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ASYMMETRIC COPLANAR WAVEGUIDE (ACPW)-FED ZEROTH-ORDER RESONANT ANTENNA WITH MONOPOLE RESONATOR LOADING

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Abstract—An asymmetric coplanar waveguide (ACPW)-fed zeroth-order resonant (ZOR) antenna with extended bandwidth is investigated. By embedding a strip connected between the metallic patch and an ACPW ground plane, another resonant frequency at 2.53 GHz is achieved. The bandwidth enhancement of designed antenna can be obtained when the zeroth-order resonant frequency and the resonant frequency at 2.53 GHz are merging together. The size of the antenna is only $15 \times 22 \times 0.8\,\text{mm}^3$ with simple planar structure. A prototype of the proposed antenna has been constructed and experimentally studied. The measured results show that operating bandwidths with 10 dB return loss are about 510 MHz (2.49–3.0 GHz), the simulated peak gain of 1.59 dBi at 2.68 GHz, which is suitable for WiMAX (2.5 GHz–2.69 GHz) application.

1. INTRODUCTION

With the drastic development in the field of wireless communications, there is a demand for antennas with small size, low cost, and wide bandwidth or several frequency bands. The metamaterial (MTM) is very attractive for the design of compact antennas and microwave devices [1–13], due to the unique properties in comparison with conventional nature materials, such as anti-parallel phase and group velocities, and a zero propagation constant [14–16]. One of the novel applications is zeroth-order resonant (ZOR) antenna. However, the ZOR antenna typically suffers from narrow bandwidths [17–19], which is not to be suitable for modern wireless communication systems.

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In recent years, many attempts have been made to extend the bandwidth of ZOR antennas [20–22]. In [20], a new type of single-layer ZOR antenna based on ACPW for a further bandwidth extension is reported. This ZOR antenna extends the bandwidth up to 10.3% by increasing shunt inductance which can decrease the Q-factor of the shunt resonator. Another method is to employ electronically tunable components in the antenna [21], by tuning the capacitance of the varactor diode. This proposed antenna is electronically tunable from 2.19 GHz to 2.51 GHz. In [22], the bandwidth enhancement is achieved by using two closely spaced zeroth-order and first-negative-order resonance modes of CRLH-TL.

In this paper, a ZOR antenna with extended bandwidth is proposed. We employ a strip connected between the metallic patch and an ACPW ground plane to introduce another frequency. Broadband performance can be achieved in a compact and low profile design by merging the ZOR mode and the frequency which is introduced by a strip. The details of the proposed antenna designs and experimental results are presented and discussed.

2. ANTENNA DESIGN

2.1. ACPW-fed ZOR Antenna

2.1.1. ACPW-fed ZOR Antenna Design

An ACPW-fed ZOR antenna consists of one unit cell of the ENG-TL structure, as depicted in Figure 1. The equivalent circuit of the proposed ZOR antenna (Antenna 1) is shown in Figure 2. The capacitive effect between the top plane and the metallic patch is modeled as C_S. The inductive effect of the top plane and the right ground plane provides the inductance of L_S. The metallic patch contributes to the series inductance (L_R), while the shunt capacitance (C_R) can be found in the coupling between the metallic patch and the ACPW ground plane.

The series impedance (Z) and shunt admittance (Y) in Figure 2 can be obtained as [23],

$$Z = jwL_R \tag{1}$$

$$Y = jwC_R + \frac{jwC_S}{1 - w^2 L_S C_S} \tag{2}$$

Applying periodic boundary conditions related with Bloch-Floquet theorem to the unit cell, the dispersion relation is obtained

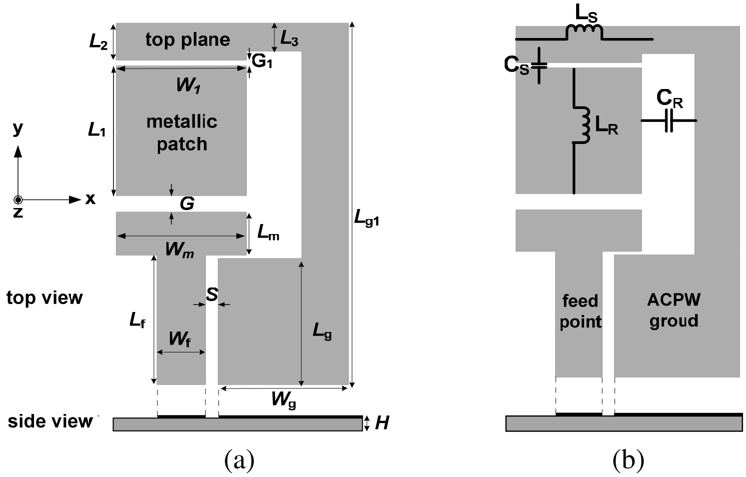


Figure 1. (a) Geometry of the ZOR antenna and (b) view of the ENG-TL structure.

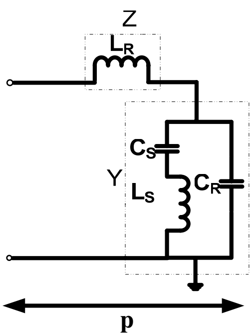


Figure 2. Equivalent circuit model for the proposed ZOR antenna.

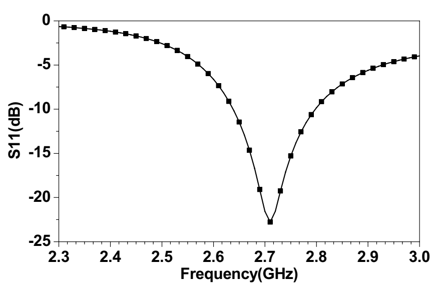


Figure 3. The simulated S_{11} for ZOR antenna.

as

$$\beta(w)=\frac{1}{p}\cos^{-1}\left(1+\frac{ZY}{2}\right)=\frac{1}{p}\cos^{-1}\left(1-\frac{1}{2}\left(w^2L_RC_R+w^2L_RC'\right)\right) \tag{3}$$

where

$$C'=\frac{C_S}{1-w^2C_SL_S} \tag{4}$$

In this antenna, there is only one unit cell. So it has only the ZOR mode. When $\beta=0$, the ZOR frequency can also be expressed as follows

$$W_{ZOR} = \sqrt{\frac{C_S + C_R}{L_S C_S C_R}} \tag{5}$$

2.1.2. ACPW-fed ZOR Antenna Result

The proposed antenna, having compact dimensions of $14 \times 20\,\text{mm}^2$ ($W \times L$), is designed on an F_4BM350 dielectric substrate with thickness of 0.8 mm, relative permittivity 3.5 and dielectric loss tangent of 0.001. The asymmetric coplanar strip feed is analogous to the coplanar wave guide feed used here for reducing the size of the designed antenna [24]. We employed a rectangle patch ($W_m \times L_m$) at the feeding point to match the antenna to the 50-Ω cable. The dimensions of the antenna element, shown in Figure 1(a), are listed in Table 1. The electrical size of the unit cell of the antenna is $0.063\lambda_0 \times 0.063\lambda_0$ (7 mm × 7 mm) at 2.71 GHz.

Table 1. The parameters of the proposed ZOR antenna (Unit: mm).

W	L	H	W_f	L_f	G	G_1	W_g
14	20	0.8	2.6	7.0	0.9	0.3	7.0
L_g	W_m	L_m	L_{g1}	W_1	L_1	L_2	L_3
6.8	7.0	2.3	19.5	7.0	7.0	2.0	1.5

The EM simulated S_{11} for the ZOR antenna is shown in Figure 3. It can be observed that the antenna is well matched around 2.71 GHz. From the simulated result, the simulated zeroth order resonant

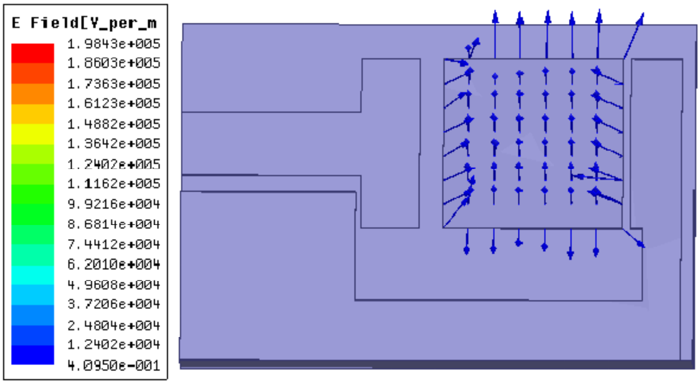


Figure 4. Electric field distributions in zeroth mode.

frequency is about 2.71 GHz. The simulated return loss bandwidth (-10 dB) is about 160 MHz (2.64–2.80 GHz), which corresponds to approximately 5.9% fractional bandwidth at 2.71 GHz. Figure 4 shows the electric field distributions of the antenna in the zeroth mode. The electric field distribution for the zeroth mode is almost in-phase.

2.2. ZOR Antenna with Bandwidth Enhancement

2.2.1. ZOR Antenna with Bandwidth Enhancement Design

In order to extend bandwidth to meet the requirement for the WiMAX application (2.50–2.69 GHz) in the responses of the ZOR antenna, a strip is inserted and connected between the metallic patch and the ACPW ground plane (Antenna 2). The strip is added to obtain a loop which consists of the inner edge of the right ground and the top of the right edge of the metallic patch. The length of loop is $L_{loop} = 2 * (L_1 - L_4 + G_1 + W_s) = 20\,\text{mm}$. For a desired resonant frequency, the wavelength is given by

$$\lambda_g = \lambda_0/\sqrt{\varepsilon_{re}} = c_0/\left(f\sqrt{\varepsilon_{re}}\right) \tag{6}$$

in which λ_0 is the free space wavelength and ε_{re} the effective permittivity given by the approximate formula of [25]

$$\varepsilon_{re} = \frac{1}{2}(\varepsilon_r + 1) \tag{7}$$

where ε_r is relative permittivity of a dielectric substrate. With $\varepsilon_r = 3.5$, $f = 2.53\,\text{GHz}$, $c_0 = 3 \times 10^8\,\text{m/s}$. We can get $\lambda_g = 79\,\text{mm}$.

The dimensions of the antenna element, shown in Figure 5, are listed in Table 2.

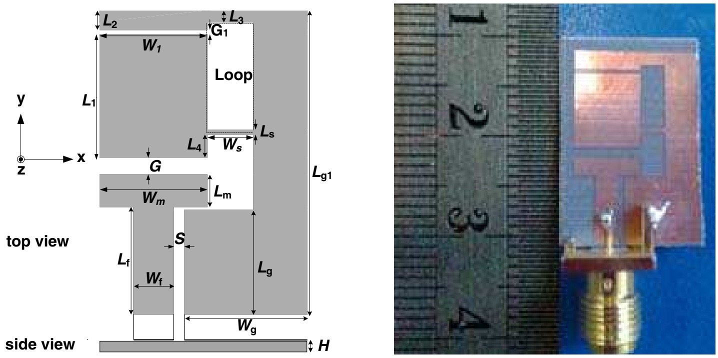
Table 2. The parameters of ZOR antenna with bandwidth enhancement (Unit: mm).

W	L	H	W_f	L_f	G	G_1	W_g	L_g
15	22	0.8	2.6	7.0	0.7	0.5	8.0	6.8
W_m	L_m	W_s	L_s	L_{g1}	W_1	L_1	L_2	L_3
7.0	2.1	3.0	0.3	20.5	7.0	8	2	1.5

With a strip inserted connected between the metallic patch and the ACPW ground plane, which can be modeled as L_L, the equivalent circuit model for Antenna 2 should be modified, as shown in Figure 6.

The series impedance (Z) and shunt admittance (Y) in Figure 6 can be obtained as,

$$Z = jwL_R \tag{8}$$



(a) (b)

Figure 5. (a) Geometry of the proposed antenna and (b) photograph of the fabricated antenna.

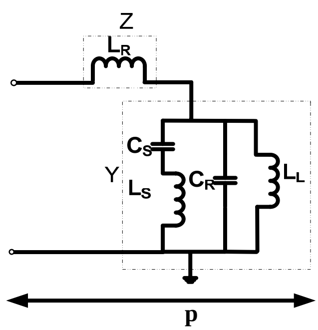


Figure 6. Equivalent circuit model for Antenna 2 with a strip.

$$Y = \frac{1}{jwL_L} + jwC_R + \frac{jwC_S \cdot \frac{1}{jwL_S}}{jwC_S + \frac{1}{jwL_S}} \tag{9}$$

Applying periodic boundary conditions related with Bloch-Floquet theorem to the unit cell, the dispersion relation is obtained as

$$\beta(w) = \frac{1}{p}\cos^{-1}\left(1 + \frac{ZY}{2}\right) = \frac{1}{p}\cos^{-1}\left(1 + \frac{1}{2}\left(\frac{L_R}{L_L} - w^2 L_R C_e\right)\right) \tag{10}$$

where

$$C_e = C_R + \frac{C_S}{1 - w^2 L_S C_S} \tag{11}$$

When $\beta = 0$, the ZOR frequency can be obtained by the following condition:

$$w_{ZOR} = \sqrt{\frac{1}{L_L C_e}} \tag{12}$$

It is shown that its resonance condition depends on the shunt parameters.

2.2.2. Extend Bandwidth Antenna Result

A fabricated prototype for the proposed antenna has been experimentally studied, as depicted in Figure 5(b). The antenna was simulated by using the ANSOFT High Frequency Structure Simulator (HFSS) and measured by an analyzer Agilent E5071C network analyzer. Figure 7 presents the measured and simulated return losses against frequency for the proposed antenna. As can be seen from Figure 7, the measured return loss bandwidth (−10 dB) is about 510 MHz (2.49–3.0 GHz), which corresponds to approximately 19.0% fractional bandwidth at 2.68 GHz. Compared to Figure 3, the strip is added to obtain a low resonance at about 2.53 GHz, when the two resonant frequencies are tuned to get close with each other and obtain the enhanced bandwidth at 2.59 GHz band.

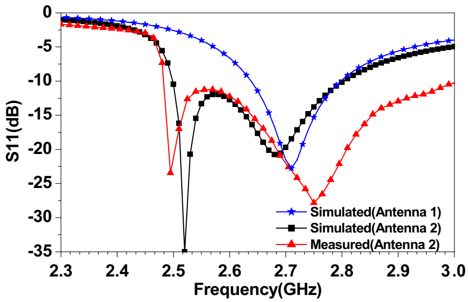


Figure 7. Measured and simulated S_{11} for the proposed antenna with bandwidth enhancement.

In order to further demonstrate the wide band antenna operation mechanism, surface current distributions on the whole proposed antenna at 2.53 GHz and 2.68 GHz are shown in Figure 8. It can be clearly seen that the current has different distributions along the antenna in different resonant frequencies. In Figure 8(a), the surface current density at 2.53 GHz is mainly concentrated along the loop. The current length is about 20 mm, which corresponds to 0.25 wave-length at 2.53 GHz. Whereas, as can be seen from Figure 8(b), the strong surface current is around the gap between top plane and the patch, the

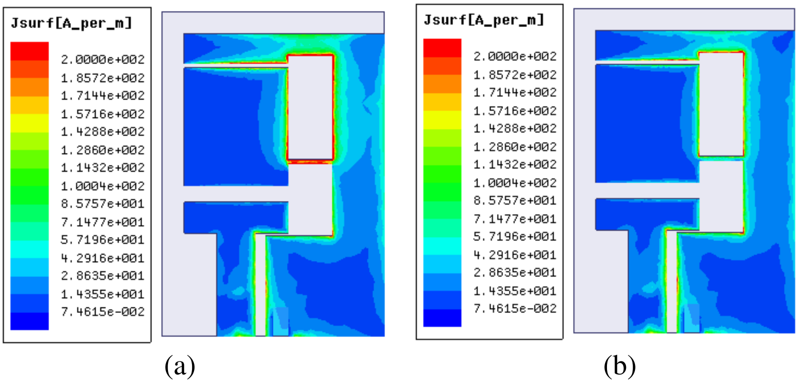


Figure 8. Simulated surface current distributions of the designed antenna at (a) 2.53 GHz, and (b) 2.68 GHz.

inner edge of the patch, the right ground and the strip, which means that the ZOR resonant frequency is generated by the L_L, C_S, L_S and C_R. Therefore, from both S_{11} responses and current distributions, the function of the related geometrical mechanism is clearly presented.

The parametric study is important for a new design because it provides some understanding of the antenna characteristics to the antenna designer. Therefore, the effects of the design parameters for the feed line length (L_m) and the strip location (L_4) on the antenna characteristics are investigated here. Figure 9 shows the simulated return loss as a function of L_m. Clearly, with the increase of L_m, the first resonant frequency is almost fixed, while the second frequency decreases, because when L_m increases, the gap between the feed and patch decreases, which will result in the increase of the coupling between the feed and patch, so the capacitance effect (C_S) will increase. At the same time, the first resonant frequency is obtained by the current length of the loop which is almost fixed.

To demonstrate the effect of the strip inserted and connected between the metallic patch and the ACPW ground plane, Figure 10 gives the S_{11} of the proposed antenna for different values of L_4. As can be seen, the location of strip can significantly affect the antenna's first frequency. When L_4 varies from 1.5 mm to 2.5 mm, the first center frequency moves to high frequency, because L_4 increases and because the length of the loop decreases.

Figure 11 shows the simulated and measured radiation patterns in the E-plane (y-z plane) and H-plane (x-z plane) for the proposed antenna which are plotted in Figure 11. Respectively, the simulated radiation patterns are approximately omnidirectional at 2.53 GHz,

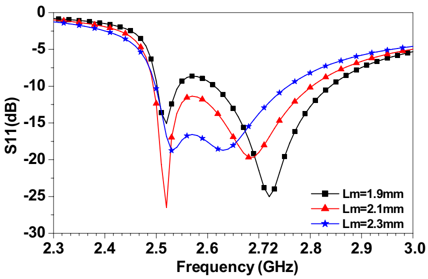


Figure 9. Simulated S_{11} for the proposed antenna with different L_m.

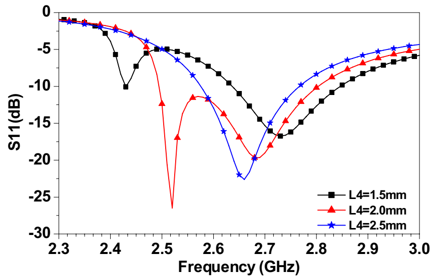


Figure 10. Simulated S_{11} for the proposed antenna with different L_4.

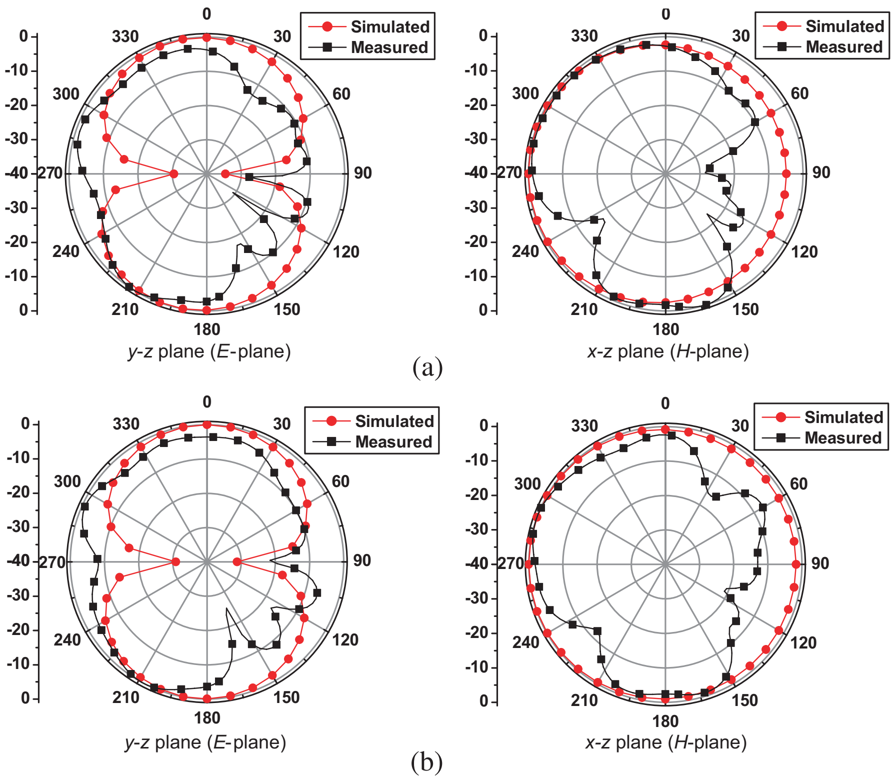


Figure 11. Simulated and measured normalized radiation patterns at (a) 2.53 GHz, and (b) 2.68 GHz.

2.68 GHz in the H-plane and monopole-like in the E-plane. The measured efficiencies at 2.53 GHz and 2.68 GHz are 51.3% and 53.8%. However, the measured radiation patterns are different from the simulated radiation patterns, and the reasons attributed to the differences are believed as 1) the spurious reflections from SMA connectors and RF cables that are not incorporated in the simulation; 2) the antenna size is very small and with an asymmetric structure which will result in the instability of the measured radiation patterns.

The overall antenna performances of the proposed antenna are compared with ZOR antennas [20, 26–29] in Table 3. Our proposed single-layer ACPW ZOR antenna achieves a significant enhancement in the antenna bandwidth. Moreover, it is easy to be fabricated and low cost owing to the single-layer. So it is suitable for the WiMAX application.

Table 3. Antenna measurement summary and comparison results of proposed and reference antenna.

	Frequency (GHz)	Unit Size (λ_0)	Bandwidth (%)	Gain (dBi)	Layer
This work	2.68	$0.071 \times 0.062 \times 0.007$	19.0	1.59	Single
[20]	2.30	$0.032 \times 0.087 \times 0.010$	10.3	2.30	Single
[26]	2.03	$0.053 \times 0.097 \times 0.011$	6.8	1.35	Single
[27]	3.38	$0.160 \times 0.080 \times 0.017$	~ 0.1	0.87	Single
[28]	1.73	$0.100 \times 0.100 \times 0.015$	8.0	1.00	Multi
[29]	1.77	$0.090 \times 0.077 \times 0.036$	6.8	0.95	Multi

3. CONCLUSION

A compact and broadband ZOR antenna has been presented, which has a compact size of $15 \times 22 \times 0.8\,\text{mm}^3$. By employing a strip connected between the metallic patch and the ACPW ground plane, a resonant frequency at 2.53 GHz is achieved. This resonant mode and ZOR mode merging together enables a wideband characteristic. Measured results show that the antenna has a bandwidth of 510 MHz (2.49 GHz–3.0 GHz). The proposed antenna features compact size, wide operating bandwidth and low cost, which indicates that it can be a good candidate for WiMAX applications.

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