Development of ZOR using Via-less CRLH-TL

Dileep Kumar Upadhyay

Abstract – **In this paper, a composite right/left handed transmission line (CRLH-TL) based design and development of novel compact zeroth-order resonator (ZOR) is proposed. The ZOR is excited by the coplanar waveguide (CPW) feed line. The ZOR is based on single unit-cell via-less CRLH-TL. The unit-cell of CRLH-TL is designed by series six fingers interdigital capacitor (IDC) in shunt with the parallel inductive stubs shorted to the ground. Due of the use of CPW-fed, the shorting of inductive stub to the ground does not require any via, which simplifies the fabrication processes and saves the valuable time wastage taken in drilling and soldering processes. The proposed ZOR exhibits the return-loss -23.13 dB, insertion-loss -0.67 dB, -10 dB bandwidth, 103 MHz and resonance frequency of 6.1 GHz. The ZOR is compact in size, 7.45 x 8.9 mm^2 i.e. 0.151 λ_0 x 0.181 λ_0 mm^2, where λ_0 is the wavelength in free space at resonance frequency. The equivalent lumped circuit model of the proposed ZOR is obtained using Ansoft Designer. The simulated results are obtained using method of moment (MoM) based electromagnetic (EM) simulator, IE3D. The measured results are obtained using Agilent vector network analyzer (VNA), 0-22 GHz. All measured results are found in close similarity with the circuit model and simulation results.**

Keywords – **Composite right/left handed transmission line, Coplanar waveguide, Interdigital capacitor, Zeroth-order resonator.**

I. Introduction

The left handed metamaterial is realized by mainly two methods (1) periodic combination of split-ring resonators and thin metallic wires, known as resonant approach [1-2], (2) periodic combination of series interdigital capacitor in shunt with the shorted inductive stub to ground, known as non-resonant approach [2-3]. Unique properties of left handed metamaterial leads to the development of many new devices and circuits such as, dominant mode leaky wave antenna [3], symmetric and asymmetric directional couplers [4], wideband bandpassfilters [5], resonant antenna [6], ultra-wideband bandpass filters [7-8] zeroth order resonators and zeroth order resonator antennas [9-15] and many more.

The zeroth order resonator reported in [9] suffers with the poor S-parameters characteristics, insertion loss of -7.0 dB and return loss of -4.5 dB at zeroth order resonance frequency of 2.5 GHz. The reported resonator in [9] does not find any practical applications rather it only proves the ZOR characteristics of CRLH-TL. The ZOR presented in [10] used the two coupling capacitors at the input and output ends, shows the good measured S-parameters characteristics, $|S_{21}| = -0.42\,dB$ and $|S_{11}| = -26.31\,dB$ at resonance frequency of 1.5 GHz. However, because of the use more fabrication steps because of the etching of rectangular geometry at the ground plane. The resonant frequency and size of the ZOR antenna [11] are 2.03 GHz and 25.4 x 21.4 mm^2 respectively. The ZOR reported in [12] is designed using via-less CRLH-TL, has the size of 21.6 x 5.2 mm^2 and operates at 2.84 GHz, but consists of comparatively complex geometry profile and lower frequency of operation as compared to the proposed ZOR. The CRLH-TL based ZOR reported in [13], uses the via to short circuit the inductive stub to ground, has the area of 120 mm^2 and operates for the resonance frequency of 3.5 GHz. The ZOR designed for resonance frequency, 1.52 GHz is of large in size, 57.8 x 22.8 mm^2 [14]. Using the ferrite substrate the ZOR reported in [15], operates at resonant frequency of 4.85 GHz and of compact in size, 8.3 x 20 mm^2, but suffers with the poor insertion loss, -1.5 dB.

The serious issues of aforementioned ZORs are (1) large in size, (2) requires more fabrication steps, tedious ground-plane processing and complex geometry profile (3) operates for lower resonant frequency, i.e. less than 4.85 GHz. The basic aim of the design and development of proposed ZOR is to ease the fabrication processes, miniaturize the size and to design for the high resonant frequency, 6.1 GHz.

In this article, the author proposes the novel compact CRLH-TL based ZOR. The reported ZOR is designed to meet the uplink frequency requirement of C-band satellite communication for resonance frequency of 6.1 GHz. The ZOR is designed and developed using single unit-cell via-less CRLH-TL excited by CPW fed. Since in CPW fed the signal and ground plane both are in same plane, inductive shorting stub to ground does not require the via, which minimizes the extra processing steps require for drilling and soldering to get the via as was in the case of conventional design of CRLH-TL.The proposed ZOR is designed using RT/duroid 5880, with relative permittivity, $\varepsilon_r = 2.2$, thickness, $h = 1.57\,mm$ and loss-tangent, $\tan(\delta) = 0.0009$. The proposed ZOR exhibits the good S-parameters characteristics, $|S_{21}| = -0.67\,dB$ and $|S_{11}| = -23.13\,dB$ at resonance frequency of 6.1 GHz with -10 dB bandwidth of 103 MHz. The equivalent lumped circuit model of the ZOR is obtained from the circuit model tool of Ansoft Designer. All simulated results are extracted from the commercially availableEM simulator, IE3D based on MoM and compared with the measured results obtained from Agilent, VNA. All measured results are found in close similarity with the equivalent lumped circuit model and EM simulation results.

II. Fundamentals of CRLH-TL Based ZOR

For non-zero values of frequency (f), in contrast to conventional right handed TLs, the left handed TLs offer the zero value of the propagation constant (β). The curve between the β and f, (β vs. f plot) is known as dispersion curve. Dispersion diagram shows that, $\beta < 0$ corresponds to LH

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region whereas, $\beta > 0$ corresponds to the RH region. The resonant frequency, f_0 of the resonator is the frequency in the dispersion curve where β becomes zero. For open-ended CRLH-TL, the resonance appears when, $\beta_n = \frac{n\pi}{l}$, $n = 0, \pm1, \pm2, \pm3, \ldots\ldots\ldots \pm(M-1)$, where, β_n is the n^{th} mode propagation constant, n is the mode number, M is the number of unit-cells associated with the CRLH-TL and, l is the total length of the CRLH-TL. The zero value of n corresponds to the zeroth order of the resonator, where β_n becomes zero. Because of the zero value of β_n, the guided wavelength, λ_g, which is defined as $\lambda_g = \frac{2\pi}{|\beta_n|}$, becomes infinite, which results the invariance in the resonant frequency irrespective to the size of the resonator [2]. The shortest length of open ended resonator designed by conventional RH materials is $\lambda_g/2$, hence the resonator designed by LH material is much smaller in size as compared to the RH material.

The composite right/left handed transmission line (CRLH-TL) consists of composition of pure right handed (RH) transmission line (PRH TL) and pure left handed (LH) transmission line (PLH TL) because of the non-realization of PRH TL and PLH TL. The unit-cell of CRLH TL consists of per-unit series LH capacitor (C_l) and parasitic RH inductance (L_r), and per-unit parallel LH inductance (L_l) and parasitic RH capacitance (C_r). The per-unit series impedance $Z_s(f)$ and parallel admittance $Y_p(f)$ of unit-cell of CRLH-TL are given as [2-3, 9]

$$Z_s(f) = j2\pi\left(fL_r - \frac{1}{4\pi^2 f C_l}\right), \qquad (1)$$

$$Y_p(f) = j2\pi\left(fC_r - \frac{1}{4\pi^2 f L_l}\right). \qquad (2)$$

Because of the formation of standing wave, if CRLH is kept open or short circuited, it works as a resonator.

The series resonant frequency, f_{se} and shunt resonant frequency, f_{sh} of the CRLH-TL are given as follows

$$f_{se} = \frac{1}{2\pi\sqrt{C_l L_r}}, \qquad (3)$$

$$f_{sh} = \frac{1}{2\pi\sqrt{C_r L_l}}, \qquad (4)$$

when, $f_{se} = f_{sh}$, the CRLH-TL is known as balanced CRLH-TL whereas, when $f_{se} \neq f_{sh}$, the CRLH-TL is known as unbalanced CRLH-TL. For balanced CRLH-TL, the ZOR resonance frequency, $f_0 = f_{se} = f_{sh}$, and for unbalanced CRLH-TL the resonance frequency is decided by the shunt LC-tank, i.e. $f_0 = f_{sh}$.

The β vs. f plot can be obtained from the following mathematical expression

$$\beta = \cos^{-1}\left(\frac{1 - S_{11}S_{22} + S_{21}2S_{12}}{2S_{21}}\right), \qquad (5)$$

where, S_{pq}, $(p, q = 1, 2)$ are the scattering parameters of input $(p, q = 1)$ and output $(p, q = 2)$ ports of the CRLH-TL. The zeroth order resonance frequency can also be determined from $\angle S_{21}$(degree) vs. frequency plot, where the $\angle S_{21}$(degree) value becomes zero.

III. Design of Proposed ZOR

The design layout schematic of proposed ZOR based on CRLH-TL is depicted in Fig. 1. As shown in Fig. 1, because of the CPW fed, the signal plate and ground plate both are in the same plane, hence shorting of the stubs to the ground planes do not require the via, which minimizes the fabrication steps. The series LH capacitance, C_l is obtained by six fingers interdigital capacitor (IDC) and LH shunt inductance, (l_l)is generatedby the four stubs shorted to top and bottom ground planes. The series and shunt RH inductance, (L_r) and capacitance, (C_r) respectively are introduced because of the parasitic effects of realization of IDC and shorted stubs. The ZOR is designed on RT/duroid 5880 substrate of dielectric constant, $\varepsilon_r = 2.2$, thickness, $h = 1.57\ mm$ and loss tangent, $\tan(\delta) = 0.0009$. The various dimensions of proposed ZOR are listed in Table 1. The ZOR is compact in size, 0.151 λ_0 x 0.181 λ_0 mm^2, where λ_0 is the wavelength in free space at centre frequency of 6.1 GHz.

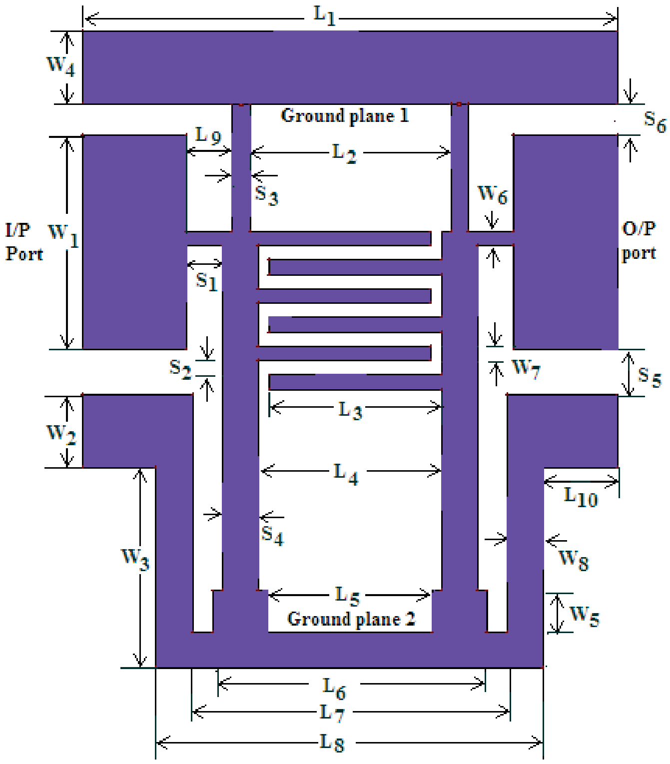

Fig. 1. Design layout of the proposed ZOR

The dispersion curve (β vs. f plot) of the proposed ZOR obtained from Eq. 5 is depicted in Fig. 2. As illustrated in Fig. 2, the CRLH-TL shows the left handed characteristics at lower frequencies and right handed characteristics at higher frequencies. Fig. 2 shows that the left handed region of CRLH-TL is from 5.82 GHz to 6.1 GHz, i.e. $5.82\ GHz \leq f_{LH} \leq 6.1\ GHz$ and right handed region is from 6.14 GHz to 6.42 GHz, i.e. $6.14\ GHz \leq f_{RH} \leq 6.42\ GHz$. From the dispersion curve, a narrow stopband, 6.1 GHz to 6.14 GHz can be observed, which occurs because of the unequal resonance frequency of shunt (L_l, C_r) tank circuit (6.1 GHz), and series (L_r, C_l) circuit (6.14 GHz). Since the resonance frequency of ZOR, f_0, is the resonance frequency of shunt (L_l, C_r) tank circuit, hence $f_0 = 6.1\,GHz$. The resonance frequency of ZOR, f_0 can also be determined from the phase of S_{21} versus frequency plot illustrated in Fig. 3. From the Fig. 3, it can be observed that the $\angle S_{21}$ is zero at the frequency 6.1 GHz, hence the resonance frequency of ZOR, f_0 will be 6.1 GHz.

TABLE 1
VARIOUS DIMENSIONS OF PROPOSED ZOR SHOWN IN FIG. 1

Parameters	L_1	L_2	L_3	L_4	L_5
Dimensions (mm)	7.45	2.79	2.4	2.55	2.28
Parameters	L_6	L_7	L_8	L_9	L_{10}
Dimensions (mm)	3.81	4.38	5.39	0.63	1.03
Parameters	W_1	W_2	W_3	W_4	W_5
Dimensions (mm)	3.0	1.0	2.8	1.0	0.58
Parameters	W_6	W_7	W_8	S_1	S_2
Dimensions (mm)	0.2	0.2	0.5	0.5	0.2
Parameters	S_3	S_4	S_5	S_6	
Dimensions (mm)	0.25	0.5	0.65	0.45	

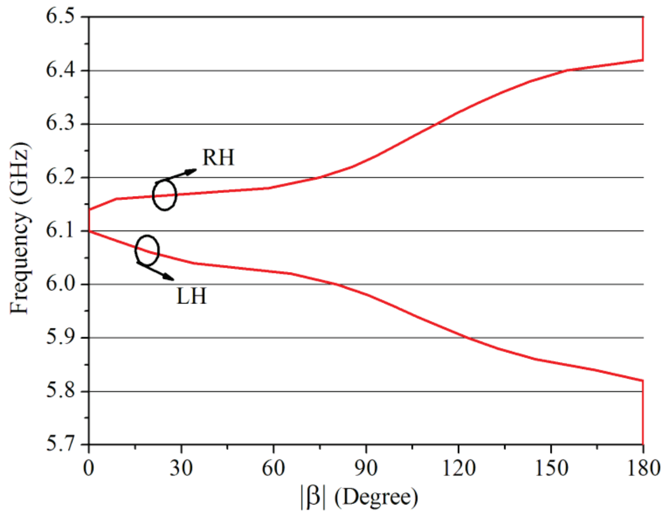

Fig. 2. Dispersion curve of ZOR

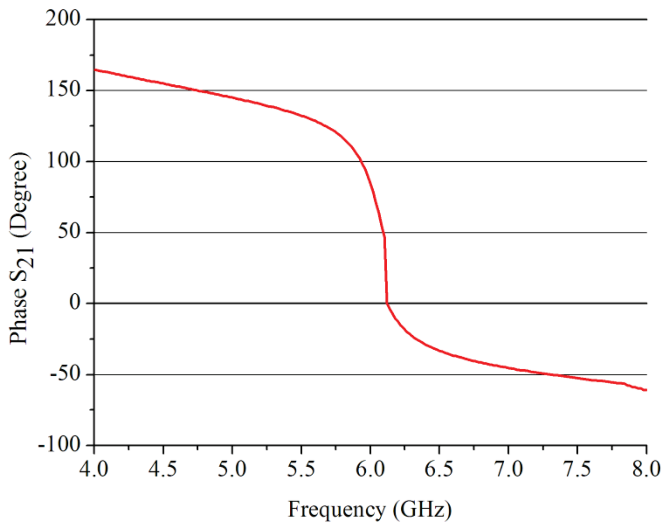

Fig. 3. $\angle S_{21}$ vs. frequency plot of ZOR

The simulated S-parameters performance of proposed ZOR is depicted in Fig. 4. From the Fig. 4, it can be seen that the resonance frequency of ZOR, f_0 is 6.1 GHz as was expected from dispersion curve and phase curve of ZOR. The ZOR exhibits the -10 dB bandwidth of 103 MHz, insertion-loss ($|S_{21}|$) and return-loss ($|S_{11}|$) of -0.67 dB and -23.13 dB respectively at $f_0 = 6.1$ GHz. Moreover, the S-parameters performance of ZOR also shows the good stopband characteristics. Fig. 4 shows that the ZOR exhibits the stop-band insertion-loss greater than 10 dB and return-loss of less than 0.57 dB at higher frequency region, 6.5 GHz to 8.0 GHz and lower frequency region 4.0 GHz to 5.7 GHz.

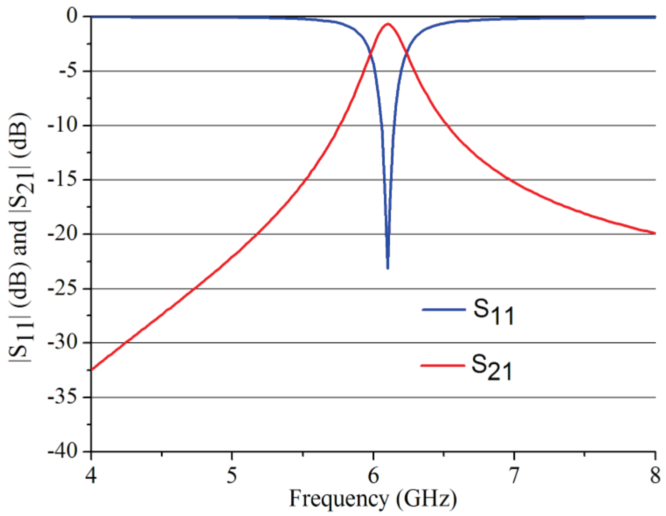

Fig. 4. Simulated S-parameters vs. frequency plot of ZOR

The simulated current distribution of proposed ZOR at $f_0 = 6.1$ GHz is shown in Fig. 5. The current distribution in Fig. 5 shows that the large density of current distribution is observed at interdigital capacitor, stubs and ground planes, and small density of current distribution is at edges of the geometry and at input and output ports. The good concentration of current distribution shows that ZOR is well matched with the impedance at $f_0 = 6.1$ GHz.

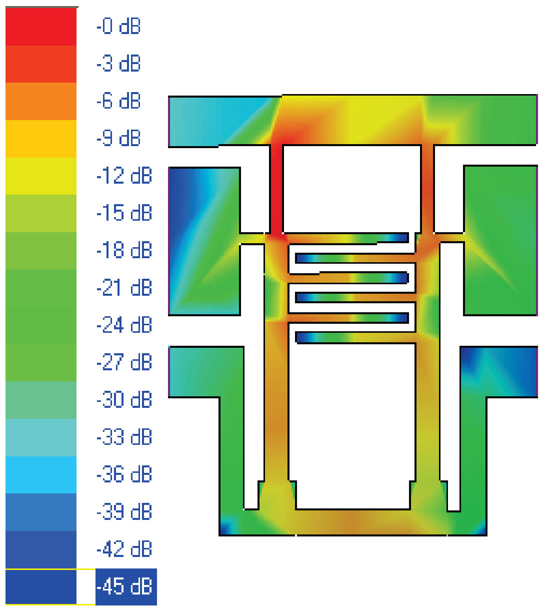

Fig. 5. Current distribution in ZOR at $f_0 = 6.1$ GHz

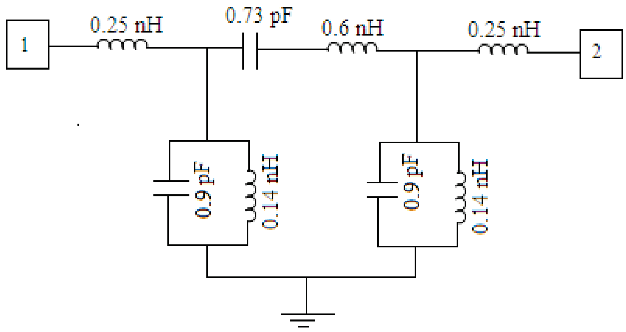

Fig. 6. Equivalent lumped circuit model of ZOR

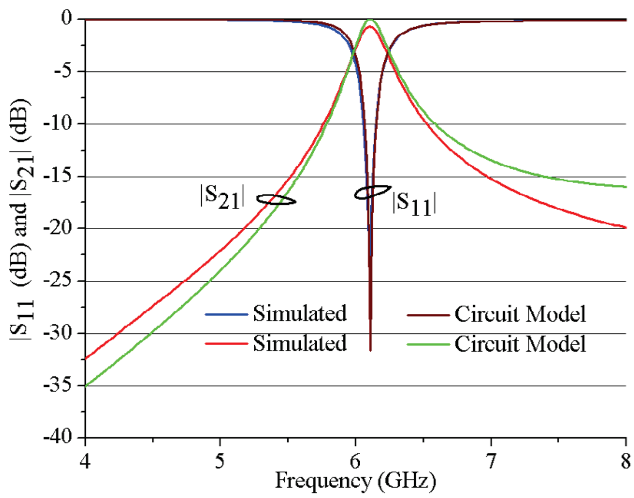

Fig. 7. Comparative simulated and equivalent lumped circuit model S-parameters vs. frequency plot of ZOR

The equivalent lumped circuit model of the proposed ZOR is shown in Fig. 6. The mutual coupling between the individual elements is not taken in to consideration. Considering the layout of the proposed ZOR, an equivalent circuit diagram is developed. The lumped element values are obtained by manually optimizing each element value so that it can have the good agreement with the simulated results obtained from the full wave simulator.The impedances of input and output ports are 50 Ω. The inductance of value 0.25 nH at input and output ends are generated due to the length S_1 at the input and output sides. The series capacitance of 0.73 pF is generated because of series interdigital capacitor and series inductance of 0.6 nH is introduced because of the parasitic effect of interdigital capacitor. The parallel input tank circuit consists of inductance 0.14 nH and capacitance 0.9 pF, are introduced because of the two input stubs and their parasitic effects. Similarly, because of the symmetrical structure, the parallel output tank circuit consists of same values of inductance 0.14 nH and capacitance 0.9 pF, which are introduced due to the two output stubs and their parasitic effects.

The comparative EM simulation and equivalent lumped circuit model S-parameters versus frequency plot of ZOR is depicted in Fig. 7. The equivalent lumped circuit model results show that the ZOR exhibits the insertion-loss of -0.01 dB and return-loss of -31.63dB at resonance frequency of 6.11 GHz. The -10 dB bandwidth of circuit model is found to be 98 MHz. A close similarity between the EM simulation results and circuit model results can be seen, however a small deviation between them can be observed at some lower frequency and higher frequency range, which may be arised because of the ignorance of the effects of mutual coupling between the elements.

IV. Experimental Results and Discussion

The fabricated photograph of the designed ZOR layout shown in Fig. 1 is depicted in Fig. 8. The comparative EM simulation and measured dispersion plot is illustrated in Fig. 9. Fig. 9 shows that the measured left handed frequency starts from 5.88 GHZ and ends at 6.08 GHz, i.e. $5.88\,GHz \le f_{LH}^{M} \le 6.08\,GHz$, whereas, right handed frequency starts from 6.12 GHZ and ends at 6.32 GHz, i.e. $6.12 \le f_{RH}^{M} \le 6.32\,GHz$. Moreover the measured resonance frequency is observed at $f_0^M = 6.08\,GHz$.

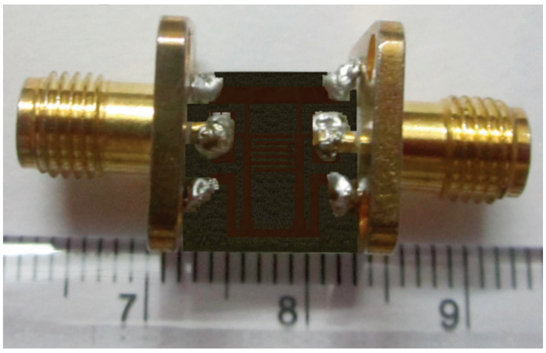
Fig. 8. Photograph of fabricated ZOR

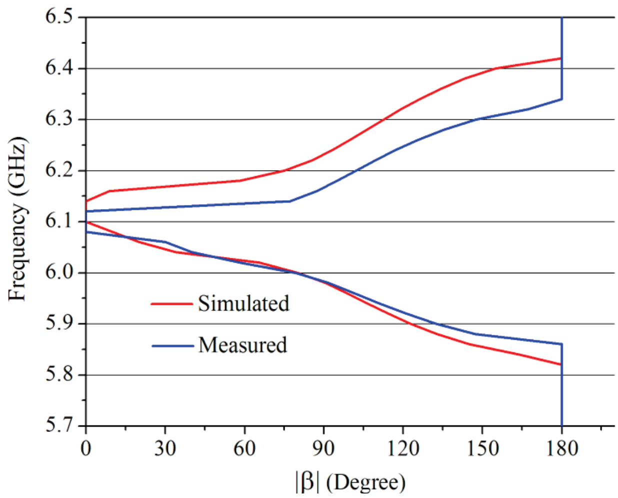

Fig. 9. The comparative simulated and measured dispersion curve

The comparative simulated and measured S-parameters versus frequency plot of ZOR is depicted in Fig. 10. Fig. 10 shows that the ZOR exhibits the measured insertion-loss, $|S_{21}|$ = -0.37 dB and return-loss, $|S_{11}|$ = -21.33 dB at resonance frequency of 6.08 GHz. The measured -10 dB bandwidth of ZOR is found as 97 MHz. A close similarity between the simulated and measured results can be observed. However, a slight deviation of measured results from the simulated results can be seen, which occurs because of the consideration of finite ground plane, improper soldering and fabrication tolerances. Table 2 shows the comparison of resonance frequency, -10 dB bandwidth, return loss and insertion loss for simulated circuit model, equivalent circuit model and measured results.

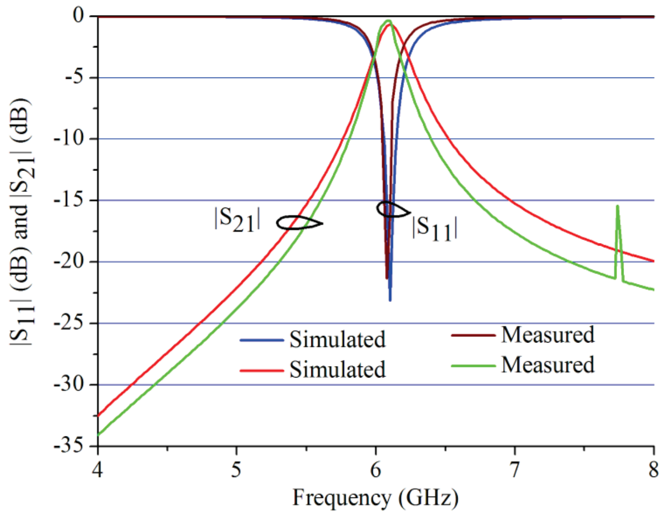

Fig. 10. The comparative simulated and measured S-parameters vs. frequency plot

TABLE 2
COMPARISON OF SIMULATED, EQUIVALENT CIRCUIT AND MEASURED RESULTS

Parameters	Resonance frequency, f_0 (GHz)	-10 dB Bandwidth (MHz)	$\lvert S_{11}\rvert\ dB$ at f_0	$\lvert S_{21}\rvert\ dB$ at f_0
Simulated	6.1	103	-23.13	-0.67
Equivalent Circuit	6.11	98	-31.63	-0.01
Measured	6.08	97	-21.33	-0.37

V. CONCLUSION

A compact via-less CRLH-TL based novel zeroth order resonator excited by CPW-fed is reported in this paper. The absence of via reduces the fabrication steps and minimizes the overall production cost. The ZOR is compact in size, 0.151 λ_0 x 0.181 λ_0 mm^2. The ZOR exhibits the measured insertion-loss of -0.37 dB and return-loss of -21.33 dB at centre frequency, 6.08 GHz. The measured -10 dB bandwidth of the resonator is 97 MHz. Moreover, the ZOR also shows the good measured stopband characteristic, $|S_{21}| > 10$ dB and $|S_{11}| < 0.53$ dB. By changing the physical dimensions of the interdigital capacitor and stubs, a ZOR can be designed for different resonance frequencies and hence this concept may also be utilized to design the reconfigurable ZORs. Because of the small size, low complexity and good performance, the proposed ZOR may find the potential application in wireless communication systems.

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