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Compact Bandwidth-Enhanced Center-Fed CPW Zeroth-Order Resonant Antenna Loaded by Parasitic Element

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Abstract—A low-profile bandwidth-enhanced zeroth-order resonant (ZOR) antenna based on composite right/left-handed transmission line (CRLH-TL) theory loaded by parasitic element is presented in this paper. The bandwidth and efficiency of the proposed ZOR antenna is improved simultaneously by introducing a parasitic element resonating within the CRLH-TL band-stop. The dispersive behavior of the ZOR antenna is analyzed by performing full-wave simulation using CST microwave studio and compared with the theoretical circuit model. The overall dimensions of the proposed antenna is $0.303\lambda_0 \times 0.248\lambda_0 \times 0.003\lambda_0$. The antenna has been fabricated and tested. The experimental results exhibit wide operational bandwidth of 87.1% and excellent radiation efficiency up to 95.7%. Owing to the symmetrical configuration of the proposed design the polarization purity better than −14 dB is obtained. The measured results are in very good agreement with the simulation. The compact, uni-planar and via-less configuration of the proposed antenna with reasonable polarization purity makes it desirable to be used for modern wireless communication systems such as GSM, UMTS, WiMAX, WLAN and LTE.

1. INTRODUCTION

In recent years, revolutionary metamaterials and their applications have been widely used and studied by different research groups. With ever growing demands on more compact electronic devices, antenna size miniaturization has become a very hot topic. Metamaterials and particularly composite right/left-handed (CRLH) structures are artificially engineered structures possessing unique properties such as supporting backward wave propagation and zeroth-order resonance (ZOR) [1]. Furthermore, the latter has been extensively implemented for the purpose of antenna miniaturization since its resonance frequency is independent of actual physical size of the antenna and merely determines by distributed element values of transmission line (TL). However, ZOR antennas suffer from narrow bandwidth and low radiation efficiency [2–5]. Various ZOR antennas with enhanced bandwidth and efficiency have been proposed in [6–12]. In [8] the bandwidth was improved up to 67.4% by merging first order resonance to the ZOR antenna, and an efficiency of 90.08% was achieved. Recently, in [9] a wideband asymmetrical coplanar-waveguide (CPW) antenna with modified ground plane has been proposed, which employs several resonances to increase the bandwidth. An enhanced bandwidth of 109.1% with efficiency better than 65% was achieved. Nevertheless, the deign took advantage of double-sided PCB and vias, which complicates the fabrication process. A CPW-fed ZOR antenna with enhanced bandwidth was reported in [11] in which a resonating ring was utilized. However, the gain and efficiency were dropped significantly around the split ring resonance, and large cross-polarization was observed that would make it undesirable for some applications.

In this work we propose a center-fed CPW ZOR antenna loaded with a parasitic element that can improve bandwidth and efficiency simultaneously. The antenna is initially designed to target GSM-1800

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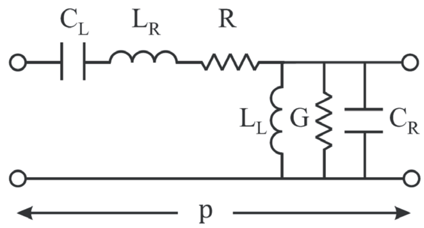


Figure 1. Equivalent circuit model of a general CRLH unit cell.

downlink frequency span (1805.2–1879.8 MHz) at the ZOR frequency. The proposed antenna has been fabricated and tested. The antenna return loss, efficiency as well as radiation pattern are presented here. The experimental results of the antenna exhibit wide operational bandwidth of 1.6 GHz corresponding to 87.1% of the fractional bandwidth and excellent radiation efficiency up to 95.7% which is in very good agreement with the simulated results.

2. ANTENNA DESIGN THEORY

The general circuit model of lossy CRLH-TL is shown in Fig. 1. Referring to the equivalent circuit model, the series capacitance and shunt inductance $C_L - L_L$ contribute to the left-handed characteristic, while shunt capacitance and series inductance $C_R - L_R$ provide the right handed property of the CRLH-TL. Moreover, resistance R and conductance G represent the conductor and substrate losses. Therefore, the characteristic impedance Z_c and bloch-propagation constant β of the periodic structure are determined by

$$Z_c = \sqrt{\frac{Z'_{series}}{Y'_{shunt}}} = \left(\frac{R + j\left(\omega L_R - \frac{1}{\omega C_L}\right)}{G + j\left(\omega C_R - \frac{1}{\omega L_L}\right)}\right)^{1/2} \tag{1}$$

$$\beta = \frac{1}{p}\cos^{-1}\left[1 + \frac{Z'_{series}Y'_{shunt}}{2}\right] \tag{2}$$

where p is the physical length of the unit cell. There are two resonant frequencies corresponding to shunt and series resonant tanks namely, ω_{sh} and ω_{se}, and they are defined as

$$\omega_{sh} = \frac{1}{\sqrt{L_L C_R}}, \quad \omega_{se} = \frac{1}{\sqrt{C_L L_R}} \tag{3}$$

It is well known that for the unbalanced unit cell, where $\omega_{sh} \neq \omega_{se}$, the resonant condition of CRLH is determined by the type of open/short-circuited termination and follows the relation:

$$\beta_n p = \frac{n\pi p}{l} = \frac{n\pi}{N} \quad (n = 0, \pm 1, \pm 2 \ldots \pm (N-1)) \tag{4}$$

where n, l and N are the mode number, total length of the resonator and number of unit cells, respectively.

Furthermore, for an open-ended lossless CRLH-TL, the input impedance can be written as

$$Z_{In,open} \overset{\beta\to 0}{\cong} Z_c \frac{1}{j\beta l} = \frac{1}{Y'_{shunt}(Np)} \tag{5}$$

Evidently, in this case the resonance is merely determined by shunt resonating tank ω_{sh}. Therefore, the quality factor of the shunt resonance under the condition that the stored magnetic energy in L_L (W_m) and stored electrical energy in C_R (W_e) to be equal [6] can be given by

$$Q = \frac{2\omega_{sh} W_m}{P_{loss}} = \frac{1/G}{\omega_{sh} L_L} = \frac{1}{G}\sqrt{\frac{C_R}{L_L}} \tag{6}$$

Since the impedance bandwidth of the antenna is inversely proportional to Q, it is found from Eq. (6) that increasing shunt inductance and/or reducing shunt capacitance can lead to a larger bandwidth. However, according to the Chu limits [13, 14] for the electrically small antennas, the maximum realizable bandwidth is restricted and follows the relation

$$FBW_{\max} = \frac{s-1}{\eta\sqrt{s}}\left(\frac{1}{k^3a^3}+\frac{1}{ka}\right)^{-1} \tag{7}$$

where k is the wavenumber of the air, a the radius of the sphere enclosing maximum dimension of the antenna and s the voltage standing wave ratio (VSWR).

In this work, we propose a novel center-fed CPW ZOR antenna loaded with a folded dipole-like parasitic element. The purpose of using the parasitic element is twofold. One is to provide an additional resonance to overcome the low bandwidth drawback of the antenna. The other is to provide a path for the trapped power on the square signal patch caused by the high impedance within the band-gap region of CRLH-TL that, in turn, effectively improves the efficiency of the proposed antenna. Thus with the proposed structure, bandwidth and efficiency can be improved simultaneously.

3. ANTENNA DESIGN

Figure 2 illustrates the configuration of the proposed antenna. The antenna is composed of dual CRLH-TL symmetrically oriented with respect to the CPW feed line and a parasitic element proximity coupled to the signal patch. Each CRLH-TL is composed of two unit cells where the left-handed parameters C_L and L_L are realized from the gap between square patches and the thin shorted meandered line, respectively. The gap between signal trace and ground plane contributes to the shunt capacitance C_R while the length of the unit-cell line determines the series inductance L_R giving rise to the right-handed property of the TL. In order to increase the bandwidth of the ZOR antenna, according to Eq. (6), the unit cell is designed in a fashion that the quality factor is initially reduced by increasing the length

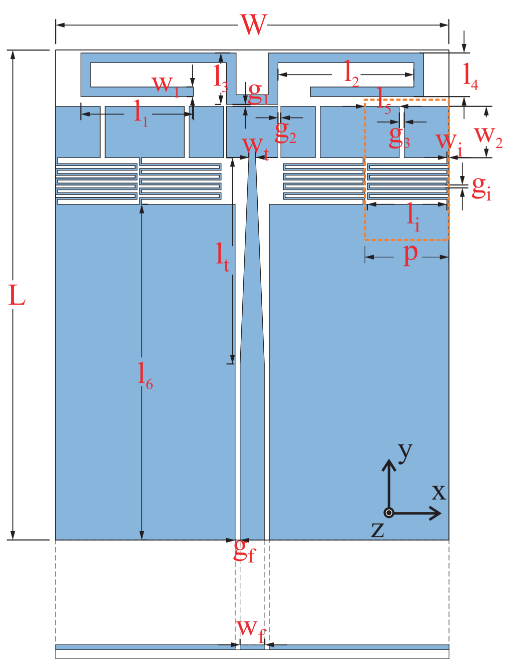


Figure 2. Configuration of the proposed bandwidth-enhanced dual CRLH-TL ZOR antenna. The optimized parameter values of the structure are: $W = 40.5$ mm, $W_1 = 1$ mm, $W_2 = 5.3$ mm, $W_t = 0.7$ mm, $W_i = 0.2$ mm, $W_f = 2.5$ mm, $g_1 = 0.2$ mm, $g_2 = 0.3$ mm, $g_3 = 0.5$ mm, $g_i = 0.3$ mm, $g_f = 0.5$ mm, $L = 50.5$ mm, $l_t = 21.25$ mm, $l_1 = 11.6$ mm, $l_2 = 14$ mm, $l_3 = 5.3$ mm, $l_4 = 4.5$ mm, $l_5 = 3.55$ mm, $l_6 = 34.6$ mm, $l_i = 8.2$ mm, $p = 8.65$ mm.

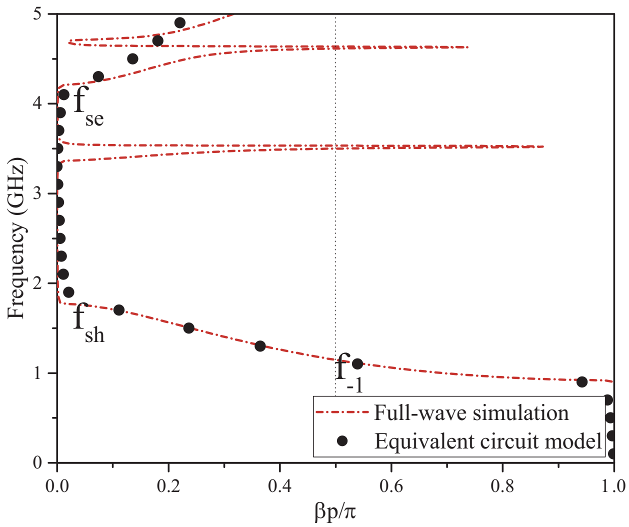


Figure 3. Dispersion diagram of the proposed CRLH unit cell. The extracted circuit parameters are: $C_L = 0.35\,\text{pF}$, $C_R = 0.52\,\text{pF}$, $L_L = 15.4\,\text{nH}$, $L_R = 4.1\,\text{nH}$, $G = 0.3\,\text{mS}$ and $R = 2\,\Omega$.

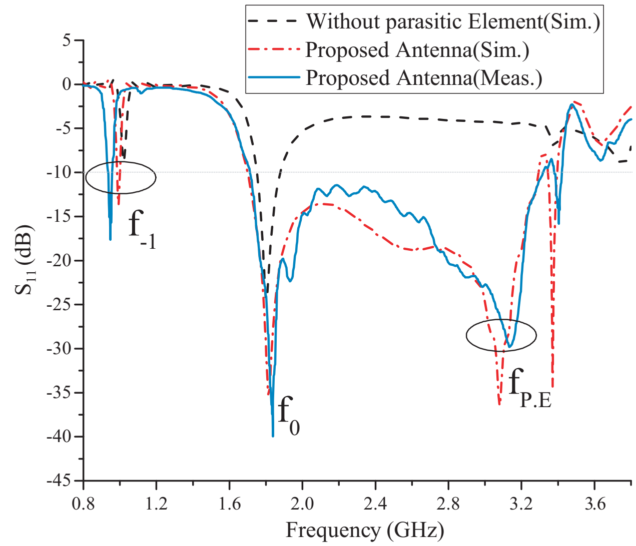


Figure 4. Simulated and measured reflection coefficients of the proposed antenna.

of the thin meandered line (L_L) and minimizing C_R by increasing the gap between the unitcell and ground plane. Furthermore, to compensate for the reduced efficiency caused by reduced quality factor, an identical CRLH-TL is added symmetrical to the CPW feeding line to form a center-fed CPW CRLH-TL. The proposed configuration allows evenly distribution of the surface current through the structure leading to a symmetric and more stable radiation pattern than its asymmetrical counterpart, thus the cross polarization is also reduced. The circuit parameter values of the CRLH-TL unit cell are obtained through the two-port parameter extraction [1] by performing full-wave simulation using CST microwave studio software. The calculated dispersion diagram from the circuit model and full-wave simulation are shown in Fig. 3 with the extracted circuit values given in the caption. According to the dispersive characteristic of CRLH-TL, the first negative order resonance (f_{-1}) and zeroth-order resonance are found to occur at 1.13 GHz and 1.815 GHz, respectively. In order to extend the bandwidth of the proposed antenna, a thin folded microstrip line as a parasitic element is loaded to the structure. The resonant length of the parasitic element is calculated by

$$\lambda_g = \sqrt{\frac{2}{\varepsilon_r + 1}}\lambda_0 \tag{8}$$

where λ_g is the guided wavelength on a low-thickness substrate, and ε_r is the relative permittivity. Using Eq. (8), the guided wavelength on a low-thickness substrate ($h = 0.508\,\text{mm}$) with $\varepsilon_r = 3.38$ at 3.08 GHz is found to be 65.8 mm that is very close to the total length of parasitic element being 67 mm.

Due to the high input impedance introduced by the loaded parasitic element, a CPW-tapered line is used to transform the impedance to the standard $50\,\Omega$ end. Fig. 4 demonstrates the effect of parasitic element on the antenna return-loss. As seen, the -10 dB bandwidth for the ZOR antenna without parasitic element is 120 MHz for the frequency range of 1.75 to 1.87 GHz corresponding to 6% of the fractional bandwidth, while it has been significantly improved to 1.6 GHz covering the frequency range of 1.7 to 3.3 GHz corresponding to the fractional bandwidth of 87%. Compared with the measurement results, an excellent agreement is observed for the ZOR frequency, but the second resonance at the higher frequencies is slightly deviated from 3.08 GHz to 3.13 GHz. This can be attributed to the length dependent resonant nature of the parasitic element and its sensitivity to the permittivity of the substrate as well as the fabrication tolerances. Notice that although the first negative-order resonance f_{-1} shows a reflection coefficient better than -10, there is no radiation from the antenna as it operates within the guiding wave region $|\beta p| > |kp|$. The measured operational bandwidth of the antenna is 1.6 GHz from

1.715 to 3.318 GHz with a dominant resonant frequency f_0 at 1.84 GHz related to the ZOR frequency. A standard 50 Ω SMA connector was included through all the simulations to take into account its effect on the overall performance of the antenna.

4. SIMULATED AND EXPERIMENTAL RESULTS

A prototype of the proposed ZOR antenna was fabricated on an RO4003C substrate with a low thickness of 0.508 mm, dielectric constant of 3.38 and loss tangent of 0.0029. The overall dimensions of the proposed antenna is $0.303\lambda_0 \times 0.248\lambda_0 \times 0.003\lambda_0$, where λ_0 is the free space wavelength at frequency of the dominant resonance ($f_0 = 1.84$ GHz). Fig. 5 shows a photograph of the fabricated prototype. The surface current distributions at 1.84 and 3.15 GHz are demonstrated in Fig. 6. As expected for the ZOR frequency, strong current exists on the meandered lines while at the second resonance (3.08 GHz) much stronger current is observed on the parasitic element and the signal patch.

Furthermore, the radiation characteristic of the proposed antenna was measured in an anechoic chamber and compared with the simulation at the resonance frequencies ($f_0 = 1.84$ GHz and $f_{P.E} =$ 3.08 GHz) demonstrated in Fig. 7. As observed in the two principal planes, E-plane (yz-plane) and H-plane (xz-plane), the radiation is approximately dipole-like. From the measured results, an isolation ratio better than 14 dB between co- and cross-polarizations is achieved, which contributes to symmetrical configuration of the antenna. The measured gain and radiation efficiency of the antenna are presented in Fig. 8. The efficiency was evaluated using the measurement system as of the ratio between the received radiated power of the antenna under the test to the power transmitted from the standard horn antenna.

The values of the gain are 2.1 and 3.35 dBi at the resonance frequencies 1.84 GHz and 3.08 GHz, respectively. The values of the gain vary from 1.85 to 3.35 dBi as the frequency goes up. An efficiency

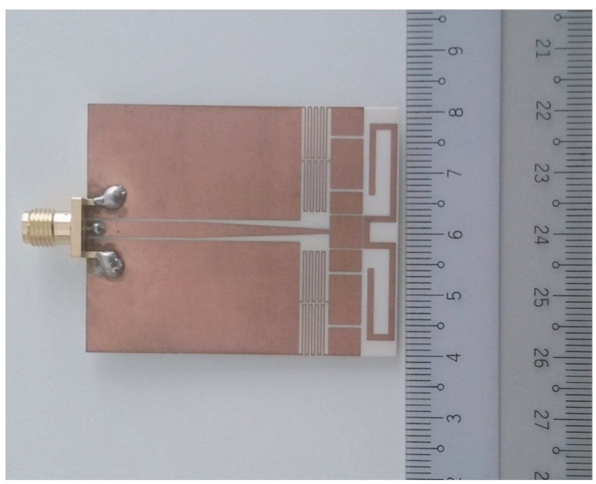
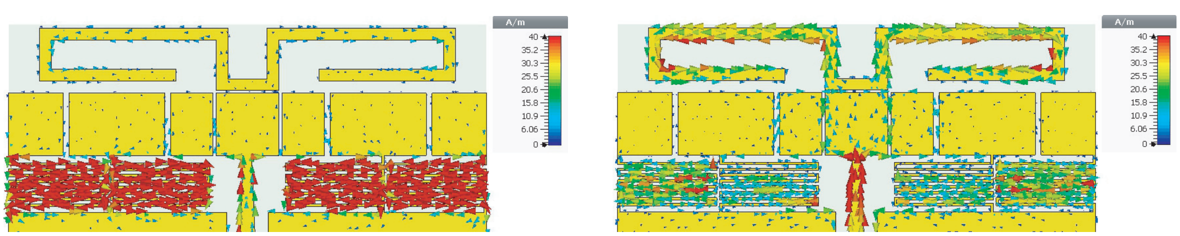


Figure 5. Photograph of the fabricated antenna.



(a) (b)

Figure 6. Simulation results of surface current distribution at (a) $f = 1.84$ GHz and (b) $f = 3.1$ GHz obtained from CST software.

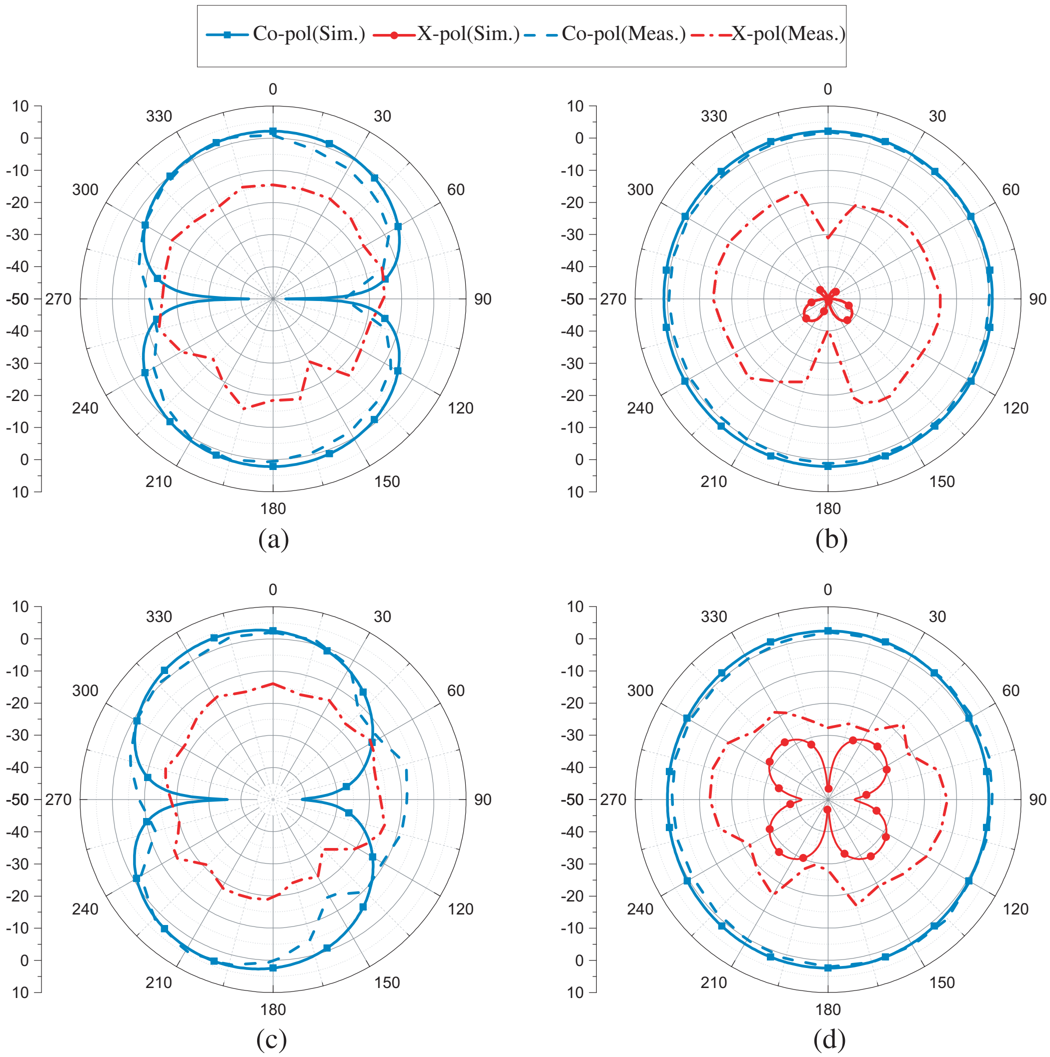


Figure 7. Simulated and measured radiation patterns of the proposed antenna: (a) yz-plane (E-plane) at 1.84 GHz; (b) xz-plane (H-plane) at 1.84 GHz; (c) yz-plane (E-plane) at 3.08 GHz; and (d) xz-plane (H-plane) at 3.08 GHz.

Table 1. Comparison results of the proposed and reference antennas.

	This work	[7]	[8]	[9]
f (GHz)	**1.84**	2.16	1.99	3.8
Area ($\lambda_0{}^2$)	0.30×0.24	0.14×0.22	0.33×0.17	0.41×0.25
B.W. (%)	**87.1**	15.1	67.4	109.1
Gain (dBi)	**3.35**	1.62	2.77	3.37
η (%)	**95.7**	72	90.08	98.01
Via process	**No**	No	No	Yes
Fabrication type	**Single-Sided**	Single-Sided	Double-Sided	Double-Sided

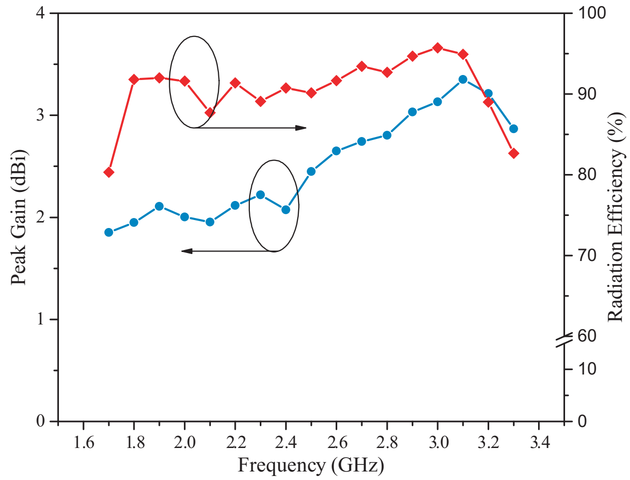


Figure 8. Measured gain and radiation efficiency of the proposed antenna.

better than 80% is achieved for the entire band and reaches as high as 95.7% at 3 GHz. The overall performance of the proposed ZOR antenna is compared with the recently reported metamaterial antennas and tabulated in Table 1. It is observed that the proposed ZOR antenna exhibits reasonable bandwidth and efficiency enhancement while fabrication simplicity and relatively compact size are maintained.

5. CONCLUSION

In this paper, a wideband and efficiency improved ZOR antenna based on CRLH theory is presented. To further increase the bandwidth a proximity coupled folded dipole-like parasitic element is loaded to the structure. Following that, the merged bandwidth of 1.6 GHz corresponding to 87.1% is obtained. An efficiency better than 80% is achieved for the entire band with the highest efficiency of 95.7% at 3 GHz. Owing to the symmetrical configuration of the proposed antenna, a polarization purity better than −14 dBi in either principal planes is attained. The compact, uni-planar and via-less configuration of the proposed antenna with wide operational bandwidth and reasonable efficiency makes it desirable to be used for modern wireless communication systems such as GSM, UMTS, WiMAX, WLAN and LTE.

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