Compact and Bandwidth-Enhanced Asymmetric Coplanar Waveguide (ACPW) Antenna Using CRLH-TL and Modified Ground Plane

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***Abstract*—A novel compact and broadband asymmetric coplanar wave guide (ACPW) antenna is presented. A method to extend the bandwidth of a metamaterial-inspired antenna based on a composite right/left-handed transmission line (CRLH-TL) and a modified ground plane is proposed. The ACPW antenna has a broadband characteristic by placing the zeroth-order resonance (ZOR), first-positive-order resonance (FPOR) of short-ended CRLH-TL and the modified ground plane's two resonances, which are half and one lambda resonances, at all different frequencies with proper frequency intervals. The prototype of the proposed antenna has been implemented and measured. The measured −10-dB fractional bandwidth is 109.1% (from 2.69 to 9.15 GHz) with high efficiency of over 65% and a low profile of $0.32\lambda_0 \times 0.19\lambda_0$ (where λ_0 is the free-space wavelength at the first resonant frequency).**

***Index Terms*—Asymmetric coplanar waveguide (ACPW), bandwidth enhancement, compact antenna, composite right/left-handed transmission line (CRLH-TL).**

I. Introduction

In THE present decade, many metamaterial (MTM)-based antennas have been widely studied. Most MTM-based antennas are constructed using composite right/left-handed (CRLH), epsilon-negative (ENG), and mu-negative (MNG) transmission lines [1]–[4]. The fundamental principle of those transmission lines is that they control the phase velocity of the input wave to resonate at desired frequency. One of their common special dispersion characteristics is zeroth-order resonance (ZOR), which has an infinite wavelength not at a dc frequency ($\beta = 0, \omega \neq 0$), so that the size of the antenna structure could be small and more compact than conventional half-wavelength antennas.

However, these antennas have shortcomings related to their narrow bandwidth. Recently, various solutions to extend the bandwidth of MTM-based antennas have been proposed [5]–[10]. The solutions are categorized according to two types. The first method is analyzing the Q-factor of the zeroth-order and/or first-order resonances and lowering it by controlling the component of transmission lines. In [6], a novel low-profile ZOR antenna based on the asymmetric coplanar waveguide (ACPW) was proposed, which extends the bandwidth up to 10.3% and has radiation efficiency of 85%. A compact ZOR antenna at 2.16 GHz, which controls CRLH-TL's series element, was reported in [7]. It has a bandwidth (−10 dB) and radiation efficiency of 15.1% and 72%, respectively. The second method to extend MTM antennas' bandwidth is placing several resonances at different frequencies with proper intervals. In [8], a method to extend the bandwidth by putting the ZOR and first-negative-order resonance (FNOR) frequencies closely was proposed and obtained a bandwidth of 20.3%. In [9], an antenna consists of CRLH-TL and resonant ring that resonate at different frequencies. Its extended bandwidth and measured radiation efficiency are up to 40.2% and 92.3%, respectively. Recently, a novel ENG antenna, which was used the first and second methods, was presented in [10]. The ENG antenna was designed by considering the low Q-factor of both ZOR and first-positive-order resonance (FPOR) of the ENG-TL and obtained an extended bandwidth up to 67.4%.

In this letter, a novel structure of ACPW antenna using a CRLH-TL and a modified ground structure is proposed. We present the wide bandwidth and high-efficiency performance. The details of the proposed antenna design and experimental results are presented and discussed.

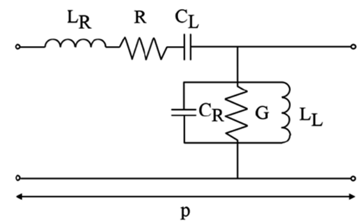

Fig. 1. Equivalent circuit model of a CRLH-TL unit cell.

II. Proposed Antenna Design

A. CRLH-TL Theory

The fundamental CRLH-TL unit cell can be expressed by an equivalent circuit model, as shown in Fig. 1. It can be represented by series capacitance (C_{L}) and shunt inductance (L_{L}) as well as series inductance (L_{R}) and shunt capacitance (C_{R}) [11]. The dispersion relation of the line can be computed by applying the Bloch–Floquet theorem to the unit cell of periodic structures [12]

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

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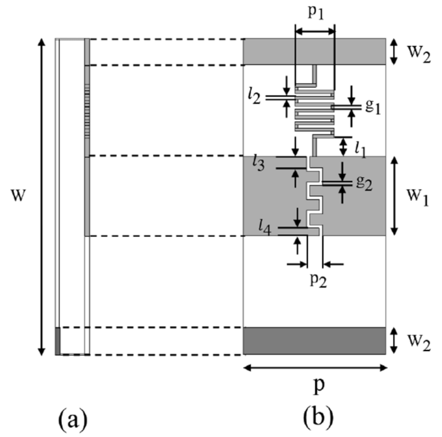

Fig. 2. Configuration of the proposed CRLH-TL unit cell design. (a) Side view. (b) Top view. ($p = 9$ mm, $W = 20$ mm, $W_1 = 5$ mm, $W_2 = 1.7$ mm, $l_1 = 1.2$ mm, $l_2 = 0.2$ mm, $l_3 = 0.7$ mm, $l_4 = 0.5$ mm, $g_1 = 0.2$ mm, $g_2 = 0.2$ mm, $p_1 = 2.5$ mm, $p_2 = 1$ mm.)

where

$$\omega_{\mathrm{L}} = 1/\sqrt{C_{\mathrm{L}}L_{\mathrm{L}}} \quad \omega_{\mathrm{R}} = 1/\sqrt{C_{\mathrm{R}}L_{\mathrm{R}}}$$
$$\omega_{\mathrm{sh}} = 1/\sqrt{C_{\mathrm{R}}L_{\mathrm{L}}} \quad \omega_{\mathrm{se}} = 1/\sqrt{C_{\mathrm{L}}L_{\mathrm{R}}}.$$

β is the propagation constant of Bloch waves, and p is the physical length of the unit cell. The resonance condition of the CRLH-TL is shown as follows [12]:

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

where n, N, and l are the resonance mode, number of unit cells, and the total length of the resonator, respectively. When $n = 0$, the wavelength becomes infinite and the resonance frequency of the ZOR mode becomes independent of the size of the antenna. In this letter, we propose a short-ended CRLH-TL, so the ZOR frequency depends on the series LCresonant elements. FPOR and FNOR have the same current distribution, and they are determined by not only the series elements, but also the shunt elements.

B. ACPW CRLH-TL and Antenna Design

The configuration of the proposed unit cell of the CRLH-TL is shown in Fig. 2. The series parameters of the proposed ACPW-type structure are obtained from the series capacitance of the interdigital capacitance (IDC) and the series inductance of the center signal patch. Shunt parameters are constructed from the shunt capacitance between the center patch and side ground planes as well as the shunt inductance of the shorted meander lines. The dispersion diagram of the unit cell is presented in Fig. 3. In addition, the dispersion diagram of the unit cell was calculated by the simulated S-parameters using CST where the periodic boundary condition was applied on both sides of the unit cell. According to the dispersion diagram, the ZOR, FNOR, and FPOR frequencies are 2.4, 1.591, and 5.67 GHz, respectively.

Fig. 4 illustrates the proposed wideband MTM antenna that cascades two unit cells periodically. The end of the CRLH-TL is connected to the upper and bottom ground planes by five via holes. The bottom ground plane resonates at half and one wavelength of certain frequencies. To obtain wide bandwidth, ZOR, FPOR, and two resonances of bottom ground plane are placed at all different frequencies with proper frequency intervals. Specifically, the length of the bottom ground plane

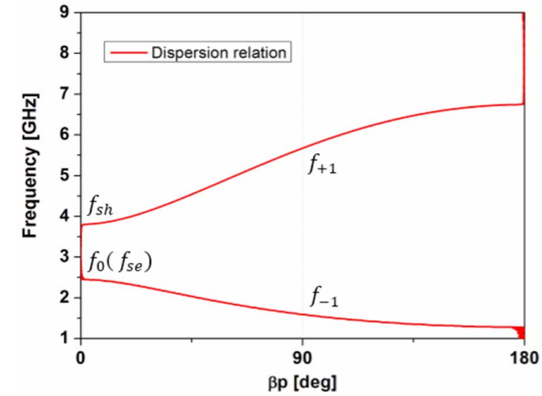

Fig. 3. Dispersion diagram of the proposed CRLH-TL unit cell.

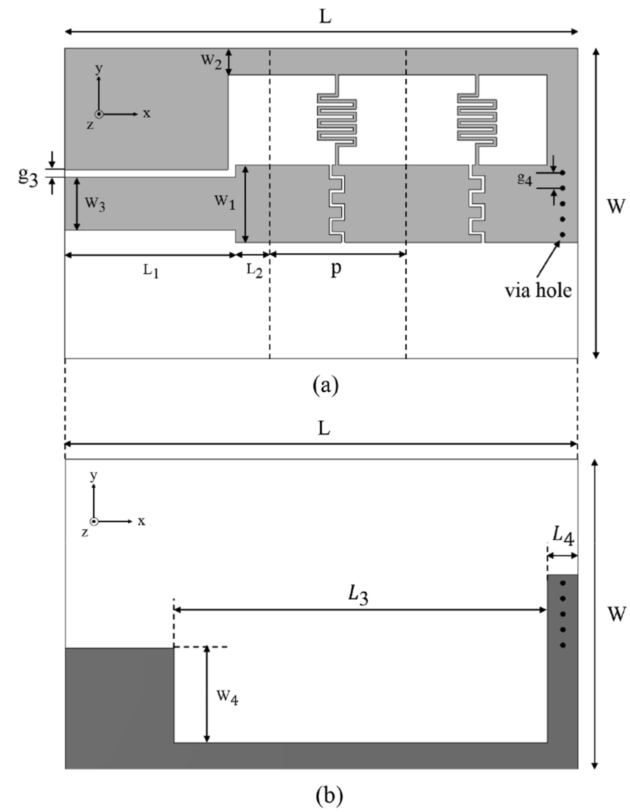

Fig. 4. Configuration of the proposed ACPW wideband metamaterial-inspired antenna that cascades two unit cells. (a) Top view. (b) Bottom view. ($L = 33$ mm, $L_1 = 11$ mm, $L_2 = 2$ mm, $L_3 = 24$ mm, $L_4 = 2$ mm, $W_3 = 3.4$ mm, $W_4 = 6$ mm, $g_3 = 0.5$ mm, $g_4 = 1$ mm, $p = 9$ mm.)

(L_3) is adjusted in order that the half-wavelength resonance frequency is located between the ZOR and FPOR and the one wavelength resonance frequency is located at higher frequency than that of the FPOR. In Fig. 3, between the series and shunt resonance frequencies ($f_{\mathrm{se}} = \omega_{\mathrm{se}}/2\pi$, $f_{\mathrm{sh}} = \omega_{\mathrm{sh}}/2\pi$) of CRLH-TL (2.4–3.8 GHz), there is a stopband. However, in the proposed CRLH unit cell, the attenuation constant (α) is not significant, and the length of the two cascaded CRLH unit cells is short. Therefore, the antenna can operate continually.

III. Simulated and Experimental Results of the Proposed ACPW Antenna

The proposed ACPW antenna was simulated and experimentally developed on the Rogers RT/Duroid 5880 substrate with a thickness of 1.57 mm, dielectric constant of 2.2, and dielectric

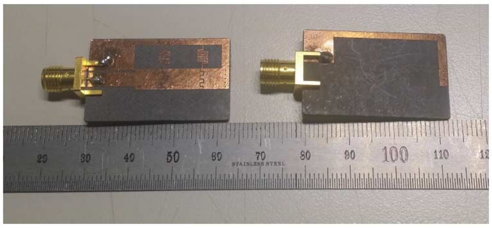

Fig. 5. Photograph of the top and bottom views of the fabricated ACPW antenna.

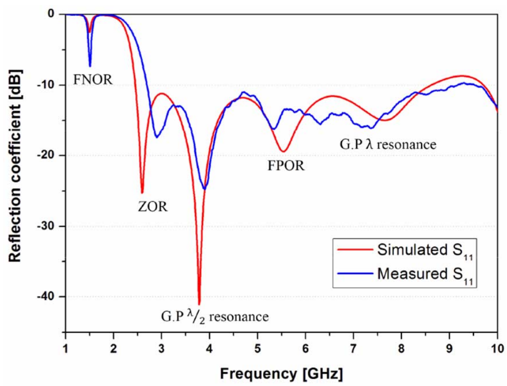

Fig. 6. Simulated and measured reflection coefficients of the ACPW antenna.

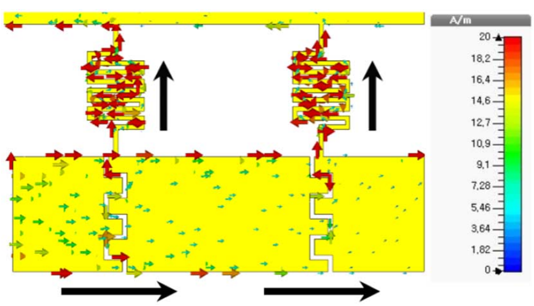

Fig. 7. Current distribution plot of the CRLH unit cells for $f = 2.59$ GHz (ZOR).

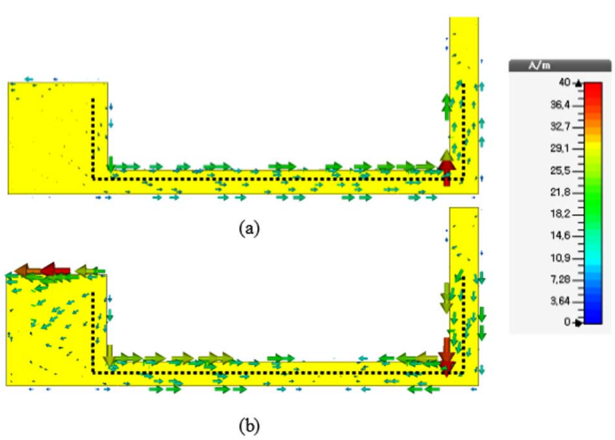

Fig. 8. Current density plot on the bottom ground plane calculated by CST for (a) $f = 3.8$ GHz and (b) $f = 7.6$ GHz.

loss tangent of 0.001. All the parameters are shown in Fig. 4, and their values are given in the caption. The electrical size of the unit cell is $0.087\lambda_0 \times 0.19\lambda_0 \times 0.015\lambda_0$ ($9 \times 20 \times 1.57$ mm^3), and the overall size of the antenna is $0.32\lambda_0 \times 0.19\lambda_0 \times 0.015\lambda_0$ ($33 \times 20 \times 1.57$ mm^3), where λ_0 is the free-space wavelength of the first resonance frequency $f_{\mathrm{ZOR}} = 2.9$ GHz. A fabricated prototype for the proposed antenna is shown in Fig. 5. The simulated and measured reflection coefficients are also plotted in Fig. 6 and are in good agreement. The measured -10-dB bandwidth is 6.46 GHz (2.69–9.15 GHz), corresponding to a 109.1% fractional bandwidth. Three resonant frequencies at $f_{\mathrm{FNOR}} = 1.5$ GHz, $f_{\mathrm{ZOR}} = 2.59$ GHz, and $f_{\mathrm{FPOR}} = 5.52$ GHz corresponding to the FNOR, ZOR, and FPOR, respectively, are observed. These resonant frequencies can be explained from the dispersion diagram in Fig. 3. A slight frequency shift for these modes may be attributed to the parasitic between CRLH-TL unit cells and the other antenna section.

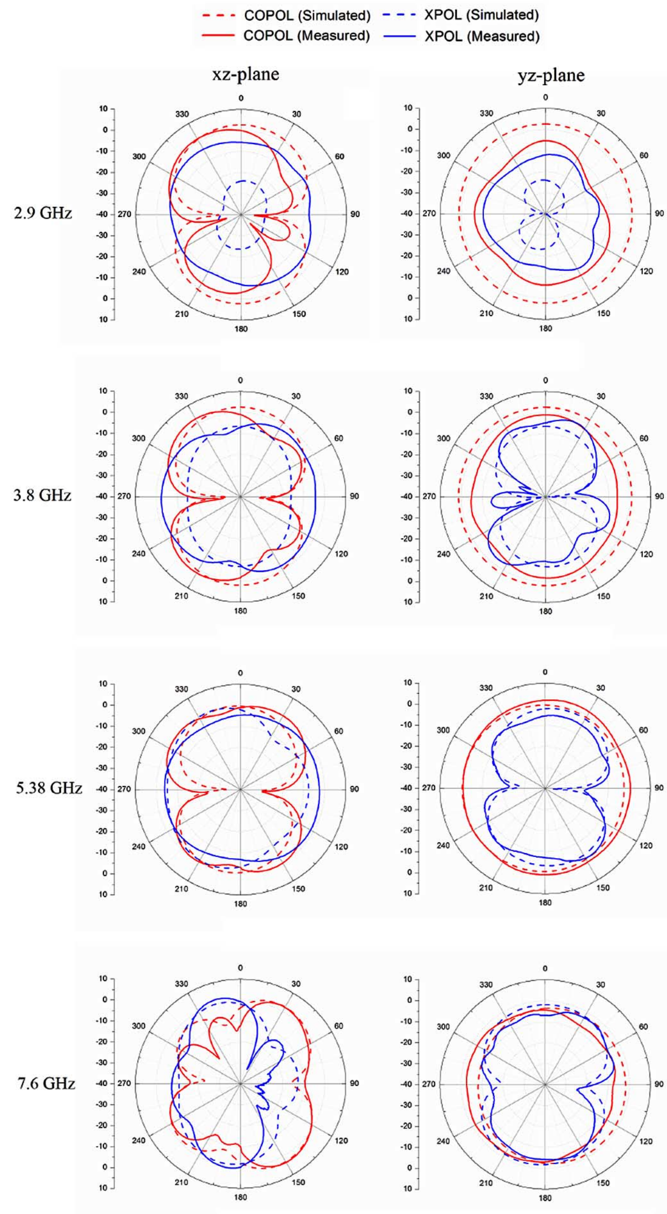

Fig. 9. Simulated and measured radiation patterns.

In Fig. 7, the current distributions of two CRLH unit cells are in phase at ZOR frequency of 2.59 GHz, as expected. The frequency shift of ZOR between the simulated and measured may be attributed to the susceptibility of the antenna fabrication tolerance about the fine interdigital gap and meander line.

TABLE I
COMPARISON OF THE EXPERIMENTAL RESULTS FOR THE PROPOSED AND REFERENCE ANTENNAS

	This work				[6]	[7]	[8]		[9]		[10]	
Resonant Frequency (GHz)	2.9 (ZOR)	3.8 ($\lambda/2$)	5.38 (FPOR)	7.6 (λ)	1.94 (ZOR)	2.16 (ZOR)	1.99 (FNOR)	2.24 (ZOR)	1.73 (ZOR)	2.42 (λ)	1.99 (ZOR)	3.0 (FPOR)
Total Size (λ_0)	0.32 × 0.19				0.182 × 0.323	0.14 × 0.22	0.267 × 0.67		0.288 × 0.173		0.173 × 0.332	
Bandwidth (%)	109.1				10.3	15.1	20.3		40.2		67.4	
Efficiency (%)	86.2	94.64	86.51	86.12	85	72	66.6	56.4	80	88	90.08	86.12
Peak Gain (dBi)	2.59	3.23	3.06	3.37	2.3	1.62	3.31	2.96	3.4	5.4	2.21	2.77

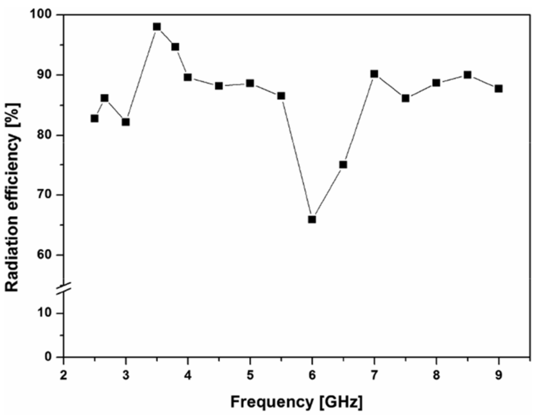

Fig. 10. Measured radiation efficiency.

The other two resonances are explained from the current distribution on the bottom ground plane shown in Fig. 8. In Fig. 8(a), the current flows on the bottom ground plane in a "U-shape" (dashed line) and resonates when the length of the U-shape is a half-wavelength at $f = 3.8$ GHz. Similarly, the current on the bottom ground plane resonates when the length of the U-shape is one wavelength at $f = 7.6$ GHz (twice the frequency of the former case), as shown in Fig. 8(b).

The radiation characteristics of the proposed antenna were measured. The simulated and experimental radiation patterns in the xz-plane (E-plane) and yz-plane (H-plane) at the resonance frequencies are shown in Fig. 9. The measured radiations show that the cross-polarization levels of the proposed antennas are higher than the simulated ones at $f = 2.9$ GHz (ZOR). These differences are due to the fabrication error resulting from the fine interdigital gap and meander lines and the measurement error from the much smaller size of the antenna compared to that of the RF cable in the test environment. The other resonance results are in good agreement. The measured peak gains of 2.59, 3.23, 3.06, and 3.37 dBi are obtained at each resonant frequency (2.9, 3.8, 5.38, and 7.6 GHz).

Fig. 10 shows the measured radiation efficiency. The radiation efficiency was calculated from the averaged ratio of the received radiation power of the rotating proposed antenna to the input power of a transmit horn antenna by the measurement system in an anechoic chamber. The radiation efficiency varies from 65.91% to 98.01%.

The overall antenna performances of our proposed antenna compared to the recently reported MTM antennas ([6]–[10]) are listed in Table I. The proposed antenna achieves a notable enhancement in its bandwidth and efficiency.

IV. CONCLUSION

In this letter, a novel antenna with a low profile and wide bandwidth is demonstrated and fabricated. The zeroth-order resonance and first-positive- and negative-order resonances were analyzed using a dispersion diagram based on CRLH-TL theory and the full-wave simulation. Furthermore, the bandwidth has been extended by managing the resonances of fundamental CRLH-TL and ground plane at all different frequencies with proper intervals. The simulated and measured results show good agreement with each other. The measured results of the proposed antenna show a bandwidth of 109.1% and radiation efficiency of over 65.91% in 2.69–9.15 GHz.

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