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Design and bandwidth enhancement of zeroth-order resonator antenna using metamaterial

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ABSTRACT

In this paper, a compact configuration of zeroth-order resonator antenna is described. The unit cell zeroth-order resonator properties are introduced by composite right/left-handed transmission line approach is fed by coplanar waveguide. The proposed resonator is analyzed by changing the coupling space and stub length of the unit cell. The size of implemented resonator is ($0.185\ \lambda_0 \times 0.185\ \lambda_0 \times 0.027\ \lambda_0$) at the centre frequency. In this work, a zeroth-order resonator antenna design with enhanced bandwidth has been presented, and the size reduction by using the metamaterial inclusion. The proposed zeroth-order resonant antenna (ZORA) achieves a 64% reduction compared to a traditional $\lambda/2$ microstrip patch antenna. The bandwidth for the 10 dB return loss is 5.66 GHz (2.76 GHz to 8.42 GHz), the peak value of gain is 0.8 dBi and radiation efficiency of the designed antenna is 87% at 5.5 GHz. The return loss is about -59.48 dB at the center frequency. The competition among the simulated performances and other antennas shows that the proposed resonator achieves wide bandwidth. The performance of zeroth-order resonator antenna is evaluated by full-wave electromagnetic (EM) simulator HFSS11.

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1. INTRODUCTION

Metamaterial (MTM) was introduced and analyzed theoretically by V.G. Veselago in 1967 [1], [2]. Recently, there have drawn increasing attention in the research of the composite right/left-handed transmission lines (CRLH-TLs) metamaterial for antenna and microwave applications. Metamaterials has been developed as artificial composites homogeneous electromagnetic materials to implement novel functionality [2], [3]. The MTMs have several unique characteristics, such as negative permeability and permittivity at the same time and negative refractive index which results to antiparallel group and phase velocities [4]-[8].

MTM structures are classified into two major kinds of configuration. The first kind is known as composite right left-handed (CRLH) transmission line (TL). CRLH-TL structures display both of the right-handed (RH) and left-handed (LH) properties. More importantly, the CRLH-TL has many applications. It can be realized with low loss and simultaneously display wide bandwidth [4], [5]. CRLH-TL antennas have increased high interest for optical, microwave and antenna applications in recent years [6]. The split ring resonator (SRR) is the second type, which is defined as resonant structure. They appear little practical attention for engineering applications because of lossy characteristics and their narrow bandwidth [2].

Zeroth-order resonant antenna (ZORA) based on CRLH-TL is a new concept. ZORA operates at the transition frequency between the RH and the LH. Additionally, it has a zero phase constant at a non-zero frequency. Thus, it can support the infinite-wavelength property. i.e., independent of the physical length. Consequently, the antenna size could be arbitrarily small to be more compact or arbitrary more big to increase the directivity of these antennas [1]-[3], [9], [10].

However, the main disadvantage of these structures is the narrow bandwidth [9], [10]. Currently, many techniques to improve the bandwidth, such as decreasing right capacitance (C_R) and increasing left inductance (L_L) caused an increase in the antenna bandwidth. Truncated grounds have been also used in a metamaterial structure which leads to improve a bandwidth. An alternative method for bandwidth improvement is a combining of the zeroth and the first-order resonances [9]. The first approach is devoted in this article.

Hence, this paper aims to design and investigate a novel structure of the ZORA based on CRLH-TL to extend the wide bandwidth performance with the antenna's miniaturization. The proposed ZORA gives different features, such as more diminutive in size than the conventional antenna, wide bandwidth and high efficiency. The coplanar waveguide (CPW) technique provides high freedom of design, since MTM unit cell is designed on a vialess single layer. Therefore, this technique makes ZORA size compact compared to a conventional microstrip patch antenna. The full wave high frequency simulator structures (HFSS) is used to simulate the antenna performances such as dispersion diagram, scattering parameters (S-parameters) and radiation pattern.

This work is organized in several sections. In section 2 the essentials and theory of metamaterial and zeroth-order resonant (ZOR) are introduced. Section 3 is the achievement of the suggested ZORA using HFSS. Simulations and study of ZORA performance are in section 4. Finally, section 5 includes the conclusions.

2. THEORY OF CRLH-TL AND ZERO ORDER RESONATOR

In this section, A 1D CRLH unit cell characteristics of the TL and ZOR will be discussed. Namely, the basic form of CRLH-TLs unit cell composed of series capacitors C_L and shunt inductors L_L to obtain left hand with conventional right-hand TL. In the (1) and (2) represent series impedance $Z\ (\Omega/m)$ and shunt admittance $Y(S/m)$ respectively.

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

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

Where: LR is RH inductance (H/m)
CL is LH capacitance (F.m)
CR is RH capacitance (F/m)
LL is LH inductance (H.m)
ω is angular frequency (rad/sec) [11], [12].

By using Bloch-Floquet theorem to determine the dispersion diagram [13].

$$\beta p = \cos^{-1}\left(1 - \frac{1}{2}\left(\left({}^{\omega}/_{\omega_R}\right)^2 + \left({}^{\omega_L}/_{\omega}\right)^2\right) - \left({}^{\omega_L}/_{\omega_L}\right)^2 - \left({}^{\omega_L}/_{\omega_{sh}}\right)^2\right) \tag{3}$$

Where: β is phase constant
ω_L is left frequency = $1/\sqrt{LLCL}$,
ω_R is right frequency = $1/\sqrt{LRCR}$,
ω_sh is shunt frequency = $1/\sqrt{LLCR}$,
ω_se is series frequency = $1/\sqrt{LRCL}$ and,
p is period length of unit cell.

The phase constant can be classified into two general cases. If the series and shunt resonances are different ($L_R C_L \neq L_L C_R$); this case is known as the unbalanced case. There are two distinct zeroth order frequencies, namely the series and shunt resonances. The first resonance is known as the series frequency w_{se} determined by right series inductance L_R and left series capacitance C_L. The second one is known as the w_sh shunt resonant frequency which is calculated by the L_L shunt inductance and C_R shunt capacitance. In practice, the resonator is realized with either open ended or short ended. Therefore, the shunt resonant occurs when input impedance ($Zin = \infty$) and the series resonant occurs when ($Zin = 0$). The second case is a balanced design if resonance frequencies ($L_R C_L = L_L C_R$) of the unit cell are equal [14]-[16]. Effective permittivity and permeability can be achieved as presented in [12], [17].

$$\mu(\omega) = L_R + \frac{1}{\omega^2 C_L} = \frac{Z}{j\omega} \tag{4}$$

$$\varepsilon(\omega) = C_R + \frac{1}{\omega^2 L_L} = \frac{Y}{j\omega} \tag{5}$$

Where μ and $^{\varepsilon}$ are the permeability and permitiviy, respectively. CRLH-TL is converted into a resonator when it becomes open or short circuits, the same as a conventional TL. CRLH-TL became a resonator when satisfying the following conditions [18], [19].

$$\beta_m p = m\pi \qquad m = 0, \pm 1, \pm 2, \pm 3, \dots \tag{6}$$

ZORA is regarded as one of the unique characteristics of the CRLH transmission line metamatrials [1]. ZOR has several features. At the resonance frequency, the first property of resonator is that zero phase shift over entire of unit cell metamatrial. As an additional interesting property, ZORA is known as an infinite wavelength feature, such that the ZORA appears infinitely long electrically. This feature can be used to design miniature antennas. In this design, the proposed resonator represents an open ended case. Then the input impedance of the antenna Z_{in} is [1].

$$Z_{in} = -jZ_o cot(\beta \mathrm{p}) \approx \frac{1}{NY} \tag{7}$$

Where Z_o is charactristics impedance, N number of unit cells and Y is admitance. Generally, resonant frequencies of traditional TL-resonators are calculated by the length of the resonators. On other hand, the ZORs based on CRLH-TL are independent of the physical length itself, but are determined only by constitute parameters (LC-parameters) provided by its ZOR [20]. Hence, ZORA dimensions can be adjusted arbitrarily without changing the operating frequency [15].

3. ZOR UNIT CELL DESIGN

Figure 1 shows geometry of ZORA unit cell as shown in Appendix. The layout of the suggested ZORA unit cell is depicted in Figure 1(a) in which all the elements are displayed. Figure 1(b) shows the perspective view of 3D structure of unit cell ZORA. The proposed antenna is comprised of unit cell metamaterial. The key component of the proposed ZORA is constituted of top metallic patch. This patch is represented by a series two capacitors which represented by space distance (s), as shown in Figure 1(a). Two anti-parallel meander lines are also placed on both sides of unit cell. The third part is represented by CPW ground plane. CPW provides the significant advantages that it is easy to construct shunt inductances (L_L) because of availability the CPW ground plane and the signal carrying conductor on the same plane and this leads to avoidance of via use. Consequently, CPW contributes to simplification of ZORA.

The feed line is designed to give 50 ohm for impedance matching. The ZOR unit cell is carried out on a low cost the substrate material of FR4 epoxy with thickness of 1.5 mm and dielectric constant is 4.4. By properly tuning of the dimensions, the design parameters of ZOR unit cell are: $L_1 = 3$, $L_2 = 5.8$, $L_3 = 2$, $L_4 = 1.68$, $L_5 = 2.11$, $L_6 = 1$, $w_1 = 4$, $w_2 = 1.8$, $w_3 = 1.15$, $\ell stub = 11.5$, $wstub = 0.15$, $L_s = 10$, $W_s = 10$, $s = 0.15, g = 0.25$, and $p = 6$ (all dimensions in mm). Figure 1(c) depicts the T-circuit diagram model of the proposed ZORA based on CRLH transmission line. The compact dimensions of the implemented resonator are 10 mm × 10 mm × 1.5 mm ($0.185\,\lambda 0 \times 0.185\,\lambda 0 \times 0.027\,\lambda 0$). Figure 1(d) displays the electric field distribution on the unit cell.

4. SIMULATION AND RESULTS

Based on the optimized physical dimensions displayed in last section, a unit cell ZORA based CRLH-TL has been investigated. The dispersion diagram for the proposed antenna design is seen in Figure 2, its characteristics are noted to be balanced, which implies that $\omega_0 = \omega_{sh} = \omega_{se} = 5.5$ GHz at zero phase constant (there is no gap). Figure 3 displays the real values of relative permittivity (ε_r) and permeability(μ_r). It is noticed that the two parameters are negative values at frequency band below the transition frequency and positive values at frequency band above the transition frequency. The scattering parameters S_{11} and transmission coefficients (S_{21}) of metamaterial unit cell versus frequency response are shown in Figure 4. The simulated bandwidth of the proposed antenna is about 5.66 GHz (from 2.76 GHz to 8.42 GHz). Figure 5 shows that the transition frequency changes with various values of the distance space (s) (as stated in Figure 1(a)).

The simulation results of ZORA display good performance such as S-parameters (S_{11} = -59.48 dB and S_{21} = -0.175 dB). It is obvious that the proposed antenna gives the lowest reflection coefficient at transition frequency. And radiation efficiency is about 87% which is acceptable for low profile ZORA. The ZORA achieves a 64% reduction in patch size compared to a traditional $\lambda/2$ resonance patch at center frequency. The simulated radiation patterns of both E and H-planes for the proposed ZORA at the transition frequency can be seen in Figure 6(a). Also, the 3D radiation pattern is shown in Figure 6(b). This antenna displays superior radiation performance. The extracted LC parameters of the equivalent network using technique in [21] are shown in Table 1. Table 2 displays comparison bandwidth, efficiency, the reflection coefficients and gain, of the suggested antennas with other reference antenna.

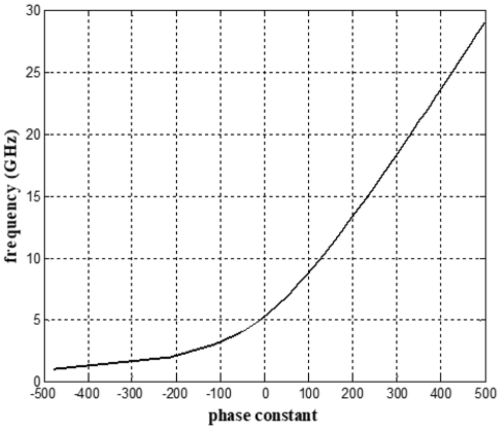


Figure 2. Unit cell ZORA dispersion diagram at 5.5 GHz

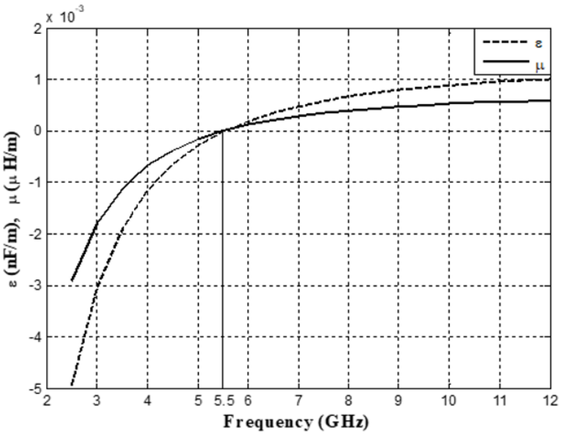


Figure 3. Real values of unit cell ZOR antenna

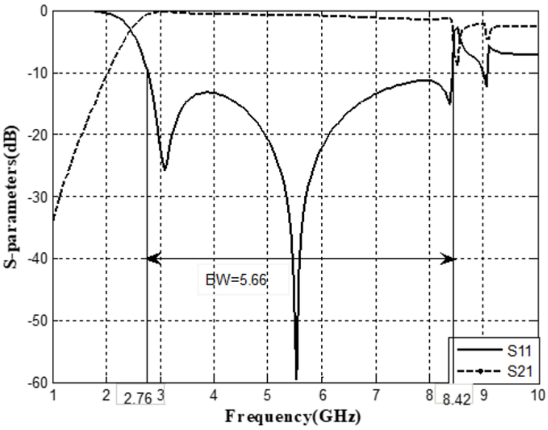


Figure 4. S-parameters (S_{11} and S_{21}) of unit cell ZOR antenna

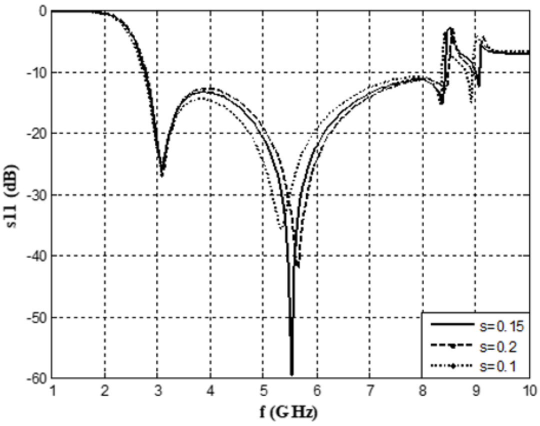


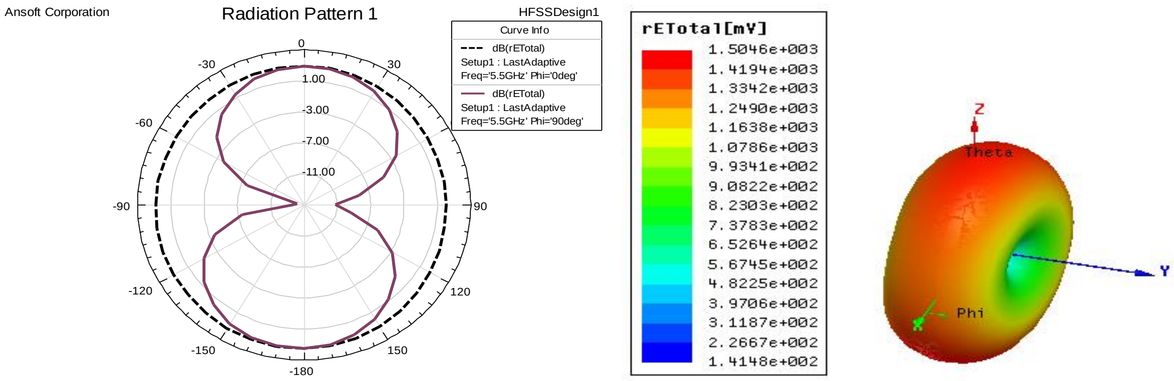
Figure 5. Different values of reflection coefficent of unit cell for various values of spaces s (as pointed in Figure 1(a))

Table 1. Constitute parameters of unit cell

$L_L(nH)$	$C_L(pF)$	$C_R(pF)$	$L_R(nH)$	$f_{se}(GHz)$	$f_{sh}(GHz)$
0.65	1.1	1.28	0.76	5.5	5.5

Table 2. Proposed design antenna comparison with other antennas published

Ref.	Proposed work	Ref. [22]	Ref. [23]	Ref. [24]	Ref. [25]
Freq. (GHz)	5.5	2.3-2.9	2.26-2.89	2	2.03
S_{11}(dB)	-59.48	-25	-20	-22	-22
BW (GHz)	5.66	1.7	---	---	6.8
η(%)	87	65	92	---	62
D(dBi)	0.8	2.27	1.6	3.5	1.35



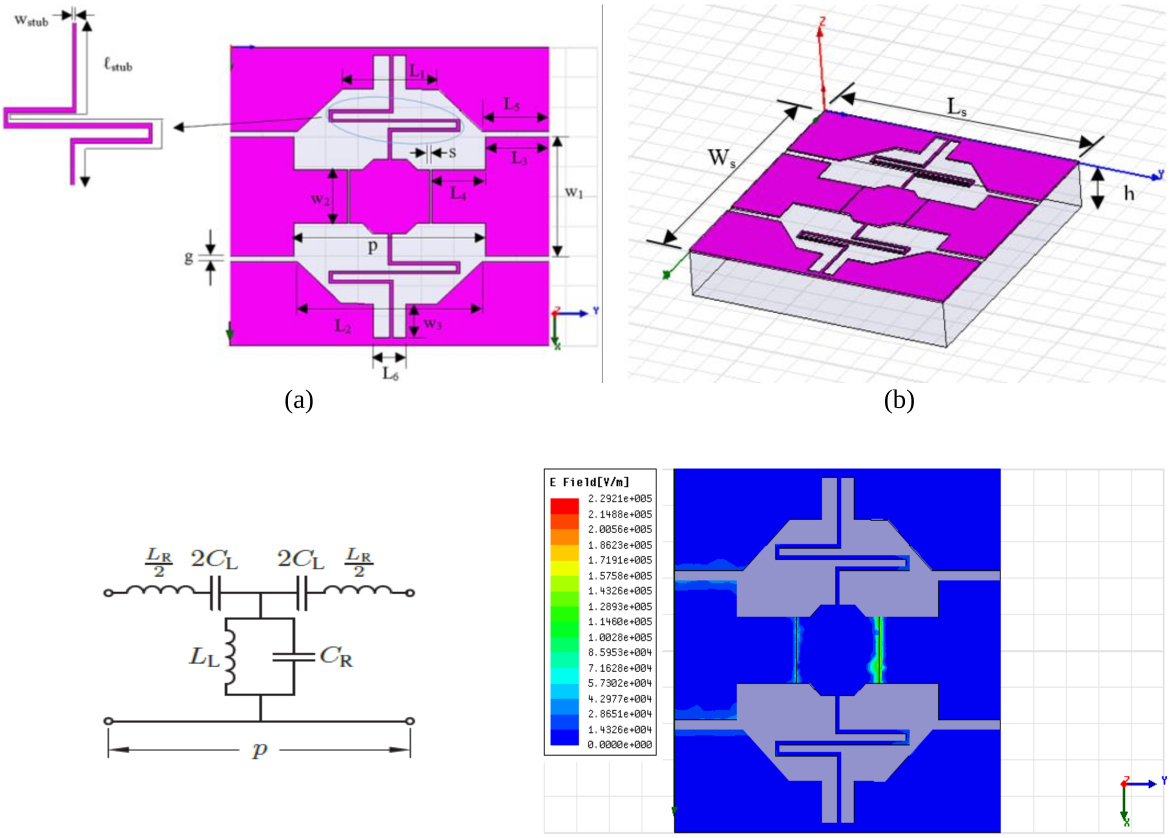
(a) (b)

Figure 6. Radiation pattern: (a) E and H-planes and (b) 3D radiation pattern

5. CONCLUSIONS

This work provides a simple and new configuration of ZORA that has been suggested and designed using the presented characteristics of a CRLH-TL metamaterial. It offers a wideband antenna. ZORA exhibits superior performances and provides high compactness. More importantly, further reduction in the proposed resonator size is achieved compared to traditional $\lambda/2$ resonator antennas. Zero order resonator displays a radiation efficiency of 87% and a peak gain of 0.8 dBi, comparable to those of other literatures that use of ZORAs. This antenna exhibits simulated bandwidth of about 5.66 GHz (from 2.76 GHz to 8.42 GHz). The proposed antenna has excellent radiation performance and impedance matching.

APPENDIX



(a) (b)

(c) (d)

Figure 1. Geometry of ZORA unit cell: (a) 2D unit cell, (b) 3D structure of unit cell, (c) equivalent T-network, and (d) electric field disribution of unit cell

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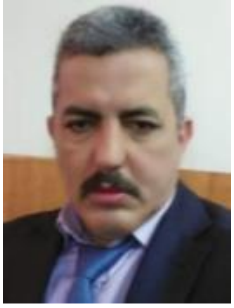

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