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A Compact Nine-Band Frequency Reconfigurable Antenna for LTE/WWAN/WLAN Handset Applications

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Abstract—A frequency reconfigurable antenna suitable for handset is proposed in this research. The antenna structure includes an inverted-L shaped monopole and two meandered shorting strips. A wide high frequency band is excited from the inverted-L shaped strip monopole by direct feeding, and then the low and middle frequency bands are excited from two meandered shorting strips. Furthermore, a PIN switch diode is added at the end of shorting strip1 to implement the frequency reconfigurable property. The antenna was fabricated on an FR4 substrate and with a volume of only $9 \times 50 \times 5\,\mathrm{mm}^3$. It can cover the operation bands of LTE700/2300/2500, GSM850/900/1800/1900, UMTS2100, and WLAN2400. The detailed considerations and analyses of the design are studied in this paper.

1. INTRODUCTION

Antenna is an important component for all kinds of wireless transmission and is also one of the necessary devices for data transmission and reception. For nowadays mobile communication, the antenna not only promotes the transmission quality, but also changes to concealed forms instead of exposed ones for good looking, convenience, and efficiency. Besides, due to multipurpose usages of handset, the design of a multiband antenna becomes an important issue for handset applications.

Most researches on handset antennas are about planar antenna structures which are easy to integrate inside handset, such as planar inverted-F antenna (PIFA) [1, 2], loop antenna [3], and monopole antenna [4]. For keeping the antenna sizes compact, more researches for three-dimensional antennas are proposed to scale down the volume of antenna [5–7].

Frequency reconfigurable antennas [8–12] were designed and proposed recently for small antenna, with PIN switch diode [8–10], RF switch [11], or micro-electro-mechanical systems (MEMS) [12] for switching paths to excite various frequencies and shorten the length of exciting elements, then scale down the antenna sizes. Furthermore, reconfigurable polarization antennas [13–15] suitable for switching radiation styles which are directional and omnidirectional.

In this research, a frequency reconfigurable antenna suitable for handset is proposed, including an inverted-L shaped monopole and two meandered shorting strips. A wide high frequency band is aroused from the inverted-L shaped strip monopole by direct feeding, and then the low and middle frequency bands are excited from two meandered shorting strips. Furthermore, an Avago HSMP3894 PIN switch diode is added at the end of shorting strip1 to implement the frequency reconfigurable property. The operation bands of the antenna can cover LTE700/2300/2500 (698 $\sim$ 787, 2305 $\sim$ 2400, 2500 $\sim$ 2690 MHz), GSM850/900/1800/1900 (824 $\sim$ 894, 890 $\sim$ 960, 1710 $\sim$ 1880, 1850 $\sim$ 1990 MHz), UMTS2100 (1920 $\sim$ 2170 MHz), and WLAN2400 (2400 $\sim$ 2488 MHz).

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2. THE PROCEDURE OF ANTENNA DESIGN

The proposed antenna consists of an inverted-L shaped monopole and two coupled-fed strips shorted to the ground plane, as shown in Fig. 1(a). The detailed dimensions of the antenna metal pattern are shown in Fig. 1(b). A 0.8-mm thickness FR4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.022$) is used as the system circuit board. The overall volume of the proposed antenna is $9 \times 50 \times 5\,\mathrm{mm}^3$, and the ground plane size is $50 \times 106\,\mathrm{mm}^2$. The size of the substrate is $50 \times 115\,\mathrm{mm}^2$ which is suitable for a slim mobile phone.

An inverted-L shaped monopole antenna is directly fed to excite high frequency band, and the coupling effects excite the low and middle frequency bands from shorting strip1 and shorting strip2, respectively. The shorting strip1 is located at the top of the substrate, and an Avago HSMP3894 PIN switch diode is added at the end of it. Two grounded paths are designed for low frequency band reconfiguration.

The HSMP3894 PIN switch diode is optimized for switching applications with good performance up to 3 GHz [16], where low resistance (at low current) and low capacitance are required. The detailed diagram of the bias circuit is shown in Fig. 2.

In the bias circuit, element values of the RF bypass capacitors (they also sever as DC blocks) are $C_{b1} = 33\,\mathrm{pF}$ and $C_{b2} = 56\,\mathrm{pF}$, respectively, and RF choking inductors are $L_{cc} = L_{c1} = L_{c2} = 10\,\mathrm{nH}$. For $V_1 = 1.5\,\mathrm{V}$ and $V_2 = 0\,\mathrm{V}$, State1 is enabled; State2 keeps open status; frequency band GSM85/900 will

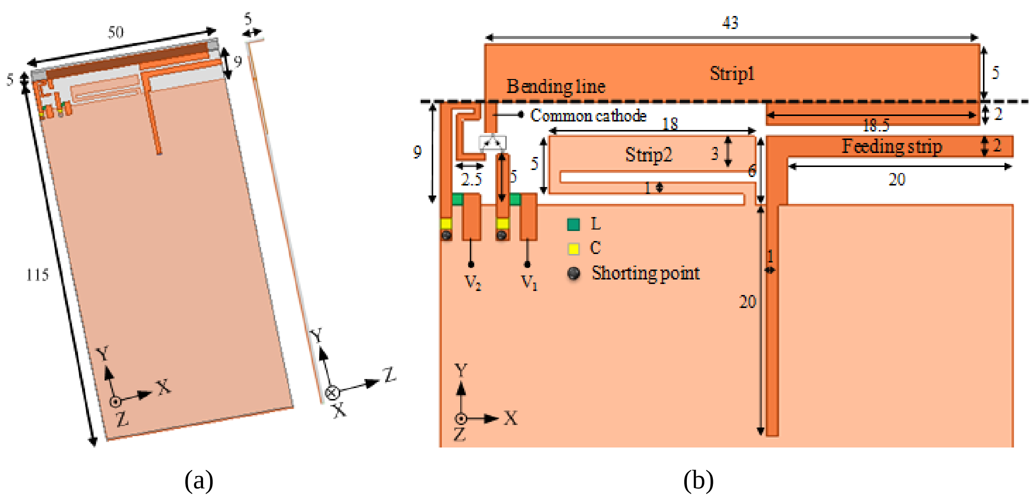

Figure 1. The configuration of proposed antenna, (a) top view and side view, (b) detailed dimensions.

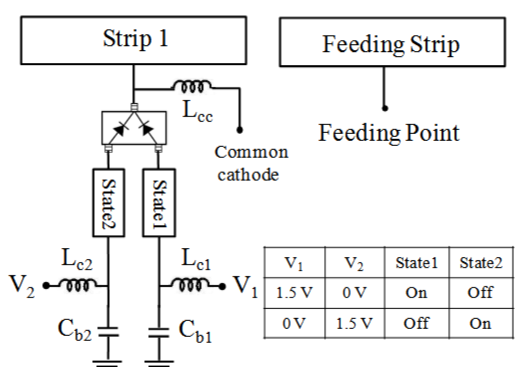

Figure 2. The PIN switch diode's detailed diagram of the bias circuit.

be excited. For $V_1 = 0\,\text{V}$ and $V_2 = 1.5\,\text{V}$, State1 keeps open status; State2 is enabled; frequency band LTE700 is excited. The state diagram is shown in the small table of Fig. 2.

The shorting strip2 is located at the other side of the substrate through coupling effect to excite frequency band of GSM1800/1900 and UMTS2100.

2.1. Analysis of the Antenna Design

The objective of this study is to design a multiband antenna for LTE/WWAN/WLAN applications. The procedures of antenna design are analyzed as following. Taking State1 as an example, three types of antennas are defined as antenna A, antenna B and the proposed antenna, as shown in Fig. 3(a). Antenna A is an inverted-L shaped monopole adopted to excite 2.3 GHz high frequency band, and the simulated return loss is shown in Fig. 3(b).

Then, a new resonant frequency at 0.9 GHz can be generated by the meandered shorting strip (strip1) which is connected to ground plane through a via, and the new structure is called antenna B. The high frequency band of antenna B does not conform to the demand of 1.8 GHz band. Therefore, a shorting strip (strip2) is added on the other side of substrate for the proposed antenna, which can excite a resonant mode at 1.7 GHz to increase the bandwidth of middle frequency band. Besides, for easy adjustment of parameters among the coupling elements the inverted-L shaped monopole, strip1 and strip2 are designed non-overlap between front and back sides of the substrate. The multiband antenna for LTE/WWAN/WLAN applications is achieved from the above design process.

The simulated surface current distributions in State1 at 850 MHz, 1700 MHz and 2200 MHz are illustrated in Fig. 4. At 850 MHz, shown in Fig. 4(a), the excited surface current path is coupled from inverted-L shaped monopole and follows strip1 into the ground plane through a via. The length of this current path is 91 mm which approximates quarter wavelength (88 mm) at 850 MHz.

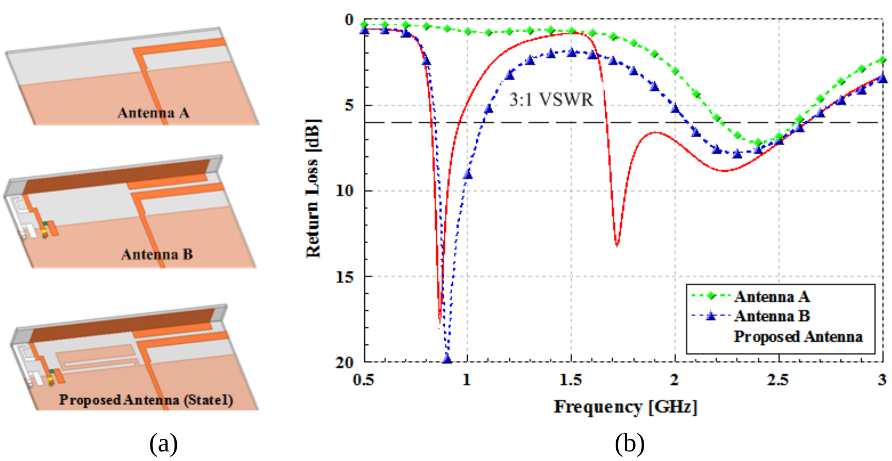

Figure 3. The comparison of structures and simulated results among three antenna types in State1, (a) antenna structure, (b) return loss.

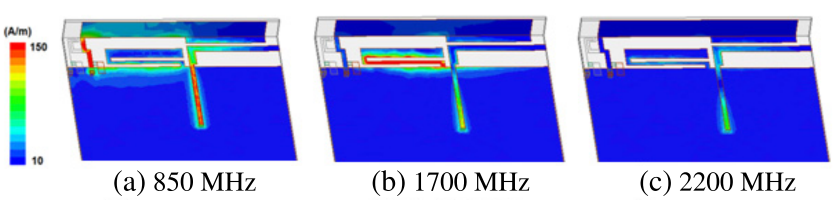

Figure 4. The simulated surface current distributions in State1, (a) 850 MHz, (b) 1700 MHz, and (c) 2200 MHz.

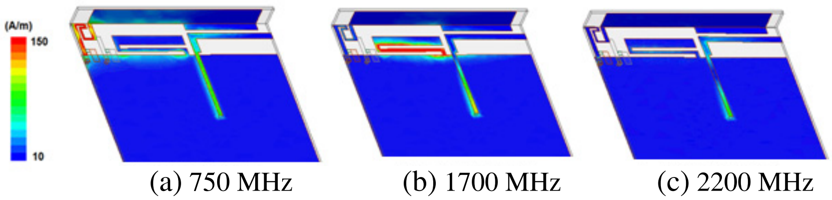

Figure 5. The simulated surface current distributions in State2, (a) 750 MHz, (b) 1700 MHz, and (c) 2200 MHz.

At 1700 MHz, shown in Fig. 4(b), strip2 has the strongest current which is coupled from the inverted-L shaped monopole and introduced into the ground plane. It means that strip2 is an excitation path at 1700 MHz, and the length of current path is 45 mm which approximates quarter wavelength (44 mm). At 2200 MHz, shown in Fig. 4(c), an inverted-L shaped feeding strip has the strongest current which is an excitation path, and the length is 26 mm which approximates quarter wavelength (31 mm).

The simulated surface current distributions in State2 at 750 MHz, 1700 MHz and 2200 MHz are presented in Fig. 5. At 750 MHz, shown in Fig. 5(a), the excited surface current path is coupled from inverted-L shaped monopole and follows strip1 into the ground plane through a via. The length of this current path is 103 mm which approximates quarter wavelength (100 mm) at 750 MHz.

At 1700 MHz and 2200 MHz, shown in Figs. 5(b) and 5(c), the current distributions in State2 are similar to State1, and the excitation paths are the same as State1.

2.2. Analysis of Parameters

To optimize the antenna design, three important parameters L_1, L_2 and C_{b1} (the lengths of strip1, strip2 and bypass chip capacitor, respectively) affecting the characteristics of antenna are discussed. The simulated return losses for the proposed antenna with different L_1, L_2 and C_{b1} values are shown in Figs. 6, 7 and 8, respectively.

Changing the length of L_1 (40, 43, 46 mm) leads to tuning the first resonant mode (low frequency band) as shown in Fig. 6. As length L_1 is increased, the first resonant mode is shifted to lower frequency, and vice versa. Although L_1 is changed, the middle and high frequency bands are preserved. The optimum length of $L_1 = 43$ mm is chosen.

In Fig. 7, it is shown that the second resonant mode (middle frequency band) is shifted to lower frequency by increasing L_2, and vice versa. The low frequency band is preserved with changing the

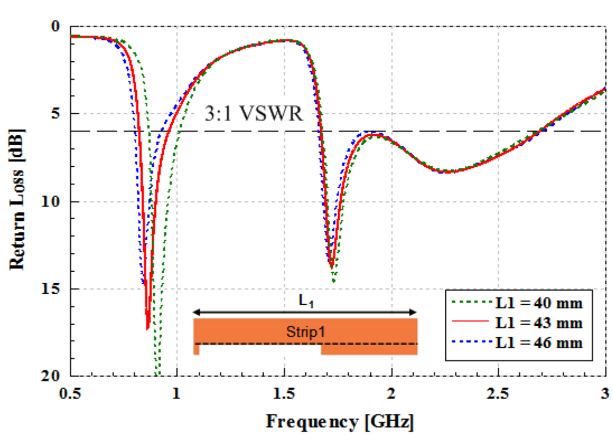

Figure 6. The simulated return losses for different length of strip1.

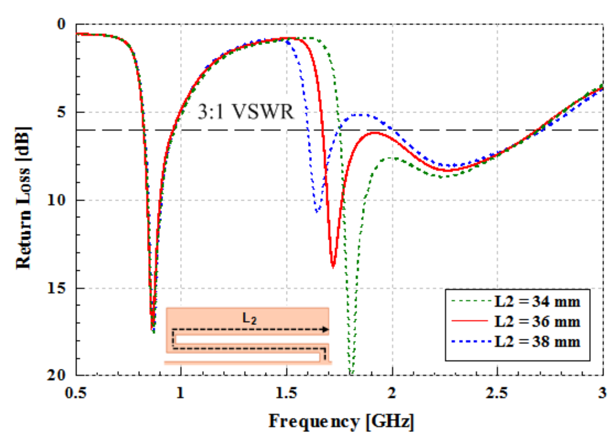

Figure 7. The simulated return losses for different length of strip2.

length of L_2. Finally, $L_2 = 36$ mm is an optimum length.

The bypass capacitors not only achieve the effect of RF bypass, but also affect the first resonant mode. In State1, the frequency of the first resonant mode is affected by the value of bypass capacitor C_{b1}. As C_{b1} is increased, the influence on the first resonant frequency can be decreased, as shown in Fig. 8. Eventually, $C_{b1} = 33$ pF is the best choice. In State2, the bypass capacitor C_{b2} has the same influence on the first resonant mode.

3. SIMULATED AND MEASURED RESULTS

Figure 9 shows a photo of the fabricated antenna which is fed on the inverted-L shaped monopole by a 50 Ω coaxial cable. The simulated and measured return losses for the proposed antenna are demonstrated in Fig. 10. The simulated results of both working states are obtained by Ansoft HFSS, while the measured results are tested by using a Rohde & Schwarz ZVL6 vector network analyzer. They have good agreements and meet the expectation. The measured result shows that the low frequency bandwidth is 268 MHz (697 ∼ 965 MHz) and suits to be used for LTE700 and GSM800/900 applications. The middle and high frequency bands have 1065 MHz (1660 ∼ 2725 MHz) bandwidth which can be used for GSM1800/1900, UMTS2100, LTE2300, LTE2500 and WLAN2400 applications.

The measured antenna gain and efficiency are presented in Fig. 11. Within 700 ∼ 960 MHz

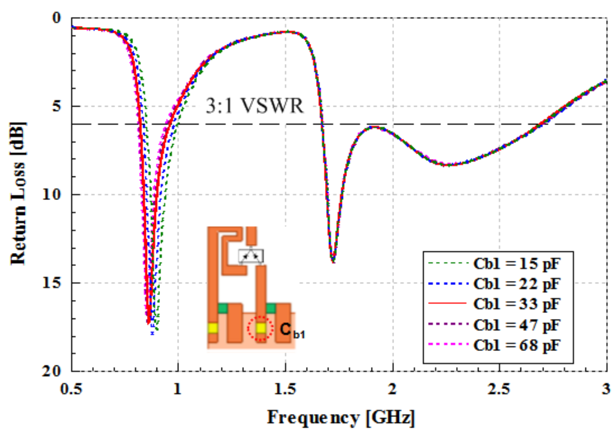

Figure 8. The simulated return losses for different value of bypass capacitor (C_{b1}).

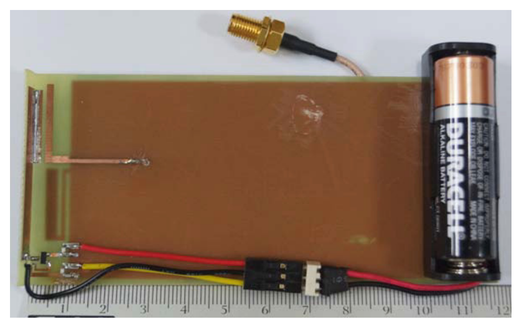

Figure 9. Photograph of the fabricated antenna.

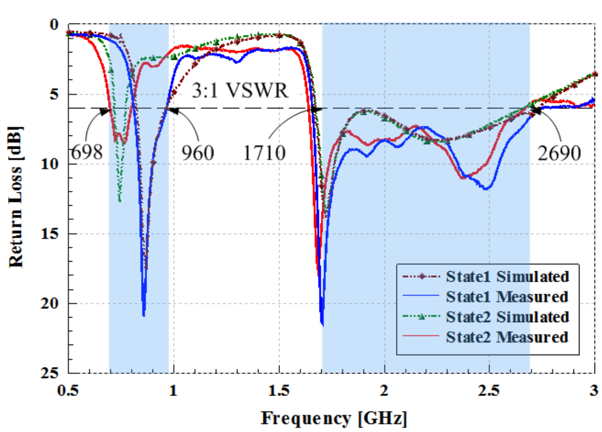

Figure 10. The simulated and measured return losses for the proposed antenna.

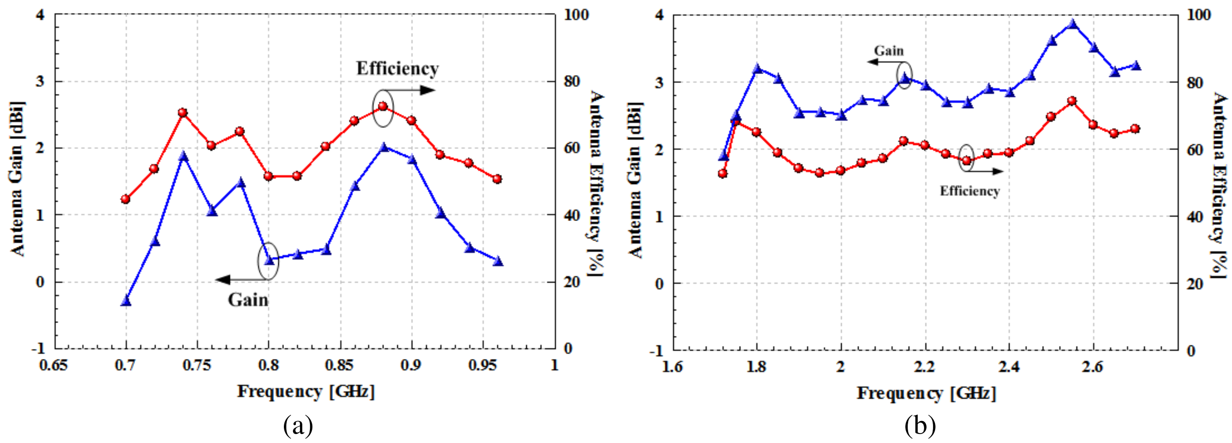

Figure 11. The measured antenna gain and efficiency at (a) $700 \sim 960$ MHz, and (b) $1700 \sim 2700$ MHz.

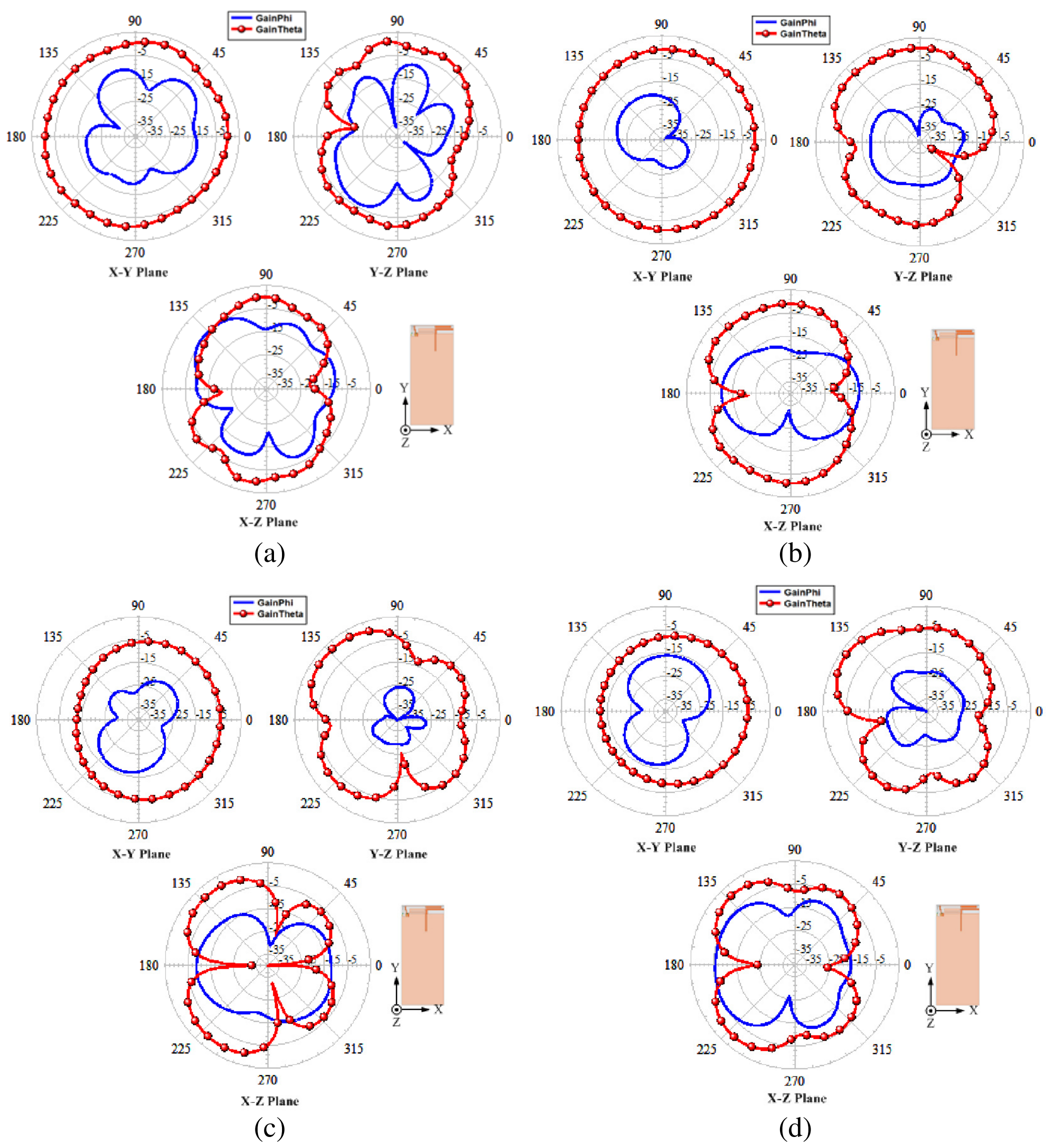

Figure 12. The measured radiation patterns at (a) 750 MHz, (b) 850 MHz, (c) 1720 MHz, and (d) 2260 MHz.

frequency band, the antenna gain is about $-0.27 \sim 2.02$ dBi and the antenna efficiency about 44.5 $\sim$ 72.3%. Within 1700 $\sim$ 2700 MHz operation band, the antenna gain is varied from 1.92 to 3.88 dBi while the antenna efficiency is about 52.5 $\sim$ 74.2%.

Figure 12 shows the measured radiation patterns (XY plane, XZ plane and YZ plane) at 750 MHz, 850 MHz, 1720 MHz and 2260 MHz for the fabricated antenna. Monopole-like radiation patterns with omnidirectional radiation in the azimuthal plane (X-Y plane) are observed, which are suitable for mobile handset antennas.

Finally, to further explain the contributions of the proposed antenna, a comparison including the previously reported antennas is shown in Table 1. Compared to the reference antennas [5–7] which have the same operation bandwidths, the proposed antenna has the advantage of smaller size. Compared with those reference antennas in [8–10] which have approximate volume, the proposed antenna has wider operating bandwidths and more suitable for LTE/WWAN/WLAN handset applications in the near future.

Table 1. Summary of the dimensions and operating bands of the previously reported antennas and proposed antenna.

Ref.	Reconfigurable Technique	Dimension (mm^3)	Operating Bands (MHz)
[5]		$10 \times 55 \times 8$	704 $\sim$ 960/1710 $\sim$ 2690
[6]		$15 \times 40 \times 4$	698 $\sim$ 960/1710 $\sim$ 2690
[7]		$13 \times 55 \times 8$	698 $\sim$ 960/1710 $\sim$ 2170
[8]	ν	$5 \times 60 \times 5$	770 $\sim$ 1010/1705 $\sim$ 2560
[9]	ν	$20 \times 62 \times 5$	676 $\sim$ 971/1710 $\sim$ 2170
[10]	ν	$5 \times 35 \times 5$	824 $\sim$ 960/1710 $\sim$ 2690
Proposed	ν	$9 \times 50 \times 5$	697 $\sim$ 960/1660 $\sim$ 2725

4. CONCLUSIONS

A compact nine-band frequency reconfigurable antenna for LTE/WWAN/WLAN handset applications has been designed and fabricated. The volume of the antenna radiator occupies only $9 \times 50 \times 5\,\text{mm}^3$. In order to shrink the size of antenna, an Avago HSMP3894 PIN switch diode is embedded in the antenna to implement the bi-status switching for frequency reconfigurable. The nine operating bands of the proposed antenna are covered with 6-dB return loss by combining the bandwidths in State1 and State2. The simulated results have good agreements with the measured ones. The measured bandwidths are 268 MHz (697 $\sim$ 965 MHz) and 1065 MHz (1660 $\sim$ 2725 MHz) that can be applied to LTE700/2300/2500, GSM850/900/1800/1900, UMTS2100, and WLAN2400 for voice and web services.

REFERENCES

1. Kang, D.-G. and Y. Sung, "Compact hexaband PIFA antenna for mobile handset applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 9, 1127–1130, 2010.
2. Wu, C.-H. and K.-L. Wong, "Ultrawideband PIFA with a capacitive feed for penta-band folder-type mobile phone antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 57, 2461–2464, Aug. 2009.
3. Wong, K.-L., W.-Y. Chen, and T.-W. Kang, "On-board printed coupled-fed loop antenna in close proximity to the surrounding ground plane for penta-band WWAN mobile phone," *IEEE Transactions on Antennas and Propagation*, Vol. 59, 751–757, Mar. 2011.
4. Lin, S. Y., "Multiband folded planar monopole antenna for mobile handset," *IEEE Transactions on Antennas and Propagation*, Vol. 52, 1790–1794, Jul. 2004.

5. Chu, F. H. and K. L. Wong, "Internal coupled-fed dual-loop antenna integrated with a USB connector for WWAN/LTE mobile handset," *IEEE Transactions on Antennas and Propagation*, Vol. 59, No. 11, 4215–4221, Nov. 2011.
6. Ban, Y.-L., J.-H. Chen, J. L.-W. Li, and Y. Wu, "Small-size printed coupled-fed antenna for eight-band LTE/GSM/UMTS wireless wide area network operation in an internal mobile handset," *IET Microwaves, Antennas & Propagation*, Vol. 7, No. 6, 399–407, Jan. 2013
7. Zheng, M., H. Y. Wang, and Y. Hao, "Internal hexa-band folded monopole/dipole/loop antenna Israa' K. Khaled, "Internal nine-band antenna for WWAN/LTE mobile handsets with four resonances for mobile device," *IEEE Transactions on Antennas and Propagation*, Vol. 60, 2880–2885, Jun. 2012.
8. Li, Y., Z. Zhang, J. Zheng, and Z. Feng "Compact heptaband reconfigurable loop antenna for mobile handset," *IEEE Transactions on Antennas and Propagation*, Vol. 10, 1162–1165, 2011.
9. Hwang, S.-G., C. Yoon, I. S. Yoon, L. Chares, C. S. Park, and W.-S. Kim, "A reconfigurable mobile antenna for multiband operation using pin-diode," *Microwave and Optical Technology Letters*, Vol. 57, No. 2, 406–409, Feb. 2015.
10. Ban, Y.-L., Z. X. Chen, Z. Chen, K. Kang, and J. L.-W. Li, "Reconfigurable narrow-frame antenna for heptaband WWAN/LTE smart-phone applications," *IEEE Transactions on Antennas and Propagation*, Vol. 13, 1365–1368, 2014.
11. Ban, Y.-L., S.-C. Sun, P.-P. Li, J. L.-W. Li, and K. Kang, "Compact eight-band frequency reconfigurable antenna for LTE/WWAN tablet computer applications," *IEEE Transactions on Antennas and Propagation*, Vol. 62, No. 1, 471–475, Jan. 2014.
12. Yamagajo, T. and Y. Koga, "Frequency reconfigurable antenna with MEMS switches for mobile terminals," *Antennas and Propagation in Wireless Communications (APWC)*, 1213–1216, 2011.
13. Lim, I. and S. Lim, "Monopole-like and boresight pattern re-configurable antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 61, No. 12, 5854–5859, Dec. 2013.
14. Cao, W., B. Zhang, A. Liu, T. Yu, D. Guo, and K. Pan, "A reconfigurable microstrip antenna with radiation pattern selectivity and polarization diversity," *IEEE Transactions on Antennas and Propagation*, Vol. 61, No. 11, 453–456, Dec. 2012.
15. Zhang, P.-F., S.-Z. Liu, and S. Zhao, "A novel reconfigurable microstrip patch antenna with frequency and polarization diversities," *Microwave and Optical Technology Letters*, Vol. 57, No. 6, 1494–1500, Jun. 2015.
16. Datasheet of HSMP-3894 PIN switch diode, [Online]. Available: http://www.avagotech.com/products/wireless/diodes/pin/hsmp-3894#overview.