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Multiband Antenna Based on Loading a CPW-Fed Monopole with One CRLH-TL Unit Cell

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Abstract—A Coplanar Waveguide (CPW)-fed monopole loaded with Composite Right/Left Handed Transmission Line (CRLH-TL) unit cell is presented in this letter. Multiband is achieved due to the nonlinear dispersion relation of the CRLH-TL unit cell. The CRLH-TL unit cell supports a fundamental LH wave (phase advance) at lower frequencies and a RH wave (phase delay) at higher frequencies. By loading CRLH-TL unit cells with a conventional monopole, the resonant frequency of higher order mode can be decreased, and zeroth-order mode or even negative-order mode can be achieved. As a result, the proposed antenna operates at 1.43 GHz, 2.58 GHz, 3.31 GHz and 4.4 GHz. Finally the modified antenna is fabricated and measured; measurements and EM simulations are in a good agreement that confirms the proposed theory.

1. INTRODUCTION

With the rapid development of wireless communication system, multi-frequency antennas with satisfactory gain and omnidirectional radiation are needed. In response to this increasing demand, metamaterials (MTMs) show unique advantages. MTMs are artificial structures designed to exhibit specific electromagnetic properties not commonly found in nature, such as negative permittivity and positive permeability. As one type of MTMs, the concept of CRLH-TL was introduced by Caloz and Itoh in [1].

Recently, many techniques of loading conventional antennas with MTM unit cells have been under investigation [2–4]. Such MTM unit cells have been used for providing multi-frequency operation, reducing the size of antennas and extending the bandwidth. In [5], several microstrip-fed monopole antennas are loaded with CRLH-TL unit cells, which allow the antennas to operate at zeroth-order mode or even negative-order mode.

In this letter, we present a CPW-fed monopole antenna loaded with one CRLH-TL unit cell. The unique dispersion relation of the CRLH-TL unit cell is combined with the resonant characteristic of the conventional monopole to achieve zeroth-order mode and lower positive-order mode. In the proposed antenna structure, the unit cell is based on Complementary Split Single Ring Resonator (CSSRR) [6]. By loading this kind of CRLH-TL unit cell, lower and multiple operating frequencies are achieved without augmenting the oversize of the antenna. And not only that, the radiation patterns of the proposed antenna are monopole-like at all operating bands. Meanwhile, the antenna without a via hole is easily fabricated.

2. THEORY

The idea of loading CPW-fed monopole antenna with CRLH-TL unit cell is conceptually illustrated in Figure 1. Mathematically, the resonant condition of the monopole antenna occurs when the total phase

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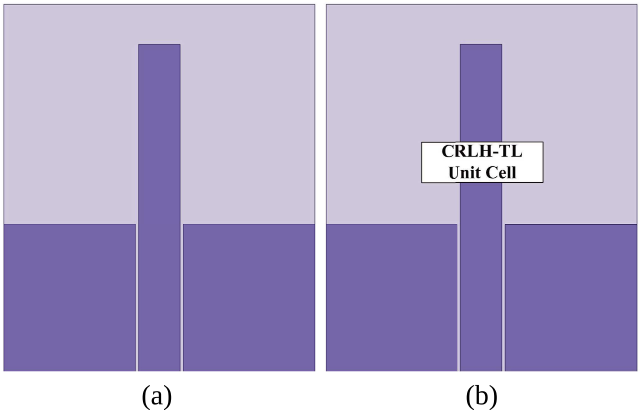


Figure 1. (a) Conventional CPW-fed monopole. (b) CPW-fed monopole loaded with one CRLH unit cell.

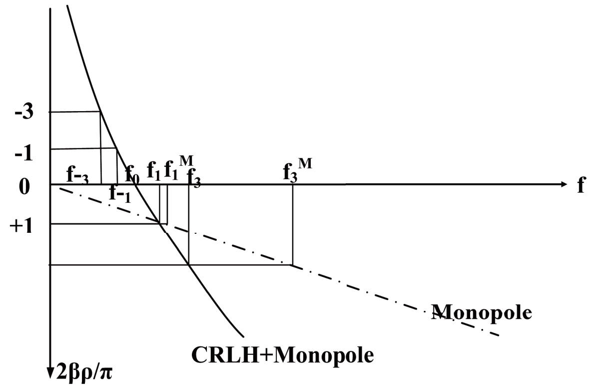


Figure 2. Resonant condition of conventional monopole and monopole loaded with CRLH-TL unit cell.

shift across the monopole satisfies (1) [7]:

$$\varphi_{total} = \beta\rho = \varphi_{mono} + \varphi_{CRLH} = n \times \pi/2 \quad n = 0, \pm 1, \pm 3, \ldots \tag{1}$$

where

φ_{total}: total phase shift;
β: phase constant;
ρ: the physical length of antenna;
φ_{mono}: phase shift corresponding to the monopole length without the CRLH-TL unit cell;
φ_{CRLH}: phase shift caused by CRLH-TL unit cell;
n: mode order.

Equation (1) is true only within the pass band of the CRLH-TL unit cell. According to the dispersion relation of the CRLH-TL and the conventional transmission line, the resonant conditions of the conventional CPW-fed monopole antenna and the modified antenna can be conceptually depicted in Figure 2.

The CRLH-TL unit cell, with a nonlinear dispersion, supports a fundamental LH wave (phase advance) at lower frequencies and a RH wave (phase delay) at higher frequencies [8]. As can be observed from Figure 2, by loading CRLH-TL unit cells with a conventional monopole, the resonant frequency of the higher order mode can be decreased and the zeroth-order mode or even negative-order mode can be achieved.

3. CRLH-TL UNIT CELL DESIGN AND ANALYSIS

Reference [5] proposes a novel CRLH-TL unit cell, which is based on the theory of conventional unit cell presented in [1]. In this article, the proposed CRLH-TL unit cell consists of a CSSRR and a gap.

Table 1. Physical dimensions and lumped equivalent circuit values of the CRLH-TL unit cell.

Physical Dimensions		Lumped elements values	
a	28 mm	L	3.86 nH
$a1$	31 mm	C_g	1.67 pF
b	2.6 mm	C	32.45 pF
$b1$	10 mm	L_c	3.12 nH
$g1$	1 mm	C_c	1.88 pF
$g2$	1 mm		

The former one is etched on the ground plane and the later on the conductor strip. The layout of the CRLH-TL unit cell is illustrated in Figure 3, and its related geometrical parameters are described in Table 1. The substrate is epoxy bonded fiber-glass board with the permittivity of 4.3, thickness of

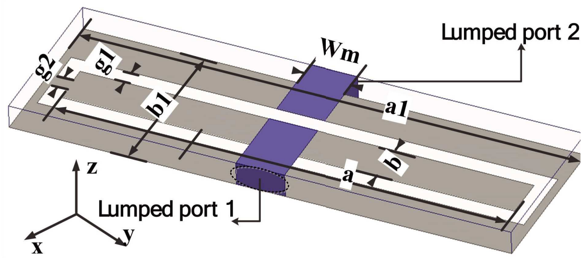


Figure 3. Layout of the CRLH-TL unit cell based on CSSRR. Dark gray is metal on top layer, light gray is metal on bottom layer.

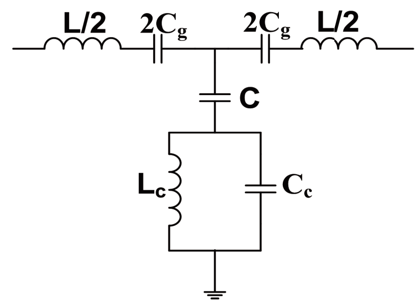


Figure 4. Equivalent circuit model of the CRLH-TL unit cell.

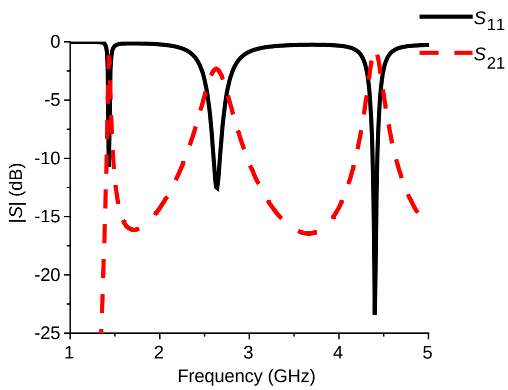


Figure 5. Transmission and reflection coefficients of the CRLH-TL unit cell scattering parameters for the CRLH-TL unit cell.

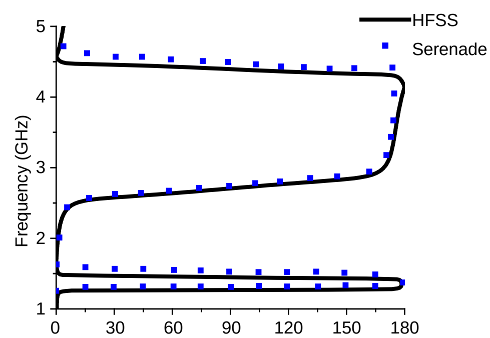


Figure 6. Equivalent circuit (Serenade) versus full-wave simulated (HFSS) dispersion relation for the CRLH-TL unit cell.

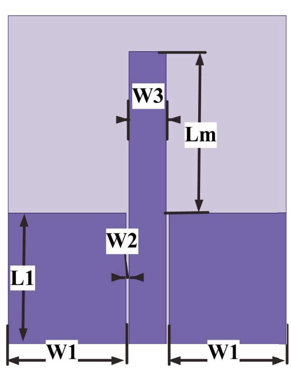


Figure 7. Layout of the conventional CPW-fed monopole antenna. Dark gray is metal on top layer.

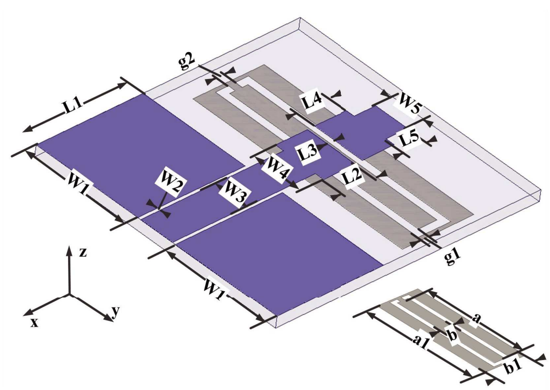


Figure 8. Layout of the CPW-fed monopole antenna loaded with CRLH-TL unit cell. Dark gray is metal on top layer, light gray is metal on the bottom layer.

1.5 mm and tangent loss of 0.001. Then simulated model is created in HFSS, the excitations are lumped ports, as shown in Figure 3. In the model, experimental setup is the same as the simulated setup of the micro-strip filter.

The equivalent circuit model of the CRLH-TL unit cell is shown in Figure 4. In this model, C_c and L_c account for CSSRR, C_g is the gap capacitance, C is the coupling capacitance between the line and the part surrounded by the slot, L is the line inductance.

The electrical parameters extracted by circuit simulation software Serenade are depicted in Table 1. And Figure 5 shows the transmission and reflection coefficients of the CRLH-TL unit cell. In addition, the dispersion relation of the CRLH-TL unit cell, which has been obtained from (2) [9], is illustrated in

Table 2. Dimensions of the CPW-fed monopole antenna loaded CRLH-TL unit cell and conventional CPW-fed monopole antenna.

Symbol	Conventional CPW-fed monopole (mm)	CPW-fed monopole loaded with CRLH-TL unit cell (mm)
L_1	15	15
L_2	-	4.5
L_3	-	1
L_4	-	4.5
L_5	-	3
L_m	18	-
W_1	15	15
W_2	0.4	0.4
W_3	4.7	4.7
W_4	-	7.1
W_5	-	4.7
a	-	28
a_1	-	31
b	-	2.6
b_1	-	10
g_1	-	1
g_2	-	1

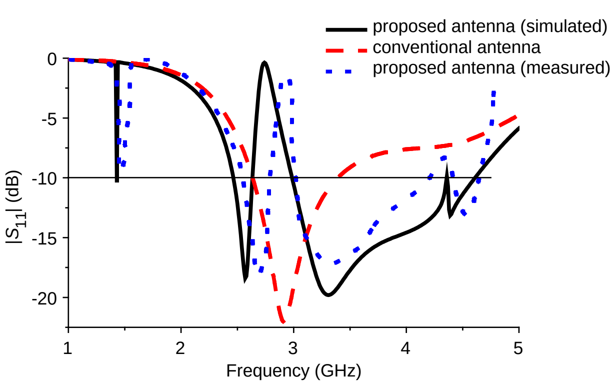


Figure 9. Reflection coefficient of the CPW-fed monopole antenna loaded with CRLH-TL unit cell and conventional CPW-fed monopole antenna.

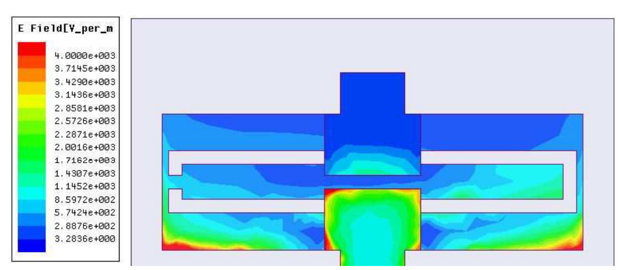


Figure 10. Magnitude of the electric field on both the top and bottom patch of the antenna at 3.31 GHz.

Figure 6. The agreement between the electrical and full-wave simulations is excellent.

$$\beta\rho = \cos^{-1}\left(\frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{12}}\right) \tag{2}$$

where β is the phase constant, ρ the length of the unit cell, and S_{11}, S_{12}, S_{21}, S_{22} are the scattering parameters of the CRLH-TL unit cell.

As can be observed from Figure 5 and Figure 6, the proposed unit cell is unbalanced with the series resonant frequency of 1.4 GHz and shunt resonant frequency of 2.51 GHz. Then the third resonant frequency of 4.4 GHz shown in Figure 5 is the first positive order mode of the CRLH-TL unit cell.

4. INTEGRATION OF THE CRLH-TL UNIT CELL WITH THE CPW-FED MONOPOLE ANTENNA

The prototypes of the conventional CPW-fed monopole and CPW-fed monopole loaded with CRLH-TL unit cell are illustrated in Figure 7 and Figure 8, respectively. Then, Table 2 shows the dimensions of both prototypes. The substrate is epoxy bonded fiber-glass board with the permittivity of 4.3, thickness of 1.5 mm and tangent loss of 0.001.

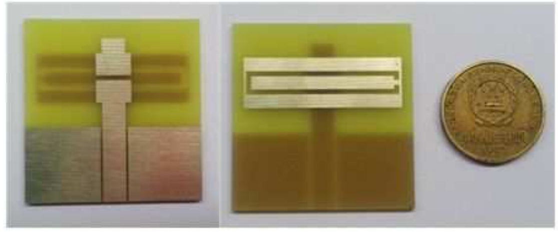
Compared to the conventional CPW-fed monopole antenna, the modified antenna operates at four bands which can be observed from Figure 9.

The first band located at 1.43 GHz lies within the LH region of the CRLH-TL unit cell. At this frequency, the CRLH-TL unit cell provides a phase advance that is exactly equals to the phase delay provided by the monopole and (1) satisfies $n = 0$. In other words, $\beta = 0$ and the antenna operates at zeroth-order resonance (ZOR) mode. The ZOR mode has an infinite wavelength so that the resonant frequency is not related with the antennas size. The second located at 2.58 GHz lies within the RH region of the CRLH-TL unit cell. At this frequency, the CRLH-TL unit cell provides a phase delay that added to the phase delay provided by the monopole is $\pi/2$, and (1) satisfies $n = 1$. The third located at 3.31 GHz lies within the stop band of the CRLH-TL unit cell at which the slot capacitor can be considered as open circuit. So the current has no place to go except coupling to the patch in the back of the substrate, and satisfies the resonant condition of the loaded patch. The conclusion can be obtained from Figure 10, which shows the magnitude of the electric field on both the top and bottom patch of the antenna. The last located at 4.4 GHz lies within the first positive order region of CRLH-TL unit cell. At this frequency, the CRLH-TL unit cell provides a phase delay that added to the phase delay provided by the monopole is $3\pi/2$ and (1) satisfies $n = 3$.

Above all, the ZOR mode is achieved with a very narrow bandwidth; meanwhile, frequencies of the first and third order mode are lower than the conventional CPW-fed monopole.

Finally, the CPW-fed monopole loaded with CRLH-TL unit cell is fabricated and measured. The photographs of the proposed antenna are shown in Figure 11.

The simulated and measured radiation patterns of proposed antenna on the E-plane and H-plane are shown in Figure 12. As illustrated, measurements and simulations are in a good agreement with theoretical predictions.



(a) (b)

Figure 11. Photographs of the proposed antenna. (a) Top layer. (b) Bottom layer.

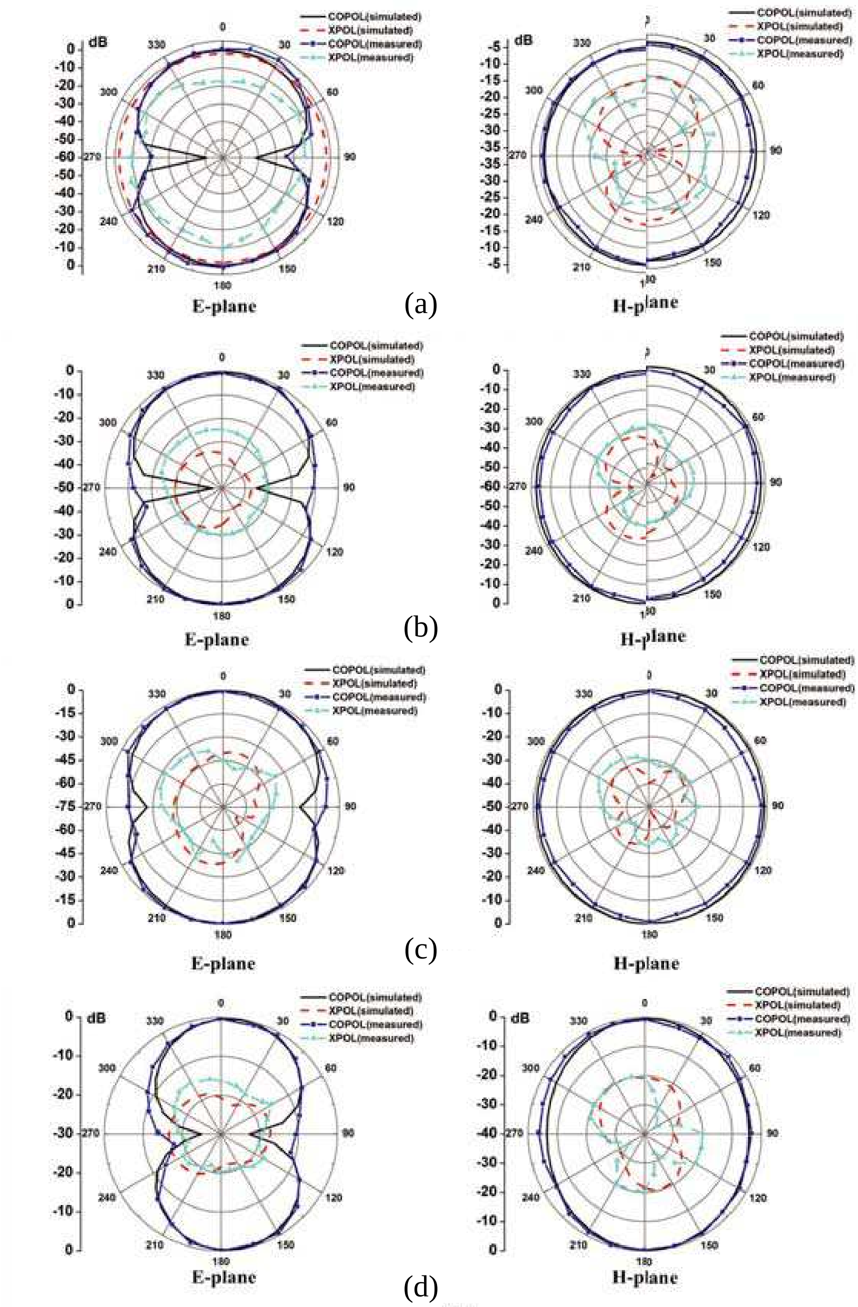


Figure 12. Simulated and measured radiation patterns of proposed antenna: (a) $f = 1.45\,\mathrm{GHz}$, (b) $f = 2.58\,\mathrm{GHz}$, (c) $f = 3.31\,\mathrm{GHz}$, (d) $f = 4.40\,\mathrm{GHz}$.

5. CONCLUSION

In this letter, a single CSSRR-based CRLH-TL unit cell has been loaded with a CPW-fed antenna in order to achieve operating at multiple bands. The proposed antenna combines the nonlinear dispersion relation of the CRLH-TL and the omnidirectional radiation of the monopole. So it can operate at zeroth-order mode and lower positive-order mode with quasi-omnidirectional radiation patterns. These characters make the idea of loading conventional antennas with CRLH-TL unit cells well suited for the emerging multiband wireless system.

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