Progress In Electromagnetics Research C, Vol. 50, 171–179, 2014

Small-Size Wideband Monopole Antenna with CRLH-TL for LTE Mobile Phone

Jie Luo, Shuxi Gong*, Pei Duan, Chunhui Mou, and Mao Long

Abstract—A planar monopole loaded with composite right/left-handed transmission line (CRLH-TL) for broadband LTE mobile phone is presented. The CRLH-TL with a propagation constant of zero is added to widen the input impedance bandwidth of the antenna. The proposed antenna covers the LTE700/2500/GSM850/900/1800/1900/UMTS2100 and WLAN2400 bands. Impedance bandwidths of VSWR < 2.5 ($S_{11} < -7$ dB) ranging from 675 to 1010 MHz and 1690 to 2550 MHz are obtained. The size of the monopole is $60 \times 16 \times 1\,\text{mm}^3$ which is smaller than most of the LTE antennas. Detailed design considerations of the monopole are described. A prototype is fabricated and tested. Both simulated and experimental results are discussed.

1. INTRODUCTION

Antennas for mobile phones are required to be more compact and support wider band because of the explosive development of wireless communications systems. Long term evolution (LTE) systems can be used in 4G wireless wide area network (WWAN) systems due to its significantly high data rate of at least 100 Mb/s in the downlink and 50 Mb/s in the uplink. Research and development in multiband LTE internal antennas have significantly increased recently, and many approaches are available [1–5]. One of the earliest forms of LTE antennas is coupling-fed antenna which can provide wide impedance bandwidth [3, 4]. The WWAN/LTE antenna in [4] uses two separated shorted strips and a T-shape monopole encircled as a coupling feed line with a volume of $55 \times 10 \times 8\,\text{mm}^3$. However, the size is too large to be practical, which is a common problem of coupling feed antenna. Besides, the feed line usually brings in undesired radiation. In some reports [5, 6], lumped elements loaded matching circuits are used to widen the operating bandwidth. Additional losses are usually inevitable in antenna with lumped elements which may deteriorate the antenna efficiency. Parasitic element and meandered structures are also employed to design wide-band and miniaturized antennas by introducing new resonant modes [7, 8]. Monopole reported in [7] uses a parasitic element, meandered strips, added branched structures and a lumped component. But too many branches and meandered parts will always end up with extra coupling and worse patterns.

In the last decade, composite right and left handed transmission line (CRLH-TL) which develops from left-handed materials (LHMs) has been applied in some microwave circuits and antenna [8–12]. Left-handed materials possess unique electromagnetic (EM) properties such as anti-parallel phase, group velocities, and zero propagation constant, with which abnormal radiation, size reduction and wideband antenna can be realized. Transmission line with zero propagation constant has a propagation constant of zero with non-zero group velocity at the zeroth-order resonance. As presented in [9], the loop antenna array which adopts CRLH-TL to achieve good matching shows enhanced gain and efficiency exceeding 85% for covering bands.

In this paper, a novel wideband CRLH-TL loaded monopole antenna for LTE mobile phones is achieved within the volume of $60 \times 16 \times 1\,\text{mm}^3$. A composite right- and left-handed (CRLH) transmission

Received 18 March 20144, Accepted 28 May 2014, Scheduled 12 June 2014
* Corresponding author: Shuxi Gong (shxgong@xidian.edu.cn).
The authors are with the Science and Technology on Antenna and Microwave Laboratory, Xidian University, Xi'an 710071, China.

line (TL) is applied in the antenna to achieve wideband. Besides, the arms of monopole antenna are bent to reduce the size further. The CRLH transmission line helps to improve the impedance matching greatly, making the antenna cover LTE700/2300/GSM850/900/1800/1900/UMTS2100 and WLAN2400 bands. The proposed CRLH transmission line is realized with periodically loaded parallel-plate lines so that its bi-layer structure is more compact than plane structures. The proposed antenna has a simpler structure and smaller size than the antennas in the latest published papers [13–16]. The dimension and performance of the designed antenna and LTE antennas designed lately are given in Table 1 for comparison. A prototype of the proposed antenna is fabricated and measured. Measured and simulated results of S_{11} exhibit reasonable agreement. The simulated results of bandwidth, radiation patterns and efficiency are discussed. The Ansoft HFSS 13 is employed to analyze the proposed antenna.

Table 1. Dimensions and performance of the designed and other antennas.

Antennas for terminal devices	Dimensions (mm^3)	B.W (MHz) Lower band/upper band	Antenna Gain (dBi)	Antenna Efficiency (%)
Proposed antenna	$60 \times 16 \times 1$	305/1100	$1.57 \sim 2.08$/ $4.04 \sim 4.74$	45.24–48.43/ 58.2–62.88
Reference [4]	$55 \times 10 \times 8$	256/980	$0.2 \sim 3.1/2.1 \sim 3.2$	$52 \sim 79/54 \sim 82$
Reference [13]	$34 \times 12 \times 6.5$	262/980	$-4.02 \sim 2.62/3.8 \sim 5.9$	$35 \sim 84/49 \sim 78$
Reference [14]	$110 \times 15 \times 8.5$	330/910	$0 \sim 3.6/1.1 \sim 5.2$	

2. ANTENNA THEORY

In order to illuminate the unusual characteristics of a CRLH-TL resonator, an equivalent circuit with equivalent capacitance and inductance is usually used. The corresponding equivalent circuit model of the CRLH-TL is given in Figure 1, which consists of series inductance L_R, shunt capacitance C_R, shunt inductance L_L, and series capacitance C_L. The series and parallel resonant frequency are given by

$$\omega_{se} = \frac{1}{\sqrt{L_R C_L}} \tag{1}$$

$$\omega_{sh} = \frac{1}{\sqrt{L_L C_R}} \tag{2}$$

Based on the theory of transmission line, the relationship between the length of TL and frequency can be expressed as:

$$\begin{gathered} l = |m|\,\lambda/2 \quad (m = \pm 1, \pm 2 \ldots) \\ \theta_m = \beta_m l = (2\pi/\lambda)\cdot(m\lambda/2) = m\pi \quad (m = \pm 1, \pm 2 \ldots) \end{gathered} \tag{3}$$

where m and l are the resonance mode and total physical length of the resonator, respectively. The values of the inductance and capacitance can be estimated from a full-wave parameter extracting technique. At this time, the resonance frequency of the TL can be expressed by Equation (3). Then, the quality factor is obtained

$$\omega_{RES} = \omega_{sh} = \frac{1}{\sqrt{L_L C_R}} \tag{4}$$

$$Q_0 = \frac{1/NR}{\omega_{se}(L_L/N)} = \frac{1/G}{\omega_{sh} L_L} = \omega_{sh}(1/NG)\cdot NC_R = \frac{1}{G}\sqrt{\frac{C_R}{L_L}} \tag{5}$$

$$BW = \frac{1}{Q_0} = G\sqrt{\frac{L_L}{C_R}} \tag{6}$$

where G is the shunt conductance of the CRLH-TL. The relative bandwidth can be derived by Equation (5). According to (6), the bandwidth in the case of the terminal open is mainly decided by the shunt inductance and shunt capacitance and not directly affected by the physical dimensions of

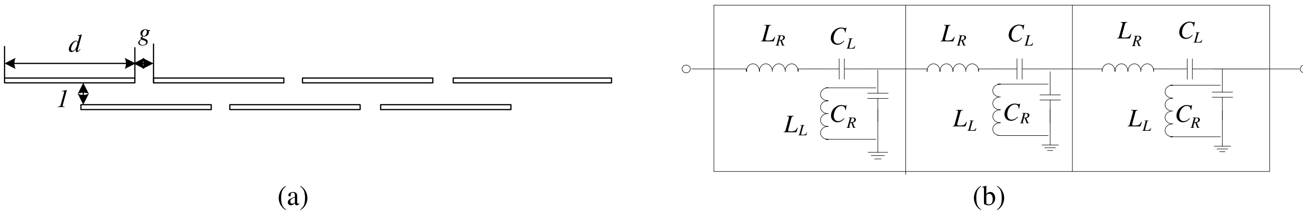


Figure 1. (a) Side view of the presented parallel-plate lines. (b) Corresponding equivalent lumped-element circuit model.

CRLH-TL. In case of an open ended CRLH-TL resonator, the zeroth-order resonance ($m = 0$), which is unique property of CRLH-TL, is derived. When $m = 0$, an infinite wavelength is supported. Thus, the resonance condition is independent of the size of CRLH-TL, which makes it possible to design a compact resonator for miniaturization. According to (6), we can introduce a large L_L and a small C_R to extend the bandwidth. There are three unit cells in the periodically parallel lines for the requirement of miniaturization.

3. ANTENNA DESIGN

Top and bottom views of the designed wideband CRLH monopole antenna are shown in Figures 2(a) and (b), respectively. The antenna is printed on both sides of a substrate with a dielectric of 2.65 and volume of $100 \times 60 \times 1\,\text{mm}^3$. The CRLH monopole antenna is mounted on the top of the substrate and occupies a volume of only $60 \times 16 \times 1\,\text{mm}^3$. The ground plane (GND) with a size of $60 \times 78\,\text{mm}^2$ is on the bottom of the substrate. The antenna should be 6 mm away from the ground plane. Point A is the feeding point which is connected to 50-Ohm coaxial line. Optimized dimensions of the proposed antenna are listed in Table 2.

Compared with LTE antennas in the terminal devices in [1–10], the monopole which consists of two arms and loaded CRLH-TL has a relatively simple structure. The left arm is designed to resonate at around 800 MHz, so the electrical length of the antenna's left arm should be approximately a quarter of the wavelength at the lowest frequency, i.e., at 0.74 GHz which is about 90 mm. The right arm

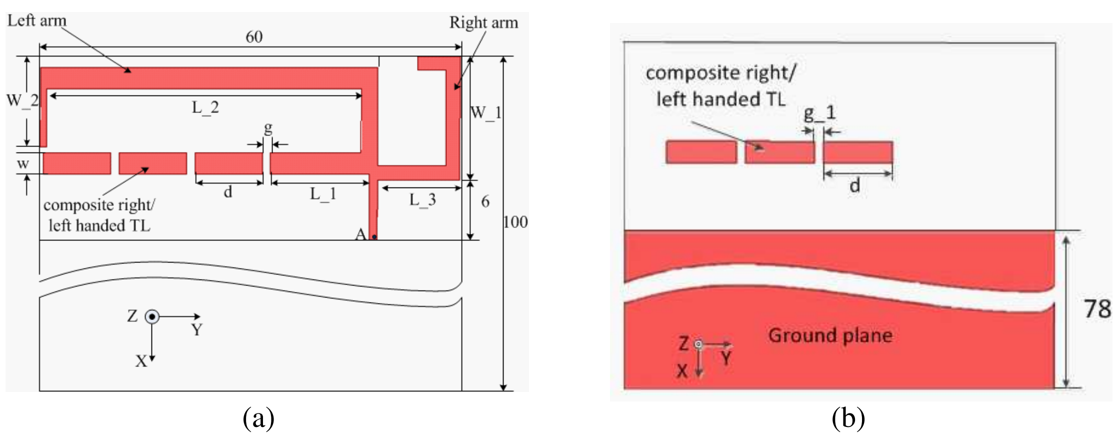


Figure 2. (a) Top view, (b) bottom view of the proposed wideband CRLH-TL monopole antenna.

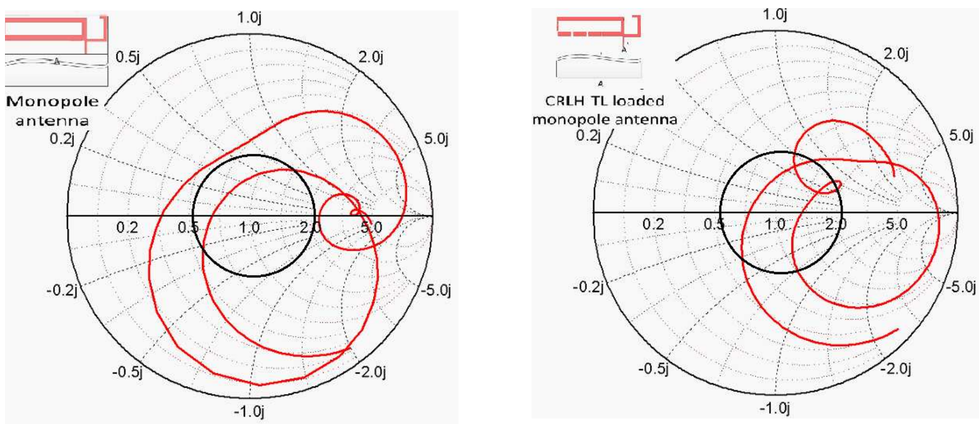
Table 2. Final dimensions of the proposed antenna (mm).

L_1	16 mm	W_1	16 mm
L_2	50 mm	W_2	12 mm
L_3	12 mm	g	1.2 mm
W	2.5 mm	d	10 mm

is supposed to be 30 mm to resonate at 2450 MHz. Both arms are bent to reduce the dimension. CRLH-TL is brought in to improve the impendence matching so that the antenna can cover the LTE2300/GSM1800/1900 and UMTS2100 bands. The CRLH-TL consists of two parallel conducting strips separated by gaps. The parallel strips are in different sides of the board, which can save a lot of space on the substrate. (Based on the CRLH-TL theory, we extend the bandwidth by adjusting the structure of CRLH-TL to introduce a large L_L and small C_R.) The final dimension of CRLH-TL is decided by simulation as $d = 10$ mm, $g = 1.2$ mm. The transmission line resonates at 1.8 GHz to 2.4 GHz, and the relative bandwidth reaches 28.6%.

4. SIMULATED AND EXPERIMENTAL RESULTS

Figure 3 shows the impedance of the conventional monopole and monopole loaded with CRLH-TL. It is obvious that the curve of the input impedance of the CRLH-TL monopole antenna shrinks around the matching point (within the VSWR = 2.5), which means that the CRLH-TL helps to provides a much



(a) (b)

Figure 3. Simulated input impedance from 0.5 GHz to 3 GHz for (a) monopole antenna, (b) CRLH-TL loaded monopole antenna.

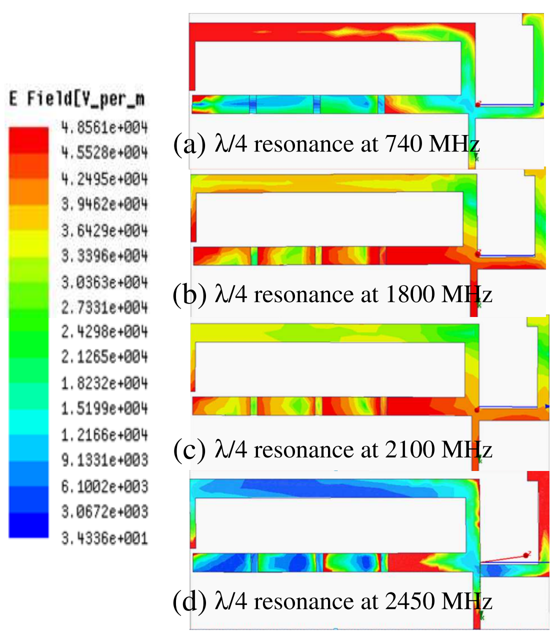


Figure 4. Surface currents on proposed monopole antenna with RLH-TL at (a) 740 MHz, (b) 1800 MHz, (c) 2100 MHz, (d) 2450 MHz.

wider impedance bandwidth.

The simulated surface current distributions on the designed monopole at 740, 1800, 2100 and 2450 MHz are given in Figure 4. It can be used to illustrate the function of the antenna. At the lower 740 MHz in Figure 4(a), strong currents distribute on the left arm, which indicates that the lower resonant mode covering LTE700/GSM850/900 is mainly contributed by the long coupling strip. In Figures 4(b) and (c), similar current distributions are due to the two adjacent frequencies working in the same mode, and strong currents concentrate on the parallel line. Apparently, the currents of the transmission line remain almost in phase from 1800 MHz to 2100 MHz. This reveals that the parallel line can be used to improve current distribution and achieve a wide band. Similar current distributions are due to the two adjacent frequencies in the same mode. In Figure 4(d), strong currents distribute on the right arm whose length is $\lambda/4$ at 2.45 GHz, which suggests that the resonant mode covering the WLAN 2.4 GHz band is provided mainly by the right arm.

In order to achieve the best performance, key parameters of parallel line and monopole are tuned. In Figure 5, as d or g increases, the wide band provided by CRLH-TL becomes slightly narrower or remains unchanged. It is confirmed that the slight parameter changes have little influence on the equivalent inductance and capacitance of transmission line. Great influence is observed in different resonant modes in Figures 5(c) and (d). The electrical length of the right arm can affect not only its resonant mode, but also the TL's resonant mode, and the dimension of left arm mainly controls the first resonance, which agrees with current distribution in Figure 4.

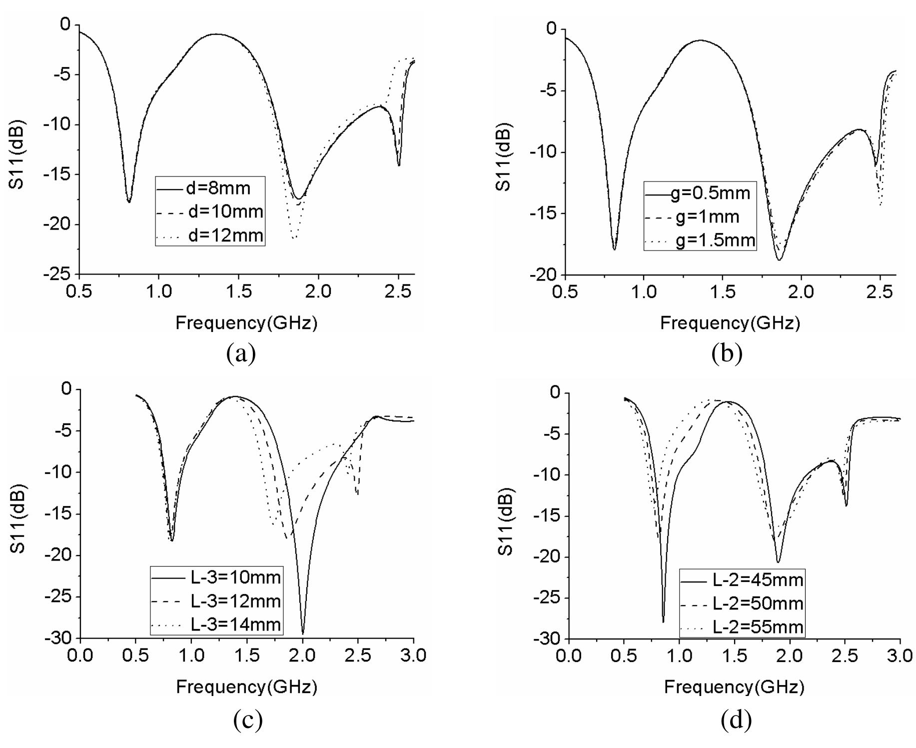
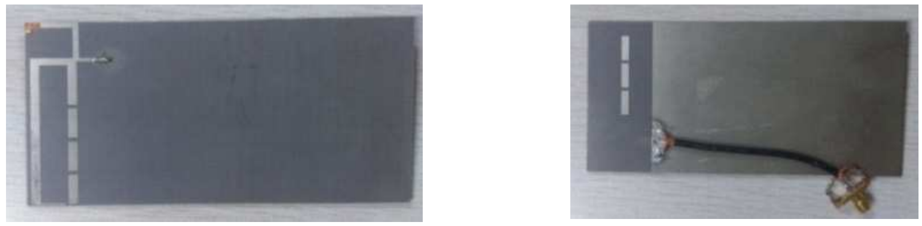


Figure 5. Simulated S_{11} of the proposed wideband monopole antenna, (a) variations in d, (b) variations in g, (c) variations in L_3, (d) variations in L_2.

As shown in Figure 6, the proposed CRLH-TL loaded antenna is fabricated and tested. Figure 7 shows the measured and simulated S_{11} of the constructed prototype. The measured and simulated results show reasonable agreement except for slight discrepancies. The measured curve has narrower band, but it still covers the target frequency. It is noticed that the first band of the monopole from 675 MHz to 1010 MHz covers LTE700/GSM850/900 in the measured result. The second band is from 1.51 GHz to 2.55 GHz which can cover GSM/1800/1900/UMTS2100/LTE2500 and WLAN2400.

Figure 8 shows the measured two-dimensional (2-D) radiation patterns at typical frequencies



(a) (b)

Figure 6. Prototype of the proposed multiband antenna, (a) top view, (b) back view.

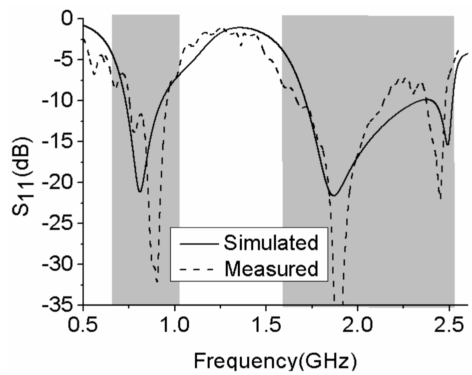
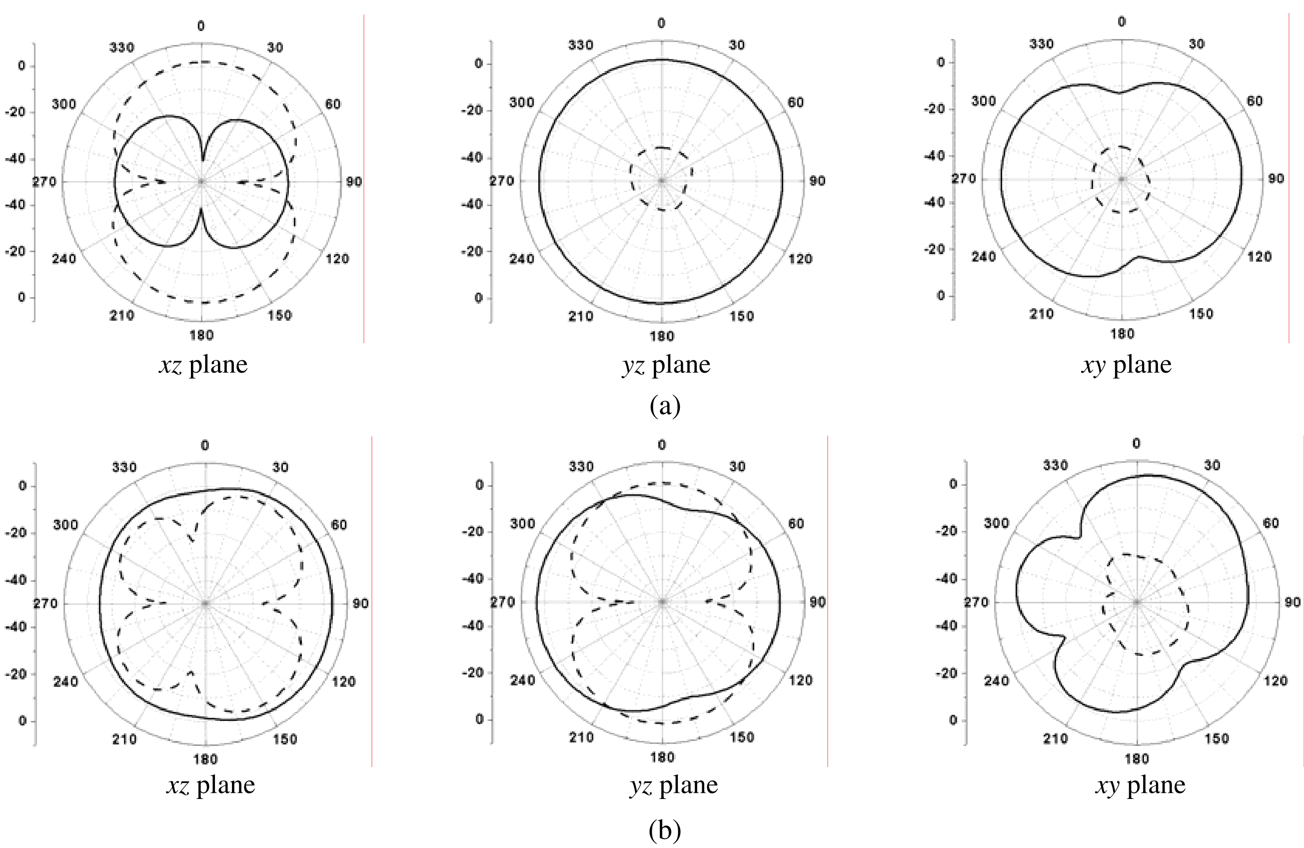


Figure 7. Measured and simulated S_{11} of the proposed antenna.



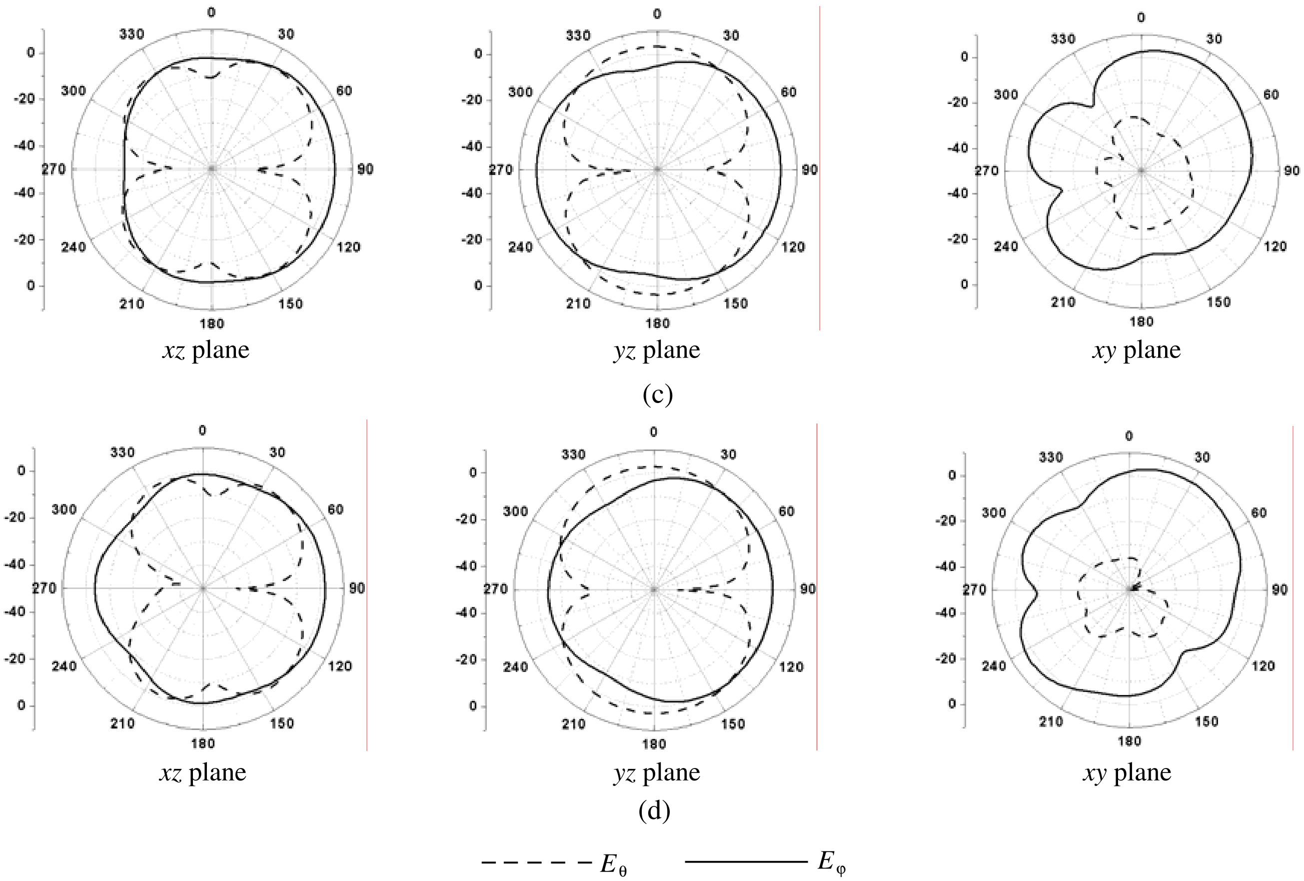


Figure 8. Measured radiation patterns of the fabricated antenna (co-polarization and cross-polarization) of the proposed antenna at different frequencies, (a) 740 MHz, (b) 1795 MHz, (c) 2.1 GHz and (d) 2.45 GHz.

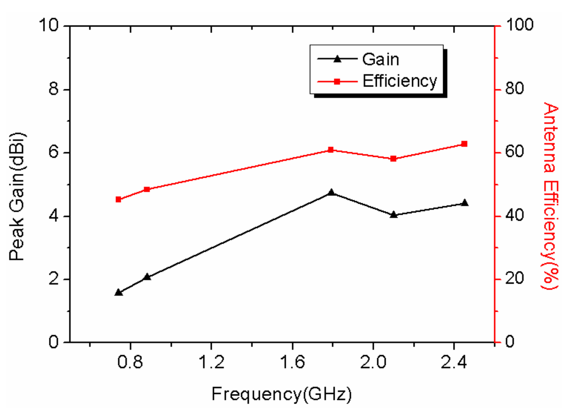


Figure 9. Gain and efficiency of the proposed antenna.

including 740 MHz, 1795 MHz, 2.1 GHz and 2.45 GHz in three principal planes. At 740 MHz, the omnidirectional radiation patterns are observed which looks like the radiation patterns of a dipole antenna. For higher frequencies at 1795, 2100 and 2450 MHz, the obtained radiation patterns are unsymmetrical just like those of many other reported terminal antennas in [3] and [4]. With the increase of frequency, the patterns in xy-plane are close to omnidirection though with some deterioration, due to the combined effect of the right arm and CRLH-TL structure. The patterns of the proposed antenna do not have multiple deep nulls and provide co-polarization and cross-polarization components, which guarantee the monopole to receive signals from all directions with both components.

Figure 9 presents the gain and efficiency of the designed antenna. For frequencies over the LTE700/GSM850/900 bands, the measured antenna gain is from 1.57 to 2.08 dBi. Meanwhile, the gain of the GSM1800/1900/UMTS /LTE/2500 bands ranges from approximately 4.74 to 4.04 dBi. The measured antenna efficiency is 45.24% at 740 MHz and 48.43% at 900 MHz. Meanwhile, the efficiency is approximately 58.20% to 62.88% over the GSM1800/1900/UMTS/LTE2500 bands. The measured results show that the radiation efficiency is larger than 50% over the higher bands.

5. CONCLUSION

A wideband CRLH-TL loaded monopole for eight-band internal LTE antenna has been proposed in this paper. Meta-material is loaded in the terminal device antenna to obtain a large bandwidth. A novel wideband monopole antenna for LTE mobile phone is achieved within the volume of $60 \times 16 \times 1\,\mathrm{mm}^3$. The lower band ($675 \sim 1010$ MHz) covers LTE700/GSM850/GSM900 bands, and the higher band ($1690 \sim 2550$ MHz) is wide enough to cover GSM1800/1900/UMTS2100/LTE2500 and WLAN2400. From simulated and measured results, good radiation characteristics including S_{11}, radiation patterns, antenna gain and efficiency over the eight operating bands are achieved. The results reveal that this design is an ideal wideband mobile antenna.

ACKNOWLEDGMENT

This work was supported by the Fundamental Research Funds for the Central Universities of China under Grant (K5051302031).

REFERENCES

1. Hu, C., W.-F. Lee, Y.-E. Lee, and C.-F. Yang, "A compact multiband inverted-F antenna for LTE/WWAN/GPS/WiMAX/WLAN operations in the laptop computer," *IEEE Antennas and Wireless Propagation Letters*, Vol. 9, 1169–1173, 2010.
2. Zhang, T., R. L. Li, G. P. Jin, and G. Wei, "A novel multiband planar antenna for GSM/UMTS/LTE/Zigbee/RFID mobile devices," *IEEE Transactions on Antennas and Propagation*, Vol. 59, No. 11, 4209–4214, 2011.
3. Lee, C.-T. and K.-L. Wong, "Planar monopole with a coupling feed and an inductive shorting strip for LTE/GSM/UMTS operation in the mobile phone," *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 7, 2479–2483, 2010.
4. 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, 2011.
5. Olaode, O. O., W. D. Palmer, and W. T. Joines, "Characterization of meander dipole antennas with a geometry-based, frequency-independent lumped element model," *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, 346–349, 2012.
6. Liao, Y., T. H. Hubing, and D. Su, "Equivalent circuit with frequency-independent lumped elements for coated wire antennas," *IEEE Transactions on Antennas and Propagation*, Vol. 60, No. 11, 5419–5423, 2012.
7. Gou, Y., Q. Wu, and J. Hua, "Design of a bandwidth extended and compact microstrip antenna based on CRLH-TL with slot loaded," *Proceedings of the Asia-Pacific Microwave Conference*, 1762–1765, 2011.
8. 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 Transactions on Antennas and Propagation*, Vol. 61, No. 7, 3889–3894, 2013.

9. Wei, K., Z. Zhang, Z. Feng, and M. F. Iskander, "A MNG-TL loop antenna array with horizontally polarized omni-directional patterns," *IEEE Transactions on Antennas and Propagation*, Vol. 60, No. 6, 2702–2710, 2012.
10. Segovia-Vargas, D., F. J. Herraiz-Martinez, E. Ugarte-Munoz, L. E. Garcia-Munoz, and V. Gonzalez-Posadas, "Quad-frequency linearly-polarized and dual-frequency circularly-polarized microstrip patch antennas with CRLH loading," *Progress In Electromagnetics Research*, Vol. 133, 91–115, 2013.
11. Sheeja, K. L. and P. K. Sahu, "Comparative study of a CRLH-TL based zeroth order resonant antenna," *2012 National Conference on Communications (NCC)*, 1–5, 2012.
12. Park, J.-H., Y.-H. Ryu, and J.-J. Li, "Mu-zero resonance antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 6, 1865–1875, Jun. 2010.
13. Dong, J., Y.-C. Jiao, Z.-B. Weng, Q. Qiu, and Y. Chen, "A coupled-fed antenna for 4G mobile handset," *Progress In Electromagnetics Research*, Vol. 141, 727–737, 2013.
14. Deng, S.-M., C.-L. Tsai, J.-P. Gu, K.-K. Tiong, and K.-W. Liu, "A novel design of LTE smart mobile antenna with multiband operation," *Progress In Electromagnetics Research C*, Vol. 42, 109–124, 2013.
15. Chang, S.-H. and W.-J. Liao, "A broadband LTE/WWAN antenna design for tablet PC," *IEEE Transactions on Antennas and Propagation*, Vol. 60, No. 9, 4354–4359, 2012.
16. Niu, B.-J. and Q.-Y. Feng, "Bandwidth enhancement of asymmetric coplanar waveguide (ACPW)-fed antenna based on composite right/left-handed transmission line," *IEEE Antennas and Wireless Propagation Letters*, Vol. 12, 563–565, 2013.