

A NOVEL BROADBAND ASYMMETRIC COPLANAR WAVEGUIDE (ACPW)-FED ZERO-ORDER RESONATOR ANTENNA BASED ON EPSILON NEGATIVE TRANSMISSION LINE

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Abstract—A broadband zeroth-order resonant (ZOR) antenna based on asymmetric coplanar waveguide (ACPW) is presented. By adopting the epsilon negative transmission line (ENG-TL), a zeroth-order resonance mode can be achieved. We employ an asymmetric coplanar waveguide structure which offers the design freedom to realize the broadband ZOR antenna, where the antenna's bandwidth is characterized by the equivalent circuit parameters. The antenna has the compact unit cell dimensions of $5 \times 13.8 \text{ mm}^2$. The measured results show that the operating bandwidth is about 1050 MHz (1.90–2.95 GHz), and the peak gain and radiation efficiency are 2.46 dBi and 91% at zeroth-order 2.3 GHz. Owing to the characteristics of broad bandwidth, high efficiency, omnidirectional radiation, and easy manufacturing, the proposed ACPW ZOR antenna is very suitable for modern wireless communication systems (UMTS, WLAN, WIMAX, LTE).

1. INTRODUCTION

Nowadays, compact antennas with wide bandwidth and good radiation characteristic are needed to satisfy the development of modern wireless communication systems [1, 2]. Due to the unique electromagnetic properties, such as anti-parallel phase and group velocities, metamaterials have been widely studied for microwave device and antenna applications [3–14]. Especially, because of the infinite wavelength propagation, zeroth-order resonant (ZOR) antennas based on the composite right/left-handed transmission line

Received 27 January 2013, Accepted 4 March 2013, Scheduled 8 March 2013

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(CRLH-TL) have attracted great interest in compact antennas. However, the reported ZOR antennas [15–21] suffer from the narrow bandwidth which restricts their wide application.

Recently, various solutions designed to enhance the ZOR antenna's bandwidth have been under investigation [17–20]. A compact ZOR antenna which consists of two metal–insulator–metal (MIM) parallel-plate capacitors and straight metal-strip lines is presented in [18]. Compared with the meander line, straight metal-strip line in a limited space introduces a small inductance, which will reduce the bandwidth according to [19]. In [20], an asymmetric coplanar waveguide (ACPW)-fed ZOR antenna with bandwidth extension is reported, which extends the bandwidth up to 10.3% and keeps radiation efficiency at 85%. However, the interdigital capacitor has disadvantages of a complex design process and large size because of small capacitance by coupling of the fingers.

In this paper, we propose a broadband epsilon negative transmission line (ENG-TL) ZOR antenna which extends the bandwidth up to 43.3%. Since that the series interdigital capacitor of the double negative transmission line (DNG-TL) complicates the fabrication process, we adopt the ENG-TL antenna which as well as the DNG-TL antenna supports the zeroth-order resonance mode. According to [19], the bandwidth of the ZOR antenna is determined by the Q -factor of the shunt resonator of the ENG-TL. The ACPW-type structure offers high design freedom to implement the shunt circuit parameters, so that large shunt inductance and small shunt capacitance can be realized to increase the bandwidth of ZOR antenna. As a result, the proposed broadband ZOR antenna with stable gain and omni-directional radiation characteristics has potential applications in mobile wireless communication systems.

2. ANTENNA THEORY

As shown in Figure 1(a), a general equivalent circuit model of the lossy ENG-TL is composed of the combination of series inductance (L_R), shunt capacitance (C_R) and shunt inductance (L_L). By applying Bloch-Floquet theory to the unit cell of periodic structure, the ENG TL dispersion relation is determined to be [16, 21]

$$\beta(\omega) = \frac{1}{p} \cos^{-1} \left(1 - \frac{\omega^2}{2\omega_R^2} + \frac{\omega_E^2}{2\omega_R^2} \right) \quad (1)$$

where $\omega_R = 1/\sqrt{L_L C_R}$, $\omega_E = 1/\sqrt{L_L C_R}$, β is the propagation constant for Bloch waves, and p is the physical length of the unit cell. The resonance of ENG-TL for resonance modes n can be obtained by the

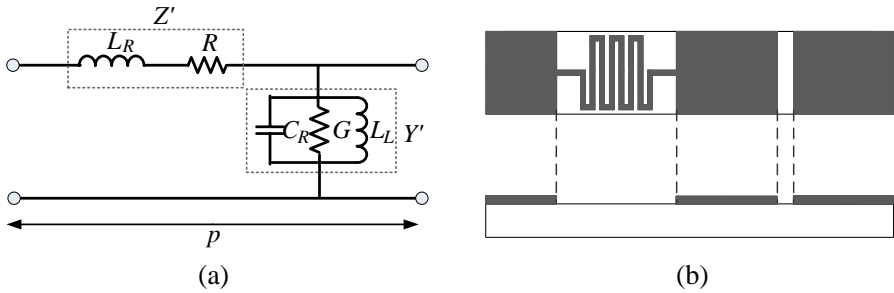


Figure 1. (a) Equivalent circuit model for ENG-TL unit cell and (b) configuration of the proposed unit cell based on ACPW structure.

following condition:

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

where n , N and l are the resonance order, number of unit cells and the total physical length of the resonator. Considering the zeroth-order resonance of an open-ended boundary condition, the input impedance Z_{in} seen from one end of the resonator toward the other end is given by

$$Z_{in} = -jZ_0 \cot \beta l |_{\beta=0} = -jZ_0 \frac{1}{\beta l} = -j\sqrt{\frac{Z'}{Y'}} \left(\frac{1}{-j\sqrt{Z'Y'}} \right) \frac{1}{l} = \frac{1}{Y'l} \quad (3)$$

where Y' is the admittance of the ENG-TL unit cell. Because Z_{in} can be expressed by the impedance of the shunt LC resonant tank, the resonance frequency is given as

$$\omega_{ZOR} = \omega_E = 1 / \sqrt{L_L C_R} \quad (4)$$

It indicates that the zeroth-order resonant frequency of ENG-TL unit cell is independent of the total physical length of the resonator but only determined by the shunt inductance and capacitance values loaded in the cell. Therefore, a ZOR antenna with the compact size can be implemented.

The geometry of the proposed ENG-TL unit cell based on ACPW structure is shown in Figure 1(b), where the epsilon negative characteristic of ENG-TL is induced by a shunt inductance of the meander line shorted to ground patch. The detailed physical dimensions of the proposed unit cell are shown in Figure 2.

The fractional bandwidth of the ZOR is given by [19]

$$BW = 1/Q_{ZOR} = G \sqrt{\frac{L_L}{C_R}} \quad (5)$$

Generally, ZOR antennas based on microstrip line (MSL) are known to have a narrow bandwidth problem compared to conventional half-wavelength resonant antennas. This is because the antennas have a small L_L which depends on the length of the shorting pin and a large C_R depends on parallel plate capacitance between the top patch and bottom ground. According to (5), the bandwidth of the ZOR antenna depends on the loss G and shunt elements of ENG-TL equivalent circuit model. Therefore, we can extend the bandwidth by introducing a large shunt inductance and a small shunt capacitance using the ACPW structure. Moreover, compared with DNG-TL, the ENG-TL simplifies the fabrication process.

3. ANTENNA DESIGN

In this paper, we proposed the broadband ACPW ZOR antenna by increasing the L_L and decreasing C_R , which result in extended bandwidth without degrading the efficiency, due to the constant shunt conductance G . As shown in Figure 2, the new configuration consists of a signal patch, shorted meander lines and ACPW ground planes. In order to form the ACPW structure, we move one of the CPW ground planes far from the signal patch and keep the other ground plane unchanged. The ENG-TL ZOR antenna is realized by cascading three unit cells periodically.

The shunt inductance L_L is obtained by the meander lines which are connected between the signal patch and the ACPW ground as the shorted stub. To extend the bandwidth, according to (5), a large L_L

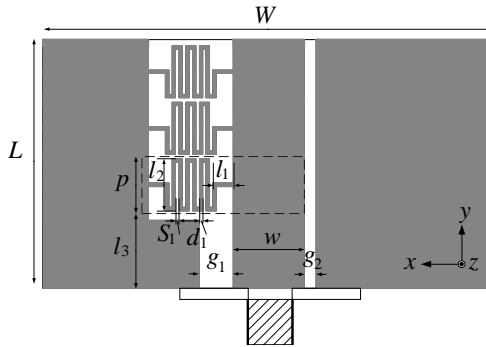


Figure 2. Geometry of the proposed ZOR antenna. (All dimensions are in millimeters: $L = 22$, $W = 50$, $w = 6.3$, $g_1 = 3$, $g_2 = 1.05$, $l_1 = 1.8$, $l_2 = 4.6$, $l_3 = 6.35$, $p = 5$, $d_1 = 0.3$, $S_1 = 0.3$).

can to be realized by the compact meander line which can be increased in proportion to the length of the shorted stub line. In addition, to further reduce the resonant frequency, the meander line in the unit cell is placed only on one side of the ACPW grounds, as shown in Figure 2.

The shunt capacitor C_R is provided by the capacitance between the signal patch and one side of the ACPW ground planes. Compared with MSL, which has a large C_R due to the fixed thickness and permittivity of substrate, the CPW-like structure which the signal and ground planes are placed on the co-plane provides a small capacitance. Moreover, the ACPW topology offers more design freedom such that the small C_R can be controlled by the gap length g_2 between signal planes and the ACPW ground plane. Thus, the proposed ACPW ZOR antenna provides a means of increasing the L_L and decreasing C_R very easily.

4. EXPERIMENTAL RESULTS

The proposed antenna, having compact unit cell dimensions of $5 \times 13.8 \text{ mm}^2$, is fabricated on a single-layer FR-4 Epoxy substrate with a dielectric constant of 4.4, thickness of 1.6 mm, and dielectric loss tangent of 0.02. The physical dimension is given in Figure 2 and the fabricated prototype is shown in Figure 4(a). The overall area of the radiating aperture is $0.4\lambda_0 \times 0.168\lambda_0 \times 0.0128\lambda_0$ ($50 \times 21 \times 1.6 \text{ mm}^3$), where λ_0 is the free space wavelength at its center frequency 2.425 GHz measured from reflection coefficients. Additional length l_3 of the antenna can be easily matched to the 50Ω coaxial probe without the employment of an external matching network or balun.

Figure 3 shows simulated and measured reflection coefficients for the fabricated ZOR antenna and the simulated resonant frequency

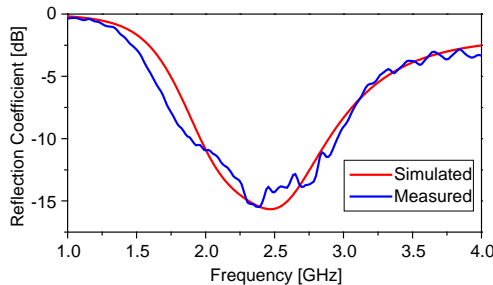


Figure 3. Simulated and measured reflection coefficients of the proposed antenna.

of zeroth-order mode is 2.3 GHz. The antenna was simulated using the CST Microwave Studio (MWS) and measured by an Agilent E5071C network analyzer. Measured results for reflection coefficient show a good agreement with electromagnetic (EM) simulation. As shown in Figure 3, the measured return loss bandwidth (-10 dB) is about 1050 MHz (1.90–2.95 GHz), corresponding to approximately 43.3% fractional bandwidth at 2.425 GHz, which is increased further compared with the previous ZOR antennas [15–21].

For giving a good physical insight into the behavior of the proposed antenna, the surface current distributions obtained from CST MWS at the simulated zeroth-mode frequency of 2.3 GHz are shown in Figure 4(b). We can observe that most of the surface currents flow on the meander lines. The amplitudes of the shunt meander lines currents are equal, and flow in the same direction. In addition, it is important to note that the ACPW ground planes also contribute to the radiation of the antenna, since there are unbalanced currents due to its asymmetrical structure.

Figure 5 plots the simulated and measured radiation patterns on

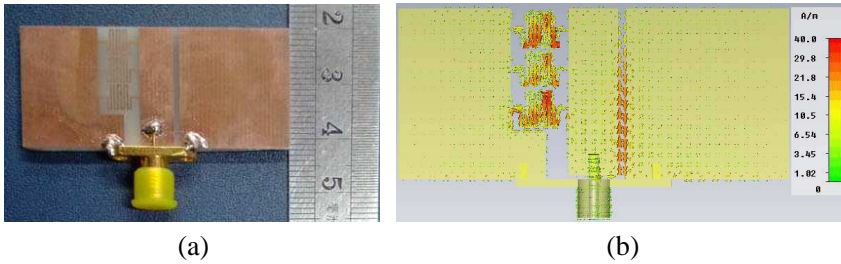


Figure 4. (a) Photograph of the fabricated antenna and (b) simulated surface current distributions at 2.3 GHz.

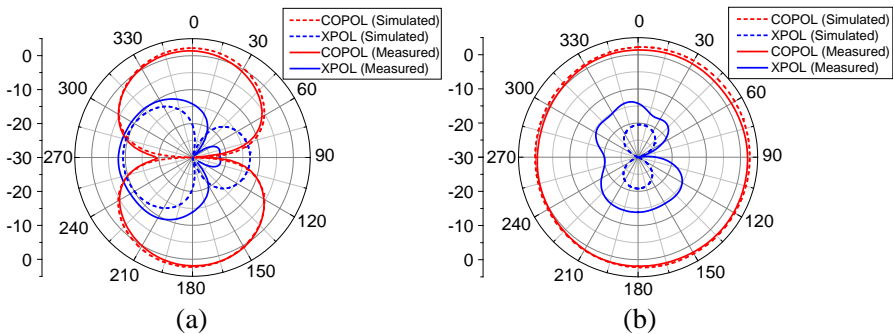


Figure 5. Simulated and measured radiation patterns of the proposed antenna at 2.3 GHz: (a) x - z plane (E -plane), (b) y - z plane (H -plane).

the x - z plane (E -plane) and y - z plane (H -plane) of the proposed antenna at 2.3 GHz. As we can see, the radiation pattern in E -plane has a monopole-like characteristic and nearly omni-directional characteristic in H -plane. The measured maximum gain of 2.46 dB is nearly the same as the simulated gain of 2.69 dB, where the differences between the simulation and measurement results are due to the fabrication tolerance.

The measured peak gains and the radiation efficiencies according to the operation band are presented in Figure 6. The antenna gains vary from about 1.9 dBi to 2.81 dBi and the radiation efficiencies vary from 81% to 92.56% at the band of 1.90–2.95 GHz. Because of stable gain, high radiation efficiency and wide bandwidth, the proposed antenna is very suitable for UMTS (1.92–2.17 GHz), WLAN

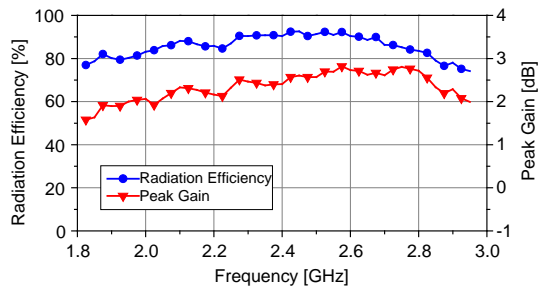


Figure 6. Measured antenna peak gain and radiation efficiency.

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

	This Work	[18]	[19]	[20]	[21]
Frequency (GHz)	2.3	2.3	2.03	1.94	3.38
Unit Size (λ_0)	$0.04 \times 0.11 \times 0.013$	$0.037 \times 0.12 \times 0.06$	$0.053 \times 0.097 \times 0.011$	$0.032 \times 0.087 \times 0.01$	$0.016 \times 0.08 \times 0.011$
Bandwidth (%)	43.3	4.3	6.8	10.3	~ 0.1
Peak Gain (dBi)	2.46	2.3	1.35	2.3	0.87
Efficiency (%)	91	79	62	85	70
Via Process	Not Required	Required	Not Required	Required	Required

(2.4–2484 GHz), WiMAX (2.5–2.69 GHz) and LTE 2300/2500 (2.305–2.4 GHz/2.5–2.69 GHz) applications.

The overall antenna performances of the proposed antenna are compared with those of the recently reported metamaterial antennas [18–21] in Table 1. Obviously, the proposed antenna achieves a significant enhancement in the bandwidth, efficiency, and gain. Moreover, the antenna is easy to fabricate owing to the single layer without vias and interdigital capacitors, and compared to the reference ZOR antennas, the antenna raises bandwidth up to 43.3%.

5. CONCLUSION

In this paper, a wideband ZOR antenna based on ENG-TL is proposed. Since the ZOR antenna's bandwidth is characterized by an equivalent circuit model, the ACPW structure provides the design freedom to realize a large shunt inductance and small shunt capacitance. To verify the proposed method, the antenna is fabricated on a single vialess layer. The simulation and measurement results show good agreement with each other. The ACPW ZOR antenna raises the bandwidth up to 43.3%, radiation efficiency of 91% and peak gain of 2.46 dBi at zeroth-order 2.3 GHz. With broad bandwidth, stable gain, high efficiency, and easy fabrication, the proposed antenna has potential applications in modern wireless communication systems.

ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China (NSFC) under Grant 60990320, 60990323 and the National 863 Project of China under Grant 2012AA012305, and Sichuan Provincial Science and technology support Project under Grant 2012GZ0101, and Chengdu Science and technology support Project under Grant 12DXYB347JH-002.

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