Compact Antenna based on a Composite Right/Left Handed Transmission Line

Mohammad Alibakhshi-Kenari[1], Mohammad Naser-Moghadasi[2], Bal S. Virdee[3], Aurora Andujar[4], and Jaume Anguera[5]

[1] School of Electrical and Communication Engineering, Shahid Bahonar University, Kerman, Iran
[2] Faculty of Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[3] Faculty of Life Sciences and Computing, London Metropolitan University, Center for Communications Technology, London N7 8DB, United Kingdom
[4] School of Telecommunication Engineering, Universitat Ramon Llull, Barcelona, Spain

Abstract — **This Letter presents a novel antenna that is based on composite right-left handed (CRLH) transmission-line unit-cells implemented using slots and spiral inductors that are etched directly on the dielectric substrate by standard manufacturing techniques. The antenna is designed to operate across 5.8−7.3 GHz, which corresponds to a fractional bandwidth of 23%. Measured results confirm the antenna exhibits a relatively wide bandwidth, high gain and high radiation efficiency characteristics. The measured radiation gain, bandwidth and efficiency of the antenna at 6.6 GHz are 4.8 dBi, 23% and 78%, respectively. The fabricated antenna is highly compact and its physical size in terms of the free-space wavelength is $0.39\lambda_0 \times 0.13\lambda_0 \times 0.015\lambda_0$.**

Index Terms — Broadband antenna, composite right-left handed transmission-lines.

I. INTRODUCTION

Transmission-lines are essential components in modern wireless systems as they are used, for example, to connect antennas to transmitters and receivers, for impedance matching in mixers and amplifiers, or as resonant elements in oscillators and filters [1]-[5]. More recently, the composite right/left-handed transmission-line (CRLH-TL) or metamaterials (MTMs) have been developed as a novel paradigm in electromagnetics engineering and have been shown to possess a rich potential for novel microwave devices with unprecedented properties [6]-[9].

In this Letter, a novel compact planar antenna is proposed that is constituted from CRLH-TLs. Size reduction and bandwidth extension have realized using the CRLH-TL unit-cells that are composed of U-shaped slot and spiral inductor that is grounded using via-holes. The CRLH-TL unit-cell behave as series left-handed capacitance (C_L) and shunt inductance (L_L), respectively [10]-[12]. It is shown the antenna's radiation characteristics can be easily modified by using an appropriate number of CRLH-TL unit-cells.

II. THE METAMATERIAL ANTENNA

The configuration of the proposed antenna, shown in Fig. 1, consists of rectangular radiating patch that includes six CRLH unit-cells, where each unit-cell is constructed from a U-shaped slot and spiral inductor that is connected to the ground-plane through a metallic via-hole. The U-shaped slot and spiral act like series left-handed (LH) capacitance (C_L) and shunt (LH) inductance (L_L), respectively. The proposed metamaterial antenna was fabricated on a Rogers RO4003 substrate with dielectric constant of 3.38, thickness of 0.8 mm and tanδ = 0.0022.
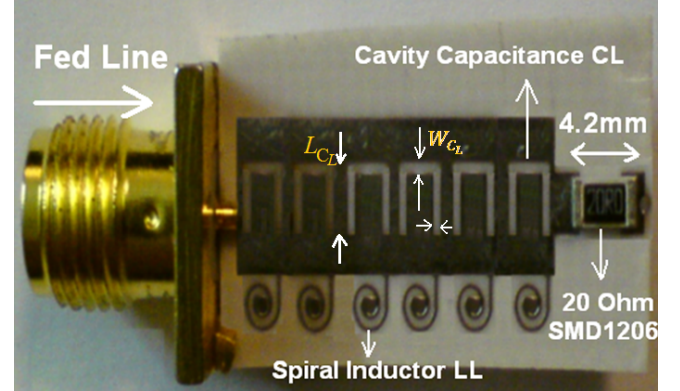

Fig. 1. Fabricated prototype of the proposed metamaterial antenna.

The criteria used to determine the number of CRLH-TL unit-cells depends on a tradeoff between the antenna dimensions, impedance bandwidth and radiation characteristics. The overall goal here was to design and implement an antenna that had a maximum length of 20 mm and exhibited a wide bandwidth with good unidirectional radiation patterns. The number of unit-cells was determined through optimization using High Frequency Simulator Structure (HFSS). Fig. 2 shows the reflection-coefficient of the antenna with increasing number of unit-cells from 1-6. Six unit-cells provide the widest impedance bandwidth of 1.75 GHz for a reflection-coefficient of -10 dB. Therefore six unit-cells were used here in the antenna design.
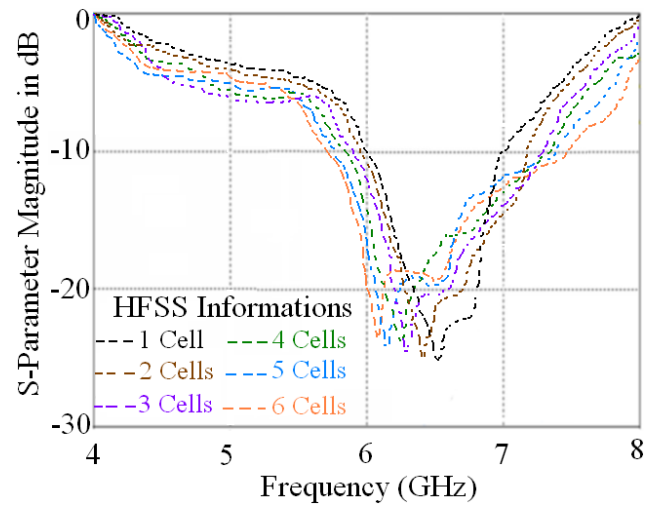

Fig. 2. Reflection-coefficient (S_{11}) response of the proposed antenna as a function of number of cells.

The proposed antenna, shown in Fig. 1, consists of a rectangular radiating patch which is embedded with six U-

shaped slots and includes six spiral inductors terminated to the ground-plane using via-holes. The antenna is terminated on the right hand side to a matched load of 20 Ω using SMD1206. The load is terminated to the ground-plane through a via-hole.

The antenna structure generates parasitic right-handed (RH) effect from the series inductance (L_R) and the shunt capacitance (C_R) resulting from current flowing over the antenna metallization, and the voltage gradient developed between the metallization and the ground-plane. The equivalent circuit model of the CRLH-TL unit-cell is shown in Fig. 3. In addition to the four reactive components (C_L, L_L, L_R and C_R) are included right-handed lossy components R_R and G_R, and left-handed lossy components G_L and R_L, which account for the dielectric loss associated with C_L and the ohmic loss associated with L_L. The magnitude of the CRLH-TL unit-cell parameters were determined from simulation, and these are: C_L = 3.2 pF, L_L = 4.5 nH, C_R = 1.5 pF, L_R = 3.44 nH, G_L = 5.6 S, G_R = 3.2 S, R_L = 6 Ω, and R_R = 4.2 Ω.
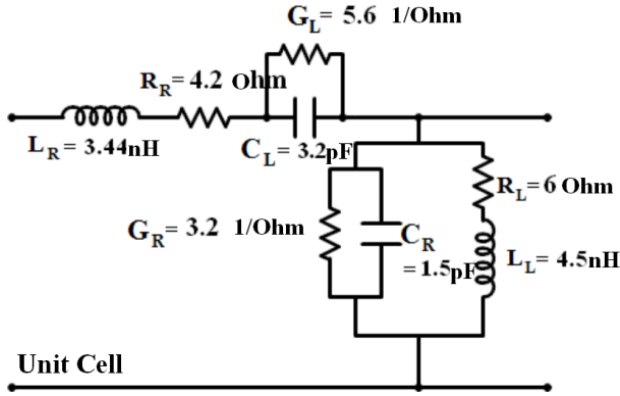
Fig. 3. Equivalent circuit model of the antenna unit-cell.

The results of the parametric study, i.e. slot length and width, are shown in Figs. 4 and 5, respectively. The results show a shorter slot length enhances the impedance bandwidth of the antenna. In fact a reduction of the slot length from 2.9 mm to 2.5 mm increases the bandwidth from 1 GHz to 1.75 GHz for reflection-coefficient of -10 dB. The slot width has the same effect on the impedance bandwidth, i.e. a reduction of slot width from 0.7 mm to 0.5 mm results in an increase of the impedance bandwidth by 68%. The optimized length and width of the U-shaped slot were determined from these results to be 2.5 mm and 0.5 mm, respectively. The proposed antenna is constructed using six CRLH-TL unit-cells, each of which occupies a space of 2.7×6.8 mm^2 or 0.052λ_0 × 0.13λ_0 in terms of the free-space wavelength at f = 5.8 GHz. The total length, width and height of the antenna are 0.39λ_0 (20.4 mm), 0.13λ_0 (6.8 mm) and 0.015λ_0 (0.8 mm), respectively.

The simulated and measured reflection-coefficients of the antenna are shown in Fig. 6. The simulated impedance bandwidths are 29%, 26.8% and 26.6% using Advanced Design System (ADS), High Frequency Structure Simulator (HFSS) and CST MWS, respectively. The measured

impedance bandwidth of the antenna is 1.5 GHz from 5.8 GHz to 7.3 GHz for a reflection-coefficient   <-10 dB, which corresponds to 23.7%. There is 13.7% differential between the averaged simulation and measurement results.
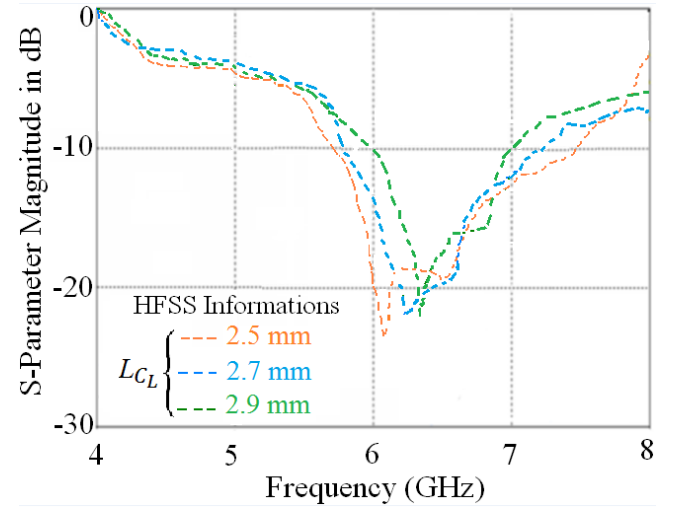
Fig. 4. Reflection-coefficient (S_{11}) response of the antenna as a function of the slot length. The slot width was kept fixed at 0.5 mm.
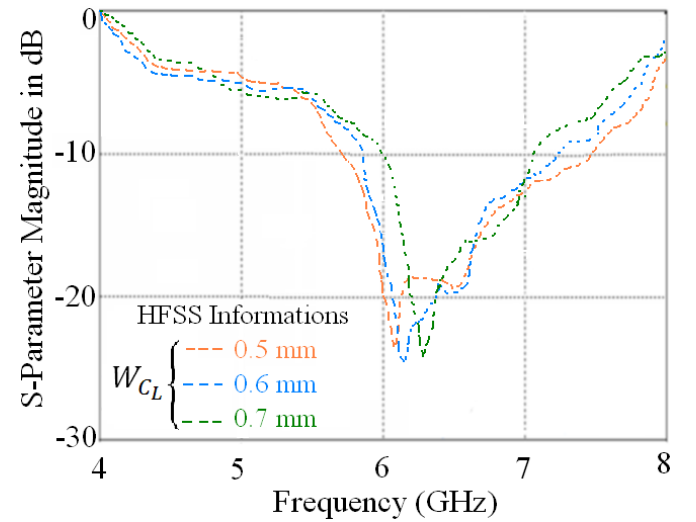
Fig. 5. Reflection-coefficient (S_{11}) response of the antenna as a function of the slot width. The slot length was fixed at 2.5 mm.
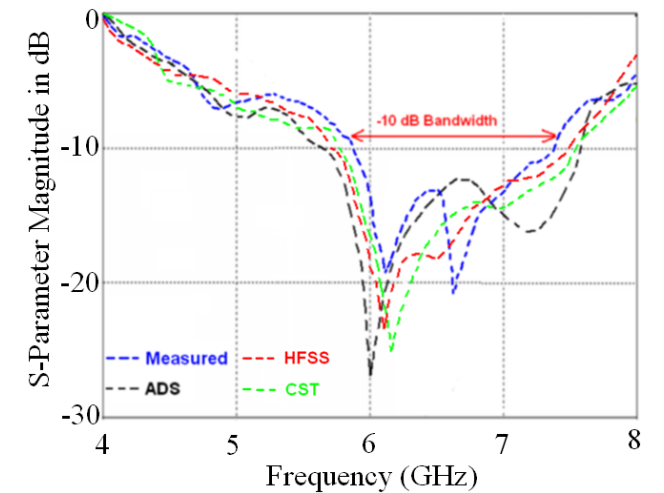
Fig. 6. Measured and simulated reflection-coefficients   of the proposed antenna.

Besides the requirement of compact size and wide bandwidth, the antenna needed to possess good radiation characteristics such as gain and efficiency. It's well known the extension of the effective aperture of the antenna improves it gain and efficiency performance. Conventionally this can be achieved by increasing the effective cross-sectional area of antenna. The proposed antenna's effective aperture was increased by simply increasing the number of CRLH-TL unit-cells, which is confirmed in Fig. 7, without increasing its physical size. Antenna with four unit-cells provides a gain and efficiency of 4.94 dBi and 74%, respectively, at 7 GHz. Increasing the unit-cells from four to six results in gain and efficiency improvement to 6.1 dBi and 85%, respectively.

The optimized dimensions of the antenna parameters and equivalent electrical circuit are given in Table I.
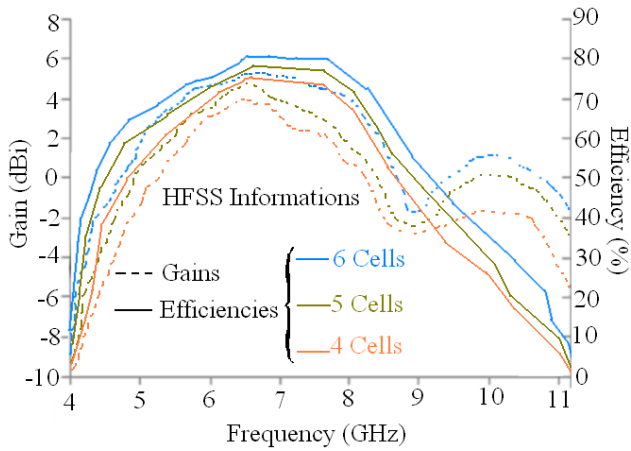

Fig. 7. Gain and efficiency performance as a function of number of CRLH-TL unit-cells.

Table I – Dimensions of Antenna and Parameter values

Number of Unit Cells	6
Length of Cavities (L_{C_L})	2.50 mm
Width of Cavities (W_{C_L})	0.50 mm
Distances between Slits	0.60 mm
Width of Spirals	0.25 mm
Spacing of Spirals	0.25 mm
Turns of Spirals	2
Height of Via Hole	0.80 mm
Length of SMD1206	4.20 mm
Amount of SMD1206	20 Ω
C_L	3.2 pF
L_L	4.5 nH
C_R	1.5 pF
L_R	3.4 nH
G_L	5.6 S
G_R	3.2 S
R_L	6.0 Ω
R_R	4.2 Ω

Three simulation tools, i.e. ADS, HFSS and CST MWS, were used to compare the performance of the antenna. The antenna's performance was measured to validate the design. The simulated averaged gain and averaged efficiency of the antenna using HFSS, CST MWS and ADS are 4.5 dBi and 76%, respectively, at 5.8 GHz; 4.9 dBi and 80%, respectively, at 6.6 GHz; and 4.65 dBi and 78%, respectively, at 7.3 GHz. The measured gain and efficiency response are plotted in Fig. 8. The measured gain and efficiency are 4.3 dBi and 74%, respectively, at 5.8 GHz; 4.8 dBi and 78%, respectively, at 6.6 GHz; and 4.6 dBi and 76%, respectively, at 7.3 GHz.
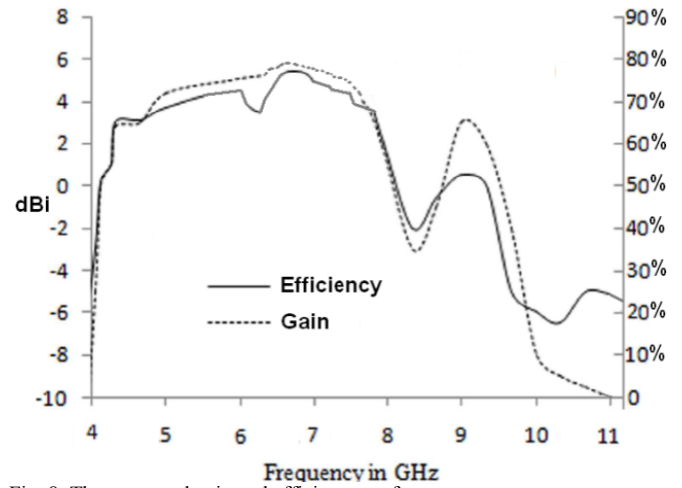

Fig. 8. The measured gain and efficiency performance.

The measured E-plane and H-plane radiation patterns at spot frequencies of 5.8 GHz, 6.6 GHz and 7.3 GHz are plotted in Fig. 9. The antenna radiates unidirectionally with 3 dB angular beamwidth of 90 degrees.
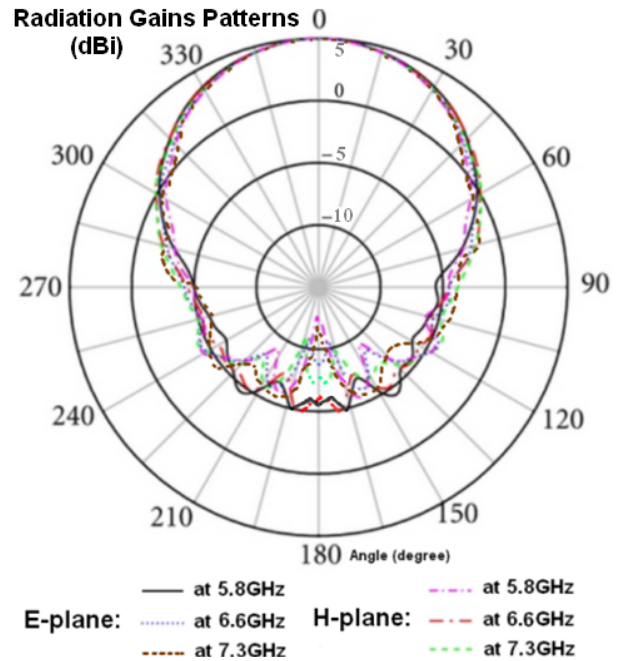

Fig. 9. E-plane and H-plane radiation patterns at 5.8, 6.6 and 7.3 GHz.

The surface current distribution over the proposed antenna at various frequencies is shown in Fig. 10. The U-shaped slots affect the current flow over the antenna to generate the radiation patterns shown in Fig. 9 that are stable across its operating frequency range of 5.8 GHz to 7.3 GHz.

Table II summarizes the antenna performance in terms of dimensions, impedance bandwidth, gain and efficiency. The proposed antenna has advantages of low profile, relatively wide impedance bandwidth, high gain, and high efficiency across 5.8 GHz to 7.3 GHz. The antenna is simple to design and cost effective to manufacture.
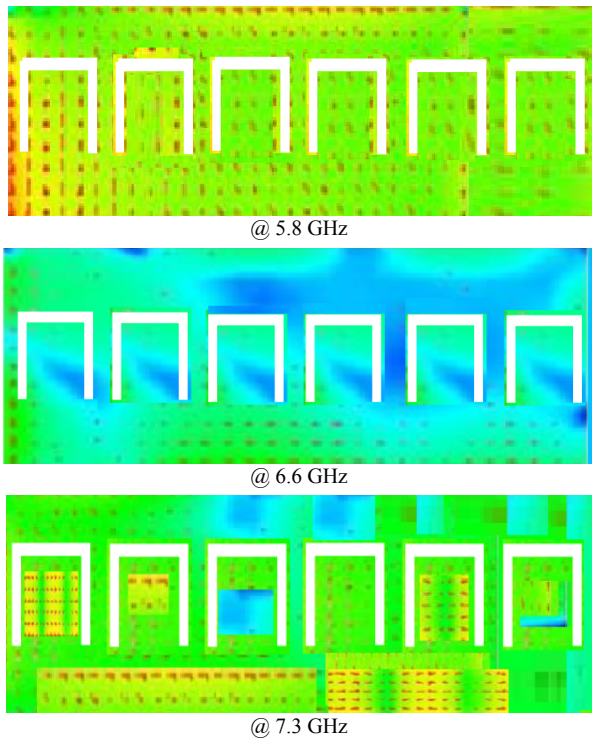

@ 5.8 GHz

@ 6.6 GHz

@ 7.3 GHz

Fig. 10. Surface current density distribution over the antenna.

Table II. Summary of Antenna Performance

Dimensions	Impedance bandwidth	Gain (dBi) @ freq. (GHz)	Efficiency @ freq. (GHz)
$20.4 \times 6.8 \times 0.8$ mm^3 or $0.39\lambda_0 \times 0.13\lambda_0 \times 0.015\lambda_0$ @ 5.8 GHz	23% (5.8-7.3 GHz)	4.3 @ 5.8 4.8 @ 6.6 4.6 @ 7.3	74% @ 5.8 78% @ 6.6 76% @ 7.3

III. CONCLUSION

A compact and low profile antenna design is proposed that is based on composite right-left handed transmission-line unit-cells consisting of a U-shaped slot and a spiral inductor that is short-circuited to ground using via-holes. The rectangular antenna which is embedded with the unit-cells and the number of unit-cells is shown to determine the antenna's impedance bandwidth. The antenna's performance

was validated through measurements. Over the operating frequency range of 5.8 GHz to 7.3 GHz it provides an average gain of 4.57 dBi and an average efficiency of 76%. Its unidirectional radiation pattern is stable over its operating frequency range.

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