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A Compact Wideband Short-Ended Metamaterial Antenna for Wireless Applications

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Abstract—In this article, design and analysis of a compact wideband short-ended metamaterial antenna based on composite right and left handed transmission line (CRLH-TL) is presented. The proposed antenna is configured with two different shapes (Half ring and simple gap) of series gaps and short ended boundary condition. It offers wide bandwidth by placing two different shapes of series gaps in such a manner, so that the first resonance frequency, i.e., zeroth order resonance (ZOR), second resonance frequency and third resonance frequency occur near each other, and hence combination offers wide bandwidth. Because of the applied boundary conditions, resonant modes can be controlled by series parameters of the proposed antenna structure. Further, coplanar waveguide feeding technique is used which replaces the requirement of via and allows the fabrication of a single layer antenna prototype. The proposed antenna is modeled by using ANSYS HFSS 14.0, and simulated results are verified with experimental ones of the prototype. The simulated fractional bandwidth of the proposed antenna is 52.38% centered at 3.57 GHz. Furthermore, the proposed antenna provides an average broadside gain of 2.30 dBi with average radiation efficiency of 94.95% in the entire working band of antenna.

1. INTRODUCTION

With the recent development of wireless communication, the demand for compact antennas has increased. The metamaterial antennas are well suited alternatives to meet the present demand for compact antennas. Metamaterial antennas are based on composite right- and left-handed transmission line (CRLH-TL) approach which proposes some unconventional properties such as negative refractive index and antiparallel phase and group velocities [1, 2]. A special case of CRLH-TL, i.e., zeroth order resonance (ZOR), provides a theoretical concept to miniaturize antennas [3]. Generally, these compact antennas have narrow bandwidth [4, 5] with poor radiation efficiency [6]. Hence some bandwidth enhancement techniques are required to make these antennas suitable for wireless applications. In last few years, several new approaches have been outlined. In [7], wide bandwidth is achieved by merging a number of originated modes. Further, bandwidth enhancement is obtained with asymmetrically fed CPW, which offers a large shunt capacitance along with small shunt inductance [8, 9]. A few more bandwidth enhancement techniques for short ended boundary conditions are reported in literature [10, 11], which reduce the value of quality factor. In [12], bandwidth enhancement is attained by short-ended semicircular patch which provides effective control on series inductance of the antenna.

This article presents a compact wideband metamaterial antenna using two different shapes of series gaps. Series gaps are adjusted in such a way so that the proposed antenna offers wide bandwidth along with stable far-field pattern. In order to design a uniplanar structure, the proposed antenna is fed with CPW (coplanar waveguide) technique. In addition to that, CPW feeding technique provides a high degree of design freedom and makes it suitable to integrate with wireless devices. The brief description of proposed antenna is discussed further in antenna design section.

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2. ANTENNA DESIGN

Configuration of the proposed antenna with captions is shown in Fig. 1. The overall footprint of the proposed antenna is $0.32\lambda_0 \times 0.20\lambda_0$ ($27 \times 16.8\,\text{mm}^2$), where λ_0 is the free space wavelength at $f_c = 3.57\,\text{GHz}$. The proposed antenna is based on the concept of CRLH-TL. It consists of two differently shaped series gaps within the patch and a strip connected between the ground planes and patch.

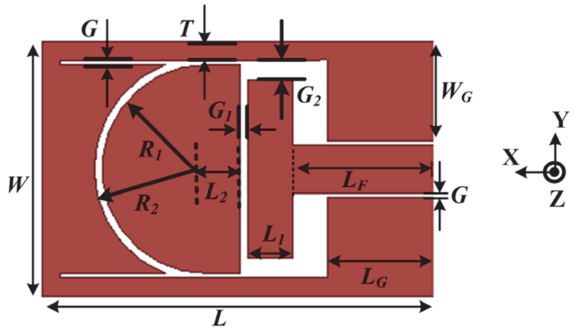


Figure 1. Layout of the short-ended wideband metamaterial antenna (All dimensions are in mm: $L = 27$, $W = 16.8$, $L_F = 10.3$, L_G= 8, $L_1 = 3$, L_2= 2.3, $R = 6.9$, $T = 1.2$, $W_G = 6.5$, G= 0.3, $G_1 = 0.5$, $G_2 = 1.3$).

Figure 2 shows the equivalent circuit modal of the suggested antenna, which is similar to the equivalent diagram of [8]. The patch with feed line plays a role for providing right-handed inductance (L_{R1}, L_{R2}, L_{R3}, and L_{R4}). Left-handed capacitance (C_{L1} and C_{L2}) is associated with both the different types of series gap. The stripline connected between ground planes and patch is responsible for offering left-handed inductance (L_L), and the coupling capacitance between the patch and strip connected between ground planes behaves as right-handed capacitance (C_{R1}, C_{R2}, C_{R3} and C_{R4}). Since the proposed antenna is applied with short-ended boundary conditions, it is well confirmed that the ZOR frequency depends on series parameter of antenna structure in Eq. (1).

$$\omega_{se} = \omega_{ZOR} = \frac{1}{\sqrt{L_R C_L}} \tag{1}$$

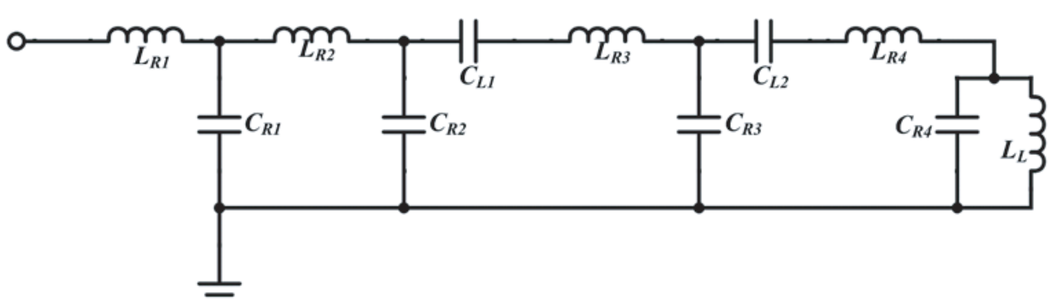


Figure 2. Equivalent circuit modal of proposed antenna.

In order to achieve wide bandwidth, ZOR has been merged with higher resonance frequencies. Fig. 3 depicts input reflection coefficient plot at distinct values of L_1. It can be noticed that as L_1 increases ZOR and second resonance frequency shift towards left side (lower frequencies), while the third resonance frequency seems almost constant. This shift in frequency is due to the increment in series inductance L_{R2}. Input reflection coefficient plot by varying R_1 is shown in Fig. 4. It is observed that increment in R_1 corresponds to the shift in ZOR and third resonance frequency towards right side (higher frequencies) while second resonance frequency is almost fixed. This shift is because of the decrement in series capacitance C_{L2}. Further, all these variations are explained by the behavior of electric filed distribution plots.

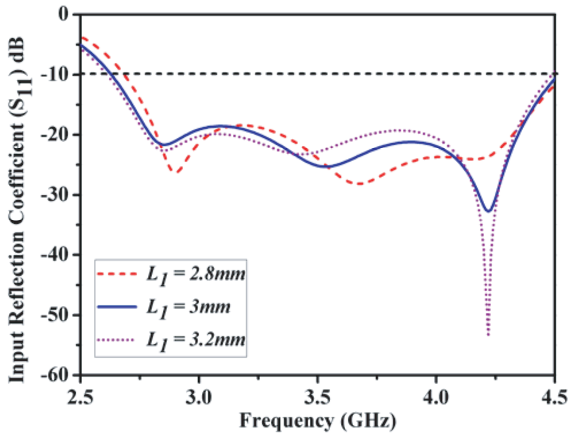


Figure 3. Input reflection coefficient plot by varying L_1 of designed antenna.

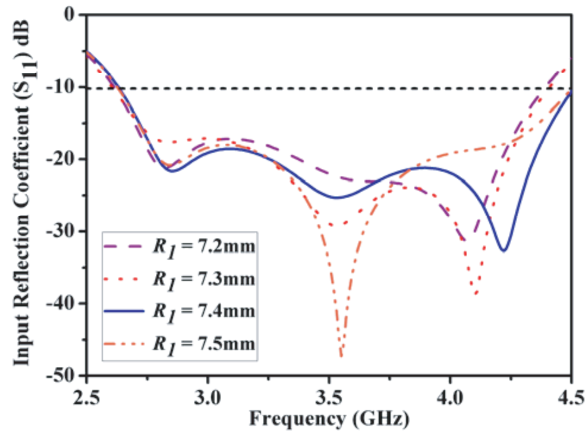


Figure 4. Input reflection coefficient plot by varying R_1 of proposed antenna.

Figure 5 shows electric field distribution plot at all three resonant frequencies. From Fig. 5(a) it can be observed that the maximum field at 2.85 GHz is confined to both the series gaps, which clearly indicates that the ZOR depends on both the series gaps. In a similar manner, Fig. 5(b) and Fig. 5(c) show that maximum electric field is confined around different series gaps, which reveals that the position of the second (3.53 GHz) and third (4.22 GHz) resonant frequencies can be controlled by these gaps, respectively.

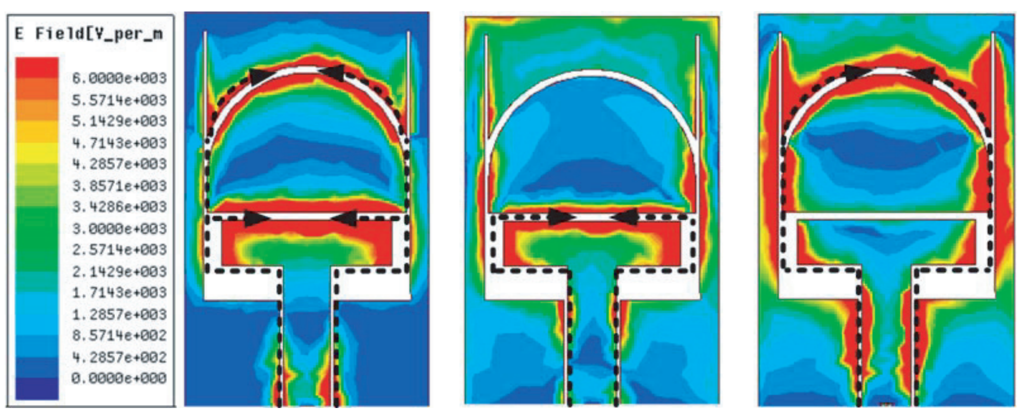


Figure 5. Electric field distribution of proposed antenna at (a) ZOR (2.85 GHz), (b) second resonance (3.53 GHz), (c) third resonance (4.22 GHz).

3. RESULT AND DISCUSSIONS

Figure 6 shows the experimentally developed antenna prototype. It is printed on an FR-4 epoxy glass substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$) of thickness 1.6 mm. Input reflection coefficient is measured using Agilent PNA-L network analyzer N-5230A. The simulated and measured input reflection coefficient graphs are shown in Fig. 7. The simulated and measured input reflection coefficients are in good agreement with each other. However, a slight difference is observed between measured and simulated second and third resonance frequencies, which may be due to substrate non-uniformity and connector soldering losses. The proposed structure offers 52.38% simulated impedance bandwidth and 49.72% measured impedance bandwidth centered at 3.57 GHZ and 3.56 GHz, respectively.

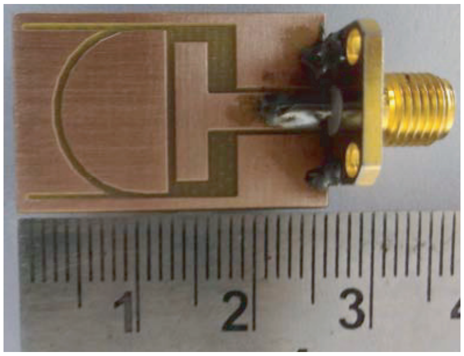


Figure 6. Experimentally developed antenna prototype.

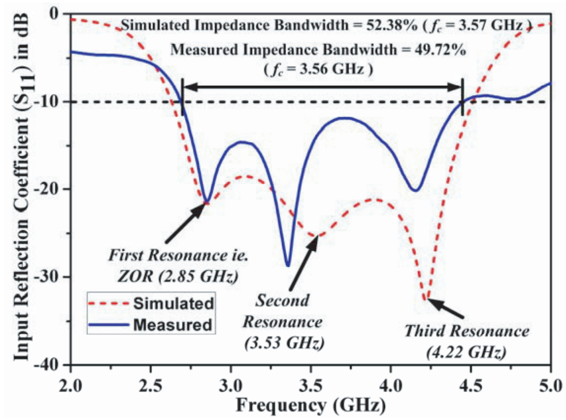
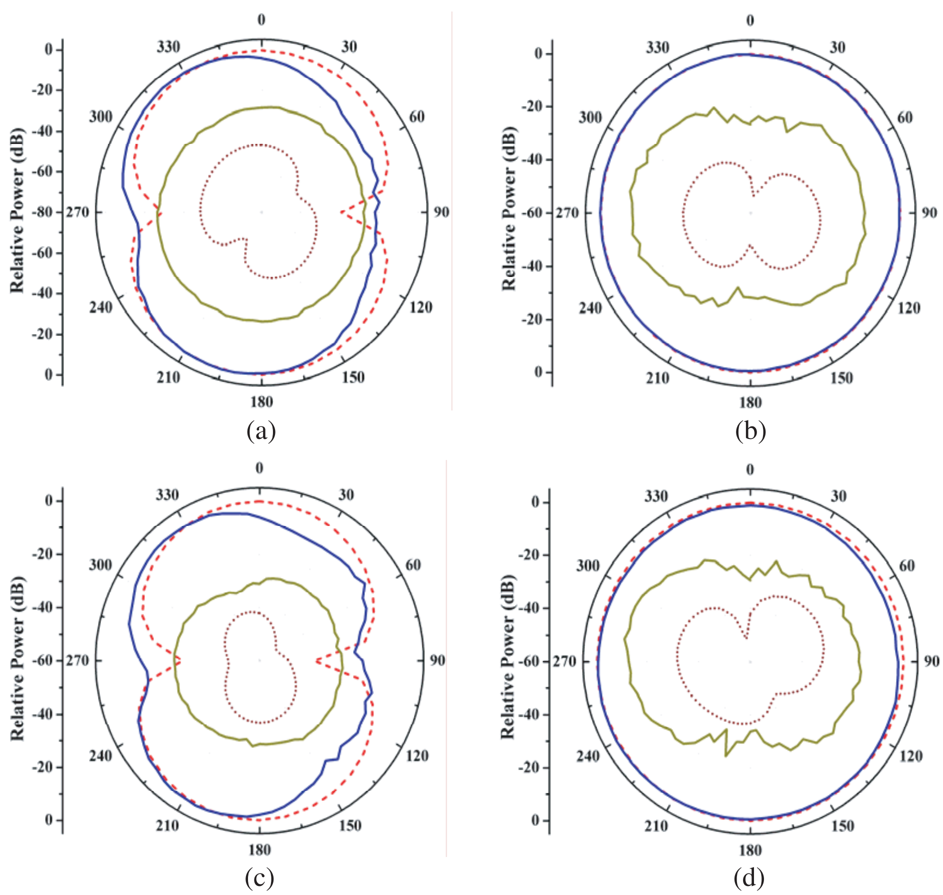


Figure 7. Simulated and measured input reflection coefficients.

Figure 8 depicts simulated and measured radiation patterns at all the resonant peaks. The proposed antenna provides dipolar radiation pattern in xz-plane and omnidirectional radiation pattern in yz-plane at all resonant frequencies. Simulated radiation efficiency along with simulated and measured broadside gains is presented in Fig. 9. Average radiation efficiency of designed antenna is 94.95% with the peak value of 96.62% throughout working band of the antenna. In addition to above, the proposed antenna also offers average simulated broadside gain of 2.30 dBi in complete working band of the antenna. Measured gain value varies near the simulated gain at all resonant frequency.



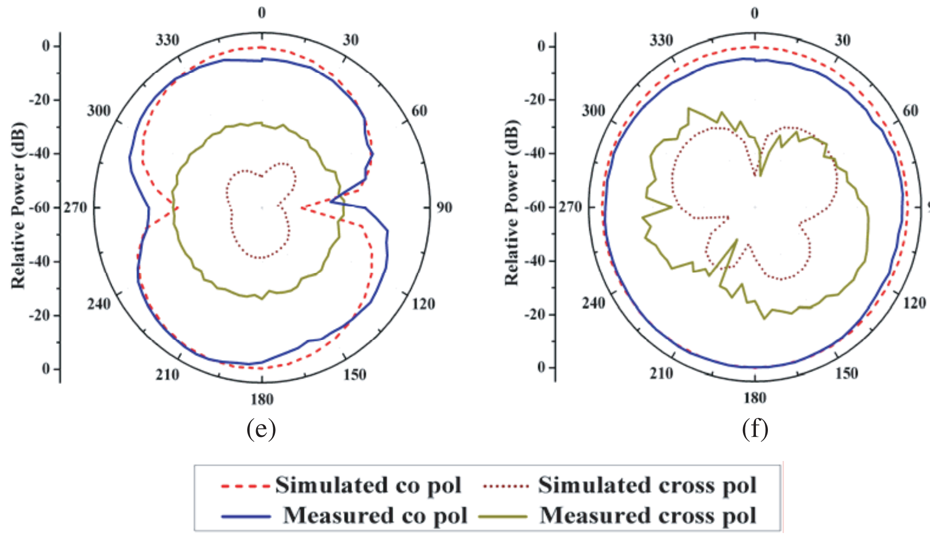


Figure 8. Simulated and measured far-field patterns of proposed antenna. (a) xz-plane at 2.85 GHz. (b) yz-plane at 2.85 GHz. (c) xz-plane at 3.53 GHz. (d) yz-plane at 3.53 GHz. (e) xz-plane at 4.22 GHz. (f) yz-plane at 4.22 GHz.

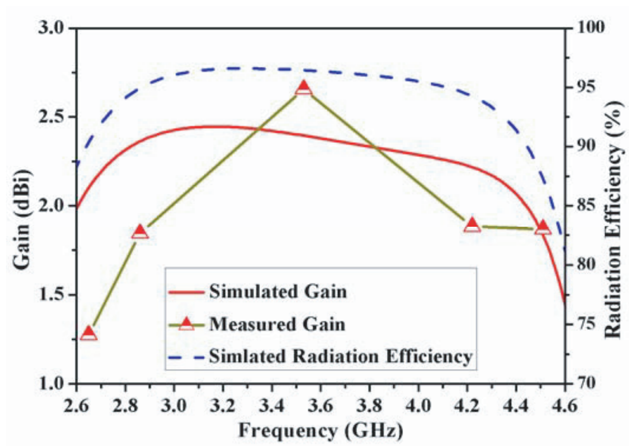


Figure 9. Simulated and measured broadside gains with simulated radiation efficiency of proposed antenna.

Table 1 shows comparison between previously published works and this work. It is clear from the table that the proposed structure offers wide bandwidth and high radiation efficiency compared with earlier published structures.

Table 1. Comparison of proposed structure with earlier reported work.

Parameter	This work	Previously reported work			
		[2]	*[10]*	*[11]*	*[12]*
Resonant Frequency (GHz)	3.57	2.15	2.21	2.16	3.60
Antenna footprint (λ_0)	0.32×0.20	0.07×0.22	0.18×0.11	0.2×0.14	0.27×0.13
Inpedance Bandwidth (%)	52.38	20.3	6.1	15.1	23.64
Gain (dBi)	2.30	3.35	1.4	1.62	2.26
Radiation Efficiency (%)	94.95	66	77	72	95.89

4. CONCLUSION

A compact wideband metamaterial antenna for wireless applications is presented in this article. The proposed antenna consists of two different shaped series gaps, which are responsible for the origin of three resonance peaks. In order to achieve wide bandwidth, all the modes are merged. The proposed antenna offers compactness ($0.32\lambda_0 \times 0.20\lambda_0$) with simulated fractional bandwidth of 52.38% centered at 3.57 GHz. The designed antenna is a monopole antenna offering dipolar and omnidirectional radiation pattern in xz-plane and yz-plane, respectively. Simulated average radiation efficiency of the proposed antenna is 94.95% in the complete operating band. Additionally, this antenna provides an average broadside gain of 2.30 dBi with a peak value of 2.44 dBi.

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