Broadband and Compact Zeroth-Order Resonant Antennas with Truncated Grounds

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Abstract **─** This paper presents the analysis and design of broadband and compact zeroth-order resonant (ZOR) antennas based on truncated grounds. A ZOR unit cell, whose physical size is independent of the operating frequency due to the fundamental infinite wavelength, can be implemented with a composite right/left-handed (CRLH) or inductor-loaded transmission line (TL). The two types of ZOR antennas with extended bandwidth and more compact size are achieved by introducing the truncated grounds. It is also shown that the supported infinite wavelength can be used to generate a monopole-like radiation pattern. The characteristics of the broadband and compact size of the proposed antennas are verified by the simulated and measured results.

Index Terms **─** CRLH, inductor-loaded, truncated grounds, ZOR antenna.

I. INTRODUCTION

Metamaterials, which do not exist in nature, have been hypothesized by Veselago in 1968 [1]. Compared with the conventional materials, metamaterials have many unique properties, such as the reversal of Snell's law, the Doppler Effect, and the Vavilov-Cerenkov effect [2]. The appearance of man-made metamaterials has allowed innovations in antennas and microwave circuits to be developed [3-10].

Particularly, the zero propagation constant property is used to design zeroth-order resonant (ZOR) antennas. A ZOR antenna has an infinite wavelength and its resonant frequency is independent of the antenna size. Therefore, a ZOR antenna can be much more compact than a conventional half-wavelength antenna [10-12]. However, the narrow bandwidth of a ZOR antenna limits its wireless applications.

In recent years, some ZOR antennas are designed to increase the bandwidth. The structure in [13] has a broad bandwidth by using air as the dielectric material. However, it is difficult to fabricate such an antenna. In [14], a strip matching ground is employed to increase the bandwidth. It is built on multiple substrates where a thin substrate with high permittivity is stacked on a thick substrate with low permittivity. Alternatively, the bandwidth of the antenna in [15] is enhanced due to two resonant frequencies which are slightly different. In addition, a broadband coplanar waveguide-fed ZOR antenna is proposed in [16] and a method to extend the bandwidth of metamaterial antennas using a composite right/ left-handed (CRLH) structure is presented in [17].

In this paper, two types of ZOR antennas based on CRLH transmission line (TL) and inductor-loaded TL unit cells are studied, respectively. A kind of truncated grounds is adopted to improve the bandwidth performance and further reduce the physical size of the ZOR antennas. By modifying the equivalent shunt capacitance and/or shunt inductance of the unit cells, the bandwidths are substantially extended and physical sizes are further miniature compared to the reference antennas. Moreover, they are built on a single layer and easy to be fabricated.

II. ZOR ANTENNA THEORY

A general CRLH TL model, shown in Fig. 1(a), consists of an inductance L_R in series with a capacitance C_L and a shunt capacitance C_R in

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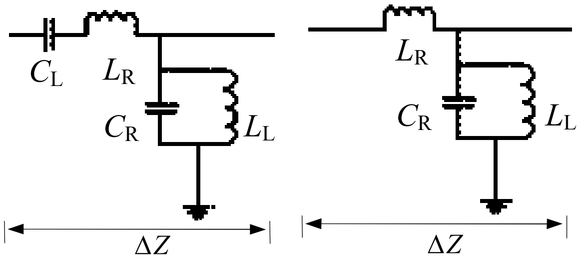
parallel with an inductance L_{L}. One structure that is commonly used to realize a CRLH TL is the Sievenpiper mushroom structure [18, 19]. When there is no gap between the adjacent patches, it simply becomes an inductor-loaded TL. Figure 1(b) plots the equivalent circuit of an inductor-loaded TL.



(a) (b)

Fig. 1. Models of (a) CRLH TL and (b) inductor-loaded TL.

By applying periodic boundary conditions related to the Bloch-Floquet theorem, the CRLH TL unit cell's dispersion relation is determined by [12]

$$\beta(\omega)=\frac{1}{\Delta Z}\arccos\left(1-\frac{1}{2}\left(\frac{\omega_{\mathrm{L}}^2}{\omega^2}+\frac{\omega^2}{\omega_{\mathrm{R}}^2}-\frac{\omega_{\mathrm{L}}^2}{\omega_{\mathrm{se}}^2}-\frac{\omega_{\mathrm{L}}^2}{\omega_{\mathrm{sh}}^2}\right)\right) \quad (1)$$

where

$$\omega_{\mathrm{L}}=\frac{1}{\sqrt{C_{\mathrm{L}}L_{\mathrm{L}}}},\ \omega_{\mathrm{R}}=\frac{1}{\sqrt{C_{\mathrm{R}}L_{R}}}$$
$$\omega_{\mathrm{se}}=\frac{1}{\sqrt{C_{\mathrm{L}}L_{\mathrm{R}}}},\ \omega_{\mathrm{sh}}=\frac{1}{\sqrt{C_{\mathrm{R}}L_{\mathrm{L}}}} \quad (2)$$

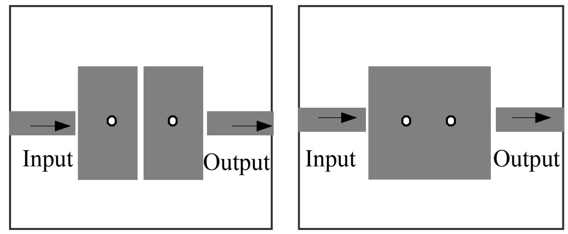
It consists of a left-handed (LH) wave at lower band and right-handed (RH) wave at upper band. It can also be predicted that non-zero frequency points (zeroth-order modes) with $\beta=0$ are presented.

In the case of open boundary conditions, the zeroth-order mode is determined by the shunt resonance (ω_{sh}). That is to say, the series components have no effect on the resonance frequency. Therefore, an inductor-loaded TL unit cell is created when the gap is eliminated. Its propagation constant is given by [12]

$$\beta(\omega)=\frac{1}{\Delta Z}\arccos\left(1+\frac{1}{2}\left(\frac{L_{\mathrm{R}}}{L_{\mathrm{L}}}-\frac{\omega^2}{\omega_{\mathrm{R}}^2}\right)\right) \quad (3)$$

It can be predicted that only the zeroth-order mode and RH wave occur in this case.

In this paper, the CRLH TL and inductor-loaded TL unit cells, shown in Fig. 2(a) and (b), are used to realize ZOR antennas.



(a) (b)

Fig. 2. Configurations of (a) CRLH TL unit cell, and (b) inductor-loaded TL unit cell.

III. PROPOSED BANDWIDTH EXTENSION TECHNIQUE

According to [16], the fractional bandwidth of the resonator is given by

$$BW=G\sqrt{\frac{L_{\mathrm{L}}}{C_{\mathrm{R}}}} \quad (4)$$

where G is the shunt conductance of the lossy CRLH TL. This expression provides a concept with which the bandwidth can be efficiently enhanced by increasing L_{L} and/or decreasing C_{R}.

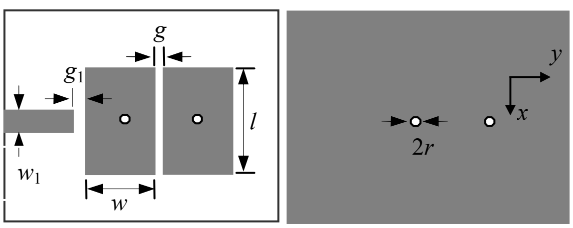
The mushroom unit cell is composed of a rectangle patch, ground plane and metallic via [18]. The LH capacitance and inductance are provided by the capacitance couplings of the top patch with adjacent patches and a metallic via between the top patch and ground plane, respectively. The magnetic flux caused by the flow of current on the top patch contributes to the RH inductance, while the parallel-plate structure between the patch and ground plane contributes to the RH capacitance. The attribute of LH capacitance is eliminated in the case of inductor-loaded TL. Since these configurations provide design freedom for the reactive parameters, both a wider bandwidth and smaller size can be achieved.

IV. ANTENNAS IMPLEMENTION AND RESULTS ANALYSIS

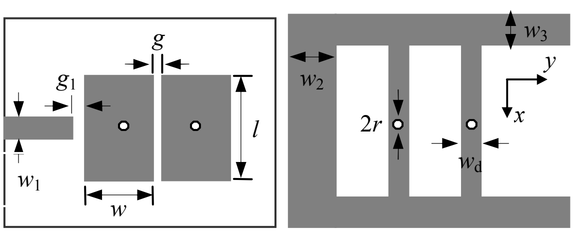
In this section, the prototypes are all built on the substrate with a relative permittivity of 2.65, loss tangent of 0.001 and thickness of 1.5 mm.

A. CRLH-based ZOR antenna with a truncated ground

The reference model of the CRLH-TL-based ZOR antenna with a whole ground is shown in Fig. 3(a) [12]. The proposed antenna with a truncated ground is illustrated in Fig. 3(b). A feeding line of 50 Ohm and proximity coupling are used as the feed network. As we know, the shunt inductance can be increased in proportion to the length of the shorted stub line. The metallic via lines connecting the metallic via and the ground enlarge the length of the shorted stub line (Fig. 3(b)). Moreover, the area between the top patch and ground plane becomes small, and the shunt capacitance is substantially reduced. Thus, a tradeoff between resonant frequency and bandwidth can be obtained from (2) and (4). In addition, by changing the value of w_2, not only the shunt capacitance and shunt inductance can be altered, but also the benefit of impedance matching can be achieved. Using the commercial software (Ansofe HFSS) [20], the geometric parameters of the truncated ground are obtained through optimization.



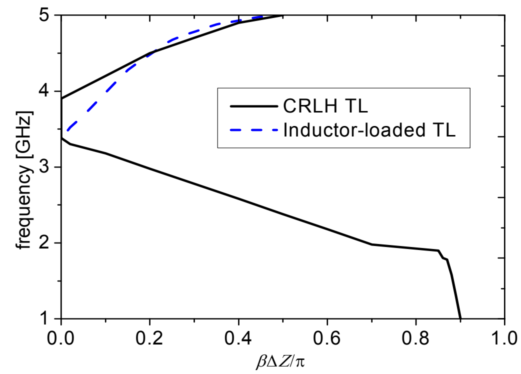
(a)



(b)

Fig. 3. Top and back views of the CRLH TL antennas: (a) reference antenna and (b) proposed antenna, where w=7.3 mm, l=15 mm, w_1=4 mm, g=0.2 mm, g_1=0.3 mm, r=0.2 mm, w_d=0.5 mm, w_2=10 mm and w_3=5 mm.

In order to verify the theoretical qualitative analysis, we extract the dispersion diagrams, as shown in Fig. 4, for the reference and proposed structures based on the CRLH TL and inductor-loaded TL unit cells in Fig. 2 [21, 22]. The shunt resonant frequencies for the reference CRLH-TL and ZOR for the reference inductor-loaded TL are almost located at 3.5GHz. The shunt resonant frequency for the proposed CRLH-TL is 2.72GHz and ZOR frequency for the proposed inductor-loaded TL is 2.4GHz.



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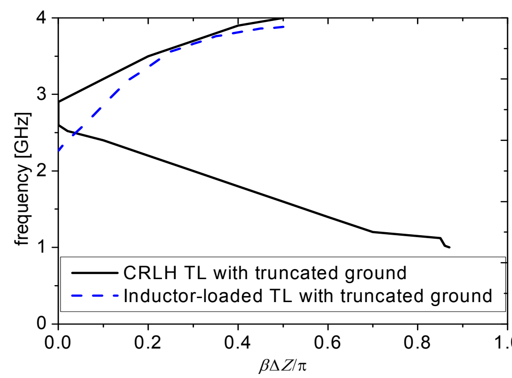
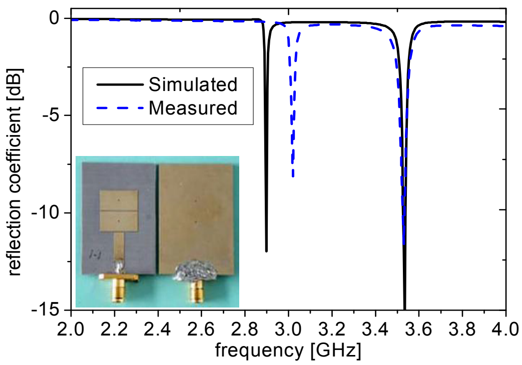


(b)

Fig. 4. Dispersion diagrams for (a) two reference unit cells and (b) two proposed unit cells.

Figure 5 shows the simulated and measured reflection coefficients of the two antennas. The -10dB bandwidth and resonant frequency of the reference CRLH TL antenna are less than 1% and 3.53GHz, respectively. And, for the proposed antenna, the bandwidth is about 7.0% and resonant frequency is about 2.75GHz. The difference between simulation and measurement is mostly due to the influences of manufactured precision and feeding cable.

The simulated radiation patterns of the CRLH TL antennas are shown in Fig. 6. The proposed antenna generates a monopole-like radiation pattern as seen in Fig. 6(b), different from a monopole radiation pattern of the reference antenna in Fig. 6(a). In terms of the radiation mechanism of the proposed antenna, the magnetic currents mainly concentrate in the slot which approaches to the feeding line. Therefore, the proposed antenna looks like an ideal magnetic dipole rather than a magnetic loop antenna [12].



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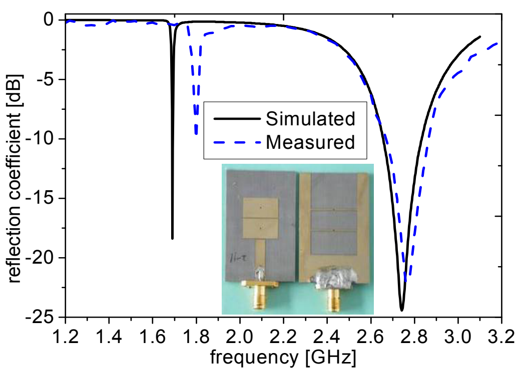
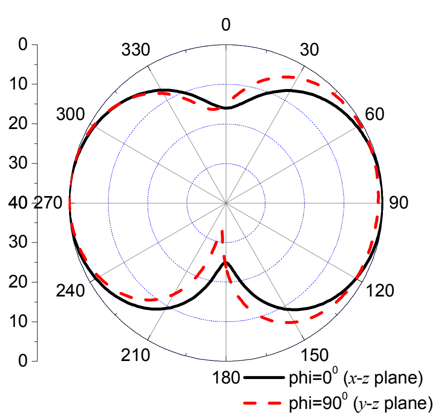


(b)

Fig. 5. Simulated and measured reflection coefficients of CRLH TL antenna (a) with a whole ground and (b) with a truncated ground.



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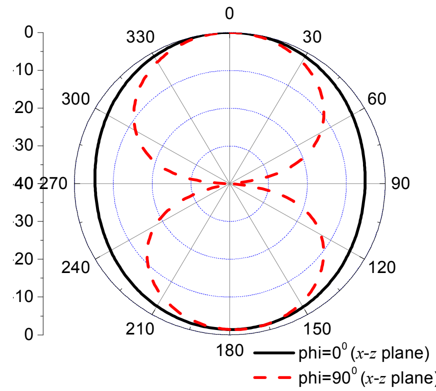
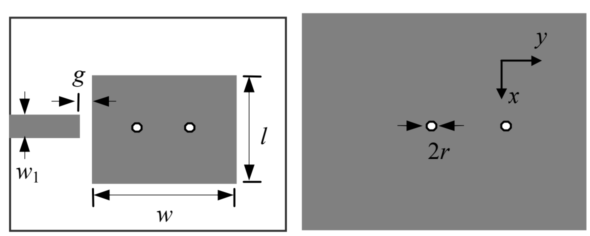


(b)

Fig. 6. Simulated radiation patterns for the two CRLH TL antennas (unit: dB) (a) with a whole ground and (b) with a truncated ground.

B. Inductor-loaded ZOR antenna with a truncated ground

The reference and proposed models of the inductor-loaded antenna are shown in Fig. 7(a) and (b), respectively. Similarly, the inductor-loaded antennas with a large L_L and small C_R which result in an improved bandwidth are studied. Figure 8 and Fig. 9 show the reflection coefficients and radiation patterns, respectively. The overall performances of the CRLH TL and inductor-loaded antennas are listed in Table 1.



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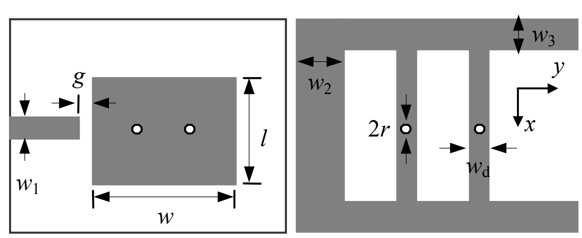
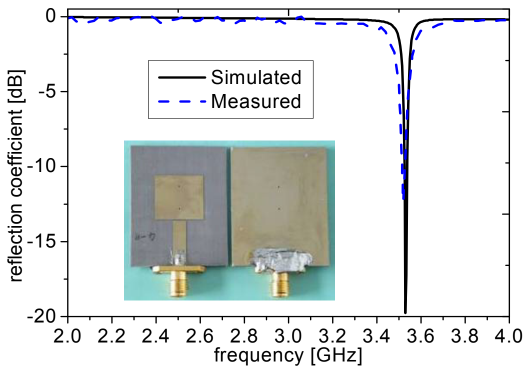


(b)

Fig. 7. Top and back views of the inductor-loaded antennas: (a) reference antenna and (b) proposed antenna, where w=14.8mm, l=15mm, w_1=4mm, g=0.3mm, w_d=0.5 mm, w_2=10mm, and w_3=5mm.



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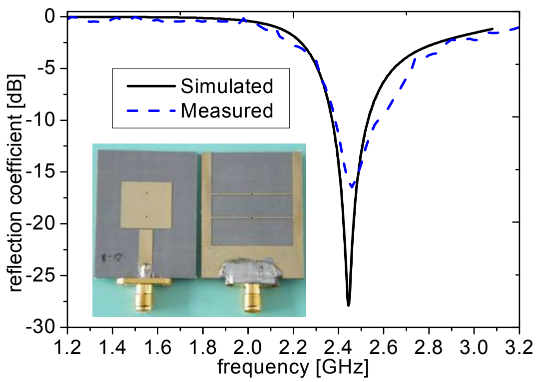
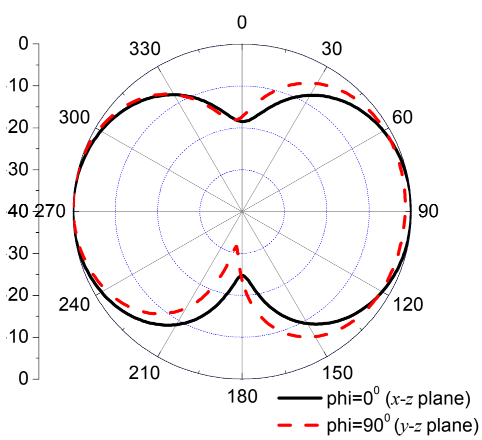


(b)

Fig. 8. Simulated and measured reflection coefficients of inductor-loaded antennas (a) with a whole ground and (b) with a truncated ground.



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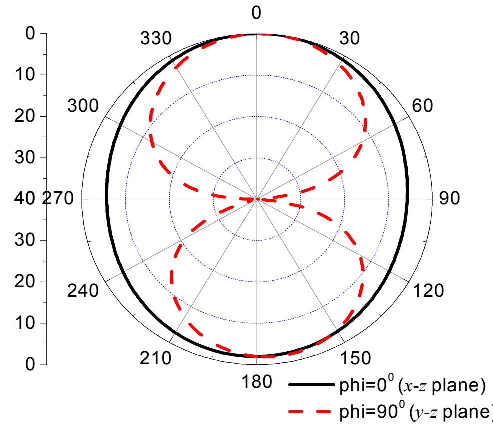

(b)

Fig. 9. Simulated radiation patterns for the reference and proposed inductor-loaded antennas (unit: dB) (a) with a whole ground and (b) with a truncated ground.

Table 1: Comparison of the reference and proposed ZOR antennas

Antenna type	CRLH-TL		Inductor-loaded	
	Whole Ground	Truncated Ground	Whole Ground	Truncated Ground
Frequency (GHz)	3.53	2.75	3.54	2.42
Size (λ_0)	0.17 ×0.169	0.13 ×0.132	0.167 ×0.169	0.116 ×0.118
BW (%)	<1	7.0	<1	7.2
Pattern	A	B	A	B
Gain (dB)	1.66	3.29	1.53	2.76
Efficiency (%)	55	67	54	65

A—monopole radiation pattern, B—monopole-like radiation pattern

V. CONCLUSION

In this paper, the extended bandwidth and compact size of ZOR antennas are obtained by introducing a truncated ground structure. The unit cells are implemented with the CRLH TL and inductor-loaded TL, respectively. A flexible design of a high shunt inductance and small shunt capacitance can realize a wider bandwidth and more compact size than those of the conventional ZOR antennas. Particularly, the maximum bandwidth of the proposed antennas can reach about 7.2%. The improved ZOR antennas are suitable for the use in wireless communication systems.

ACKNOWLEDGMENT

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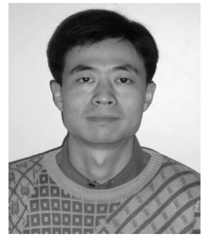

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