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Experimental Verification of a Compact Zeroth Order Metamaterial Substrate Integrated Waveguide Antenna

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Abstract—This paper presents a zeroth order metamaterial substrate integrated waveguide antenna. The antenna is designed to have a compact size based on employing only one composite right/left-handed cell. The antenna resonates at 6.1 GHz with overall radiator size of 14.4 mm × 8 mm which represents 50% size reduction compared to conventional microstrip patch antenna that operates at the same frequency. The zeroth order mode of the antenna has been verified using analytical explanation and full wave simulations. Moreover, the full wave simulations and experimental measurements have been employed to confirm the antenna matching properties and radiation characteristics.

1. INTRODUCTION

The increasing demands in wireless communication require the development of antenna designs and configurations. One of the interesting novel antenna designs was based on employing metamaterials due to their unique features associated with electromagnetic waves propagation. Left-handed metamaterials (LHMs), which can exhibit simultaneous negative permittivity and permeability, have been realized in planar form by loading a transmission line (TL) with series capacitors and shunt inductors. Due to both parasitic inductance and capacitance of the TL, these structures can be treated as a negative refractive index TL [1] or composite right/left-handed (CRLH) TL [2]. CRLH TL has a nonlinear progressive propagation phase coefficient which can be negative, positive or zero. Based on this unique property, many ultra-compact antennas [3–5] have been introduced. One of the novel properties of the CRLH TL is its zeroth order mode which enables the design of ultra-compact microwave devices. Examples for these components include resonators [6], filters [7], phase shifter [8] and antennas [9–13].

On the other hand, the Substrate Integrated Waveguide (SIW) was suggested for designing a high performance microwave and millimeter wave components. They introduce a trade-off between the low loss of waveguide and low cost of planar transmission lines. Recently, a CRLH SIW structure was introduced for the first time in [14]. The CRLH SIW structure was based on the similarity between equivalent circuits of CRLH TL and SIW except the series capacitance in CRLH TL that can be added on the top plane of an SIW structure. Different realizations of CRLH SIW TL were reported by Dong and Itoh for low microwave band [14] and by Okubo et al. [15] for high microwave bands. CRLH SIW TL has been employed in many microwave components such as filters [16], triplexer [17], coupler [18], phase shifter [19] and impedance transformer [20]. A big deal of research on CRLH SIW was devoted into antennas. This starts with forward/backward leaky wave antennas [21] and then resonant antennas [22–27].

In this paper, we introduce a compact zeroth order mode resonant CRLH SIW antenna. The theoretical design procedures are discussed. The antenna performance is investigated using the electromagnetic full wave simulations and measurements with good agreements between results.

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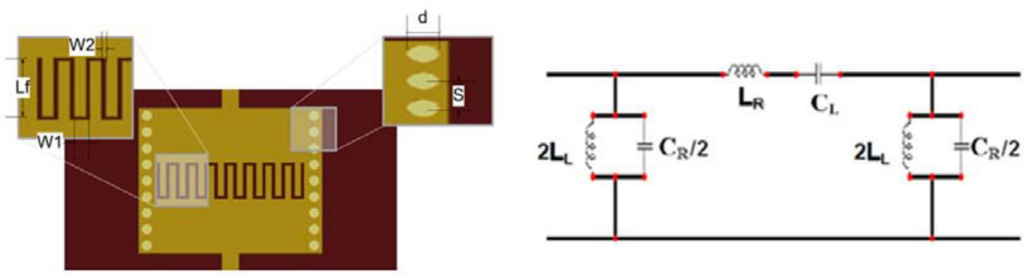
2. ZEROTH ORDER CRLH SIW ANTENNA ANALYSIS

The proposed antenna has been designed using only one cell of CRLH SIW TL. The CRLH SIW antenna is designed to operate at 6.1 GHz. The antenna is fed by a microstrip line as shown in Fig. 1(a). The CRLH SIW unit cell equivalent circuit model is shown in Fig. 1(b). The elements (L_R and C_R) are the parasitic inductance and capacitance, respectively, whereas the elements (L_L and C_L) represent the loading inductance and capacitance, respectively. The capacitor (C_L) is realized using interdigital capacitor (IDC) etched on the top surface of SIW. The inductor (L_L) is realized as a series of metallic via holes. The employed substrate is Rogers 5880 with dielectric constant = 2.2 and thickness = 0.508 mm. The relation between SIW structure and CRLH transmission line has been analysed in details in [28].



(a) (b)

Figure 1. (a) The 2D structure of a microstrip fed CRLH SIW transmission line, ($W_1 = 0.51$ mm, $W_2 = 0.35$ mm, $L_f = 3$ mm, $d = 0.95$ mm, and $S = 1.45$ mm). (b) The equivalent circuit model of a CRLH SIW unit cell.

2.1. CRLH SIW Antenna Design Procedures

A block diagram for the antenna is shown in Fig. 2. The single band CRLH SIW antenna is designed as one CRLH SIW cell with open circuit termination. The design of the antenna has been started by designing a 50 Ω CRLH TL with zero phase at the operating frequency (6.1 GHz). This can be expressed as:

$$\phi_{\text{CLRH}} = \left(\sqrt{\left(j\omega L_R + \frac{1}{j\omega C_L}\right)\left(j\omega C_R + \frac{1}{j\omega L_L}\right)}\right)\Bigg|_{f=6.1e^9} = 0. \tag{1}$$

$$77/Z_{\text{CLRH}} = \sqrt{\left(j\omega L_R + \frac{1}{j\omega C_L}\right)\Big/\left(j\omega C_R + \frac{1}{j\omega L_L}\right)}\Bigg|_{f=6.1e^9} = 50\,\Omega. \tag{2}$$

The interdigital capacitor and via inductor dimensions are calculated using formulas in [2, 29]. Given that h is the substrate thickness, l_f the capacitor finger length, and all fingers spacing and width

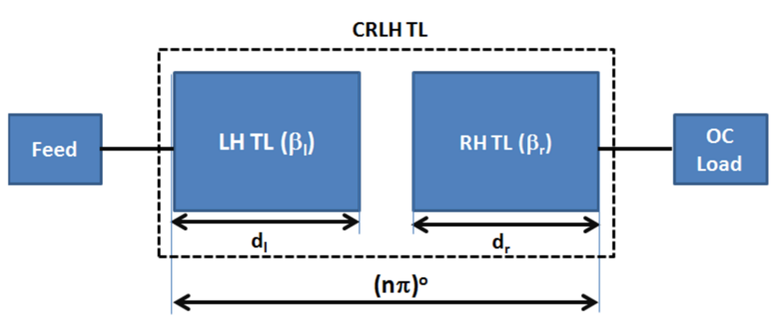


Figure 2. The schematic block diagram of the CRLH SIW antenna with open circuit termination.

$= 0.2\,\text{mm}$, due to the fabrication limits, this is expressed as

$$C_L\,(\text{pF}) = 3.937 \times 10^{-5} l_f\,(\varepsilon_r + 1)\,(0.11\,(n-3) + 0.252)\,, \quad l_f \text{in } [\mu\text{m}] \tag{3}$$

$$L_L = (\mu_0 h) \tag{4}$$

where μ_0 is the free space permeability. Since elements C_R and L_R are patristic, they are adjusted to enclose physically the SIW CRLH unit cell and their final values obtained through final curve fitting stage. For modelling the transition from the SIW configuration to microstrip one, two inductors (L_{ext}) and two capacitors (C_{ext}) are added at the end of the CRLH cell as shown in Fig. 3(a). The circuit model in Fig. 3(a) is simulated using the commercial circuit simulator (advanced circuit simulator (ADS)). A comparison with the simulated circuit and full wave scattering parameter magnitudes for one unit cell is

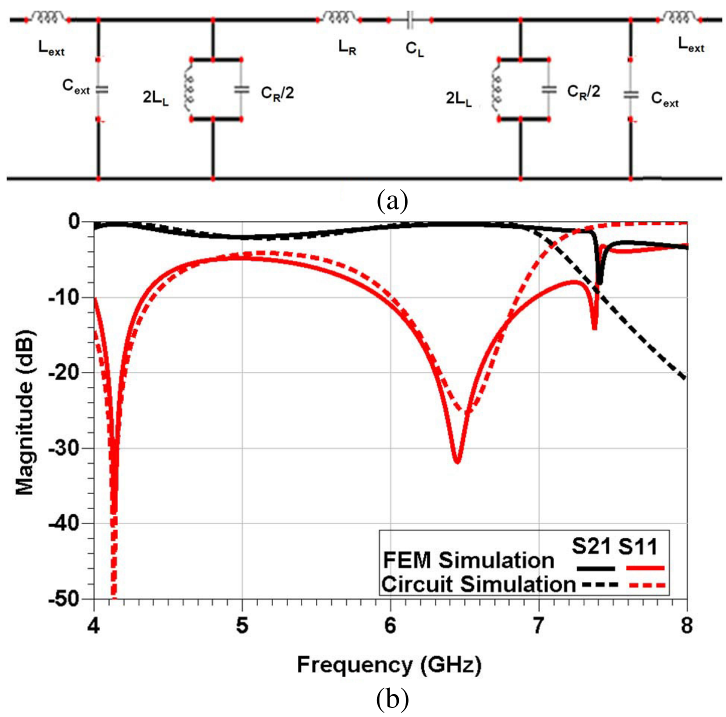


Figure 3. (a) The equivalent circuit of a CRLH SIW unit cell with microstrip feeding. (b) A comparsion between the circuit/full wave scattering parameter magnitudes of the SIW CRLH unit cell.

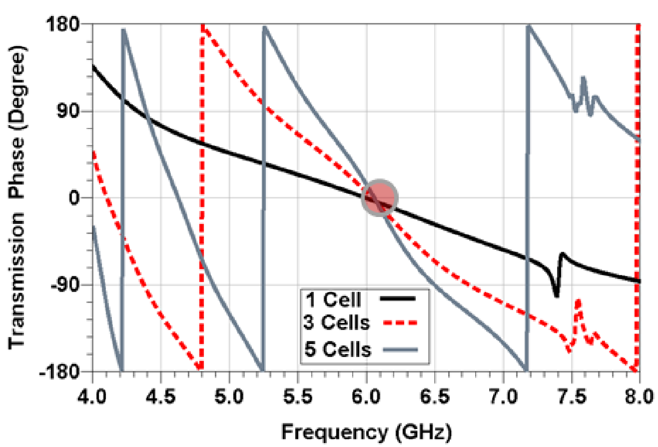


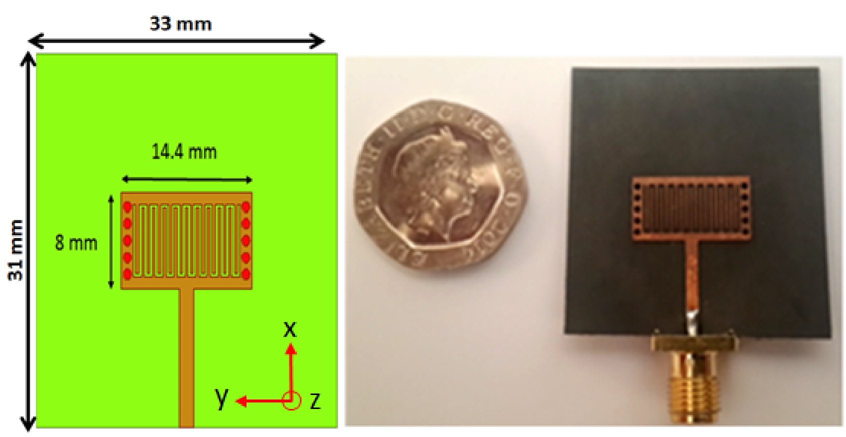
Figure 4. The progressive simulated phase of S_{21} of 2 port CRLH SIW unit cell, three unit cells and five unit cells.

shown in Fig. 3(b). The obtained values are $C_L = 2.2\,\mathrm{pF}$ and $L_L = 1.3\,\mathrm{nH}$, $C_R = 1.3\,\mathrm{pF}$, $L_R = 6.2\,\mathrm{nH}$, $C_{\mathrm{ext}} = 0.45\,\mathrm{pF}$ and $L_{\mathrm{ext}} = 6.2\,\mathrm{nH}$. It is clear that good agreement is achieved between the circuit and full wave simulations.

A confirmation of the zeroth order mode of the designed antenna has been done by comparing the phases of one, three and five CRLH SIW unit cells based on full wave simulations. The results are depicted in Fig. 4 where it is quite clear that the three cases have zero phase at 6.1 GHz, approximately. Below 6.1 GHz, the 5 cells have higher positive phase that confirms the LH passband, whereas above 6.1 GHz, the 5 cells have lower negative values which confirm the RH passband.

2.2. CRLH SIW Antenna Structure and Results

From pervious discussion, it has been concluded that by terminating the designed SIW unit cell with an open circuit termination, a zeroth order CRLH SIW antenna can be achieved at 6.1 GHz. Hence, as shown in Fig. 5(a), the proposed antenna has a total size $= 33 \times 31\,\mathrm{mm}^2$ (the employed cell is $14.4 \times 8\,\mathrm{mm}^2$). The fabricated antenna prototype is shown in Fig. 5(b). It is worth to mention here that some changes have been carried out for the used cell in order to achieve good matching at the designed frequency. The main change is performed on the total size of the patch from ($16.42\,\mathrm{mm} \times 13\,\mathrm{mm}$) in the unit cell to ($14.4\,\mathrm{mm} \times 8\,\mathrm{mm}$) in the antenna. Also the number of fingers in interdigital capacitor has been changed from 15 fingers in the unit cell to 19 fingers in the antenna in addition to slight modifications on the length of fingers (L_f), spacing (W_1 and W_2), and spacing between vias (S) as depicted in Fig. 5. Finally, the proposed zeroth order CRLH SIW antenna has a smaller size with a reduction factor about 50% when it is compared with the conventional patch, and such patch has a size ($19.2\,\mathrm{mm} \times 16.2\,\mathrm{mm}$) at the same resonance (6.1 GHz) and over the same substrate.



(a) (b)

Figure 5. Prototype of the zeroth order CRLH SIW antenna, (a) antenna 2D layout ($W_1 = 0.3\,\mathrm{mm}$, $W_2 = 0.3\,\mathrm{mm}$, $L_f = 5.7\,\mathrm{mm}$, $d = 0.95\,\mathrm{mm}$, and $S = 1.45\,\mathrm{mm}$), (b) fabricated antenna prototype.

The simulated and measured reflection coefficients are shown in Fig. 6. The simulated results demonstrate that an antenna resonance is at 6.1 GHz. On the other hand, the measured results confirm the same results with resonance at 6.15 GHz. For another confirmation of the zeroth order mode of the designed antenna, the current distribution of conventional patch antenna is compared to the proposed CRLH SIW antenna as plotted in Fig. 7(a) and Fig. 7(b), respectively. As shown in the figure, for the conventional patch antenna, the current is in one direction with maximum at the centre and zeros at the edges which is typical for half-length patch length. In contrast, the current in the case of CRLH SIW antenna is minimum at the CRLH middle with similar current direction on both sides. This can be claimed as a constant zero phase which supports the zeroth order mode of the antenna.

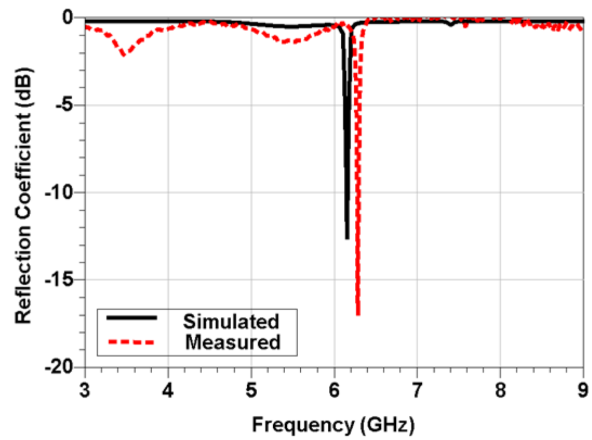


Figure 6. The simulated and measured reflection coefficient of the zeroth order CRLH SIW antenna.

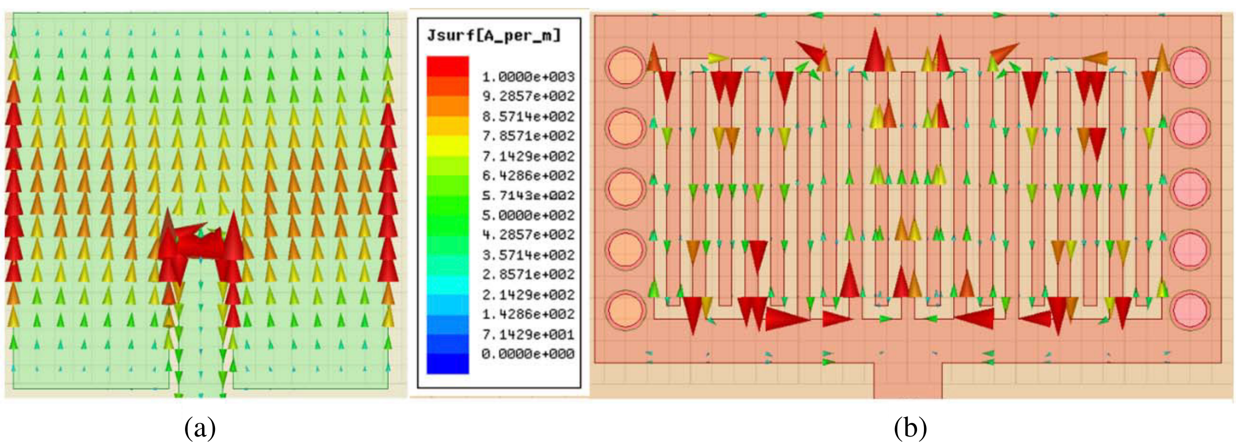


Figure 7. Current distribution along (a) half wave patch antenna , (b) zeroth order CRLH SIW antenna.

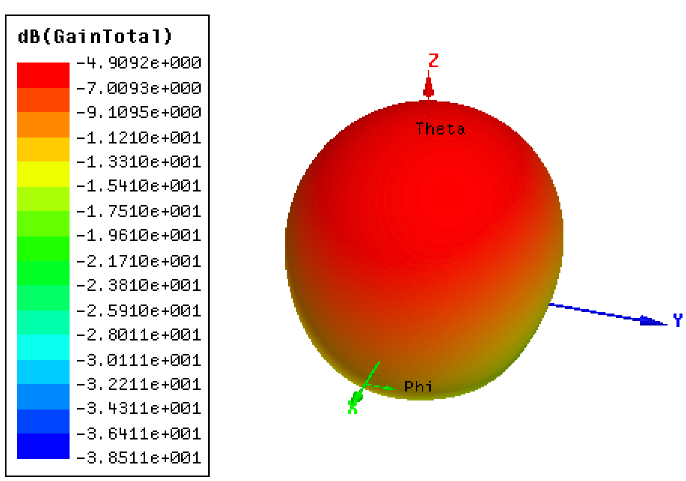


Figure 8. The simulated 3D radiation pattern (gain) of the proposed zeroth order CRLH SIW antenna.

3. ZEROTH ORDER CRLH SIW ANTENNA RADIATION CHARACTERISTICS

The simulated 3D radiation pattern at the resonant simulated frequency (6.1 GHz) is shown in Fig. 8. It is shown that the pattern is close to a typical broadside pattern. However, as a result of the antenna compactness, the gain of the antenna has a relatively small value (−4 dB) due to low efficiency of the antenna. For confirmation of the radiation properties, the simulated and measured normalized radiation patterns are compared to each other in Fig. 9. It has to say that since the antenna should work at resonant frequency, the radiation pattern comparison is done based on 6.1 GHz simulated pattern and 6.15 GHz measured pattern. It is clear that the measured pattern has a good agreement with the

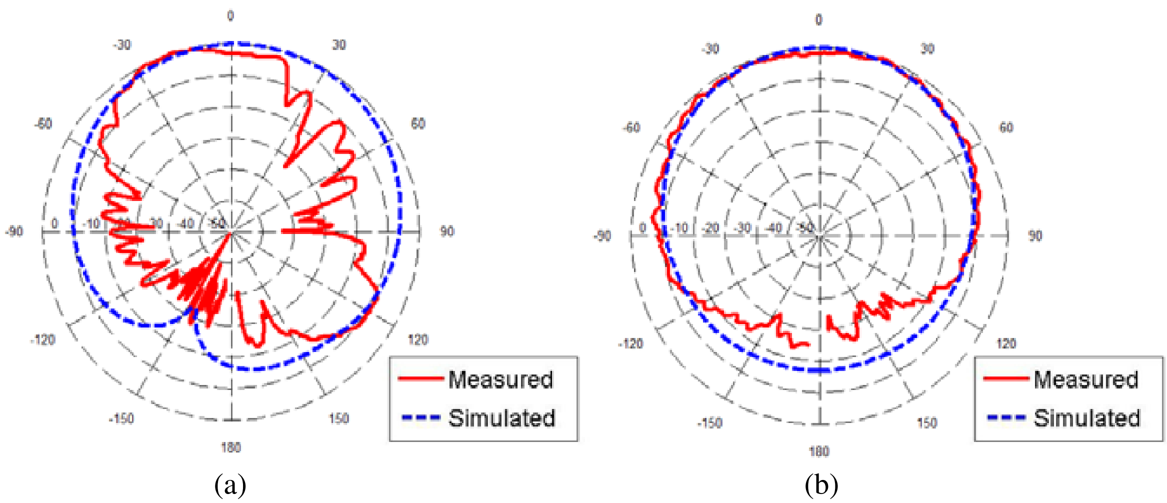


Figure 9. The measured and simulated normalized radiation pattern of the the proposed zeroth order CRLH SIW, (a) E-plane (XZ), (b) H-plane (YZ).

Table 1. A comparison between proposed antenna and recent previous published work.

Reference	Resonant Frequency	Substrate parameters	Physical Size (mm^2)	Electrical Antenna size (in terms of free space wavelength)	Antenna gain
This Work	6.1 GHz	Rogers 5880, $\varepsilon_r = 2.2$, Thickness = 0.508 mm	$14.4 \times 8\,\text{mm}^2$	$0.4\lambda_o \times 0.2\lambda_o$	−4 dB
[30]	10 GHz	FR4, $\varepsilon_r = 4.4$, Thickness = 1.57 mm	$14 \times 14\,\text{mm}^2$	$0.47\lambda_o \times 0.47\lambda_o$	5.2 dB
[31]	10 GHz 12.5 GHz	RT/Duroid 5880, $\varepsilon_r = 2.2$, Thickness = 1.575 mm	$20 \times 20\,\text{mm}^2$	$0.66\lambda_o \times 0.66\lambda_o$ $0.83\lambda_o \times 0.83\lambda_o$	2.933 dB 7.752 dB
[32]	13.4 GHz 17.9 GHz	RT/Duroid 5880, $\varepsilon_r = 2.2$, Thickness = 1.575 mm	$16.75 \times 16.75\,\text{mm}^2$	$0.75\lambda_o \times 0.75\lambda_o$ $1\lambda_o \times 1\lambda_o$	NA
[33]	5.14 GHz	RT/Duroid 5880, $\varepsilon_r = 2.2$, Thickness = 1.575 mm	$21 \times 21.8\,\text{mm}^2$	$0.36\lambda_o \times 0.37\lambda_o$	6.08 dB
[34]	5.8 GHz	RT/Duroid 5880, $\varepsilon_r = 2.2$, Thickness = 1.27 mm	$12 \times 12.1\,\text{mm}^2$	$0.232\lambda_o \times 0.234\lambda_o$	1.55 dB
[35]	1.2 GHz 1.56 GHz	Rogers 5880, $\varepsilon_r = 2.2$, Thickness = 1.508 mm	$67.5 \times 39.1\,\text{mm}^2$	$0.27\lambda_o \times 0.156\lambda_o$ $0.351\lambda_o \times 0.203\lambda_o$	3.77 dB 3.82 dB
[36]	3.67 GHz	Rogers 5880, $\varepsilon_r = 2.2$, Thickness = 1.575 mm	$28.6 \times 28.6\,\text{mm}^2$	$0.35\lambda_o \times 0.35\lambda_o$	4.46 dB

simulated one in H-plane while some differences exist between two patterns in E-plane. These can be claimed due to some imperfect measurement conditions that can not be avoided. As an example for these imperfect conditions is the divergence of the measured radiation pattern at the end of the rotary antenna mast, i.e., near the angles $\pm 180°$. Another factor is some reflections near the antenna mounting on the mast, especially when measuring the radiation pattern in the E plane.

For completeness of our work, a comparison between the proposed antenna and some recent dual-band compact size antennas [30–36] is summarized in Table 1. It is worth to mention that the antenna size comparison is based on the radiator size. The comparison can tell that the antenna size is in a range (15%–50%) smaller than compared antennas. On the other hand, the antenna gain is lower than the larger antennas by amount (5 dB–8 dB). In other words, the comparison demonstrates that the ultra-size advantage of the proposed antenna is achieved at the expense of the small antenna gain and cost.

4. CONCLUSION

A compact zeroth order SIW CRLH antenna is introduced. The antenna is designed using only one CRLH SIW unit cell. The antenna size is only $33 \times 31\ \text{mm}^2$ which represents 50% size reduction compared to conventional microstrip patch antennas. The antenna design and circuit modeling are discussed. The antenna performance parameters are extracted based on the electromagnetic full wave simulations. The radiation properties of the antenna have been confirmed using experimental measurements.

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