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Small-Size Folded Monopole Antenna with Switchable Matching Circuit for Ultra-Thin Mobile Applications

Hao Wang[1], Zheqiang Wu[1], Yibo Wang[1], Chow-Yen-Desmond Sim[2], and Guangli Yang[1, *]

Abstract—A small-size ultra-thin and narrow frame antenna with a switchable matching network to achieve LTE dual-wide band operation in the 700–980 and 1710–2500 MHz bands is presented for mobile phone applications. The highlight of the antenna is that it has a low profile of only 2 mm and occupies a small ground clearance of $45 \times 4.5\,\mathrm{mm}^2$, which are very attractive for ultra-thin mobile antenna applications. A folded monopole is used as a radiator fed via a switchable two-state matching circuit controlled by a PIN diode. The PIN type switchable matching network is mainly designed to tune the low band (700–980 MHz). By combining the two working states of the PIN diode, the proposed antenna can cover GSM850/GSM900/DCS1800/PCS1900/UMTS2100 and two LTE bands, LTE700/LTE2300. Details of the antenna are described in this study.

1. INTRODUCTION

With the rapid development of wireless communication, ultra-thin mobile phone antennas with compact size and low profile are widely studied for practical application. To achieve multiband performances with very low profile of approximately 3 mm above the circuit board, simple techniques, such as bending the monopole, are applied [1, 2]. However, to further improve the lower operating band for covering LTE700 and GSM850/900 bands, further techniques such as embedding a parallel resonant structure and loading an additional chip inductor into the antenna are also employed into the antenna designs. To avoid using the above techniques, a folded monopole antenna similar to a loop antenna type that can excite traditional loop modes (0.5λ, 1λ, and 1.5λ) and additional dipole mode (2λ) have been reported [3, 4] to achieve multiband operation for ultra-thin smartphone. However, such loop antenna designs have exhibited higher antenna's height of 5 mm than that in [1, 2].

Recently, various frequency reconfigurable antenna designs for mobile handset or smartphone applications have been reported [5–10]. Here, simple methods, such as using a single PIN diode to shorten and lengthen the monopole, are applied to switch between GSM850 and GSM900 bands [5], and the technique reported by [6] has used two PIN diodes to achieve reconfigurable feedings, so that the antenna can switch between DCS and PCS bands. Besides applying the aforementioned reconfigurable techniques (tuning the monopole length and switching the feeds), by using PIN diode as their preferred switching component, depending on different states of the PIN diodes, reconfigurable antenna types between PIFA (planar inverted-F antenna) and monopole [7], or between PIFA and loop types [8–10] can also be achieved. Nonetheless, as far as the authors' concern, the technique of applying a switchable matching circuit [11] is rarely applied in any ultra-thin mobile phone applications, as the work in [11] has exhibited reconfigurable frequencies across 470–770 MHz bandwidth for the Integrated Services Digital Broadcasting-Terrestrial (ISDB-T) application.

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* Corresponding author: Guangli Yang (guangli.yang@shu.edu.cn).
[1] The Key Lab of Specialty Fiber Optics and Optical Access Network, Shanghai University, Shanghai 200072, China. [2] Department of Electrical Engineering, Feng Chia University, Taichung 40724, Taiwan.

In this paper, an ultra-thin folded multiband monopole antenna with a switchable matching circuit is proposed. The antenna has a simple structure and small volume of $45 \times 4.5 \times 2\,\text{mm}^3$. The folded antenna alone can generate three resonances, namely, 0.25λ, 0.5λ, 0.75λ modes, corresponding to around 0.9 GHz, 1.8 GHz and 2.4 GHz. By applying the technique of switchable matching circuit with the use of a single PIN diode, the proposed antenna can generate another resonant mode at around 0.78 GHz. All of the four resonant modes can be utilized to cover the GSM850/GSM900/DCS1800/PCS1900/UMTS2100 bands and two LTE bands of LTE700/LTE2300. Detailed operating principles of the proposed antenna are described, and a prototype antenna is fabricated and experimentally investigated.

2. PROPOSED ANTENNA STRUCTURE AND CONFIGURATION

The configuration of the proposed antenna is illustrated in Figure 1. The overall geometry as shown in Figure 1(a) indicates that the system circuit board of proposed antenna is built on a 0.8-mm thick FR4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$) with a size of $65 \times 114.5\,\text{mm}^2$. On the top side of the FR4 substrate is a $65 \times 110\,\text{mm}^2$ system ground plane printed with a protruded ground of $4.5 \times 19\,\text{mm}^2$. Thus, a $4.5 \times 46\,\text{mm}^2$ no-ground region can be observed on the left side of this protruded ground. In this case, a 2 mm thick ABS (Acrylonitrile Butadiene Styrene) substrate antenna carrier ($\varepsilon_r = 3.3$, $\tan\delta = 0.01$) is used to support the proposed antenna, and a gap distance of 1 mm is set between the antenna carrier and the protruded ground plane. The total volume of the radiating antenna element (built on the ABS) is only $45 \times 4.5 \times 2\,\text{mm}^3$, and it is located in the no-ground region. Detailed dimensions of the proposed antenna fed by a 50-Ω coaxial feed line are shown in Figure 1(b).

The proposed antenna is composed of two monopole branches, namely, Branch 1, a bending-type radiating monopole branch along section A–F, and Branch 2, a tuning branch along section B–G. The folded monopole (Branch 1) can excite three resonant modes in the desired lower, middle and higher operating bands, while the tuning branch (Branch 2) is used to perform impedance matching for the higher operating bands (1700–2500 MHz). Besides the use of Branch 2 as an impedance matching element, at the feeding point, a series capacitor C1 (5 pF) and a series inductor L1 (5 nH) are also used for impedance matching to obtain wider frequency coverage in the higher operating band. The schematic

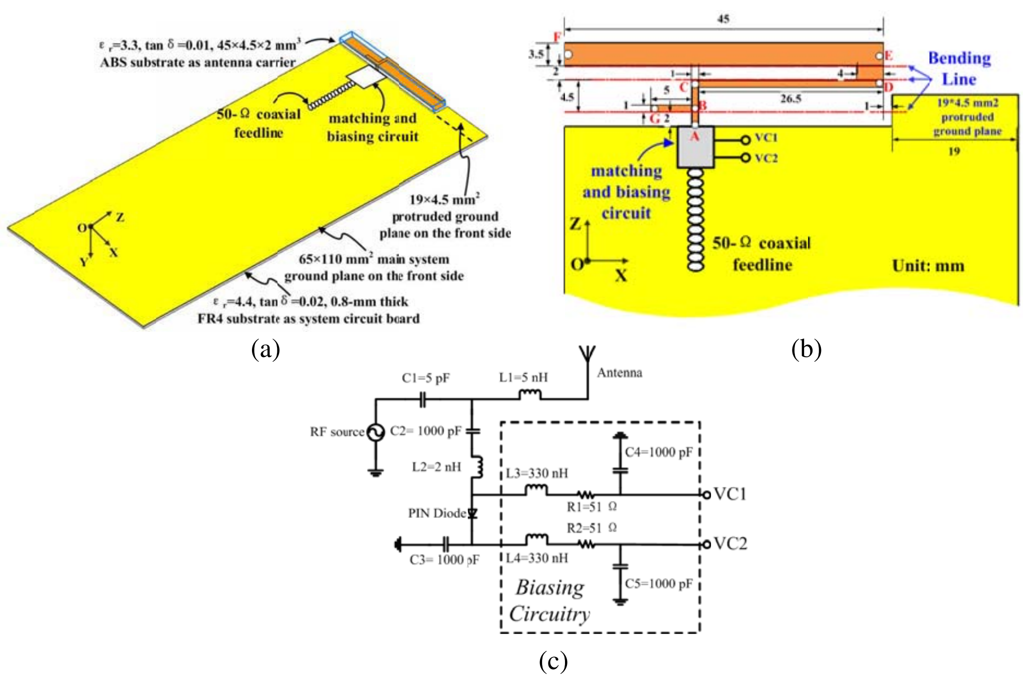


Figure 1. Proposed antenna configuration. (a) Geometry of proposed antenna. (b) Detailed dimensions of the proposed antenna. (c) Details of the matching circuit.

diagram of a two-state switchable matching network with PIN biasing circuit is shown in Figure 1(c). In this diagram, only one PIN diode (Skyworks SMP1322-079) is used to give two matching states. Within the dotted line area is a PIN biasing circuitry, in which the biasing resistances (R1, R2) are 51 Ω. The two inductors (L3, L4) with a value of 330 nH are used as RF choke between the matching circuit and voltage source. The DC block capacitances (C2, C3) and RF shorting capacitances (C4, C5) are 1000 pF each. Two AA batteries are used to supply 3 Volts to control the two working states of the PIN diode. At State 1 (PIN ON: $VC1 = 3\,\mathrm{V}$, $VC2 = 0\,\mathrm{V}$), the PIN diode is forward biased with a low impedance (about 0.35 Ω), and at State 2 (PIN OFF: $VC1 = 0\,\mathrm{V}$, $VC2 = 3\,\mathrm{V}$), the PIN diode is reversely biased with a very low capacitance value of 0.1 pF. In this case, when switching to State 1, the inductor L2 (2 nH) will appear as a shunt inductor type and the lower band resonant frequency will be decreased as compared to State 2. This phenomenon will be further discussed in Section 3.

3. PROPOSED ANTENNA DESIGNS

The simulated and measured reflection coefficients of the proposed antenna embedded with only a simple matching network (C1 and L1) is presented in Figure 2. The two results agreed well with each other. From the measured results, without loading the PIN diode matching and biasing network circuitry, the proposed antenna can only exhibit one lower band resonant mode at approximately 867 MHz, and two upper band resonant modes at 1884 MHz and 2382 MHz. Here, the two upper band resonant modes can combine and form a wide higher operating band with 6-dB impedance bandwidth (along VSWR 3:1) of 34.54% (1775–2516 MHz). Unfortunately, S_{11} of the lower resonant mode is around -5 dB, hence unable to cover any of the lower GSM operating bands. Therefore, in this work, additional PIN diode matching circuitry (including L2, C2, and C3) and biasing circuitry are further loaded (together with C1 and L1) into the antenna. Besides improving the impedance matching of the lower band resonant mode, switching the PIN diode will also allow the lower band resonant mode to cover three operating bands, namely, LTE 700 (704–787 MHz), GSM 850 (824–894 MHz) and GSM 900 (88–960 MHz). Furthermore, minimum impact can be observed in the higher operating band.

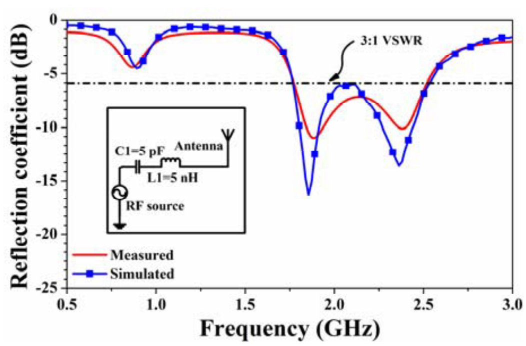


Figure 2. Simulated and measured reflection coefficient of proposed antenna with a simple match (C1 and L1) only.

To identify the excitation paths of the three resonant modes shown in Figure 2, simulated surface current distributions at 900 MHz, 1800 MHz, and 2300 MHz are plotted in Figure 3. As shown in Figure 3(a), the current distribution path at 900 MHz is approximately one-quarter wavelength (0.25λ) long from point A to point F of Branch 1. As shown in Figure 3(b), the current distribution path at 1800 MHz is approximately one-half wavelength (0.5λ) long, because two maximum currents and one surface current null are observed between point A and point F of Branch 1. As depicted in Figure 3(c), two maximum currents and two surface current nulls are observed between point A and point F of Branch 1, thus, the current distribution path at 2300 MHz can be estimated approximately 0.75λ long. From the current distribution paths shown above, it is obvious that the folded monopole (Branch 1) can generate up to three resonant modes (0.25λ, 0.5λ and 0.75λ) simultaneously.

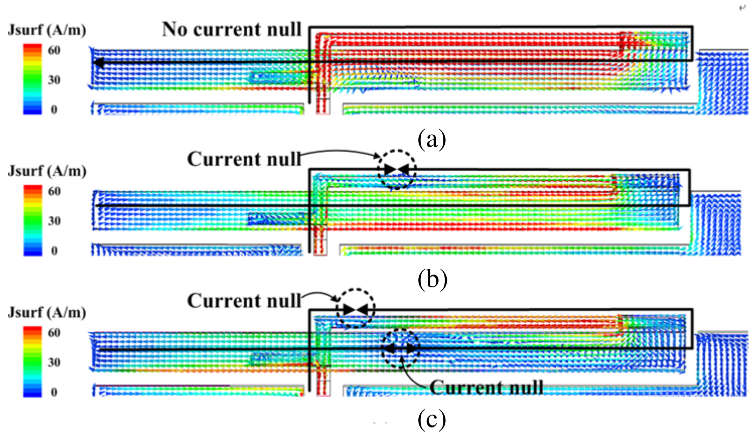


Figure 3. Simulated surface current distributions on the antenna's metallic pattern at (a) 900 MHz, (b) 1800 MHz, (c) 2300 MHz.

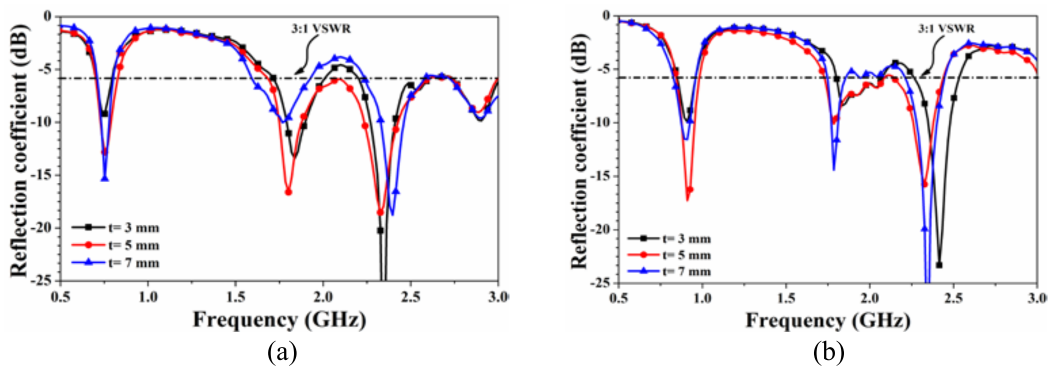


Figure 4. Measured reflection coefficients as a function of the branch length t in (a) State 1 (PIN ON), (b) State 2 (PIN OFF).

The two series components (L1 and C1) are important parameters for achieving the desired resonant frequencies of the two upper resonant modes, while the length of the tuning branch (denoted as t) is also a vital parameter to attain better impedance matching bandwidth ($S_{11} < -6$ dB) for the higher operating band (aid in combining the two upper resonant modes). In order to further comprehend how length t can affect the higher operating band, Figures 4(a) and 4(b) show the effects on reflection coefficients of the proposed antenna when tuning length t in two states, State 1 and State 2, respectively. As shown in both figures, an increase (from 5 mm to 7 mm) or decrease (5 mm to 3 mm) in length t will result in splitting the two upper resonant modes into two individual operating bands. Thus, the optimum length t is selected to be 5 mm, because it can combine the two upper resonant modes and not affecting the lower resonant mode at all. It is noteworthy that tuning the length of the main bending-type radiating monopole (Branch 1) will highly affect the frequency of all three resonant modes, thus, it is not discussed here, for brevity.

4. RESULTS AND DISCUSSION

Photographs of the fabricated antenna are shown in Figure 5. The measured reflection coefficients of the proposed antenna when switching between the two states (State 1 and State 2) are shown in Figure 6. At State 1 (PIN ON), the lower resonant mode of the proposed antenna is shifted to the lower frequency band at 753 MHz, and at State 2 (PIN OFF), it will shift to the higher frequency band at 910 MHz. Thus, by simply switching between the two states, a broad lower operating band can be attained from 700–980 MHz, which is enough to cover the LTE700/GSM850/GSM900 operating bands

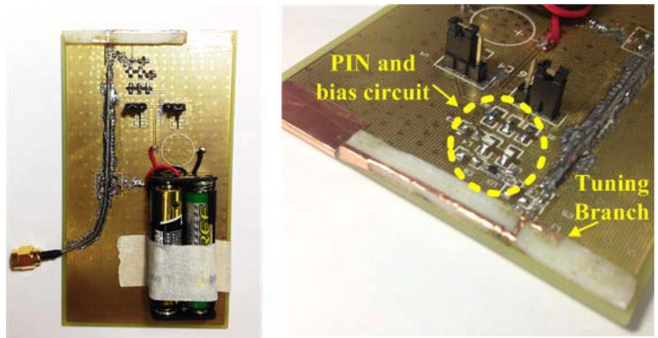


Figure 5. Photographs of the fabricated antenna with pin diode and biasing circuit.

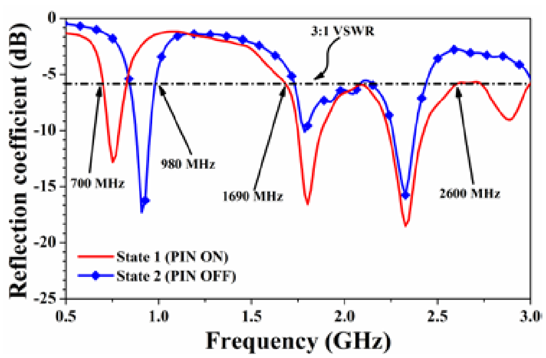


Figure 6. Measured reflection coefficient of the proposed antenna when switching between the two states.

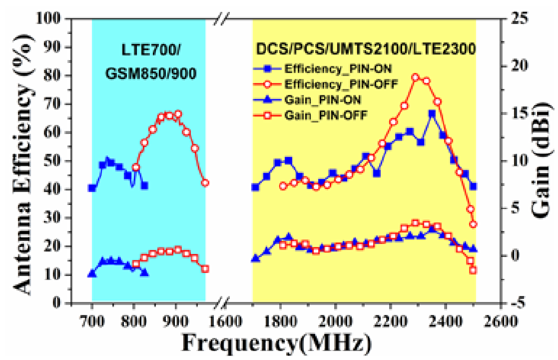
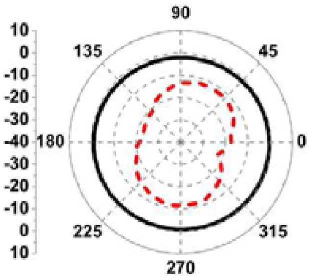


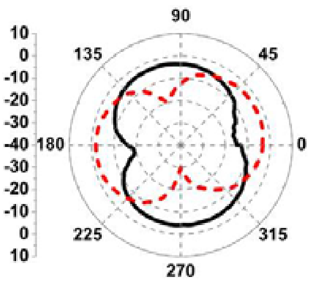
Figure 7. Measured antenna gains and efficiencies of proposed antenna in the two states.

Table 1. Comparisons between proposed antenna and reference antennas (* Not Available).

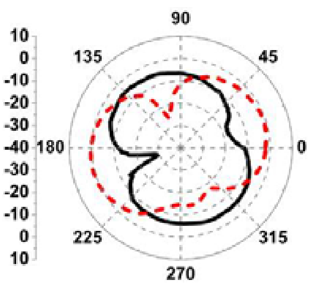
Antenna	Dimension	Bandwidth (MHz)	Efficiencies (%)
Ref. [1]	$40\times15\times3.5\,\mathrm{mm}^3$	700–865/1660–2710	45–52/52–75
Ref. [2]	$40\times5\times3\,\mathrm{mm}^3$	822–970/1662–3000	50–65/65–80
Ref. [3]	$50\times13\times5\,\mathrm{mm}^3$	698–960/1710–2170	42–70/49–79
Ref. [4]	$60\times8\times5\,\mathrm{mm}^3$	800–1100/1700–2580	50–76/57–84
Ref. [5]	$35\times5\times5\,\mathrm{mm}^3$	824–960/1500–2690	51–56/55–90
Ref. [6]	$50\times7\times7\,\mathrm{mm}^3$	776–984/1708–2080	*/*
Ref. [7]	$35.5\times13.5\times\mathrm{m}^2$	690–1038/1700–2825	55–81/51–82
Ref. [8]	$60\times5\times5\,\mathrm{mm}^3$	790–870/1490–2225	>64.7/>47.4
Ref. [9]	$36.5\times10\times\mathrm{m}^2$	690–1030/1710–3080	53–76/52–85
Ref. [10]	$62\times8\times5\,\mathrm{mm}^3$	699–960/1710–2690	>40/>40
Ref. [11]	$80\times10\times10\,\mathrm{mm}^3$	470–770	*
Ref. [12]	$46\times11\times7\,\mathrm{mm}^3$	698–1200/1710–2800	55–71/33–98
Ref. [13]	$55\times10\times8\,\mathrm{mm}^3$	700–1170/1705–2740	63–83/70–91
Ref. [14]	$40\times15\times4\,\mathrm{mm}^3$	698–960/1710–2690	>43/>54
Proposed	$45\times4.5\times2\,\mathrm{mm}^3$	700–980/1690–2600	40–67/41–79



(a)



(b)



(c)

Figure 8. Measured 2-D radiation patterns of the proposed antenna at (a) 900 MHz of State 2, (b) 1850 MHz of State 1, (c) 2350 MHz of State 1 (dotted line is E_{phi}, and solid line is E_{theta}).

(704–960 MHz). Furthermore, when switching between the two states, the two upper resonant modes remain nearly constant at approximately 1800 MHz and 2378 MHz, and the 6-dB impedance bandwidth in State 1 for the higher operating band is 1690–2600 MHz, which is more than enough to cover the DCS1800/PCS1900/UMTS2100/LTE2300 operating bands (1690–2400 MHz).

Figure 7 shows the measured antenna efficiencies and gains of the proposed antenna at State 1 (PIN ON) and State 2 (PIN OFF). At State 1, within the lower operating band 700–840 MHz, the gain and efficiency variations are -1.9 to -0.4 dBi and 40% to 51%, respectively, while in the higher operating band 1690–2500 MHz, the gain and efficiency variations are 0.7 to 3.4 dBi and 41% to 79%, respectively. In State 2, within the lower operating band 840–980 MHz, the gain and efficiency variations are -1.2 to 0.6 dBi and 42% to 67%, respectively, while in the higher operating band 1730–2450 MHz, the gain and efficiency variations are 0.7 to 3.3 dBi and 41% to 78%, respectively. The measured efficiencies and gains of the proposed antenna are feasible for practical mobile phone application.

Figure 8 shows the measured 2-dimensional radiation patterns of the proposed antenna in three principal planes (x-y, x-z, and y-z planes). Three representative frequencies at 900 MHz (State 1), 1850 MHz (State 2), and 2350 MHz (State 2) are plotted. The radiation pattern at 900 MHz in the x-y plane is near omnidirectional as a result of a dominant half-wave dipole resonant mode. At 1850 MHz and 2350 MHz, near omnidirectional and bi-directional radiation patterns are shown in x-z and x-y planes, respectively. The obtained radiation patterns are similar to those in modern mobile phone antennas.

To further illustrate the merits of the proposed antenna, Table 1 shows the comparison between the proposed antenna and those reported in [1–14]. Compared with the reference ones, the proposed antenna has exhibited the advantages of simple structure and small volume of $45 \times 4.5 \times 2\,\mathrm{mm}^3$ (equivalent to $405\,\mathrm{mm}^3$), with two broad bandwidths. Furthermore, the proposed antennas have a low profile of 2 mm and required only a small antenna clearance of $45 \times 4.5\,\mathrm{mm}^2$. However, due to the restriction of the antenna size, the efficiencies of the proposed antenna in the lower and upper operating bands are affected. The radiation efficiencies demonstrated in all the working bands are better than 40%, which is acceptable for practical application in modern mobile antenna.

5. CONCLUSION

A small size monopole antenna with a switching matching circuit for ultra-thin smart phone application has been successfully studied. The proposed antenna has a simple structure and a compact volume of $45 \times 4.5 \times 2\ \mathrm{mm}^3$, which is formed by a folded monopole as the main radiation branch and a small stub as tuning branch. A reconfigurable lower operating band (700–980 MHz) can be achieved by employing only one PIN diode to switch the matching network. By combining the two working states of a PIN diode, the proposed antenna can cover GSM850/GSM900/DCS1800/PCS1900/UMTS2100, and two LTE bands LTE700/LTE2300. A prototype of the proposed antenna has been designed, fabricated and measured. The measured reflection coefficients, antenna efficiencies and gains of the proposed antenna can meet the requirements of modern mobile phone antenna. Because the height of proposed antenna is only 2 mm, it is therefore a good candidate for slim smart phone antenna design.

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REFERENCES

1. Ban, Y. L., J. H. Chen, S. Yang, J. L. W. Li, and Y. J. Wu, "Low-profile printed octa-band LTE/WWAN mobile phone antenna using embedded parallel resonant structure," *IEEE Trans. Antennas Propag.*, Vol. 61, No. 7, 3889–3894, 2013.
2. Ban, Y. L., Y. F. Qiang, Z. Chen, K. Kang, and J. L. W. Li, "Low-profile narrow-frame antenna for seven-band WWAN/LTE smartphone applications," *IEEE Antennas Wireless Propag. Lett.*, Vol. 13, 463–466, 2014.
3. Zheng, M., H. Wang, and Y. Hao, "Internal hexa-band folded monopole/dipole/loop antenna with four resonances for mobile device," *IEEE Trans. Antennas Propag.*, Vol. 60, No. 6, 2880–2885, 2012.
4. Wu, D., S. W. Cheung, and T. I. Yuk, "A compact and low-profile loop antenna with multiband operation for ultra-thin smartphones," *IEEE Trans. Antennas Propag.*, Vol. 63, No. 1, 2745–2750, 2015.
5. Ban, Y. L., Z. X. Chen, Z. Chen, K. Kang, and J. L. W. Li, "Reconfigurable narrow-frame Antenna for heptaband WWAN/LTE smartphone applications," *IEEE Antennas Wireless Propag. Lett.*, Vol. 13, 1365–1368, 2014.
6. Li, Y., Z. Zhang, W. Chen, Z. Feng, and M. F. Iskander, "A quadband antenna with reconfigurable feedings," *IEEE Antennas Wireless Propag. Lett.*, Vol. 8, 1069–1071, 2009.
7. Lee, S. W., H. S. Jung, and Y. J. Sung, "A reconfigurable antenna for LTE/WWAN mobile handset applications," *IEEE Antennas Wireless Propag. Lett.*, Vol.14, 48–51, 2015.
8. Li, Y., Z. Zhang, J. Zheng, Z. Feng, and M. F. Iskander, "A compact hepta-band loop-inverted F reconfigurable antenna for mobile phone," *IEEE Trans. Antennas Propag.*, Vol. 60, No.1, 389–392, 2012.
9. Lee, S. W. and Y. Sung, "Compact frequency reconfigurable antenna for LTE/WWAN mobile handset applications," *IEEE Trans. Antennas Propag.*, Vol. 63, No. 10, 4572–4577, 2015.

10. Choi, M., H. Wi, B. Mun, et al., "A compact frequency reconfigurable antenna for LTE mobile handset applications," *International Journal of Antennas & Propagation*, 2015.
11. Li, Y., Z. Zhang, W. Chen, Z. Feng, and M. F. Iskander, "A switchable matching circuit for compact wideband antenna designs," *IEEE Trans. Antennas Propag.*, Vol. 58, No. 11, 3450–3457, 2010.
12. Yang, C. W., Y. B. Jung, and C. W. Jung, "Octaband internal antenna for 4G mobile handset," *IEEE Antennas Wireless Propag. Lett.*, Vol. 10, 817–819, 2011.
13. Chu, F. H. and K. L. Wong, "Internal coupled-fed dual-loop antenna integrated with a USB connector for WWAN/LTE mobile handset," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 11, 4215–4221, 2011.
14. 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," *Microw., Antennas Propag.*, Vol. 7, No. 6, 399–407, 2013.