Asymmetric Coplanar Waveguide (ACPW) Zeroth-Order Resonant (ZOR) Antenna With High Efficiency and Bandwidth Enhancement

Po-Wei Chen and Fu-Chiarng Chen

***Abstract*—A novel low-profile zeroth-order (ZOR) antenna is presented. The feature of ZOR based on periodic structures is employed to reduce the antenna size, while these antennas generally suffer from narrow bandwidth. A single-layer asymmetric coplanar waveguide (ACPW) structure is proposed to realize a bandwidth-extended ZOR antenna, where the antenna bandwidth is characterized by an equivalent circuit model. The ACPW structure not only provides the design freedom, but also overcomes the design constraint of the traditional CPW. The ACPW ZOR antenna is verified by both full-wave simulations and experiments. As an advantage of the proposed method, the size of antenna is reduced, and the resonant frequency of zeroth-order mode is 1.94 GHz with radiation efficiency of 85%, measured 10-dB fractional bandwidth up to 10.3%, and omnidirectional peak gain of 2.3 dBi.**

***Index Terms*—Composite right/left-handed transmission line (CRLH-TL), coplanar waveguide (CPW), zeroth-order resonant (ZOR) antenna.**

I. INTRODUCTION

IN RECENT years, metamaterials (MTMs) have been widely used for microwave circuits and antenna designs due to their unique electromagnetic properties, such as anti-parallel phase and group velocities and zero propagation constant at a certain frequency [1]–[4]. One of the novel applications is the zeroth-order resonant (ZOR) antenna, which is based on composite right/left-handed (CRLH) transmission lines (TLs) periodic structures. The ZOR antenna operates at resonant frequency that has zero propagation constant ($\beta = 0, \omega \neq 0$)—in other words, it supports infinite wavelength at a finite nonzero frequency. As a result, the ZOR antenna is independent of the physical length, so that the size of the structure could be arbitrary small and more compact than the conventional half-wavelength antennas [5]–[8]. However, these antennas suffer from the narrow bandwidth such that it is hard to be applied to wireless communication systems.

There have been a number of studies that have investigated how to enhance the bandwidth of ZOR antennas [9]–[12]. In this letter, we propose a new type of single-layer ZOR antenna that is based on asymmetric coplanar waveguide (ACPW) for a further bandwidth extension. This ZOR antenna extends the bandwidth up to 10.3% while keeping high radiation efficiency at 85%. According to [11], the bandwidth of the ZOR antenna depends on the Q-factor of the shunt resonator, i.e., the shunt inductance and capacitance of the CRLH-TL. As a result, modulating the shunt reactance can increase the bandwidth of ZOR antenna. Our proposed ACPW ZOR antenna keeps the design freedom of CPW and also utilizes the ACPW ground to evade the design challenge about the large shunt inductance at CPW. As an advantage of the proposed method, it is easy to manufacture a low-profile omnidirectional ACPW ZOR antenna with good radiation efficiency, good bandwidth, and without any lumped components to achieve good antenna gain.

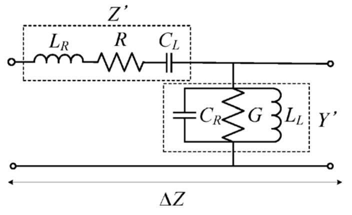

Fig. 1. Equivalent circuit model for the CRLH-TL unit cell.

II. ANTENNA THEORY AND DESIGN

A. Theoretical Background

An infinitesimal circuit model of general CRLH-TL model is shown in Fig. 1, which consists of right-handed (RH) series inductance $L_{\rm R}$ and shunt capacitance $C_{\rm R}$ and left-handed (LH) series capacitance $C_{\rm L}$ and shunt inductance $L_{\rm L}$. The dispersion diagram can be obtained by applying Bloch–Floquet theorem to the unit cell of periodic structures [8]

$$\beta p = \cos^{-1}\left[1 - \frac{1}{2}\left(\frac{\omega^2}{\omega_{\rm R}^2} + \frac{\omega_{\rm L}^2}{\omega^2} - \frac{\omega_{\rm L}^2}{\omega_{\rm se}^2} - \frac{\omega_{\rm L}^2}{\omega_{\rm sh}^2}\right)\right] \quad (1)$$

where $\omega_{\rm L} = 1/\sqrt{C_{\rm L}L_{\rm L}}, \omega_{\rm R} = 1/\sqrt{C_{\rm R}L_{\rm R}}, \omega_{\rm sh} = 1/\sqrt{C_{\rm R}L_{\rm L}}$, and $\omega_{\rm se} = 1/\sqrt{C_{\rm L}L_{\rm R}}$. β is the propagation constant of Bloch waves, and p is the physical length of the unit cell. The resonance of the CRLH-TL for resonant modes n can be obtained by the following condition [6]:

$$\beta_n p = \frac{n\pi p}{l} = \frac{n\pi}{N}, \qquad n = (0, \pm1, \pm2, \ldots, \pm(N-1)) \quad (2)$$

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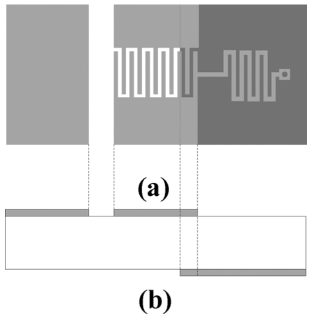

Fig. 2. Configuration of the proposed CRLH-TL unit-cell design based on ACPW structure. (a) Top view. (b) Side view.

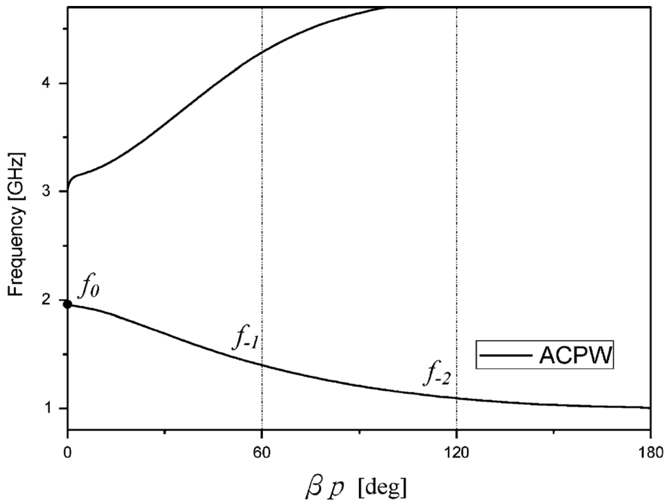

Fig. 3. Dispersion diagram of the proposed CRLH-TL-based ACPW unit cell.

where N and l are the number of unit cells and total physical length of the resonator. When $n = 0$, the zeroth-order resonant frequencies ω_{se} and ω_{sh}, which are independent of physical length of resonators, can be excited with propagation constant $\beta = 0$.

The geometry of the proposed unit cell of the artificial CRLH-TL line is shown in Fig. 2, where the LH characteristic of CRLH-TL is induced by a series capacitance of the interdigital capacitance and a shunt inductance of the meander line shorted to ground through the via. Fig. 3 presents the dispersion diagram for the unit cell, which is based on (1). The values of the circuit parameters $(C_{\mathrm{R}}, C_{\mathrm{L}}, L_{\mathrm{R}}, L_{\mathrm{L}})$ are extracted from the S-parameter [2]. The detailed physical dimensions of the proposed unit cell are shown in Fig. 4.

For the open-ended boundary condition of the zeroth-order resonator, the resonator frequency depends on the shunt LC resonant tank given by [13]

$$\omega_{\mathrm{ZOR}}^{\mathrm{open}} = \omega_{\mathrm{sh}} = 1/\sqrt{L_{\mathrm{L}} C_{\mathrm{R}}}. \tag{3}$$

It indicates that the zeroth-order resonant frequency is independent of the total physical length of resonator but determined only by the shunt inductance and capacitance. Therefore, a small antenna based on ZOR can be implemented. However, these antennas suffer from narrow bandwidth compared to the conventional half-wavelength resonant antennas generally.

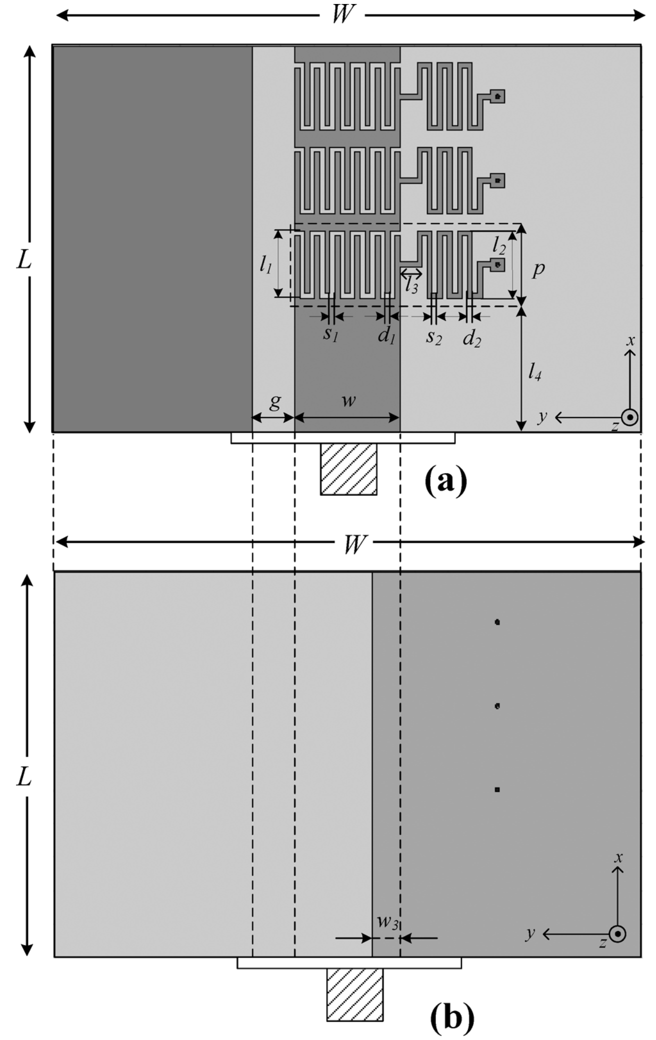

Fig. 4. Geometric of the proposed ACPW ZOR antenna. (a) Top. (b) Bottom. ($W = 50$ mm, $L = 28$ mm, $w = 6.3$ mm, $g = 3.5$ mm, $l_1 = 4$ mm, $l_2 = 4$ mm, $l_3 = 2$ mm, $l_4 = 12.5$ mm, $p = 5$ mm, $d_1 = d_2 = 0.3$ mm, $s_1 = s_2 = 0.3$ mm, $w_3 = 0.6$ mm, $\mathrm{Rvia} = 0.12$ mm).

The fractional bandwidth of ZOR is given by [4], [11]

$$\mathrm{BW} = (Q_0^{\mathrm{open}}) = G\sqrt{\frac{L_{\mathrm{L}}}{C_{\mathrm{R}}}}. \tag{4}$$

According to (4), the bandwidth of the open-ended ZOR antenna depends on the loss G and shunt element of CRLH-TL equivalent circuit model in the shunt tank. Therefore, we can increase the bandwidth by introducing a high shunt inductance and a small shunt capacitance using our proposed ACPW structure.

Generally, ZOR antenna based on microstrip line (MSL) has narrow bandwidth by small L_{L}, which depends on the length and the cross section of the shorting via. In addition, MSL has large C_{R} by the capacitance of the upper metallic strip and grounded slab, which is confined by the thickness of the substrate. Therefore, the MSL ZOR antennas encounter narrow bandwidth, which can be overcame by our proposed topology.

B. Antenna Design

In this letter, we proposed the bandwidth enhancement ACPW ZOR antenna by increasing the L_{L} and decreasing C_{R}

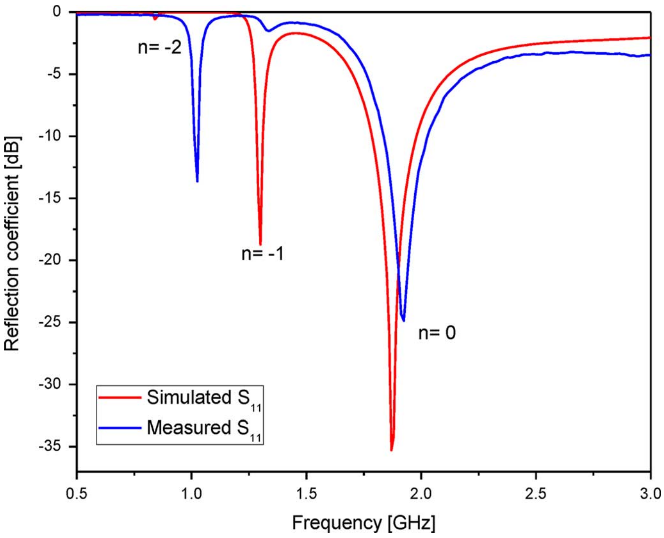

Fig. 5. Simulated and measured reflection coefficients of the asymmetric CPW ZOR antenna.

according to (4). Fig. 4 illustrates the proposed ACPW-based open-ended ZOR antenna that cascades three unit cells periodically. We put one of the ground planes of CPW to the bottom layer of the substrate to form the ACPW structure and maintain the unit cell printed on the top layer.

To increase the bandwidth, by applying (4), first we increase the L_{L} of the proposed unit cell. Since it is difficult to fulfill compact meander lines on the conventional CPW, we take advantage of one side of ACPW to realize large L_{L} such that it is an MSL-like structure at this side, while the ground plane is located at the bottom. Therefore ,we can design compact meander lines in the ACPW while maintaining the feature of CPW simultaneously. In addition, C_{R} is obtained from the distance between the signal line and the both sides of the ground planes of the CPW. Distinct from MSL, which has large C_{R} due to the fixed thickness of substrate, maintaining a CPW-like structure on the other side provides design freedom such that the small C_{R} can be controlled by the dimension of the gap g. Moreover, by adjusting the overlapping area of the signal line and the bottom ground plane (W_3) appropriately, small C_{R} is obtained and also easy for impedance matching.

III. EXPERIMENTAL RESULTS

It is fabricated on a single-layer substrate of Rogers RT/Duroid 5880 with relative dielectric constant 2.2, thickness 1.57 mm, and $\tan\delta = 0.0009$, and the physical dimension is given in Fig. 4. The physical size of the unit cell is $5 \times 13.5 \times 1.57$ mm^3 $(0.032\lambda_0 \times 0.087\lambda_0 \times 0.01\lambda_0)$, and the overall area of the radiation aperture is $28 \times 50 \times 1.57$ mm^3, $(0.182\lambda_0 \times 0.323\lambda_0 \times 0.01\lambda_0$, where λ_0 is the free-space wavelength at its zeroth-order 1.94 GHz measured from S-parameter). Additional length l_4 of the antenna is added appropriately to match the port to 50 Ω. The C_{R} and L_{L} are 0.59 pF and 10.83 nH by parameter extraction. Fig. 5 shows the simulation and the measurement reflection coefficients (S_{11}) of the proposed antenna and where the measured resonant frequency of zeroth-order mode is 1.94 GHz, and the others two negative modes are also obtained. The antenna was simulated using the ANSOFT High Frequency Structure Simulator (HFSS) and measured by an Agilent E8364B vector network analyzer. The measured return loss (S_{11}) is observed to be -25 dB at 1.94 GHz. In addition, the measured return loss bandwidth (-10 dB) is about 200 MHz (1.83–2.03 GHz), corresponding to approximately 10.3% fractional bandwidth, which is increased compared to the previous ZOR antennas [8]–[11].

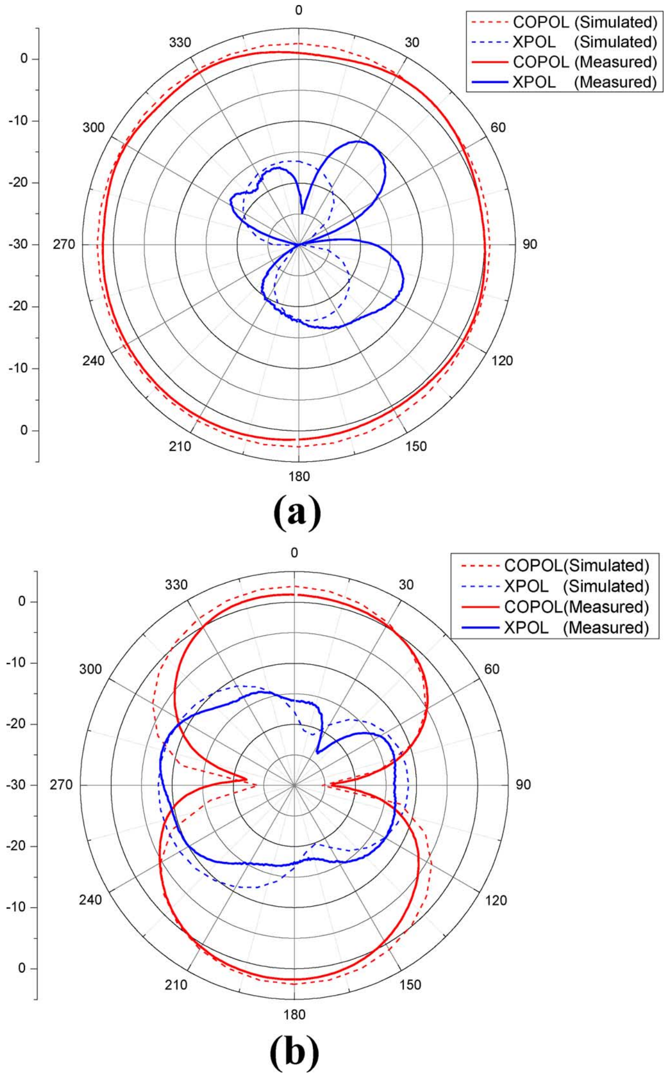

Fig. 6. Simulated and measured total radiation patterns at 1.94 GHz: (a) in xz-plane (H-plane) and (b) in yz-plane (E-plane).

The simulated and measured radiation patterns on the xz-plane and yz-plane of the fabricated antenna at zeroth-order resonant frequency 1.94 GHz are plotted in Fig. 6(a) and (b). Good agreement between the simulation and measurement results is obtained. The measured maximum gain of 2.3 dB is nearly the same as the simulated gain of 2.5 dB where the radiation pattern in xz-plane has a nearly omnidirectional characteristic. The differences between the simulation and measurement results are due to the fabrication tolerance. The gain of the cross polarization is less than the copolarization by 20–30 dB in xz-plane as shown in Fig. 6(a), and the measured radiation efficiency is 85% at 1.94 GHz. The measured peak

TABLE I

ANTENNA MEASUREMENT SUMMARY AND COMPARISON RESULTS OF PROPOSED AND REFERENCE ANTENNAS

	This Work	[8]	[9]	[10]	[11]
Frequency (GHz)	1.94	3.38	1.77	1.73	2.03
Unit Size (λ_0)	0.032 x 0.087 x 0.01	0.16 x 0.08 x 0.017	0.09 x 0.077 x 0.036	0.1 x 0.1 x 0.015	0.053 x 0.097 x 0.011
Bandwidth (%)	10.3	~0.1	6.8	8	6.8
Gain (dBi)	2.3	0.87	0.95	1	1.35
Efficiency (%)	85	70	54	-	62
Layer	Single	Single	Multi	Multi	Single

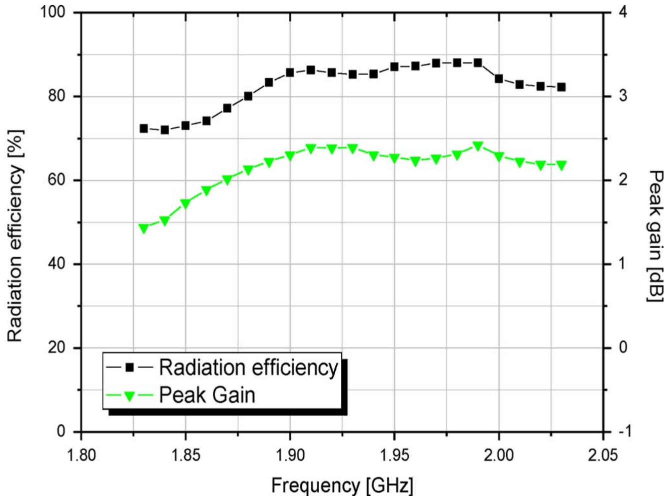

Fig. 7. Measured antenna peak gain and radiation efficiency.

gain and the radiation efficiency according to the operation band are presented in Fig. 7. The antenna gain varies from about 1.4 to 2.4 dBi, and the radiation efficiency varies from 72% to 88% at the band of 1.83–2.03 GHz.

The overall antenna performances of our proposed antenna compared to the previously reported ZOR antennas [8]–[11] are listed in Table I. Our proposed single-layer ACPW ZOR antenna achieves a significant enhancement in the antenna bandwidth, efficiency, and gain.

IV. CONCLUSION

In this letter, a novel antenna with a compact size and low profile is demonstrated and fabricated. The zeroth-order resonant characteristics were analyzed using dispersion relation based on CRLH-TL theory and the full-wave simulation. Furthermore, the bandwidth has been extended by realizing a high shunt inductance and small shunt capacitance based on the proposed design of a single-layer ACPW structure. It shows a good agreement in the simulation and measurement results. In addition, the ACPW ZOR antenna prototype raises the bandwidth to 10.3%, radiation efficiency up to 85% and peak gain of 2.3 dBi at the operating frequency of 1.94 GHz. Moreover, the measured data show that it has good features at 1.83–2.03 GHz, which is suitable for broadband wireless communications.

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