Design and Analysis of Zeroth-Order Resonator-Coplanar Waveguide Antenna using CRLH-TL Metamaterial

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***Abstract* — This paper presents design and analysis of a novel configuration of the zeroth order coplanar waveguide (CPW) resonator (ZOR). It is based on composite right/left-handed transmission line (CRLH-TL) metamaterial unit cell, it provides size reduction, extended bandwidth and better efficiency. The realized antenna has a compact size of ($0.183\lambda_0\times 0.183\lambda_0\times 0.027\lambda_0$) at 5.5 GHz, and gives high flexibility in the design, due to the fact that metamaterial resonant antenna is printed on a single layer CPW, without using vias. The bandwidth, directivity and radiation efficiency of the proposed antenna is about 123.3%, 0.65 dB and 76% at 5.5GHz, respectively. Its bandwidth is improved compared with the other ZOR antennas. The antenna was designed to operate from 4.55 to 11.33 GHz and possesses a reflection coefficient of -23.7 dB at the zeroth order resonance frequency. The proposed antenna (1-cell ZOR) achieves a 61.5 % reduction in patch size compared to a conventional half-wavelength patch antenna at the frequency 5.5GHz. The proposed ZOR antenna are also very compact in size and has a via-free coplanar structure. Therefore, making the proposed antenna suitable for use in wireless hand-held devices.**

Keywords - component; Metamaterials; CRLH-TL; ZOR-CPW antenna.

I. INTRODUCTION

In the last decade, there has been interesting in the study of the CRLH-TL metamaterial (MTM). Electromagnetic metamaterials are defined as synthetic composites effectively homogeneous electromagnetic materials to achieved unique properties, which are not ordinarily available in nature. Such materials are also called left-handed media (LHM) [1]. Metamaterials have been widely used in antenna applications, optical and emerging microwave circuits [2]. Due to an unusual properties of left-handed metamaterials (LHMs) in comparison with traditional natural materials, such as simultaneously negative permittivity and permeability, negative refractive index which leads to anti-parallel phase and group velocities, the nonlinear dispersion diagram, and a zero propagation constant at a resonant frequency have brought new notions in electromagnetic propagation characteristics and new applications [3], [4].

There are two main types of structures for physically realizing metamaterial structures in the microstrip line. The first kind is called the split-ring resonator (SRR) known as resonant structures. And the second type is called composite right left-hand transmission line (CRLH TL) and known as non-resonant structures. The resonant structures (SRR) seem of little practical interest for engineering applications due to the following reasons: narrow-bandwidth, bulky in size, and display high loss. On the other side, the CRLH-TL is non-resonant and used in more applications. It can be designed to display simultaneously broad bandwidth and low loss (under balanced matched condition) [3]. CRLH-TL can be realized with microstrip circuits which can be easily implemented in antennas and microwave circuits. There are three main techniques for implementing the CRLH in TL configuration: the first technique is conventional microstrip implementation which consists of series capacitance (inter-digital capacitor or gap capacitor) and shunt stub grounded by via [2]. The second technique uses the microstrip coplanar waveguide [5]. The third technique uses metal-insulator-metal (MIM) series capacitors and shunt stub inductors [6].

The objective of this work is to design and analyze of a new configuration of the zeroth order resonator coplanar waveguide (CPW) based on CRLH-TL metamaterial. The proposed antenna is composed of top metallic patches with two interdigital capacitors and shorted meander lines to a CPW ground plane. The proposed antenna displays various advantages, such as simplicity, small size, improved efficiency, and extended bandwidth. The frequency parameters (S-parameters and dispersion diagram) and the properties of the antenna such as co-cross polarization patterns, Bloch impedance, and directivity of ZOR-CPW are evaluated by using the commercial full-wave simulator, HFSS. This paper is organized as follows: Section II discusses the principles and theory of CRLH-TL unit cell and ZOR, section III is the implementation of the proposed antennas in HFSS, section IV is simulations and analysis the properties of the antenna, and section V is parametric study, and section VI contains conclusions.

II. THEORY OF CRLH-TL AND ZOR

A. *Composite Right left –Handed transmission lines*

Composite right/left-handed transmission lines (CRLH-TLs), have drawn growing attention because of several unique properties. The basic form of metamaterial unit cell consists of a specific (per-unit length) series impedance Z' (Ω/m) constituted by a right hand (RH) specific inductance L'_R (H/m) in series with a left hand (LH) capacitance C'_L (F.m) of unit length times capacity. And per-unit length shunt admittance constituted by a RH per-unit-length capacitance C'R (F/m) in parallel with (LH) unit-length times inductance L'L (H.m) [7].

$$Z'(\omega) = j\left(\omega L'_R - \frac{1}{\omega C'_L}\right) \tag{1-a}$$

$$Y'(\omega) = j\left(\omega C'_R - \frac{1}{\omega L'_L}\right) \tag{1-b}$$

The complex propagation constant γ is given by.

$$\gamma = \alpha + j\beta = \sqrt{Z'Y'} \tag{2}$$

Where α is the attenuation and β is phase constant. By applying the periodic boundary condition, the dispersion relation can be calculated analytically by using Bloch-Floquet theorem, and it is given to a good approximation by [1].

$$\cos(\beta p) = 1 - \frac{1}{2}\left[\omega^2 L_r C'_R + \frac{1}{\omega^2 L'_L C'_L} - \left(\frac{L'_R}{L'_L} + \frac{C'_R}{C'_L}\right)\right] \tag{3}$$

There are two cases of the phase constant, the first case is the unbalanced design if the series and shunt resonances of CRLH-TL are different($\omega_{se} \neq \omega_{sh}$), and the second case is called balanced design if the series and shunt resonances of the CRLH-TL are equal($\omega_o = \omega_{se} = \omega_{sh}$). The characteristic impedance Z_c is given by [8]

$$Z_c(\omega) = \frac{Z'}{\gamma} = \sqrt{\frac{Z'}{Y'}} \tag{4}$$

And resonant frequency is given by [1].

$$\omega_o = \frac{1}{\sqrt[4]{L'_R C'_R L'_L C'_L}} \tag{5}$$

Bloch impedance Z_B can be represented as the ratio of voltages and currents in the network (input impedance), Bloch impedance can be determined from S-parameters.

$$Z_B = Z_o\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}} \tag{6}$$

B. Zeroth Order Resonating Antenna (ZOR)

Like any TL, when terminating the CRLH-TL with an open or a short circuit, a structure is transformed into a resonator (supports a standing wave) and it resonates at some specific frequencies [5]. Zeroth-order resonator (ZOR) is considered as one of the important applications of the CRLH-TL structures which support an infinite wavelength at a certain frequency, this means that the currents or voltage distribution are uniform along the structure [9]. ZOR works at the mode (n = 0), and it is considered a unique property of CRLH structures. If the structure is unbalanced, there are two different zeroth order frequencies, the first frequency is called the shunt resonant frequency w_{sh} which is determined by the left shunt inductance L_L, and right shunt capacitance C_R. The second frequency is called the series resonance w_{se} determined by left series capacitance C_L and right series inductance L_R [10]. However, only one of the two resonances would be excited in practice since the ZOR antennas are designed with either an open or a short termination [5]. Another property of zeroth order resonator, there is no phase shift between the input and the output of the structure at the resonance frequency, since θ=β×p=0. CRLH RAs operate in the standing wave regime and work therefore regardless of on whether the CRLH structure is balanced or not. While the CRLH LWAs (Leaky Wave Antennas) which require fulfillment of the balance condition, $\omega_{se}= \omega_{sh}= \omega_0$, which corresponds to the matching of the TL ($Z_L = Z_R = Z_c$) and therefore broad bandwidth is achieved. The main advantage of ZOR is that the physical size of the antenna can be changed at a certain frequency. Since the resonance frequencies of the zeroth-order resonators are determined only by LC parameters provided by its unit cells and independent of the physical length of the entire structure, therefore, antenna size can be tuned arbitrarily without changes in the operation frequency [9]. Reduction in size of an antenna enables them to be more compact than conventional resonators. The miniaturization of antenna leads to decreasing of its directivity. On the other side, increasing the physical length (ℓ=Np, where N is the number of cells) of the antenna may results in the increasing of its directivity without any change in frequency.

Let us discuss two cases an open- and short-ended resonator with CRLH-TL resonator of N unit cells and physical length ℓ=Np which displays 2N−1 resonance frequencies [1]. These resonances naturally correspond to TL lengths ℓ=nλg/2. These frequencies are calculated from the dispersion diagram by the condition given by [5].

$$\theta_n = \beta_n \ell = \beta_n (Np) = n\pi \quad or \quad \beta_n = \frac{n\pi}{Np} \tag{7}$$

Where n=0, ±1, ±2, …, ∞

The first case represents open-ended ZOR and at zero order frequency, the input impedance Z_{in} is given by [1].

$$Z_{in}^{open} = -j\,Z_c \cot(\beta\,\ell) \cong -jZ_c \frac{1}{\beta\,\ell} \quad (\beta \to 0)$$

$$Z_{in}^{open} = -j\sqrt{\frac{Z'}{Y'}}\left(\frac{1}{-j\sqrt{Z'Y'}}\right)\frac{1}{\ell} = \frac{1}{Y'\ell} = \frac{1}{Y'(Np)} \tag{8}$$

Where Y' is the admittance of the CRLH unit cell, given by Eq. 1(b). This means that the input impedance of an open-ended is inversely proportion to N, (Z_{in} α 1/Y' N). The resonance of the resonator is the same as the resonance of the admittance Y'. Hence, there is a single resonance frequency [1].

$$\omega_{res}^{open} = \omega_{sh} = \frac{1}{\sqrt{L_L C_R}} \tag{9}$$

The resonant angular frequency depends only on the shunt resonant frequency, and does not depend on the physical length ℓ of the ZOR. On other side, no resonance occurs at ω_{se}. This resonator with transverse polarization because

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resonance occurs in the stub. The second case represents short-ended case or zero order series mode f_{se}. The input impedance Z_{in} is given by [1].

$$Z_{in}^{short} = jZ_c \tan(\beta\ell) \cong -jZ_c\beta\ell \quad (\beta \to 0)$$
$$Z_{in}^{short} = -j\sqrt{\frac{Z'}{Y'}}\left(j\sqrt{Z'Y'}\right)\ell = Z'(Np) \tag{10}$$

Where Z is the impedance of the CRLH unit cell, given by Eq. 1(a). This means that the input impedance of a short ended is proportion to N, ($Z_{in} \propto N Z'$). The resonance of the entire resonator is the same as the resonance of the series impedance Z. Therefore, there is a single resonance frequency.

$$\omega_{res}^{short} = \omega_{se} = \frac{1}{\sqrt{L_R C_L}} \tag{11}$$

The resonant angular frequency depends only on the series resonant frequency. This resonator with longitudinal polarization because resonance occurs in series mode. In the special case of balanced resonances (since $\omega_0 = \omega_{se} = \omega_{sh}$), the zeroth-order resonance occurs for both the open-ended and the short-ended resonators [1].

III. Geometry of CPW Metamaterial Unit cell Design

Figs. 1(a) display the layout of a ZOR-CPW based on CRLH unit cell metamaterial with parameters. The ZOR resonator is represented by unit cell which consist of two inter digital capacitors (IDC) in series which represent a trace of CPW, and two grounded meander stubs in shunt on both sides. The main advantage of using CPW is the ease to build shunt stub inductor due to availability of the ground plane on the same layer with the trace and this leads to avoid the use of vias. Therefore, leads to simplify the antenna. This antenna is implemented on the substrate of FR4 epoxy with a dielectric constant of ε_r=4.4, the thickness of the substrate of h =1.5 mm; and loss tangent tan δ=0.02. The field distribution of unit cell is shown in Fig. 1(b). The equivalent circuit network is represented in Fig. 1(c), in which the ZOR-CPW based on CRLH metamaterial is modeled as the equivalent π-network. The realized antenna has a compact size of 10×10×1.5 mm ($0.183\lambda_0 \times 0.183\lambda_0 \times 0.027\lambda_0$). When unit cell is terminated to open end, the resonant frequency of the proposed antenna is determined by the shorted meander line (L_L) and capacitance (C_R) between the trace and CPW grounds. The details of the common dimensions (in mm) used for the design of one unit cell and proposed design are given in table (I).

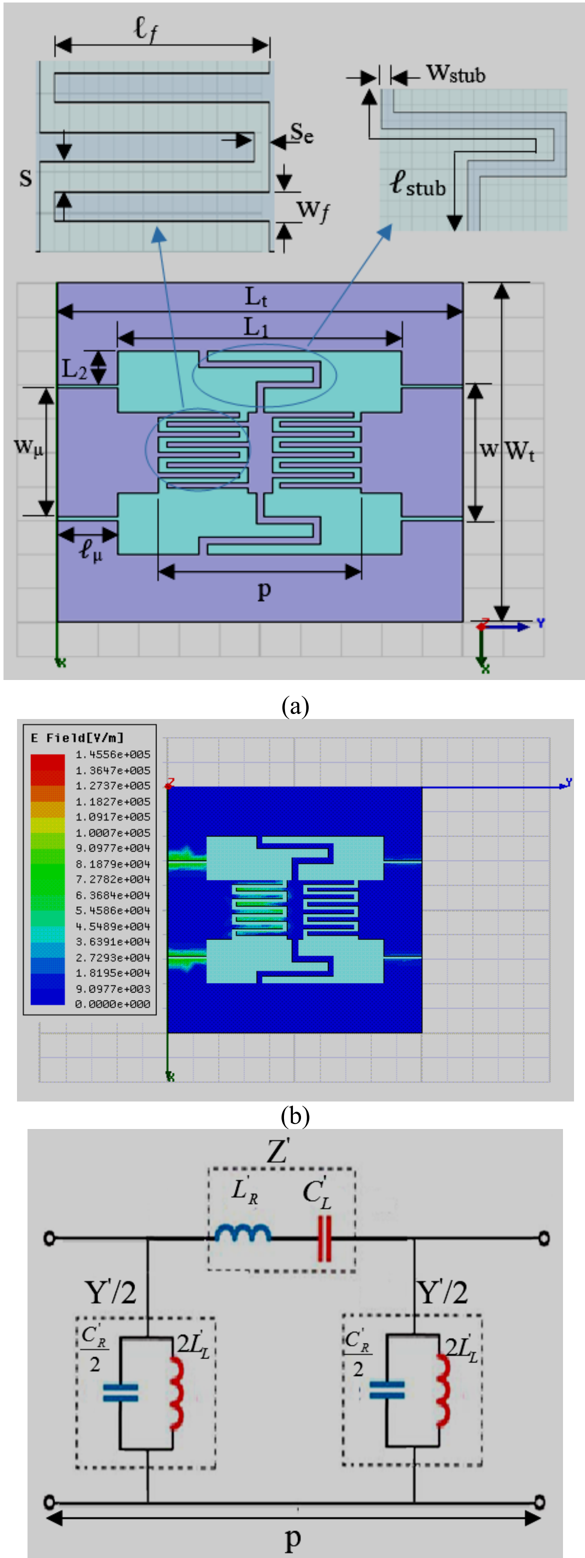

Figure 1. Metamaterial unit cell and its characteristics (a) Unit cell geometry (b) field distribution (c) Equivalent π-model

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TABLE I. DIMENSIONS OF ZOR-CPW DESIGN (IN MM) REFERS TO FIG. 1(A).

ℓ_f	w_f	s	s_e	ℓ_{stub}	w_{stub}	ℓ_μ
2	0.15	0.15	0.2	6	0.2	1.5/1
w_μ	p	w	W_t	L_t	L_1	L_2
3.8 /2.4	5	4	10	10	7	1

IV. SIMULATION AND RESULTS

With those dimensions is shown in Fig. 1(a), and using technique in [14] to extract the equivalent circuit parameters. The LC parameters of the unit cell are: L'_R of 1.533 nH, C'_R of 0.546 pF, C'_L of 2.778 pF and L'_L of 0.3013 nH.

The ZOR-CPW based on CRLH-TL is shown in Fig. 1(a). This antenna is built with a CPW technology and placed on the top of the substrate without using vias. Thus, the proposed antenna has the features of easy implementation and low profile configuration. According to the theory of ZOR in section II, the resonant frequency is determined by w_{sh} (open circuit). In the other words, the resonant frequency depends on meander line L'_L and right capacitor C'_R. The dispersion diagram (ω-β curve) for the design of ZOR-CPW CRLH-TL is shown in Fig. 2, it is observed that the dispersion diagram is balanced, and this means that $w_{se}=w_{sh}=w_0=5.5$ GHz at $\beta=0$. The dispersion diagram displays three distinct frequency regions: left-handed, zero order, and right-handed regions. Fig. 3 shows the reflection (S_{11}) and transmission (S_{21}) coefficients of one unit cell, it is found that S_{11} of -23.7 dB and S_{21} of -0.75 dB at the resonance frequency of 5.5 GHz.

The simulated 10 dB return loss bandwidth of the proposed antenna extends from 4.55 GHz to 11.33 GHz, this means that the bandwidth and fractional bandwidth are 6.78 GHz and 123.3% are achieved respectively. The proposed antenna achieves a 61.5% reduction in patch size compared to a conventional half-wavelength patch antenna at frequency 5.5GHz. Fig. 4 displays the simulated co-cross polarization radiation patterns of the proposed antenna at 5.5 GHz. The simulation results reveal that the co-cross polarization discrimination in E-plane ($\varphi=90^0$) is about 21.8 dB and in H-plane ($\varphi=0^0$) is 21.1 dB. The radiation efficiency is 76%. And the maximum directivity of the antenna is 0.65 dB. Table (II) shows the comparison of the reflection coefficients, bandwidth, efficiency, and directivity, of the proposed antenna with other reference antennas.

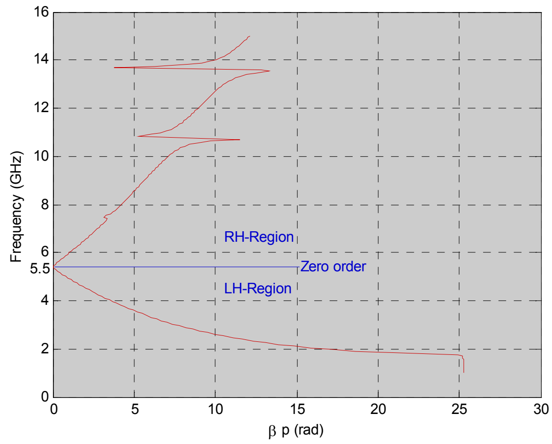


Figure 2. Dispersion diagram of unit-cell CRLH used for ZOR antenna at frequency 5.5GHz.

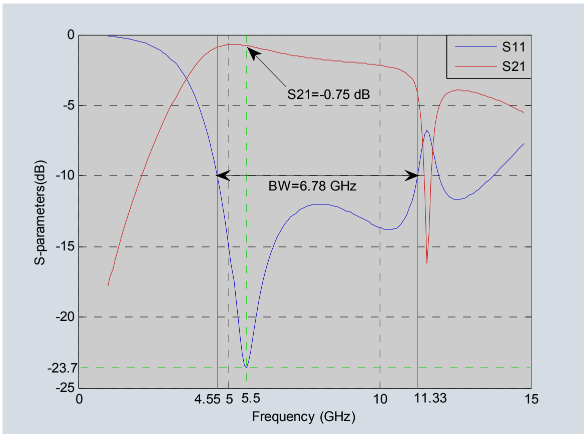
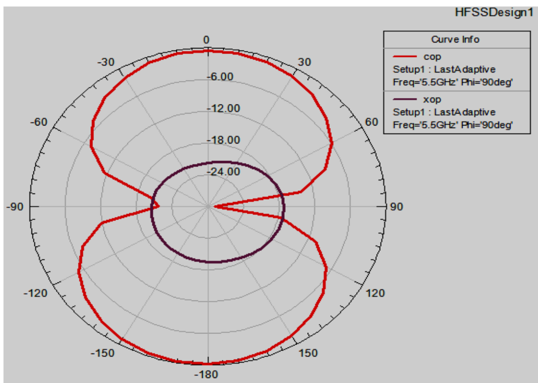
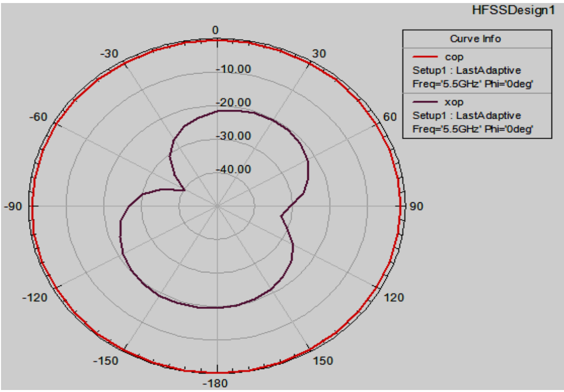


Figure 3. Simulated the magnitude of s-parameters (reflection and transmission coefficients) vs. frequency plot for the design of unit cell ZOR-CPW at frequency 5.5GHz.



(a)



(b)

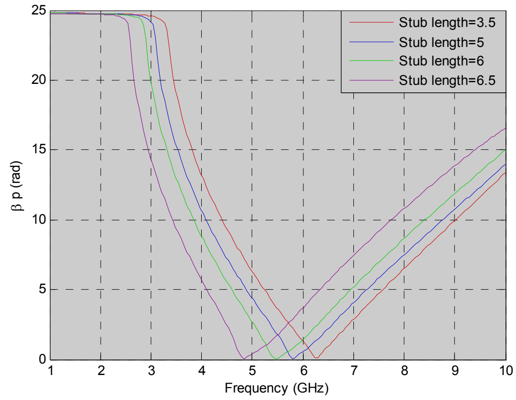
Figure 4. Normalized simulated radiation patterns: (a) E –plane (yz-plane) (co-cross polarization pattern) and (b) H-plane (xz-plane) (co-cross polarization pattern).

TABLE II. COMPARISON OF PROPOSED ANTENNA WITH OTHER ANTENNAS REPORTED.

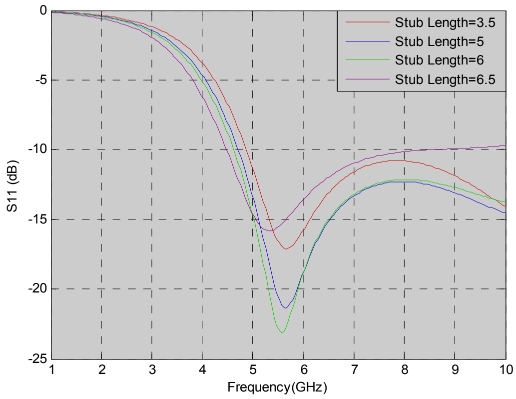
Ref.	Freq. (GHz)	S_{11} (dB)	BW (%)	η (%)	D (dB)
Proposed design	5.5	-23.7	120	76	0.65
Ref. [5]	2.3 2.9	-25 -12	0.6 1.7	62 65	2.27 0.45
Ref. [11]	2.26 2.89	-20	___	92	1.6 2.48
Ref. [12]	2	-22	___	___	3.5
Ref. [13]	2.03	-22	6.8	62	1.35

V. PARAMETERIC STUDY

In this section, a parametric study is applied to realize the performance of the ZOR-CPW based on CRLH-TL unit cell π-network. This study is performed by tuning the IDC fingers dimensions and the meander stub length. Fig. 5 shows the dispersion diagram, reflection coefficient characteristics, phase constant of the unit cell, and Bloch impedance with different stub lengths. From Fig. 5(a and b), the resonance frequency shows a significant dependence on the stub length (refers to Fig. 1(a)); this is due to the fact that the resonance occurs in the shunt terminal. From Fig. 5(b), it is noticed that the best value of matching takes place at the stub length of 6 mm, thereby establishing design criteria. Nevertheless, it is noticed that the stub length of 6 mm yields the S_{21} shows a zero phase shift between the input and output ports as seen Fig. 5(c). This property indicates ideal response condition.



(a)



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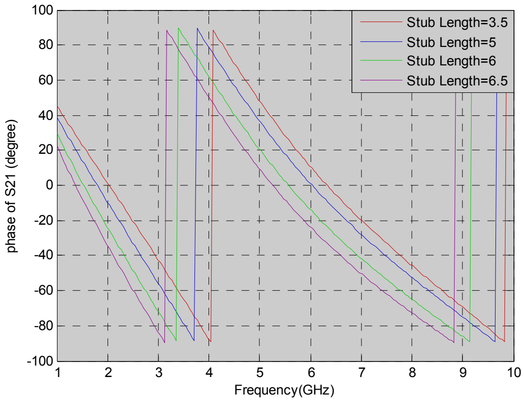

(c)

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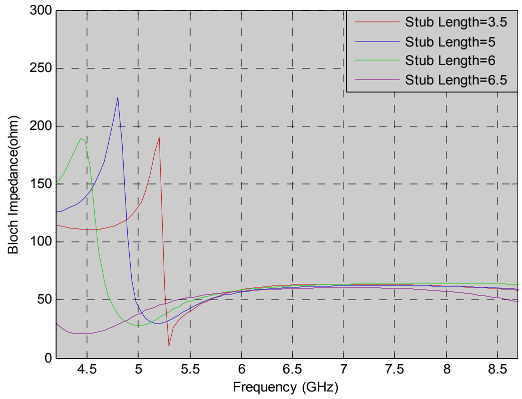
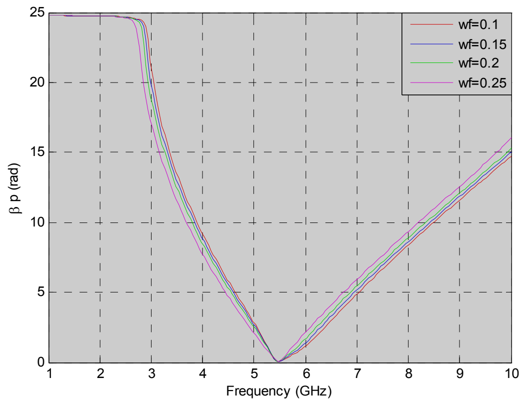


(d)

Figure 5. A parametric study with different stub lengths (a) Phase change (b) S_{11} (c) Phase change of S_{21} spectrum and (d) Bloch impedance.

Figs. 6 and 7 show the dispersion diagram, return-loss characteristics, the phase of the unit cell and Bloch impedance for various IDC fingers width and length, respectively. It is noticed that the width and the length show no effects on the phase spectrum as seen in Figs. 6(a) and 7(a). Thus, the series C_L connection is added to the trace in order to affect the matching without any effect on the resonant frequency. From Figs 5(d), 6(d) and 7(d), in this part, it is confirmed that the proposed stub length of 6 mm, finger length of 2 mm and a finger width of 0.15 mm for the final design generate a Bloch impedance of 50Ω at the desired operating frequency.



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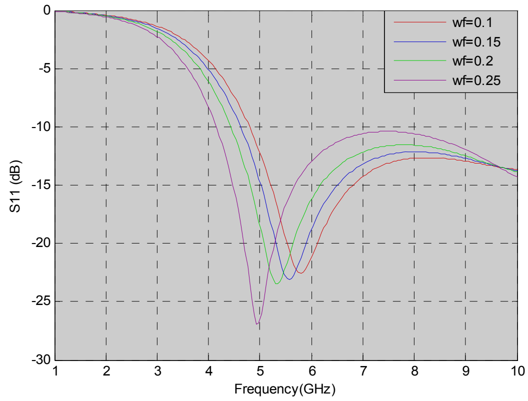

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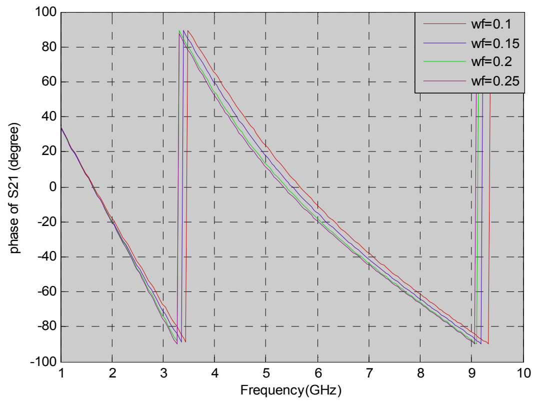

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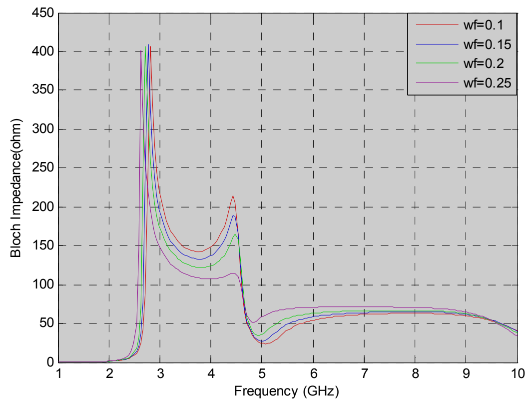
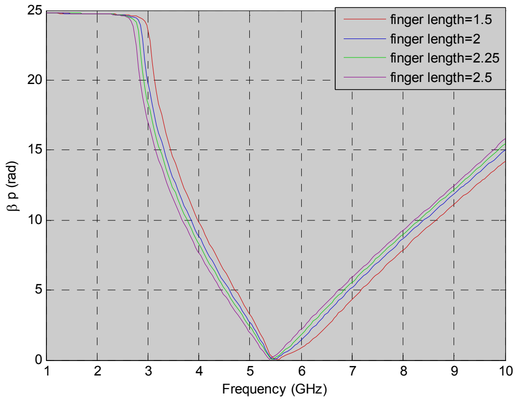
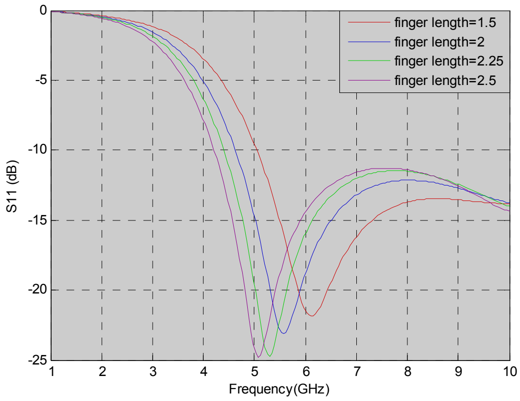


(d)

Figure 6. A parametric study with different finger width (a) Phase change (b) S_{11} (c) Phase change of S_{21} spectrum and (d) Bloch impedance.



(a)



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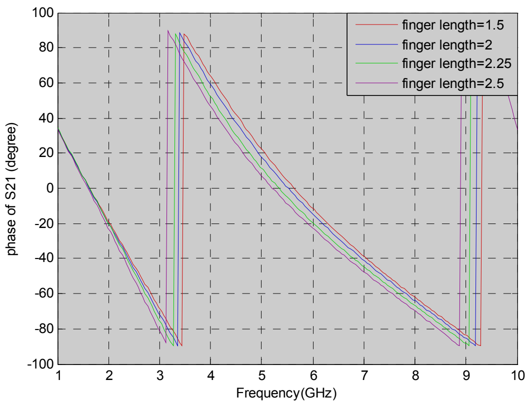
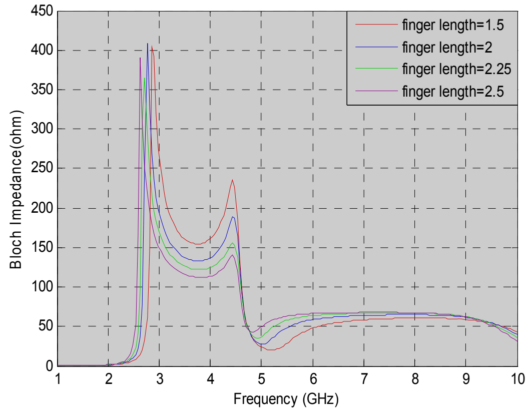


(c)



(d)

Figure 7. Parametric study with various finger lengths (a) Phase change (b) S_{11} (c) Phase change of S_{21} spectrum and (d) Bloch impedance.

VI. CONCLUSION

In this paper, a novel zeroth order resonator-coplanar waveguide, based on the presented properties of a CRLH-TL metamaterial unit cell, wideband antenna, has been proposed and analyzed. The ZOR antenna has very compact size compared to the conventional resonator microstrip antenna. More importantly, the proposed ZOR antenna achieves a 61.5 % reduction in patch size compared to a conventional half-wavelength patch antenna. Though implemented on a FR4 substrate, ZOR exhibits a peak gain of 0.65 dB and a radiation efficiency of 76%, comparable to those of other published ZOR antennas using low dielectric constant. The simulated 10 dB return loss bandwidth of the proposed antenna extends from 4.55 GHz to 11.33 GHz, this means that the bandwidth and fractional bandwidth are 6.78 GHz and 123.3% respectively. Co-cross polarization discrimination in the E-plane is equal to 21.8 dB and in the H-plane is 21.1 dB.

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