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Low-Profile Frequency-Reconfigurable LTE-CRLH Antenna for Smartphones

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ABSTRACT This paper presents a monopole antenna loaded with one frequency-reconfigurable composite right/left-handed (CRLH) unit cell. This antenna is designed by means of two varactor diodes and with changing capacitance operating at LTE700 (698-798 MHz), LTE850 (824-894 MHz), LTE900 (880-960 MHz), LTE1700 (1710-2155 MHz), LTE1800 (1710-1880 MHz), LTE1900 (1850-1990 MHz), LTE2100 (1920-2170 MHz), LTE2300 (2305-2360 MHz), LTE2500 (2496-2690 MHz), LTE2600 (2500-2690 MHz), and GPS (1176 MHz, 1227 MHz) frequencies that cover most of the LTE bands for smartphone handsets, which is a combination of two distributed and compact modes, in which the varactor diodes, as compact elements, play a significant role in reducing the antenna dimensions. By changing the capacitance, the entire frequency band of 700 MHz and 900 MHz was achieved. The CRLH structure, in turn, reduces the dimensions of the antenna and generates resonant frequencies less than the resonance frequency of the monopole. At these frequencies, the radiation patterns are quasi-omnidirectional.

INDEX TERMS Antenna, CRLH, LTE, reconfigurable antenna, smartphone.

I. INTRODUCTION

In recent years, the development of smart handsets as an indispensable part of modern life has rapidly grown. To satisfy many standards, these handsets need a modern antenna that occupies a small space while providing good radiation performance and qualities [1]–[5]. Reconfigurable antenna research is becoming increasingly interested in the applications of cellular radio systems, radar systems, and satellite communication due to their lighter weight, smaller dimension, and lower price compared to those of conventional antennas. Based on antenna characteristics, reconfigurable antennas can be categorized into operation frequency (as an alternative to multiband antennas), radiation pattern or polarization tunable antennas. The performance characteristics of antennas can be changed by altering the antenna flow of the current and using active materials, phase shifters, diodes, attenuators, adjustable materials, or mechanically movable parts [6]–[10]. In the last few years, LTE technology has grown in popularity because it offers a variety of applications utilized in handheld cellular devices. In fact, the implementation of this technology requires modern mobile antennas that cover all frequency bands, are low profile and cost-effective and have an omnidirectional radiation pattern [11]–[13].

Over the last decade, in parallel with the development of new wireless communication techniques, the demand for compact mobile phones has grown. These devices should support different communication plans with low profile antennas as well as the desired bandwidth, efficiency, low cost, and proper form factor. An important challenge in antenna design is designing a multiband, desired gain, and omnidirectional radiation pattern antenna. According to microwave research, metamaterials (MTMs) facilitate the attainment of these objectives for designing compact antennas. The abovementioned challenge is overcome by one type of MTM, i.e., a composite right/left handed (CRLH) unit cell. When the CRLH unit cell (usually with more than one cell) is loaded on conventional antennas, the antennas can operate in the zeroth-order mode or negative-order modes to achieve size miniaturization and multiband operation [15]–[22].

A planar monopole antenna loaded with a reactive single cell metamaterial, whose antenna enabled operation in two modes with orthogonal radiation patterns, employed a defective ground plane that proposed a compact tri-band antenna fed by co-planar waveguide (CPW) [16]. The extension concept of loading monopole antennas with the CRLH unit cell consists of loop antennas and printed inverted-F antennas

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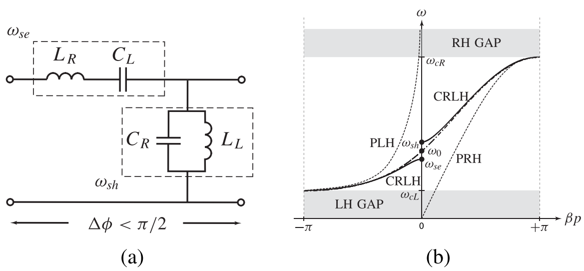


FIGURE 1. **Fundamental of CRLH MTMs. (a) Unit cell prototype. (b) Dispersion diagram [14].**

[18]. The increment of the electrical length of the based antennas is achieved by hybrid termination as well as by adding the possible frequency bands at a low profile size [19]. In another case, the dipole antenna is loaded with two new and different CRLH unit cells that cause smaller sized dipole antennas with three bands [20]. The series interdigital capacitors and shunt spiral inductors that compose a CRLH unit cell loaded on a monopole antenna are introduced and fed by a microstrip and provide two distinct frequencies below the monopole fundamental frequency [21]. Two narrow bands and one wide band are provided by a conventional planar monopole antenna loaded with a CRLH unit cell that covers multiple communication standards [22].

The present article discusses the improvement of the CRLH multiband monopole antenna from reference [21] for full coverage of the LTE700 and LTE900 frequency bands that consists of two parts: optimization of the antenna unit cell size, which includes a distributed segment, and the addition of varactor diodes to enable antenna frequency reconfigurability to select and access the frequencies that provide the antenna's compression portion. The proposed antenna is simulated by ANSYS HFSS software using the FEM. For every capacitance that the varactor diodes create for each applied voltage, the proposed antenna produces two additional frequencies below the monopole resonance.

II. MONOPOLE ANTENNA LOADED WITH RECONFIGURABLE CRLH UNIT CELL

MTMs are artificial composite materials suitable for dispersion engineering with unusual properties not found in nature. This study focuses on CRLH propagation as one of the many variations of MTMs, which represents the most general MTM structure possible. Fig. 1 displays a circuit indicative of a typical unit cell with a dispersion diagram [14].

A loss-less CRLH unit cell includes an impedance Z equal to an RH series inductor (L_R) and an LH series capacitor (C_L), whereas an admittance Y equals an LH shunt inductor (L_L) and an RH shunt capacitor (C_R) [14].

$$Z = j(\omega L_R - \frac{1}{\omega C_L}) \tag{1}$$

$$Y = j(\omega C_R - \frac{1}{\omega L_L}) \tag{2}$$

At low frequencies, the CRLH is equal to a PLH ($L_R = C_R = 0$), and at high frequencies, the CRLH is equal to a PRH ($L_L = C_L = 0$). At all other frequencies, the characteristics depend on the combination of the LH and RH contributions. To design a real CRLH structure, the standard guidelines are suggested in [14].

Today, due to the popularity of wireless communications and services, there has been an increase in the number of users using the same spectrum, creating interference between users. One way to reduce or eliminate interference is to use reconfigurable antennas, which can act as filters and reduce the need for receiver filters, leading to the reduction of the size and volume of the antenna [23], [24]. Reconfigurable antennas have the ability to change their geometry and behavior to adapt to various conditions. These antennas can deliver the same operational power as a multiband system. Single-antenna geometry dynamically varies and is adaptive without the need to increase the area to embed multiple antennas. The proposed reconfigurable techniques are divided into four categories: electrical, optical, mechanical, and material changes. Electrical reconfigurable antennas that have the components of electrical switching (RF MEMS, pin diodes, or varactors) rely on the redistribution of surface currents and changes of the topology of the radiative structure of the antenna and/or the edges of the radiation. The advantages of reconfigurable antennas, which have attracted much attention, include volume reduction, multistandardization, multiband nature, simplification of integration, cost savings, adaptive capability, multifunctional capabilities, functional change as a mission change, and potential to act as a single entity or as a provider and support for narrowband or broadband operations [25]–[28]. It is worth noting that the white TV (TVWS) refers to the unused frequency band on the TV band, which has a frequency of 470 to 862 MHz. With a bandwidth of approximately 58%, as well as the ability to transmit signals for long distances, this frequency band has high potential for communication. The retrieved antenna is one of the best solutions for achieving this type of standard by redistributing the frequency, miniaturization, and operation [29]. A reference monopole antenna is shown in Fig. 2a. This antenna is implemented on a Rogers RT Duroid-5880 with a dielectric constant equivalent to 2.2, $\tan(\delta) = 0.0009$, and substrate thickness of 1.57 *mm*. This antenna operates at 2.13 GHz by choosing the length of the monopole. To shape the radiation pattern and operating bandwidth of conventional monopole antennas, the ground size plays a significant role [5], [22]. The optimal size is $L_g \times W_s = 55\ mm \times 56\ mm$.

Fig. 2b shows the design of the proposed antenna consisting of a conventional monopole antenna loaded with one CRLH unit cell that can reconfigure the frequency using varactor diodes. The schematic diagram and equivalent circuit of the frequency reconfigurable unit cell are displayed in Fig. 3a and Fig. 3b, respectively. Only one frequency is available for the single monopole. However, adding one CRLH unit cell can add two frequencies lower than the monopole frequency. Therefore, more operating bands were obtained by inserting

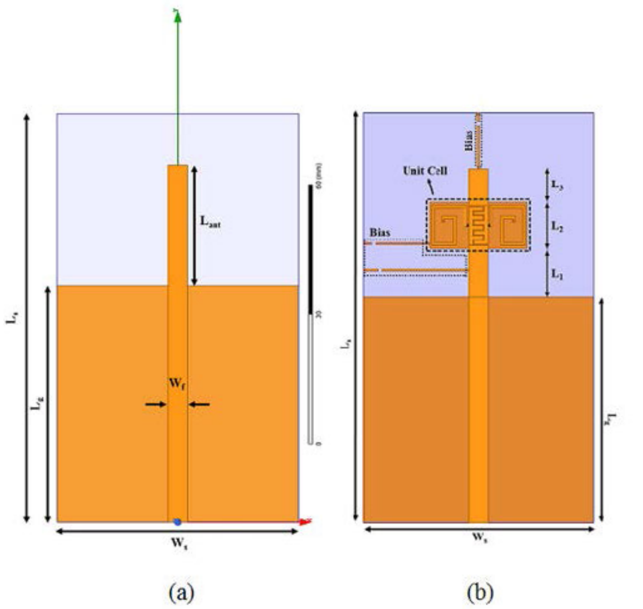


FIGURE 2. Schematic of the proposed CRLH-loaded monopole [21], (a) conventional monopole antenna (b) monopole loaded by unit cell and varactor diodes.

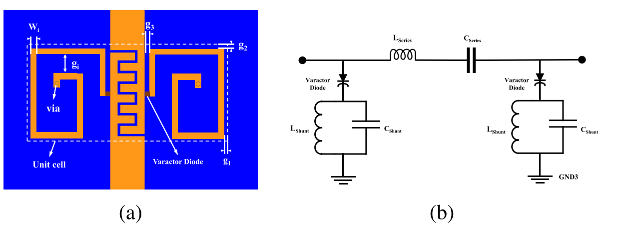


FIGURE 3. (a) Schematic diagram of unit cell (varactor diode between IDC and spiral inductance) (b) equivalent circuit.

more CRLH unit cells. The unit cell layout of this antenna was taken from [21]. The antenna can support twelve bands, which are LTE700, LTE850, LTE900, LTE1700, LTE1800, LTE1900, LTE2100, LTE2300, LTE2500, LTE2600, and GPS (1176 MHz, 1227 MHz). The frequency reconfigurable unit cell consists of a series interdigital capacitors (IDCs), shunt spirals, and two varactor diodes. The capacitance is generated by the interdigital capacitor and varactor diodes, and a shortened shunt stub creates the parallel inductance. By changing the dimensions of the interdigital capacitor and the shunt inductance and changing the capacitance of the varactor diodes, the working frequencies of the unit cell can be determined. The resonating condition occurs when the entire phase shift across the CRLH varactor diode-loaded monopole (φ_{total}) fulfills the following condition. The following equation is valid only in the CRLH unit cell passband [5]:

$$\varphi_{total} = \varphi_{monopole} + m \times \varphi_{CRLH} + 2 \times \varphi_{varactor} = n \times 90^0, \; n = 0, \; \pm 1, \pm 3 \qquad (3)$$

$\varphi_{monopole}$ is the phase shift caused by the monopole without the frequency reconfigurable CRLH unit cell; φ_{CRLH} is the phase shift is due to a single CRLH unit cell without varactor diodes; $\varphi_{varactors}$ is the phase shift is due to the varactor diodes; m refers to the number of CRLH unit cells; and n stands for the mode order.

TABLE 1. Dimensions of the proposed antenna.

Symbol	Conventional monopole	Modified monopole with CRLH unit cell
L_1	12.74	12.74
L_2	6.52	9.72
L_3	8.79	8.79
W_c	-	0.9
S_c	-	0.28
W_i	-	0.6
g_i	-	2.1
W_s	56	56
L_g	55	55
L_ant	31.25	31.25
W_f	4.5	4.5
R_via	-	0.2
g_1	-	0.5
g_2	-	0.5
g_3	-	0.5

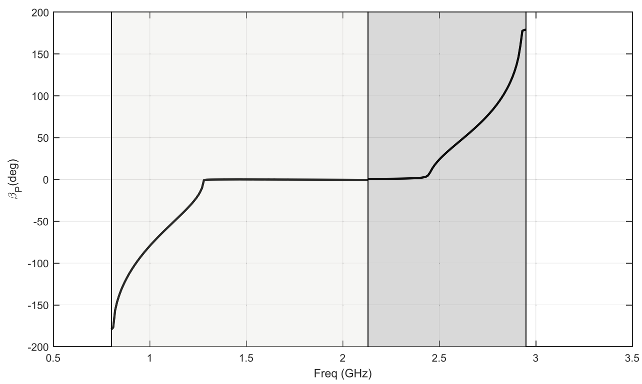


FIGURE 4. Dispersion relation for modified CRLH unit cell.

Generally, there are two types of elements in the unit cell: distributed and compact. A distributed capacitor can be realized using an interdigital capacitor and a spiral inductance. One disadvantage of this type of unit cell is that the length of the CRLH unit cell is analogous to the monopole length on the latitudinal side. Covering lower bands such as 700 MHz is troublesome. To overcome this problem, compact elements, which are a type of capacitor equivalent to a varactor diode, are used. In the compact state, compact elements of the inductor and capacitor are used. In this paper, the frequency reconfigurable design is a combination of compact and distributed models. The optimal antenna dimensions for covering the bands mentioned above are shown in Table 1.

The proposed antenna is designed on a 1.57 *mm* thick Rogers 5880 substrate. The dispersion relation of the microstrip-fed modified CRLH unit cell is calculated and shown in Fig. 4. Fig. 5 shows the simulated S_{11} as a function of the frequency for the proposed antenna without varactor diodes. Compared to the conventional microstrip-fed monopole antenna, three operating bands are observed, as shown in Fig. 5. Three distict bands located at 0.63, 1.04, and 2.24 GHz are achieved. The realized impedance

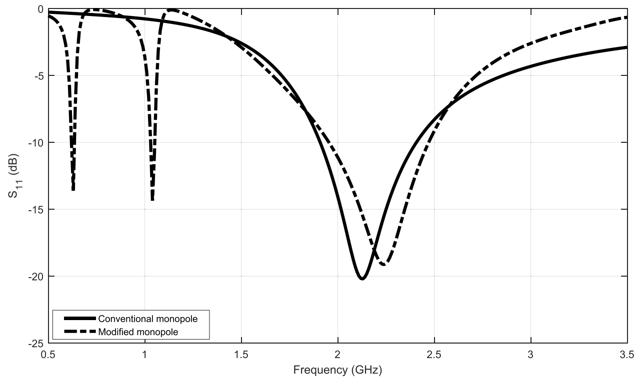


FIGURE 5. Simulated S_{11} as a function of frequency for the proposed antenna without varactor diodes.

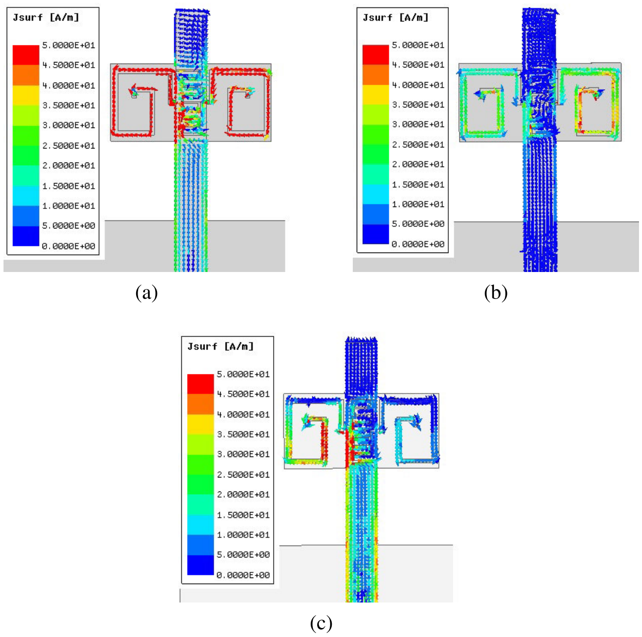


FIGURE 6. For the proposed antenna, the simulated current distributions, (a) 0.63 GHz, (b) 0.104 GHz, and (c) 2.24 GHz frequencies.

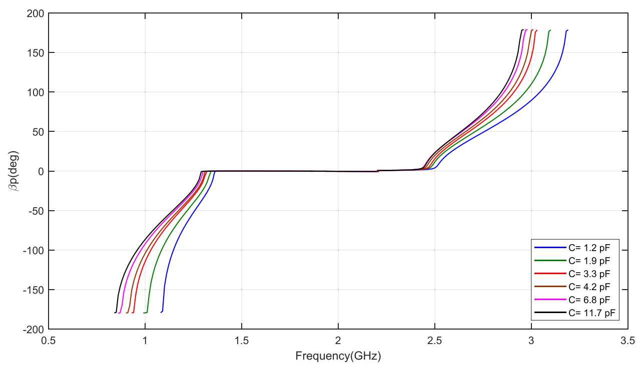


FIGURE 7. Dispersion diagram of the proposed reconfigurable CRLH unit cell shown in Fig. 3a.

bandwidth ($S_{11} < 10$ dB) is 2.5% at 0.63 GHz, 2.1% at 1.04 GHz, and 23% at 2.24 GHz. These three bands can be

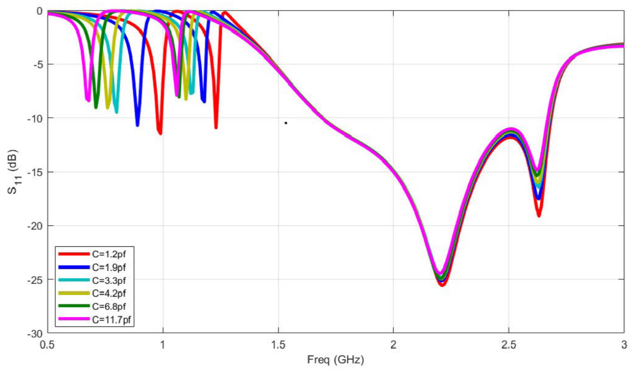


FIGURE 8. Simulated S_{11} as a function of frequency for the proposed reconfigurable CRLH-loaded monopole.

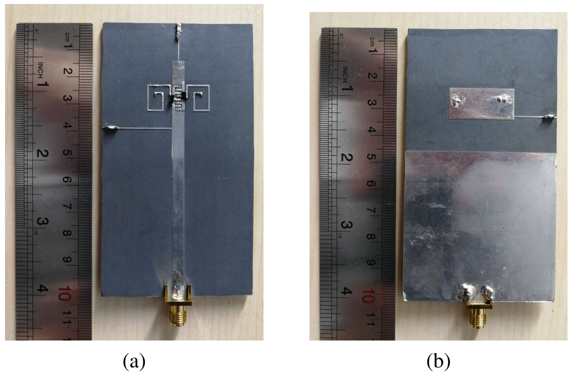
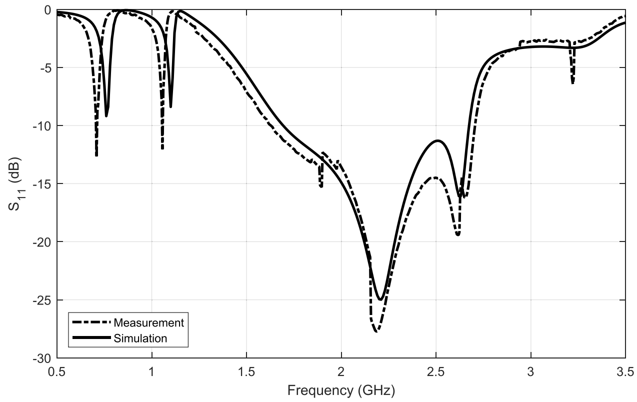
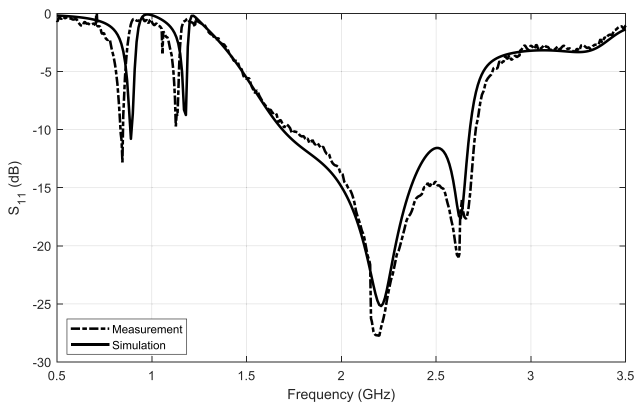


FIGURE 9. The prototype of the proposed antenna. (a) Top view and (b) bottom view.

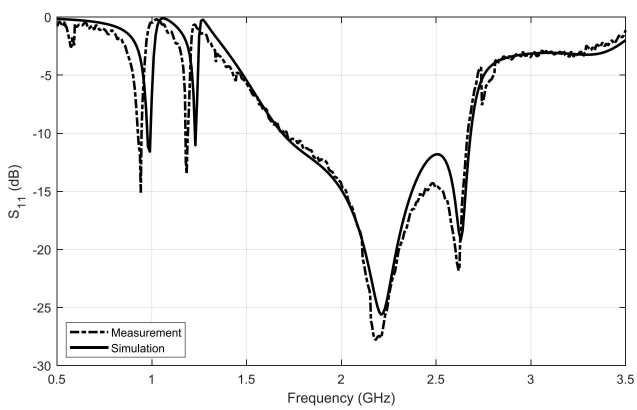
explained based on the dispersion relation shown in Fig. 4. It can be observed that the LH region ranges from 0.8-2.13 GHz, and the RH region ranges from 2.13-2.95 GHz. The current distributions are shown in Fig. 6 for frequencies of 0.630 GHz, 1.04 GHz, and 2.24 GHz, which apparently show that the CRLH circuit plays a minor role in radiation. In fact, the monopole is the effective radiation element. The CRLH circuit controls the matching of low-frequency bands. Therefore, the proposed circuit has two independent mechanisms for controlling the specification. The first resonant frequency, situated at 0.63 GHz, lies in the lower stopband of the unit cell, which allows the antenna to be considered a monopole loaded with a spiral inductor; all the current goes through the shunt branch, and the IDC can be regarded as an open circuit (Fig. 6a). The second band, situated at 1.04 GHz, is in the LH region of the reconfigurable unit cell that the varactor diodes and the unit cell provide, which is a phase lead that is equivalent to the phase lag provided by the conventional monopole, and Eq. (3) is fulfilled with $n = 0$ (Fig. 6b). The third band, situated at 2.24 GHz, is within the RH region of the reconfigurable unit cell and is the resonance frequency of the monopole ($n = 1$) (Fig. 6c). This band is shifted from 2.13 to 2.24 GHz because at 2.13 GHz, the frequency-reconfigurable CRLH unit cell pro-



(a)

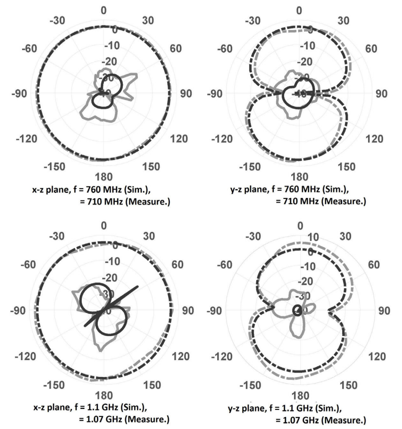


(b)

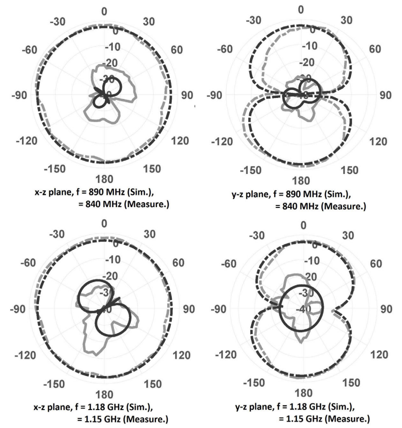


(c)

FIGURE 10. Simulated and measured S_{11} of the proposed antenna. (a) C = 4.2 pF (V = 3v), (b) C = 1.9 pF (V = 6v), (c) C = 1.2 pF (V = 12v).



(a)



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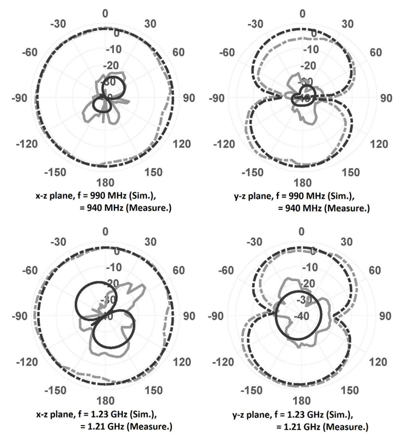


(c)

FIGURE 11. Radiation patterns of reconfigurable CRLH antenna (a) C = 4.2 pF (V = 3v), (b) C = 1.9 pF (V = 6v), (c) C = 1.2 pF (V = 12v) (The dashed lines indicate co-polarization patterns, while the solid lines indicate cross-polarization, black lines for simulation and gray lines for measurement).

vides a zero phase shift, and consequently, the electrical length of the modified monopole at this frequency agrees with ($L_1 + L_3$), which is shorter than that of the original monopole ($L_1 + L_2 + L_3$).

The obtained frequencies are LTE700, LTE850, LTE900, LTE1700, LTE1800, LTE1900, LTE2100 LTE2300, LTE2500, LTE2600, and GPS (1176 MHz, 1227 MHz). Complete 700 MHz and 900 MHz bands can be achieved by replacing the varactor diode with the capacitor between 1.2 pF and 12 pF. The dispersion curves [30] of the frequency-reconfigurable CRLH unit cell (Fig. 3a) calculated for capacitances of 1.2 pF, 1.9 pF, 3.3 pF, 4.2 pF, 6.8 pF, and 11.7 pF

TABLE 2. Simulated and measured gain and simulated radiation efficiency of proposed antenna for three capacitances (C = 4.2, 1.9, and 1.2 pF).

C (pF)	Frequencies(GHz)	Simulated Gain(dB)	Measured Gain(dB)	Simulated Efficiency(%)
4.2	0.76	1.7	1.35	95.1
	1.10	2	1.88	79.2
1.9	0.89	2	1.9	92.9
	1.18	2	2.1	76.8
1.2	0.99	2.2	2.1	92.5
	1.23	2.3	2.12	84.3
	2.21	4.3	4.24	93.7
	2.63	3.2	2.63	91.6

are shown in Fig. 7. The dispersion relation of the unit cell controls the new frequencies, which are lower than the normal resonance of the monopole. It can be observed that for the antenna with a 1.9 pF capacitance, the LH region ranges from 1-2.21 GHz and the RH region ranges from 2.21-3.1 GHz, and for the antenna with a 11.7 pF capacitance, the LH region ranges from 0.84-2.20 GHz and the RH region ranges from 2.20-2.96 GHz.

Fig. 8 shows the simulated S_{11} as a function of the frequency for the proposed antenna with varactor diodes.

The CRLH unit cell ground is not connected to the main ground of the microstrip-fed monopole and is floating. Adding a unit cell will cause a frequency shift on the monopole frequency because the length of the monopole is shortened. Furthermore, the unit cell can provide a leading phase shift opposite to the lagging shift of the monopole. Adding the varactor diodes does not create any noticeable change in the antenna dimensions but provides reconfigurability to the antenna. For every value of the varactor diode, three distinct bands are achieved. For example, if the value of capacitance is 1.2 pF (V = 12 V), then four bands are located at 0.99, 1.23, 2.21, and 2.63 GHz, which can be explained based on the dispersion relation of the frequency reconfigurable CRLH unit cell, as shown in Fig. 7.

The proposed reconfigurable CRLH unit cell occupies only $0.05\lambda_0 \times 0.02\lambda_0$ of the monopole, where λ_0 is the free-space wavelength corresponding to the lowest resonant frequency of the antenna.

III. ANTENNA PROTOTYPE AND MEASUREMENT RESULT

The fabricated structure is shown in Fig. 9, which was designed on a Rogers 5880 ($\varepsilon_r = 2.2$, $\tan(\delta) = 0.0009$) with a thickness of 1.57 *mm*. The simulated and measured s11 are shown in Fig. 10. The S-parameters are measured on a Hewlett Packard 8720C network analyzer. Good agreement is achieved between the S_{11} simulation and measurement for three measurements at V = 3 V (C = 4.2 pF), V = 6 V (C = 1.9 pF), and V = 12 V (C = 1.2 pF), except for the frequency shifts of 50 MHz and 30 MHz in the first and second bands for C = 4.2 pF and C = 1.9 pF, respectively, and the frequency shifts of 50 MHz and 20 MHz in the first and second bands for C = 1.2 pF. The dimensions of the reconfigurable CRLH unit cell are optimized to cover the LTE700, LTE850, LTE900, LTE1700, LTE1800, LTE1900, LTE2100, LTE2300, LTE2500, and LTE2600 bands and GPS (1176 MHz, 1227 MHz) bands.

For the first and second bands, the reflection coefficient is approximately 9 dB, and for the third band, the reflection coefficient is greater than 10 dB from 1.7 to 2.7 GHz. The antenna design achieves two wide continuous tuning ranges using dual varactor diodes (SMV1204-99A). The minimum varactor capacitance value limits the upper band of the high-frequency tuning range. If the minimum and maximum reverse bias voltages are applied, at 0.2 and 12 V (12 to 1.2 pF), the antenna achieves its maximum tuning range of 670 to 990 MHz and 1.05 to 1.23 GHz for the first and second bands, respectively. On the other hand, to have complete control over the first and second resonance frequencies, two varactor diodes are used. These two varactor diodes are sufficient to completely tune the first and second operating frequencies of the antenna to the desired frequencies. The reconfigurable CRLH unit cell is designed to operate as a phase shifting element and does not contribute to the radiation process.

Fig. 11 shows the simulated and measured two-dimensional radiation patterns of the proposed antenna in the two principal planes (x-z and y-z planes) at three capacitances: 4.2 pF, 1.9 pF, and 1.2 pF. The radiation patterns exhibit quasi-omnidirectional properties at the mentioned bands in Fig. 10. At each frequency, the co-polar and cross-polar patterns are shown for each orthogonal cut-plane. The patterns show that the antenna achieves good co-polar omnidirectional radiation across the tuning range. The high cross-polarization is acceptable since the antenna will often have random orientations when used in its intended wireless applications.

TABLE 3. Performance comparison of different antenna types for mobile application.

Ref.Num	antenna types	Lowest Frequency (GHz)	gain(dB)	Electrical Size of the Antenna	Number of the LTE Frequency Bands
1	PIFA antenna	0.88	1	$0.14\lambda_0 \times 0.05\lambda_0$	5
13	Planar antenna	0.818	1.85	$0.04\lambda_0 \times 0.12\lambda_0$	7
16	Monopole antenna with single cell metamaterail loading	2.45	0.98	$0.16\lambda_0 \times 0.19\lambda_0$	3
19	Hybrid termination metamaterial CRLH antenna	2.4	-8.05	$0.17\lambda_0 \times 0.25\lambda_0$	2
21	CRLH unit cell loaded monopole antenna	0.89	-1.87 (realized gain)	$0.05\lambda_0 \times 0.08\lambda_0$	3
25	Reconfigurable antenna	0.824	-3.2	$0.1\lambda_0 \times 0.01\lambda_0$	7
proposed work	Reconfigurable CRLH antenna	0.67	1.4	$0.05\lambda_0 \times 0.07\lambda_0$	10

λ_0 is the free-space wavelength corresponding to the lowest resonant frequency of the antenna

The simulated and measured gain and simulated efficiency for three capacitances (4.2, 1.9, and 1.2 pF) are shown in Table 2. It is noted that the conventional monopole has 92.8% efficiency at 2.13 GHz.

The key features of the proposed antenna design are based on its low-profile reconfigurable-CRLH design along with its ability to cover ten LTE frequency bands with only two integrated varactor diodes. A comparison table, including the previous reference antennas and proposed work, is given in Table III. Compared to the reference antennas, the proposed antenna has the following advantages.

1) The proposed antenna reconfigures the CRLH part of the antenna, in which a novel reconfigurable antenna helps in efficient utilization of the spectrum.

2) This work presents a low-profile reconfigurable antenna, in terms of electrical size, with less complexity.

3) The proposed antenna does not require a complex matching network.

4) It can be seen that the number of LTE frequencies is more than that of the others.

5) This work covers the frequency band of 700 MHz and 900 MHz completely.

IV. CONCLUSION

Our antenna was designed and simulated by HFSS. It was a frequency-reconfigurable monopole antenna loaded by one CRLH unit cell. This CRLH-based antenna was powered by a microstripe and provided ten LTE standard bands included LTE700, LTE850, LTE900, LTE1700, LTE1800, LTE1900, LTE2100, LTE2300, LTE2500, and LTE2600 and two GPS frequencies included 1176 and 1227 MHz. The loaded monopole was a compact and distributed antenna in which the varactor diodes comprised the compact part and the CRLH and a monopole provided the distributed part, both of which compressed the antenna. It should be noted that the antenna can be loaded with more than one cell, which generates more frequencies. In the single CRLH unit cell antenna, two diodes were used. The lowest band (LTE700 MHz) was the hardest band to implement. The antenna was flat, compact, and applicable for modern communication systems, namely, smartphones. The radiation patterns were quasi-omnidirectional, with a good return loss.

REFERENCES

[1] D.-G. Kang and Y. Sung, "Compact hexaband PIFA antenna for mobile handset applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 1127–1130, 2010.

[2] A. Locatelli, D. Modotto, C. De Angelis, S. Boscolo, M. Midrio, and A. D. Capobianco, "Design of fully printed omnidirectional CRLH loop antennas for WLAN technology," *Microw. Opt. Technol. Lett.*, vol. 56, no. 6, pp. 1405–1408, Jun. 2014.

[3] Z. Eskandari, A. Keshtkar, J. Ahmadi-Shokoh, and L. Ghanbari, "A novel fractal for improving efficiency and its application in LTE mobile antennas," *Microw. Opt. Technol. Lett.*, vol. 57, no. 10, pp. 2429–2434, Oct. 2015.

[4] M. R. I. Faruque, M. I. Hossain, N. Misran, M. Singh, and M. T. Islam, "Metamaterial-embedded low SAR PIFA for cellular phone," *PLoS ONE*, vol. 10, no. 11, Nov. 2015, Art. no. e0142663.

[5] A. A. Ibrahim and A. M. E. Safwat, "Microstrip-fed monopole antennas loaded with CRLH unit cells," *IEEE Trans. Antennas Propag.*, vol. 60, no. 9, pp. 4027–4036, Sep. 2012.

[6] H. Xu, H. Wang, S. Gao, H. Zhou, Y. Huang, Q. Xu, and Y. Cheng, "A compact and low-profile loop antenna with six resonant modes for LTE smartphone," *IEEE Trans. Antennas Propag.*, vol. 64, no. 9, pp. 3743–3751, Sep. 2016.

[7] Y. P. Selvam, M. Kanagasabai, M. G. N. Alsath, S. Velan, S. Kingsly, S. Subbaraj, Y. V. R. Rao, R. Srinivasan, A. K. Varadhan, and M. Karuppiah, "A low-profile frequency- and pattern-reconfigurable antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 3047–3050, 2017.

[8] R. L. Haupt and M. Lanagan, "Reconfigurable antennas," *IEEE Antennas Propag. Mag.*, vol. 55, no. 1, pp. 49–61, Feb. 2013.

[9] O. El Maleky, F. Ben Abdelouahab, M. Essaaidi, and N. Abdelfatah, "Miniature design of T-Shaped frequency Reconfigurable antenna for S-band application using switching technique," *Int. J. Electr. Comput. Eng.*, vol. 7, no. 5, pp. 2426–2433, Oct. 2017.

[10] N. Haider, D. Caratelli, and A. G. Yarovoy, "Recent developments in reconfigurable and multiband antenna technology," *Int. J. Antennas Propag.*, vol. 2013, Mar. 2013, Art. no. 869170.

[11] H. Jian-Rong, L. Jiu-Sheng, and W. Di, "A small planar antenna for 4G mobile phone application," *Int. J. Antennas Propag.*, vol. 2016, May 2016, Art. no. 4791831.

[12] O.-Y. Kwon, R. Song, and B.-S. Kim, "A fully integrated shark-fin antenna for MIMO-LTE, GPS, WLAN, and WAVE applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 4, pp. 600–603, Apr. 2018.

[13] T. Zhang, R. Li, G. Jin, G. Wei, and M. M. Tentzeris, "A novel multiband planar antenna for GSM/UMTS/LTE/Zigbee/RFID mobile devices," *IEEE Trans. Antennas Propag.*, vol. 59, no. 11, pp. 4209–4214, Nov. 2011.

[14] C. Caloz and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*. Hoboken, NJ, USA: Wiley, 2006.

[15] M. Alibakhshi-Kenari, M. Naser-Moghadasi, R. A. Sadeghzadeh, and B. S. Virdee, "Hexa-band planar antenna with asymmetric fork-shaped radiators for multiband and broadband communication applications," *IET Microw., Antennas Propag.*, vol. 10, no. 5, pp. 471–478, Apr. 2016.

[16] J. Zhu, M. Antoniades, and G. Eleftheriades, "A compact Tri-band monopole antenna with single-cell metamaterial loading," *IEEE Trans. Antennas Propag.*, vol. 58, no. 4, pp. 1031–1038, Apr. 2010.

[17] M. Alibakhshi-Kenari, M. Naser-Moghadasi, R. A. Sadeghzadeh, B. S. Virdee, and E. Limiti, "New compact antenna based on simplified CRLH-TL for UWB wireless communication systems," *Int. J. RF Microw. Comput. Aidied Eng.*, vol. 26, no. 3, pp. 217–225, Mar. 2016.

[18] A. R. Raslan, A. A. Ibrahim, and A. M. E. Safwat, "Resonant-type antennas loaded with CRLH unit cell," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 23–26, 2013.

[19] M. A. Abdalla, "Hybrid termination metamaterial CRLH resonant antennas: Analysis and design," *Microw. Opt. Technol. Lett.*, vol. 59, no. 11, pp. 2721–2728, Nov. 2017.

[20] M. A. Abdalla, M. H. Ghouz, and M. Abo El-Dahab, "Loaded dipole antennas with new CRLH cell configuration," *AEU-Int. J. Electron. Commun.*, vol. 80, pp. 165–171, Oct. 2017.

[21] S. V. Reddy, D. Sarkar, K. Saurav, and K. V. Srivastava, "A compact CRLH unit cell loaded triple-band monopole antenna," *Microw. Opt. Technol. Lett.*, vol. 57, no. 1, pp. 115–119, Jan. 2015.

[22] A. A. Ibrahim, A. M. E. Safwat, and H. El-Hennawy, "Triple-band microstrip-fed monopole antenna loaded with CRLH unit cell," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 1547–1550, 2011.

[23] V. Arun, L. KarlMarx, K. K. Jegadish, and C. V. Christy, "N-shaped frequency reconfigurable antenna with auto switching unit," *Appl. Comput. Electromagn. Soc.*, vol. 33, no. 6, pp. 710–713, 2018.

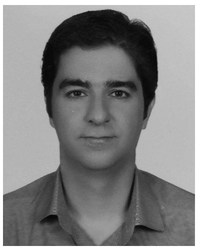
[24] M. W. Young, S. Yong, and J. T. Bernhard, "A miniaturized frequency reconfigurable antenna with single bias, dual varactor tuning," *IEEE Trans. Antennas Propag.*, vol. 63, no. 3, pp. 946–951, Mar. 2015.

[25] Y.-L. Ban, Z. Xiang 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, pp. 1365–1368, 2014.

[26] L. Hinsz and B. D. Braaten, "A frequency reconfigurable transmitter antenna with autonomous switching capabilities," *IEEE Trans. Antennas Propag.*, vol. 62, no. 7, pp. 3809–3813, Jul. 2014.

[27] Y. Tawk, J. Costantine, and C. G. Christodoulou, "A varactor-based reconfigurable filtenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 716–719, 2012.

[28] F. A. Asadallah, J. Costantine, and Y. Tawk, ‘‘A multiband compact reconfigurable PIFA based on nested slots,’’ *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 2, pp. 331–334, Feb. 2018.
[29] L.-H. Trinh, ‘‘Reconfigurable antennas for mobile phone and wsn applications,’’ Ph.D. dissertation, Université Nice Sophia Antipolis, Nice, France, 2015.
[30] J. Bonache, M. Gil, I. Gil, J. Garcia-Garcia, and F. Martin, ‘‘On the electrical characteristics of complementary metamaterial resonators,’’ *IEEE Microw. Wireless Compon. Lett.*, vol. 16, no. 10, pp. 543–545, Oct. 2006.



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