was bent and placed carefully to minimize its influence on other resonate modes. S_{11} and surface currents distribution are illustrated in Fig. 2 and Fig. 3. Strong surface currents at 3.50 GHz are noticeable on the strip. Finally, an additional strip with a length of p is added for better impedance matching. Simulated S_{11} of the complete antenna is given in Fig. 3.

To demonstrate the effects of the dimensions of the proposed antenna and location of the parasitic element, a parametric study was conducted. Fig. 4(a) shows the parametric study for h_1 which reveals that the antenna's performance was very sensitive to the dimensions of IFA. When the height of the antenna was less than 3.2 mm, the performance worsened, so h_1 was chosen as 3.2 mm for a low profile. In Fig. 4(b), when the parameter r_1 varied from 6.5 to 7.4 mm, the resonant mode at 2.45 GHz was tuned without any effect on other

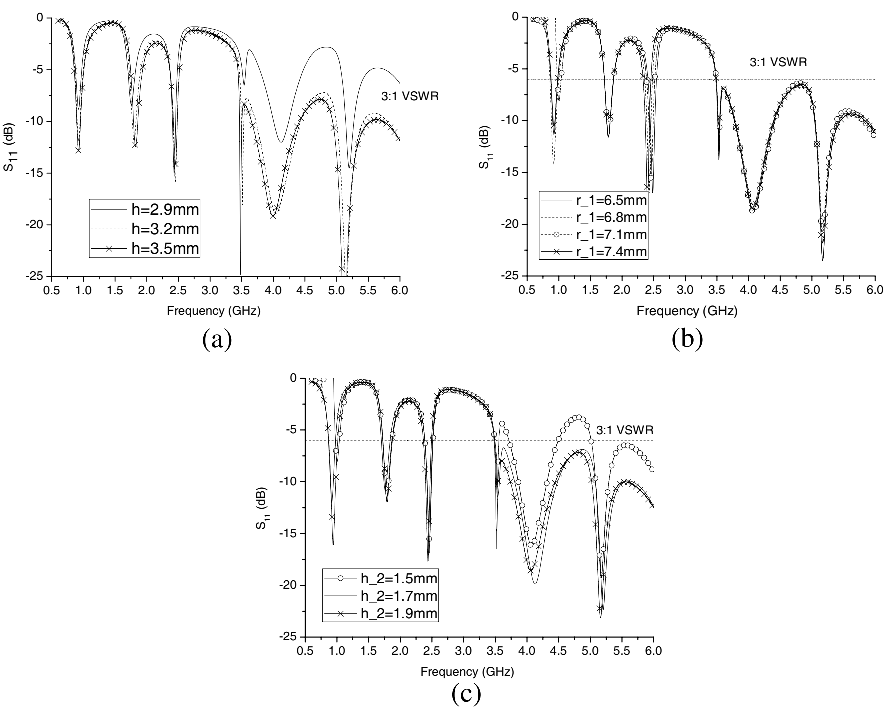


Figure 4. Simulated S_{11} of the proposed multiband antenna, (a) variations in h, (b) variations in r_1, (c) variations in h_2.

modes. As analyzed in Fig. 4(c), location of the parasitic strip had a large effect on the first mode at 0.9 GHz and higher modes at 3.5 and 5.2 GHz because the parasitic strip could change the coupling between folded parts.

Besides the dimensions of design, the antenna performance may depend on the ground size, which needs to be discussed. The results in Fig. 5 showed that all modes were influenced by the size of ground especially the higher ones. This is because the distribution of excited currents changed with the change of the dimensions of ground. In fact, nearly all IFA and PIFA are affected by excited currents on the ground. The ground size was chosen to be $84.6 \times 60\,\mathrm{mm}^2$ so that PCB is $90 \times 60\,\mathrm{mm}^2$ which is general size of a mobile phone. If antenna is installed in mobile phones with different size, parameters of the IFA need to be tuned to serve the best performance.

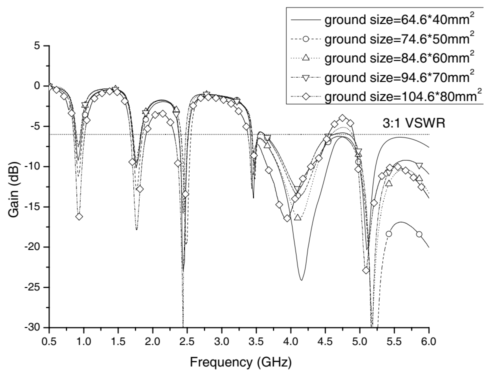


Figure 5. Simulated S_{11} of the proposed antenna variations in ground size.

4. RESULTS AND DISCUSSION

A prototype antenna, shown in Fig. 6, was fabricated to verify the simulation results. The simulated and measured S_{11} of the proposed antenna are presented in Fig. 7 for comparison. The simulated and measured S_{11} are in good agreement across all of the targeted frequency bands whereas slight discrepancies, especially in the WiMAX band around 3.5 GHz. Measured resonance modes at 5.2 and 5.8 GHz were a little higher than simulated ones. This disagreement could be attributed to the manufacturing and assembling errors because the proposed antenna was so small that little deviation could lead to a huge relative error. Just as analyzed above, higher modes are sensitive to dimensions of the antenna. From the measured results, the

(a) (b)

Figure 6. Prototype of the proposed multiband antenna (a) 3-D view, (b) strips on the board.

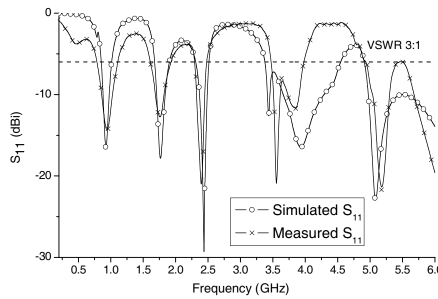
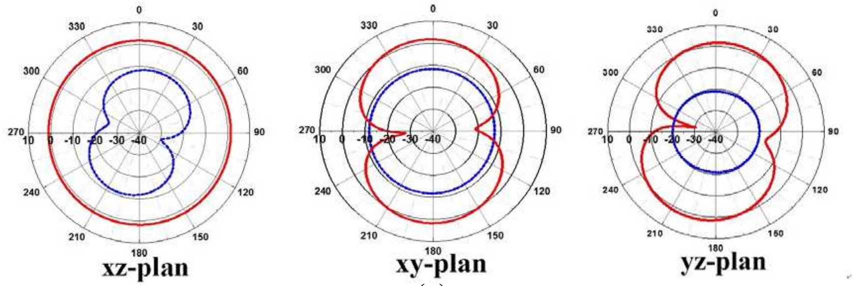


Figure 7. Measured and simulated S_{11} of the proposed antenna.

fabricated antenna had a 3 : 1 VSWR ($S_{11} < -6$ dB) bandwidth from 0.790 to 1.110 GHz for the GSM900 frequency band and from 1.620 to 1.993 GHz for the DCS/GSM1800 frequency bands. The resonance at 2.45 GHz offered 170 MHz from 2.31 to 2.48 GHz which is sufficient to cover Bluetooth and Wi-Fi bands. At the WiMAX band, the measured bandwidth was 370 MHz ranging from 3.43 to 3.80 GHz. The measured bandwidths at two WLAN frequency bands were from 5.02 to 5.40 GHz and from 5.70 to 6.0 GHz respectively.

Figure 8 presents the simulated radiation patterns (both co-polarization and cross-polarization) at 0.90, 1.76, 2.45, 3.500, 5.2 and 5.8 GHz, which fall on the center frequency of GSM900, DCS, Bluetooth, WLAN 5.2 and WLAN 5.8 frequency bands. The radiation patterns at 0.90 GHz were omni-directional, similar to the radiation patterns of a dipole antenna. The proposed antenna was still valid for applications even if the radiation patterns at high resonance modes had distortions. The high cross-polarization level of radiation patterns in Fig. 8 was attributed to the folded structure and parasitic strip. In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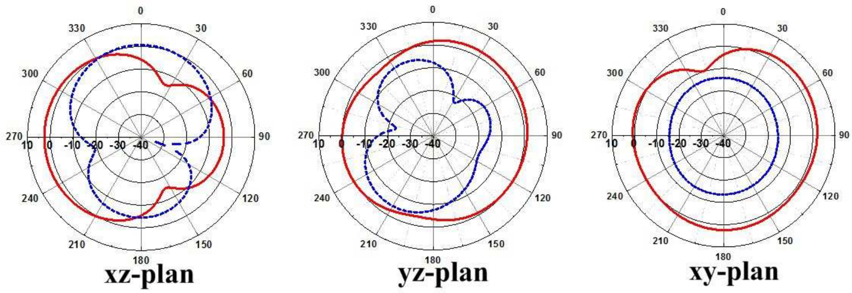
(a)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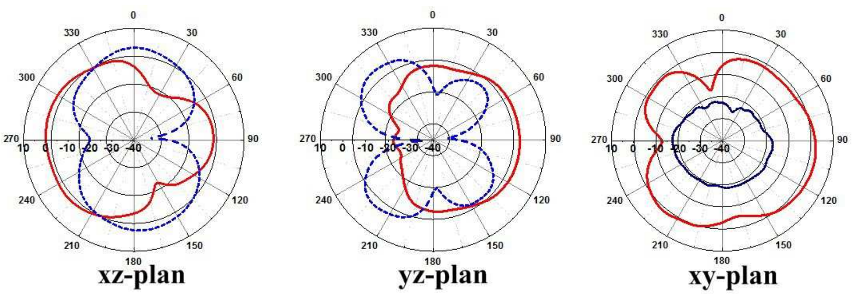
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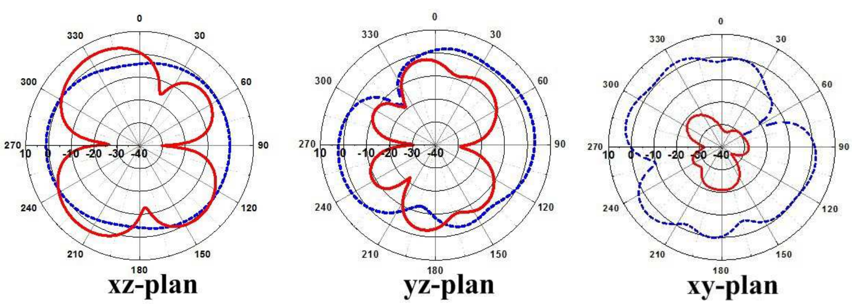
(c)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(d)

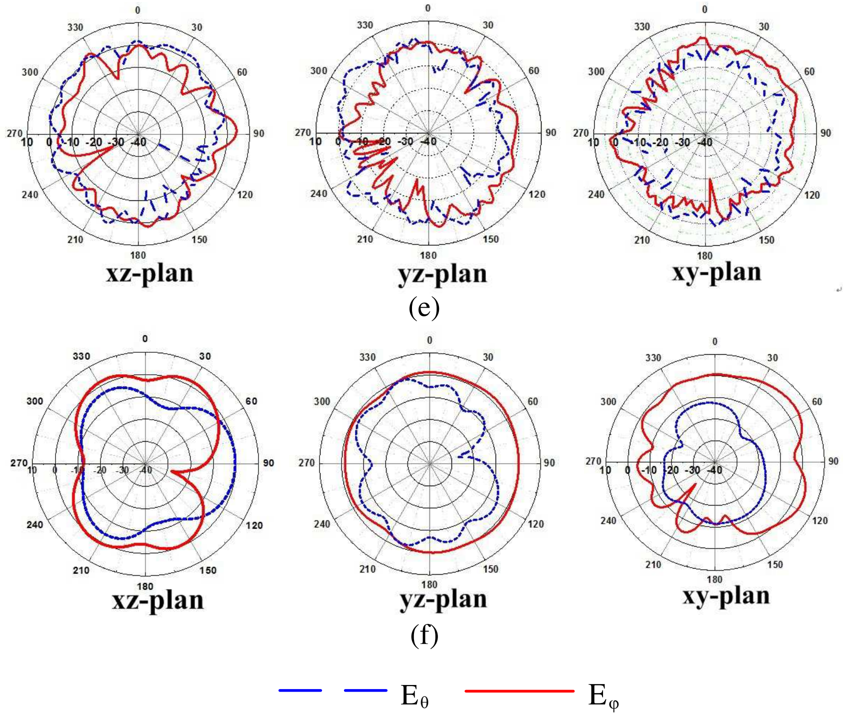

Figure 8. Radiation patterns (co-polarization and cross-polarization) of the proposed antenna at different frequencies (a) 0.9 GHz, (b) 1.76 GHz, (c) 2.45 GHz, (d) 3.5 GHz, (e) 5.2 GHz and (f) 5.8 GHz.

mobile communication systems, the orientation of mobile phones and other terminals are unfixed and the incoming signals are depolarized due to multiple reflections and scattering during propagation, so it is important that the mobile application antenna should be able to receive both the co-polarization and cross-polarization components. Furthermore, the patterns of the proposed antenna were reasonable and did not have multiple deep nulls which were undesirable in mobile terminal antennas. Table 2 shows the simulated peak gain and measured total efficiency at different frequencies of the proposed antenna respectively. The results were acceptable.

Comparison of this new design versus designs in literatures published recently is given in Table 3. As shown in Table 3, Volume of the proposed antenna is reduced by over 70% than antennas in reference [6, 8] without affecting its performance. The obtained gains are acceptable and even better than those of reference antennas, which indicated great advantages of the antenna used in mobile phones.

Table 2. The simulated gain and measured efficiency of the proposed antenna at different frequencies.

Frequency (GHz)	0.90	1.76	2.45	3.50	5.20	5.80
Gain (dBi)	1.78	2.58	3.25	3.61	4.60	5.2
Efficiency (%)	48.2	54.33	63.82	65.85	69.96	72.05

Table 3. Comparison between proposed design versus designs in reference literatures.

Design	Overall Antenna Volume (mm^3)	Gains (dB) at some frequencies				
		0.9 GHz	1.8 GHz	3.5 GHz	5.2 GHz	5.8 GHz
Ref. [6]	$40 \times 20 \times 8$	1.85	2.27	2.34	4.6	4.56
Ref. [8]	$47 \times 20 \times 5.5$	1.56	2.95		2.15	2.2
Proposed	$39.6 \times 4.3 \times 3.4$	1.78	2.58	3.61	4.6	5.2

5. CONCLUSION

A novel 3-D design of a compact eight-band IFA for mobile terminal applications has been presented The antenna covered the GSM900, GSM1800, DCS, Bluetooth, Wi-Fi, WiMAX bands and the two bands for WLAN at 5.2 GHz and 5.8 GHz within a volume of $39.6 \times 4.3 \times 3.4\,\text{mm}^3$. Compared to most compact multiband designs known so far, the proposed antenna is smaller by about 70% and operates in more bands. The antenna has been explained by both the structure analysis and surface currents on the antenna at different frequencies. Good agreement was noticed between measured and simulated S_{11} and simulated radiation patterns were acceptable, which means the proposed antenna is a good candidate for mobile applications.

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