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# Design of a Miniaturized Zeroth- and First-order Resonant Antenna with Mushroom Cells and Interdigital Capacitors

**Ke Li***, **Yuan-Ming Cai, Long Li, and Chang-Hong Liang**

**Abstract**—A novel design of miniaturized dual-band antenna based on mushroom cell and interdigital capacitor is presented in this paper. Four transmission line (TL) elements are loaded in a microstrip antenna, and each one is composed of a mushroom cell and interdigital capacitors. The interdigital capacitors contribute to the series capacitance and metallic via-hole of mushroom structures result in the shunt inductance in the equivalent circuit model. The antenna works as a zeroth-order ($f_0 = 2.51\,\text{GHz}$) and first-order ($f_1 = 3.78\,\text{GHz}$) resonant antenna with varied radiation patterns. Omnidirectional radiation pattern and unidirectional radiation pattern are obtained at 2.51 GHz and 3.78 GHz, respectively. The overall size of the antenna is only $0.25 \times 0.25 \times 0.017\lambda_0^3$ (at $f_0 = 2.51\,\text{GHz}$). The proposed antenna features compact structure, low profile and easy fabrication. Good agreement between the simulated and measured results is also achieved, validating our design concept.

## 1. INTRODUCTION

In recent years, compact antennas with low profiles and multi-frequency support are greatly needed with the rapid development of wireless communication systems, antenna design turns to focus on multiband antenna with small size, simple structures and low profile. Microstrip antennas have attracted interests as they have the advantages of light weight, low profile, easy fabrication and conformability to mounting hosts [1–4].

Metamaterials are widely used in antenna and microwave circuit design due to their exotic feature compared with conventional material [5, 6]. Right/left handed transmission line has been applied in multiband antenna design and miniaturized antenna design, such as zeroth-order antenna which has the characteristic that resonant frequency is independent of physical dimensions [7]. In [8], two unbalanced composite right-/left handed transmission line unit cells are employed in the antenna which inspires a resonant frequency, and the profile of the antenna is 10 mm. In [9], the antenna consists of two-dimensional artificial metamaterial transmission line (TL) which is working in three resonant modes with varied radiation patterns, and the thickness of the substrate is 6 mm. A zeroth-order resonant composite right/left-handed (CRLH) antenna based on dual-arm spiral structure is presented in [10], and only one resonant band is obtained.

In this design, four TL elements including three-dimensional mushroom structures connected with interdigital capacitors are loaded in a square microstrip patch to realize the zeroth- and first-order resonant modes. The overall the size of the antenna is only $30 \times 30 \times 2\,\text{mm}^3$. Two resonant frequencies of 2.51 GHz and 3.78 GHz are inspired with varied radiation patterns, corresponding to zeroth-order resonant (ZOR) and first-order resonant (FOR) mode. Monopole-type radiation pattern is achieved for 2.51 GHz and unidirectional radiation pattern for 3.78 GHz. The proposed miniaturized antenna features simple structure and low profile which can be used in wireless communication system.

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## 2. ANTENNA DESIGN AND ANALYZE

The geometry of the proposed antenna is shown in Figure 1. The antenna is designed on a rectangular dielectric substrate with a relative permittivity of 2.65, loss tangent of 0.0012 and a thickness of 2 mm. Four TL elements, shown in Figure 2(a) including three-dimensional mushroom cells connected with interdigital capacitors, are loaded in a square microstrip antenna to inspire the lower frequency resonant at 2.5 GHz, and each unit occupies only $0.037\lambda_0 \times 0.037\lambda_0$. In addition, a capacitive annular-ring slot is employed in this design to improve the impedance match in both frequencies. The optimized radiuses of inner circle and outer circle are 1.1 mm and 1.6 mm, yielding a good impedance match at each resonant frequency.

The dimensions of the TL element is shown in Figure 2(a) while the equivalent circuit model of that is shown in Figure 2(b). In this design, the interdigital capacitors between mushroom structures contribute to the series capacitance $C_L$ and metallic via-holes of mushroom structure result in the shunt inductance $L_L$, the series inductance $L_R$ and shunt capacitance $C_R$ are parasitic effect elements [10].

The antenna is an electrically small resonator with four TL elements, and it radiates as a composite right/left-handed (CRLH) resonator, therefore the resonant frequency fits the following equation:

$$\beta_n = \frac{n\pi}{Np} \quad (n = 0,\ n = \pm 1,\ \pm 2,\ \ldots,\ (N-1)) \tag{1}$$

where $\beta_n$ is the propagation constant of$n$-th resonant mode, $p$ represents the physical length of the unit cell, and $N$ is the number of the element [7]. When $n = 0$, the antenna radiates in zeroth-order mode of which the resonant frequency is independent of the physical length of CRLH sections, and the resonant

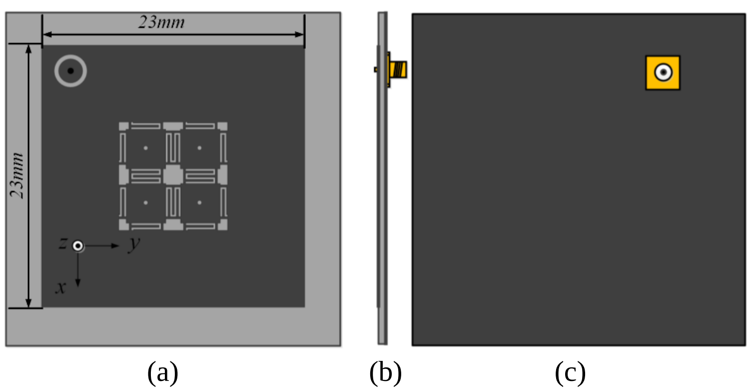



**Figure 1.** Geometry of proposed antenna, (a) top view, (b) side view, (c) bottom view.

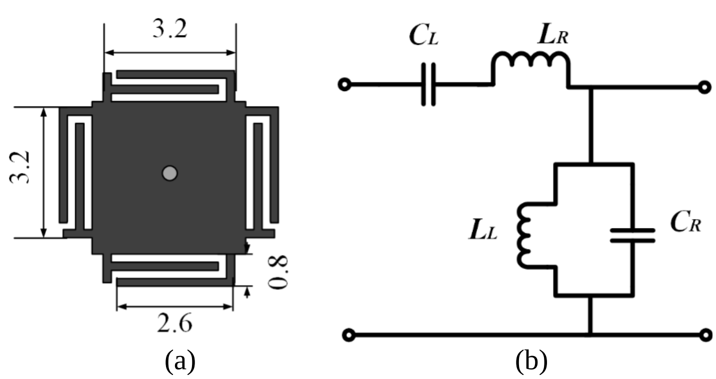



**Figure 2.** (a) Geometry of TL element (unit: mm), (b) circuit model of the TL element.

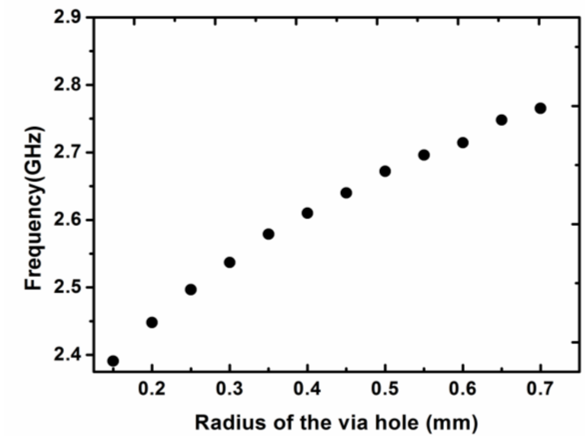



**Figure 3.** Resonant frequency of the antenna at zeroth-order mode with variation of $r$.

frequency is

$$f_0 = \frac{1}{2\pi\sqrt{L_L C_R}} \tag{2}$$

From the equations above, the zeroth mode resonant frequency is derived to be determined by $L_L$ and $C_R$, and $L_L$ is related to the dimension of via-hole in this design. Therefore, resonant frequency of zeroth-order varies with different radiuses of the metallic via-hole. It is observed in Figure 3 that with $r$ increases from 0.15 mm to 0.7 mm, other parameters remain the same, the zeroth-order resonant frequency increases from 2.4 GHz to 2.75 GHz.

## 3. MEASUREMENT AND DISCUSSION

Based on the dimensions and structure above, the proposed antenna is fabricated as shown in Figure 4. The $S_{11}$ of the fabricated antenna is measured by using a network analyzer 8719ES, and a great agreement is observed between the simulated and measured results in Figure 5. Two resonant modes including zeroth-order resonant (ZOR) and the first- order resonant (FOR) mode are obtained in this design, corresponding to the frequencies of $f_0 = 2.51$ GHz and $f_1 = 3.78$ GHz. The little deviation may come from dielectric substrate and measurement error.

To further analyse the zeroth- and the first-order resonant modes of the antenna, the electricfield distributions on top metal patch at ZOR mode and FOR mode are plotted in Figure 6. At 2.5 GHz, an

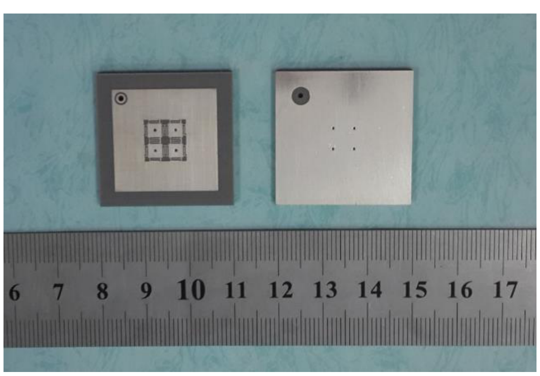



**Figure 4.** The photograph of the fabricated antenna.

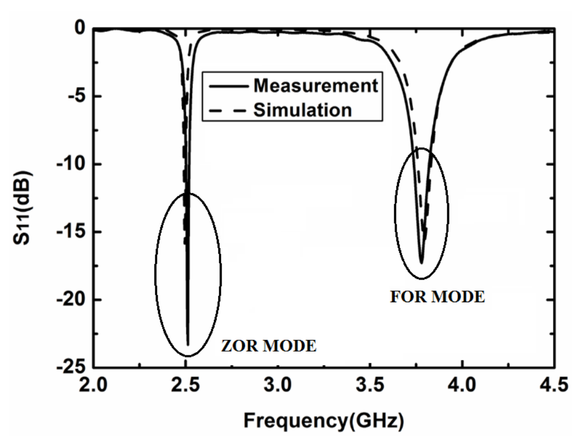
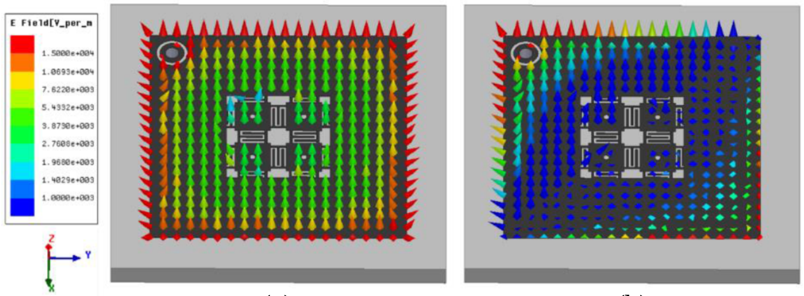
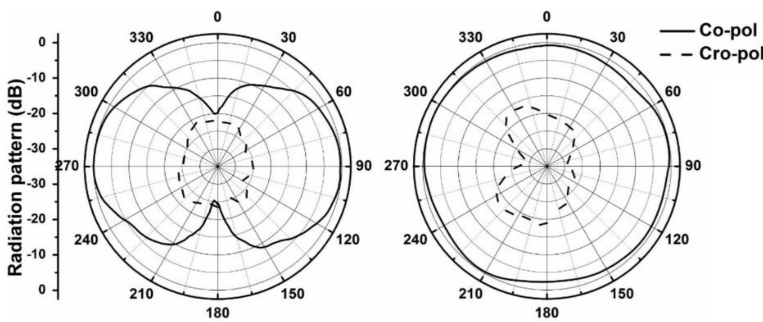



**Figure 5.** Measured and simulated $S_{11}$.



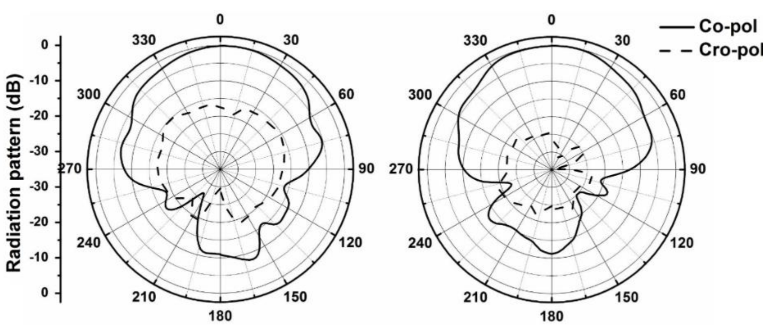

(a) (b)

**Figure 6.** The electricfield distribution of the antenna at (a) ZOR mode (2.5 GHz), (b) FOR mode (3.78 GHz).




(a) (b)

**Figure 7.** Measured radiation pattern in (a) $E$-plane, (b) $H$-plane at 2.51 GHz.




(a) (b)

**Figure 8.** Measured radiation pattern in (a) $E$-plane, (b) $H$-plane at 3.78 GHz.

in-phase vertical electric field can be observed which indicates that an infinite wavelength is supported for ZOR mode. However, at 3.78 GHz, the electricfield is out of phase alone the 45° diagonal, indicating a half wavelength distribution for FOR mode.

The measured radiation patterns of the antenna at frequency of 2.51 GHz are shown in Figure 7, and 8-shaped radiation pattern in $E$-plane with omnidirectional radiation pattern in $H$-plane can be observed. Meanwhile, unidirectional radiation pattern of the antenna at 3.78 GHz is also shown in Figure 8. The measured peak gain in first band and second band are about 1.2 dBi and 6.54 dBi, respectively.

## 4. CONCLUSIONS

A compact miniaturized zeroth-order is proposed and discussed in this paper. The TL element is well designed by using mushroom cell and interdigital capacitors, and each element is only $0.037\lambda_0 \times 0.037\lambda_0$ at operating frequency. Four elements are introduced in the proposed antenna, yielding two resonant modes of zeroth-order $f_0 = 2.51\,\text{GHz}$ and first order $f_1 = 3.78\,\text{GHz}$, with compact size of $0.25 \times 0.25 \times 0.017\lambda_0^3$ (at $f_0 = 2.51\,\text{GHz}$). Omnidirectional radiation pattern and unidirectional radiation pattern is observed at 2.51 GHz and 3.78 GHz, respectively. Good agreement is observed between the experimental and calculated results. The proposed antenna features simple structure, low profile and easy fabrication. The varied radiation pattern will allow the antenna to receive or emit wave in different angels. Therefore, the antenna can be a good candidate for wireless communication systems.

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## REFERENCES

1. Wong, K.-L., *Compact and Broadband Microstrip Antennas*, Vol. 168, John Wiley & Sons, 2004.
2. Sun, X., G. Zeng, H.-C. Yang, and Y. Li, "A compact quadband CPW-fed slot antenna for M-WiMAX/WLAN applications," *IEEE Antennas Wirel. Propag. Lett.*, Vol. 11, 395–398, 2012.
3. Dang, L., Z. Y. Lei, Y. J. Xie, G. L. Ning, and J. Fan, "A compact microstrip slot triple-band antenna for WLAN/WiMAX applications," *IEEE Antennas Wirel. Propag. Lett.*, Vol. 9, 1178–1181, 2010.
4. Augustin, G., P. C. Bybi, V. P. Sarin, P. Mohanan, C. K. Aanandan, and K. Vasudevan, "A compact dual-band planar antenna for DCS-1900/PCS/PHS, WCDMA/IMT-2000, and WLAN Applications," *IEEE Antennas Wirel. Propag. Lett.*, Vol. 7, 108–111, 2008.
5. Majedi, M. S. and A. R. Attari, "A compact and broadband metamaterial -inspired antenna," *IEEE Antennas Wirel Propag. Lett.*, Vol. 12, 345–348, 2013.
6. Gupta, D., P. Gupta, P. Chitransh, and P. K. Singhal, "Design and analysis of low pass microwave filter using metamaterial ground structure," *2014 International Conference on Signal Processing and Integrated Networks (SPIN)*, 388–392, 2014.
7. Caloz, C. and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications,* John Wiley & Sons, 2005.
8. Gong, J. Q., J. B. Jiang, and C. H. Liang, "Low-profile folded-monopole antenna with unbalanced composite right-/left-handed transmission line," *Electron. Lett.*, Vol. 48, No. 14, 813–815, 2012.
9. Xu, H.-X., G.-M. Wang, and M.-Q. Qi, "A miniaturized triple-band metamaterial antenna and polarization diversity," *Progress In Electromagnetics Research*, Vol. 137, 275–292, 2013.
10. Liu, C.-C., P.-L. Chi, and Y.-D. Lin, "Compact zeroth-order resonant antenna based on dual-arm spiral configuration," *IEEE Antennas Wirel. Propag. Lett.*, Vol. 11, 318–321, 2012.