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A Design of Compact Meta-material CRLH Antenna for Wireless Applications

Ahmed A. Ibrahim[1], Mahmoud A. Abdalla[2], Islam H. Abdelaziem[3*], Hesham F. A. Hamed[1,4]

[1] *Communications and Electronics Engineering Department, Faculty of Engineering, Minia University, Egypt*

[2] *Electronic Engineering Department, Military Technical College, Cairo, Egypt*

[3] *Communications and Electronics Engineering Department, Faculty of Engineering, Sohag University, Egypt*

[4]*Faculty of Engineering, Egyptian Russian University, Cairo, Egypt*

* Corresponding author *E-mail: islam_hassan@eng.sohag.edu.eg*

ABSTRACT

This article presents a compact design of a composite-right-left-handed (CRLH) antenna for wireless applications. The antenna is fed using a coplanar waveguide (CPW) feed structure. The CRLH-antenna is comprised of one CRLH unit cell. The CRLH unit cell has a series capacitance (interdigital capacitor) and a shunt inductor (stub meander inductor). The antenna achieves compactness with a small size of 16.5 mm × 26 mm × 1.6 mm, thanks to the CRLH features such as nonlinear phase. The proposed antenna achieves a size reduction of better than 50 % with respect to the microstrip patch antenna operated at the same frequency band. The operating frequency band of the proposed antenna is from 5.83GHz to 6.3 GHz for WLAN applications, dedicated short range communications (DSRC), and intelligent transportation systems (ITS). Also, the antenna fulfills a radiation performance of omnidirectional pattern. To confirm the antenna design performances, a prototype is fabricated, and the reflection coefficient and radiation patterns are measured. Furthermore, the measured results have a good match with the simulation results.

Keywords: *Composite-right-left-handed antenna, metamaterial antenna, omnidirectional antenna, compact size.*

1. INTRODUCTION

The necessity of handheld devices for wireless applications needs designing high-performance antennas with compact size [1]-[2]. CPW-fed structure has various advantages like simple configuration, small losses, compactness, and easy to integrate with other microwave circuits [3-5]. The traditional monopole-antenna has a length about quarter-wavelength of the operating resonance frequency; thus, for lower frequencies these antennas have a large size. As a result, researchers establish a new design approach to obtain antennas with small size configurations, such as composite-right-left-handed (CRLH) antennas. Recently, artificial structures with unusual characteristics not found in natural materials, such as negative permittivity and/or negative permeability can be achieved by composite-right-left-handed transmission lines (CRLH-TL). CRLH-antennas have acquired high consideration in the last few years [6-8]. CRLH cells consist of capacitors in series and inductors in shunt. In addition, due to the remarkable features such as nonlinear phase, positive, negative, and zero-propagation of antenna properties, which make them very useful for controlling the electrical-length of the antenna resulting in more compactness than traditional half-wavelength antennas with multi-band configurations [9-12].

The authors in [13] proposed a planar metamaterial antenna operates at 5.9 GHz with size of 29 × 27 mm^2. While in [14] a 5.9 GHz rectangular patch of size 32.4 × 36.54 mm^2 is proposed. On the other hand, a half-mode CRLH antenna for single band operation at C-band (5.9–6.5 GHz) is investigated by the authors in [15] with dimension of 22 × 27 mm^2. Furthermore, a patch antenna of circular shape is proposed for WBAN application (5.8 GHz) with size of 1809 mm^2 as reported in [16].

Here, we present a compact-size CRLH-antenna that can be used for wireless applications. The proposed CRLH-antenna is comprised of single CRLH unit cell. The antenna size equals only 16.5 × 26 mm^2. The antenna achieves a bandwidth up to 500 MHz over frequency range from 5.8 GHz to 6.3 GHz, with centre frequency of 6 GHz. All simulation and analysis are done using electromagnetic simulator CST software. Also, to verify the antenna design the experimental performances of the fabricated prototype are compared with the simulation results. This article is divided as follows: Sec. 2 involves the antenna configuration and theory of operation of the proposed CRLH-antenna, while in Sec. 3 the measured and simulated antenna performances are discussed. Finally, a conclusion of the proposed work is presented in Sec. 4.

2. CRLH-ANTENNA THEORY AND DESIGN

A. Design Theory

The design methodology of the CRLH-TL resonant antennas can be explained as following. Let us assume an open-ended CRLH-TL with a physical length of *l*. The condition of the resonance is obtained using the antenna resonance condition through Eq. (1) [7].

$$\beta = \frac{n\pi}{l} \qquad ; n = 0, \pm 1, \pm 2, ... \qquad (1)$$

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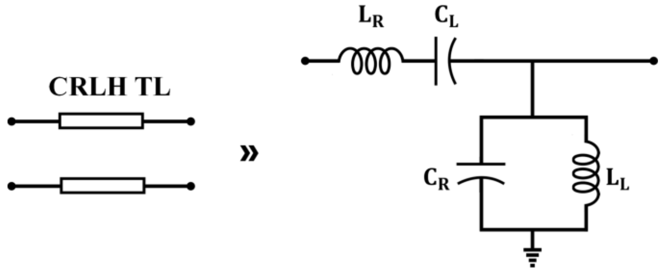

Fig. 1. CRLH-TL Equivalent circuit.

The CRLH-TL is supposed to be lossless. The equivalent circuit model of the CRLH-TL is shown in Fig. 1. The left-handed (LH) elements are provided by capacitor in series and inductor in shunt, whereas the series inductor and the shunt capacitor configure the right-handed (RH) elements. As a result, the resonance frequencies can be obtained as solution of the resonant condition of the CRLH-TL using the values of the right-handed and left-handed components as following [17]:

$$\beta = \omega\sqrt{L_R C_R} - \frac{1}{\omega\sqrt{L_L C_L}} = \frac{n\pi}{l} \qquad ; n = 0, \pm 1, \pm 2, \ldots \quad (2)$$

where L_R, and C_R are the right-handed components, while L_L and C_L are the left-handed components. The main concept in our work is that n can be zero, which delivers the size compactness of the design.

B. CRLH Antenna Configuration

In the following, we describe the design structure of the proposed small size CPW-fed CRLH-antenna. The CRLH-antenna geometry is shown in Fig. 2, with two different of views. The CRLH-antenna is suggested to be realized using one CRLH unit cell. The design structure has symmetric configuration which is fed using 50 Ω CPW feeding line. The antenna configuration is printed on RO4003 substrate (ε_r=3.38) with 1.6 mm in height. The antenna is constructed to have an operating frequency of 6 GHz to be utilized in wireless applications.

In our design we choice n=0 which corresponding to more compact size due to the nonlinear behaviour of the CRLH cell. The CRLH-TL can be constructed with left-handed components of series capacitance (C_L) and shunt inductance (L_L), and right-handed components from parasitic series inductance (L_R) and shunt capacitance (C_R). In order to match the CRLH-cell with the 50 Ω CPW-fed structure, the unit cell is configured to be balanced. The left-handed components are constructed by a series capacitance (C_L) of six interdigital fingers, and a two sections of meander stub inductor as the shunt inductance (L_L).

Consistently, the design dimensions for the interdigital-capacitance and the meander-stub inductance are initially estimated through the following Equations [17]:

$$C_L = (\varepsilon_r + 1)\, L_{idc} \left[(N_f - 3) B_1 + B_2 \right] \ (pF) \quad (3)$$

$$B_1 = 4.409 tanh \left[0.55 \left(\frac{h}{W_{idc}} \right)^{0.45} \right] \times 10^{-6} \ (pF/\mu m) \quad (4)$$

$$B_2 = 9.92 tanh \left[0.52 \left(\frac{h}{W_{idc}} \right)^{0.5} \right] \times 10^{-6} \ (pF/\mu m) \quad (5)$$

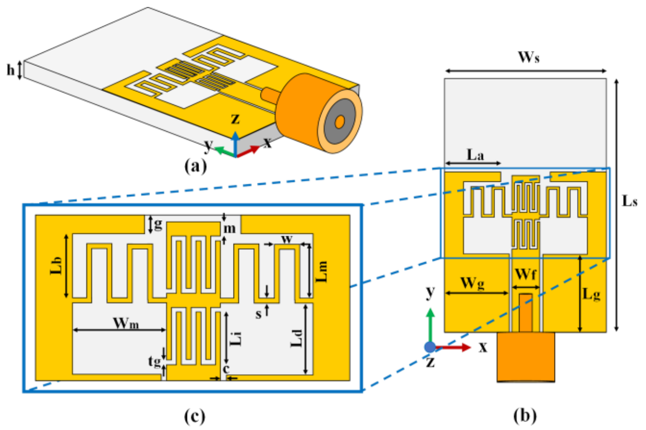

Fig. 2. Configuration of CRLH antenna (a) 3D layout (b) Top view, and (c) Zooming view for CRLH cell dimensions.

$$L_L = N_m (L_s) + M_m \ (nH), \qquad M_m \approx 0 \quad (6)$$

$$L_s = 2 \times 10^{-4} L_m \left[ln \left(\frac{L_m}{W_m + t} \right) + 1.193 + \frac{W_m + t}{3 L_m} \right] . K \quad (7)$$

$$K = 0.57 - 0.145\, ln\left(\frac{W_{idc}}{h}\right) \quad (8)$$

where, ε_r is the substrate relative permittivity, N_f is the interdigital-capacitor fingers numbers, L_{idc} is the finger length, W_{idc} is the total width of the fingers, t is the printed copper thickness, and h is the substrate thickness. Furthermore, N_m is the meander stub segments number, L_m is the length of meander stub segment, and W_m is the width of meander stub. It is important to mention that we ignore the mutual coupling between the elements. After calculation, the values of these elements are C_L=1pF and L_L=0.625 nH.

On the other side, the parasitic series inductor between the interdigital-capacitor terminals and the shunt capacitance between the ground of the CPW-fed line and unit cell provide the right-handed components. Because of the length of CRLH unit cell is very short, their dimensions were obtained as a 50 Ω microstrip-line, results in L_R=6.16 nH, and C_R=2.69 pF. It is worth to mention that the final dimension of the design is optimized using the EM simulator. The optimized values of the proposed antenna parameters are summarized as shown in TABLE I and all units in mm.

TABLE I. THE CRLH-ANTNNA PARAMETERS VALUES

Parameter	Value	Parameter	Value
W_S	16.5	L_i	2.8
L_S	26	L_a	5.7
h	1.6	L_b	3.35
W_f	2.8	g	1
W_g	6.6	m	0.8
L_g	3.8	w	1.35
W_m	4.95	s	0.3
L_m	2.85	c	0.25
L_d	3.75	t_g	0.2

The proposed CRLH-antenna equivalent circuit is shown in Fig. 3. The return loss of the circuit model and the full EM simulations is obtained and reported as shown in Fig. 4. From the curves it is observed that the antenna resonates at 6 GHz as expected. Also, the EM simulated results are agreeing well with the circuit model results.

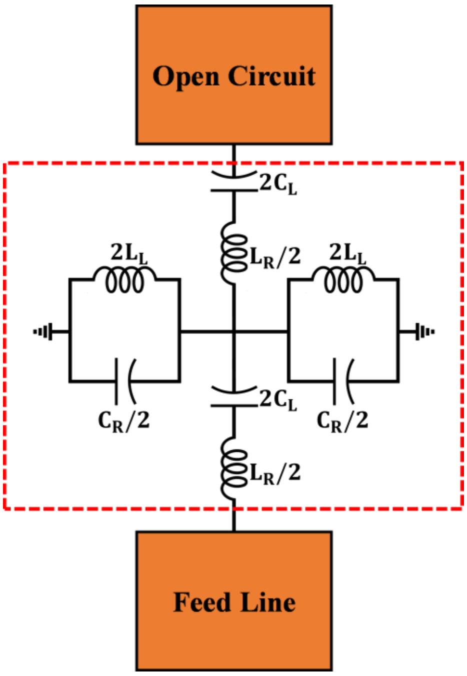

Fig. 3. The equivalent circuit model of the proposed CRLH antenna.

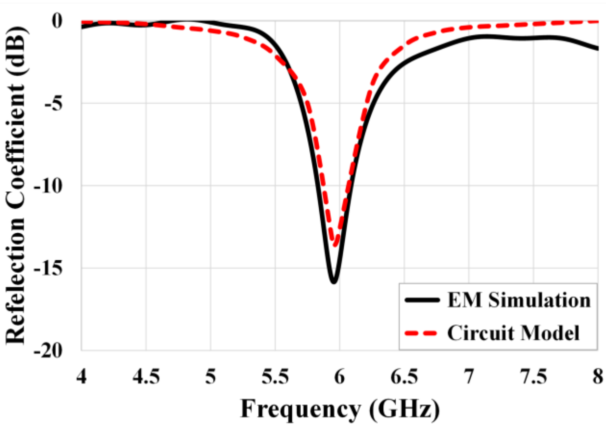

Fig. 4. The simulated reflection coefficient of the CRLH-antenna for the EM simulator and the equivalent circuit results.

3. ANTENNA PERFORMANCES AND DISCUSSION

A. Simulation Results

The proposed CRLH antenna is designed and simulated using the EM simulation software (CST). The CRLH-antenna reflection coefficient and radiation pattern are studied. As illustrated in Fig. 4 the reflection coefficient (S_{11}) has a good impedance matching over bandwidth of 270 MHz from 5.83 GHz to 6.1 GHz with best matching better than -16 dB at the resonant frequency of 6 GHz. Also, the antenna 3D radiation pattern, as well the co-polarization and cross-polarization radiation patterns are investigated and reported as reported in Fig. 5 (a), and Fig. 5 (b), respectively. It is noticed from the figures that the radiation patterns are almost omnidirectional in the two planes. Furthermore, the cross-polarization isolation is lower than -18 dB and -35 dB in the x-z and y-z planes, respectively.

On the other hand, the simulated antenna gain and efficiencies within the operating frequency bands are plotted in Fig. 6. It is observed from the figure that the antenna exhibits a radiation efficiency of around 98.5%, while the total efficiency is better than 95 % at the resonant frequency. Besides that, the antenna achieves a gain more than 3 dB over the operating frequency band.

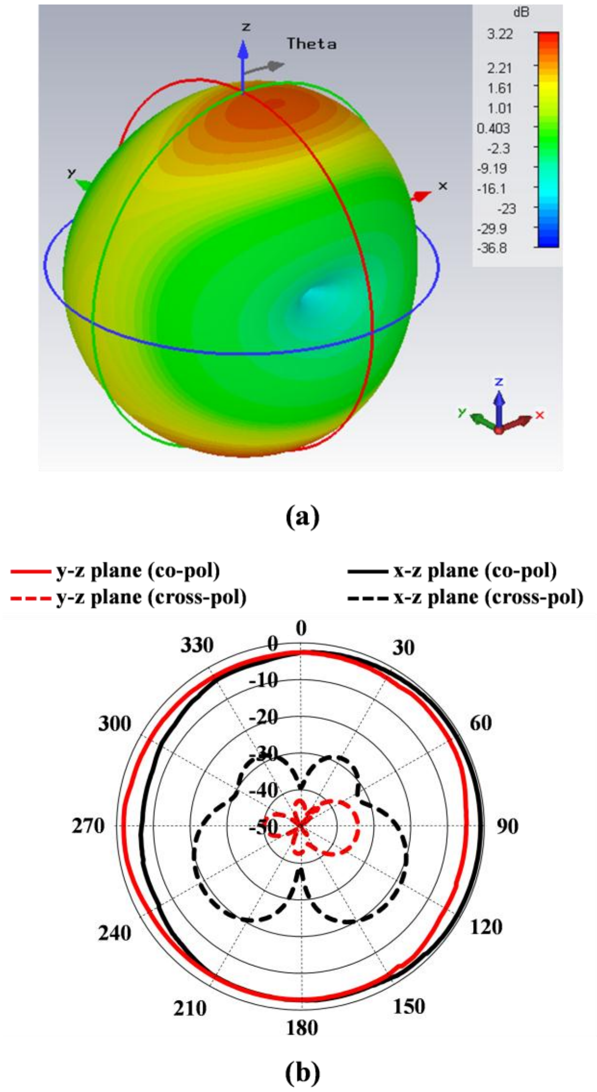

Fig. 5. The simulated CRLH-antenna radiation pattern at frequency of 6 GHz (a) 3D pattern, and (b) The normalized 2D co-pol and cross-pol patterns.

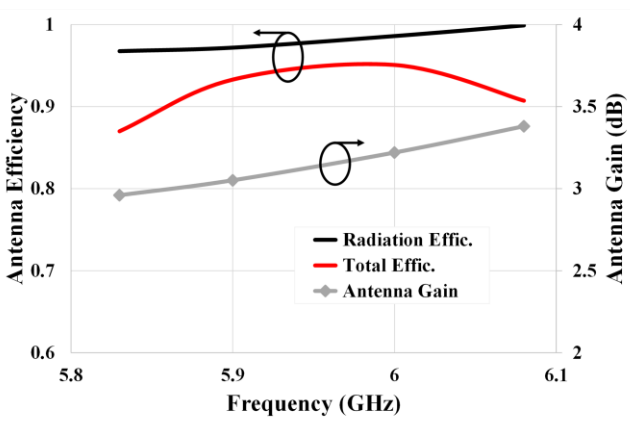

Fig. 6. The simulated gain and efficiencies of the proposed antenna at various values of frequency.

B. Measurements Results

Moreover, to validate the antenna performances the fabricated CRLH-antenna is measured, and the photo of the fabricated prototype is illustrated in Fig. 7. The R&S ZVB 20 vector network analyzer (VNA) is used to measure the reflection coefficient of the antenna. The measured and simulation results are compared and displayed in Fig. 8. From curves, the measured results show that the antenna is working around 6 GHz with very good matching with the simulations.

The measured reflection coefficient (S_{11}) has a good impedance matching over range of frequencies from 5.8 GHz to 6.3 GHz with bandwidth (S_{11}<-10dB) of 500 MHz. Also, a best matching with return loss better than -16 dB at the resonant- frequency of 6 GHz is achieved. On the other side, the antenna normalized gain in both x-z and y-z planes are measured using NSI 800F-30 system inside anechoic chamber and compared with the simulated ones as illustrated in Fig. 9 (a) and Fig. 9 (b), respectively. It is very clear from the curves that the two results have a good matching with little differences between them due to the compact size of the antenna structure and the connection between the feeding line and the connector.

TABLE II. summarizes the performance comparisons of the proposed antenna with previously published works. It is observed from the table that our proposed antenna offers a compact size compared to the other reported works. Also, the obtained bandwidth is better than [13], [14], and [16]. However, in [15] the bandwidth is better than our work, but the design has large size compared with our antenna.

TABLE II. PERFORMANCE COMPARISON OF THE PROPOSED ANTENNA WITH RESPECT TO PREVIOUS WORKS

Ref.	Frequency (GHz)	Bandwidth (MHz)	Thickness (mm)	Size (mm²)
[13]	5.9	200	1.6	783
[14]	5/5.9	90/80	1.6	1183
[15]	6.2	600	1.6	594
[16]	5.9	131	1.6	1809
Our work	6	500	1.6	429

Fig. 7. A photo of the fabricated CRLH-antenna prototype.

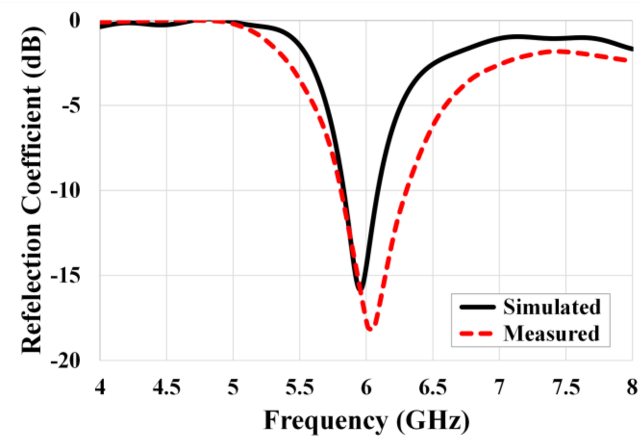

Fig. 8. The measured and simulation reflection coefficient of the CRLH antenna.

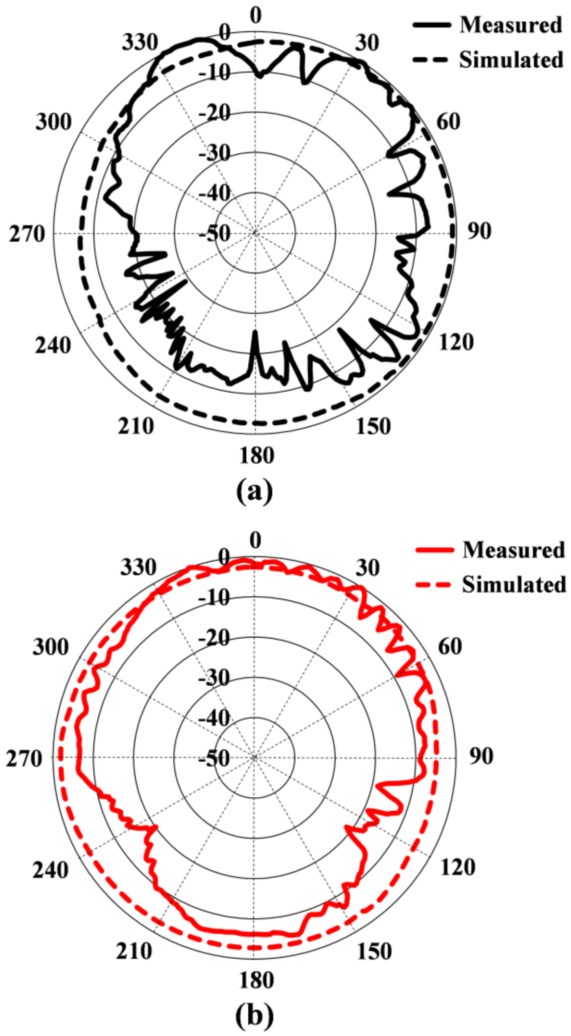

Fig. 9. The measured and simulated normalized gain pattern of the proposed CRLH antenna at frequency of 6 GHz, (a) x-z plane, and (b) y-z plane.

4. CONCLUSIONS

CPW-fed CRLH antenna has been designed and fabricated. The propose antenna comprised of single CRLH unit cell with interdigital-capacitor in series and meander stub inductor in shunt. The size of the CRLH antenna is

16.5×26 mm^2 which provides a reduction in size better than 50% with respect to the traditional patch antenna that operating with the same resonant frequency. The antenna performances such as the radiation pattern and reflection coefficient have been studied. The simulation results are matched well with the measured ones. The antenna achieves a compact size with good performance, allowing it to be used in the wireless applications such as WLAN, DSRC and ITS systems.

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تصميم هوائي صغير الحجم باستخدام المواد المستحدثة المركبة لليد اليمنى واليسرى للتطبيقات اللاسلكية

الملخص:

في هذا العمل ، تم تقديم هوائي صغير الحجم يعتمد على استخدام المواد المركبة لليد اليمنى واليسرى (CRLH) للاستخدام فى التطبيقات اللاسلكية. يتم استخدام بنية تغذية الدليل الموجي متحد المستوى (CPW) لتغذية الهوائي. يتكون الهوائي المقترح من خلية CRLH واحدة. تحتوي خلية CRLH على مكثف توالى من مكثف الأصابع المتداخلة وملف توازى باستخدام طريقة الخط المتعرج. وقد حقق الهوائي حجماً صغيراً يبلغ 16.5 مم × 26 مم × 1.6 مم وذلك بفضل مميزات CRLH مثل الطور غير الخطي. وقد ساهم هذا العمل فى تحقيق تصغيراً فى حجم الهوائي بمقدار أفضل من 50٪ مقارنة بهوائي الرقعة عند نفس النطاق الترددى. تم تصميم الهوائي ليعمل خلال الحيز الترددى من 5.8 جيجاهرتز حتى 6.3 جيجاهرتز وذلك لاستحدامه فى تطبيقات الشبكات اللاسلكية و الاتصالات المخصصة قصيرة المدى ونظم النقل الذكية. كما أن أداء إشعاع الهوائي يشبه نمط الاشعاع متعدد الاتجاهات. تم تصنيع الهوائي وقياسه للتحقق من صحة تصميم الهوائي ، كما أن معامل انعكاس الطاقة ونمط الإشعاع له متوافق جيدا مع نتائج المحاكاة.