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Research Article

Broadband Circularly Polarized CPW-Fed Monopole Antenna with a Via-Free CRLH-TL Unit Cell

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This article presents a broadband circularly polarized composite right/left-hand (CRLH) antenna. A compact microstrip line inductor and an interdigital capacitor are used to form a left-handed parallel inductor and a left-handed series capacitor. The metamaterial parameters of the series inductor and the parallel inductor are optimized. The asymmetric perturbation is introduced to excite the circularly polarized (CP) electromagnetic wave. The influence of interdigital capacitance on the electrical performance of the antenna is analyzed theoretically and experimentally. The value of C_L is changed to reduce the electrical size of the antenna, and the resonant frequency of the antenna is reduced accordingly. The physical dimensions of this CPW-Fed monopole antenna are 25 mm ∗ 24 mm ∗ 1 mm. The measured 10 dB wide impedance bandwidth is 79.5%, and the measured 3 dB axial ratio (AR) bandwidth is 56.2%.

1. Introduction

Caloz and Itoh have presented the transmission line theory of left-handed (LH) materials. A transmission line structure with periodic inductance and capacitance loading is used to realize left-handed materials [1]. The input impedance and radiation patterns of an antenna can be manipulated by loading parameters of a metamaterial transmission line (TL) unit cell. This approach can reduce the resonant frequency and result in multiband impedance matching [2]. Based on the composite right/left-hand transmission lines, a kind of artificial structure with special phase characteristics and an electrically small zeroth-order resonant antenna are analyzed in [3]. However, the radiation models of those electrically small antennas are of linear polarization [1–3].

A circularly polarized antenna can suppress the multipath effect, reduce the polarization mismatch, and improve the receiver gain. The development trend of circularly polarized microstrip antenna is miniaturization, broadband, multiband, and multifunction. At present, the main disadvantages of circularly polarized microstrip antennas are large size, narrow bandwidth, and low radiation efficiency.

Several kinds of broadband circularly polarized antennas are reported in [4, 5]. However, the overall electrical size of the traditional microstrip circularly polarized antenna is relatively large. The electrical length of the antenna is proportional to the operating wavelength. Some researchers use microwave metamaterial loading to reduce the size of microstrip antennas and introduce phase perturbation to make the antennas radiate circularly polarized electromagnetic waves.

However, the bandwidth of these antennas is narrow [6, 7], which limits their application in mobile communication systems. A compact circularly polarized antenna is designed by microwave metamaterial loading, but its 3 dB axial ratio bandwidth is narrow [8]. By loading the conventional right-handed TL feeding network, the 3 dB AR bandwidth of the CRLH-TL CP antenna is broadened [9]. By loading the mushroom metamaterial structure, a dual-band CP patch antenna was excited −1st and +1st resonance modes [10]. Based on metamaterial zeroth-order resonance (ZOR) resonance, a narrow band CP antenna is proposed [11]. Their size is relatively large. A radio frequency identification reader CP antenna based on the CRLH negative order resonance is proposed by loading a metamaterial gap capacitor and metallic screws. The AR bandwidth of these metamaterial CP antennas is relatively narrow [12, 13]. In order to overcome the shortcomings of traditional microstrip circularly polarized antennas, researchers have used microwave metamaterial loading to design miniaturized circularly polarized antennas. That is to say, on the basis of an ordinary microstrip circularly polarized antenna, the left-handed phase compensation effect of microwave metamaterial is introduced to design a miniaturized circularly polarized antenna, which can improve the performance of traditional microstrip circularly polarized antennas, reduce the size, and increase the bandwidth. The compact CP antennas use an epsilon negative transmission line [14].

In this paper, a compact circularly polarized microstrip antenna is designed by loading an asymmetric CRLH-TL into the traditional coplanar waveguide-fed microstrip antenna. The asymmetric CRLH-TL line structure is equivalent to the introduction of perturbation. The phase difference is 90°. Two orthogonal modes are excited. The microstrip line embedded between the metal patch and the ground acts as a left-handed shunt inductance. The interdigital capacitor on the right side of the patch acts as a left-handed series capacitor. By adjusting its structure and size, the antenna radiates circularly polarized waves in a wide frequency band. The asymmetric coplanar CRLH-TL antenna has the advantage of wide 3 dB axial bandwidth and compact antenna configuration. The CP antenna is a good candidate for broadband mobile communications systems, such as satellite communication systems and navigational systems.

2. Antenna Design

The structure of the proposed CP antenna is shown in Figure 1. The antenna consists of three parts: a metal patch, a coplanar waveguide feed, and a coplanar ground. In order to achieve miniaturization and improve antenna bandwidth, one microstrip line is used as a parallel inductor. A group of interdigital capacitors are used as series capacitors, which are printed on an F4B-2 dielectric substrate with a relative permittivity of 2.65 and a thickness of 1.0 mm. The circular polarization wave is excited by a perturbation in an asymmetric structure.

By controlling the equivalent circuit parameters, the asymmetric CRLH-TL structure overcomes the limitations of the traditional microstrip line. It is easy to manufacture a low-profile, wide bandwidth, high-radiation efficiency antenna. The adaptive optimization algorithm is used to optimize the structure and size of the CRLH-TL antenna, so that the impedance matching characteristic of the structure is very good. The CPW feed structure is simple. This structure can directly match the source without any other matching network. The CRLH-TL structure not only reduces the antenna size but also broadens the antenna bandwidth. Table 1 provides the optimized parameter values of the proposed CP antenna.

Figure 2 shows the equivalent circuit model of the CRLH-TL. The metal patch, interdigital capacitor, and coplanar floor constitute a microwave metamaterial CRLH-TL,

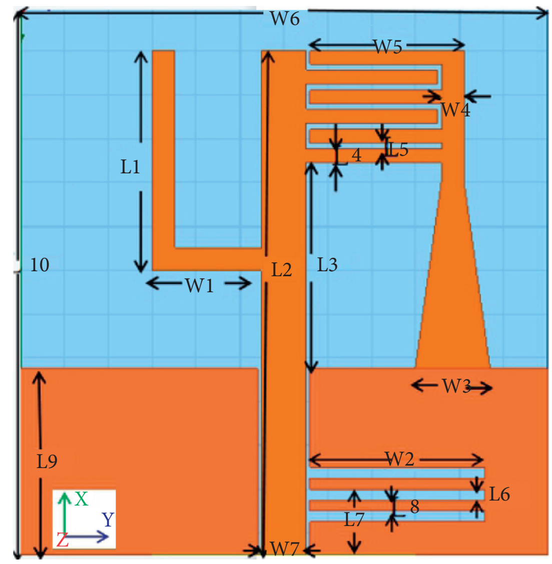


Figure 1: Configuration of the CP antenna.

Table 1: Optimized parameter values (unit: mm).

L1	L2	L3	L4	L5	L6	L7	L8	L9
10	22.5	9	0.6	0.3	0.5	3.2	0.5	8.5
L10	W1	W2	W3	W4	W5	W6	W7	
25	4.8	7.8	3.2	1.0	6	24	2.2	

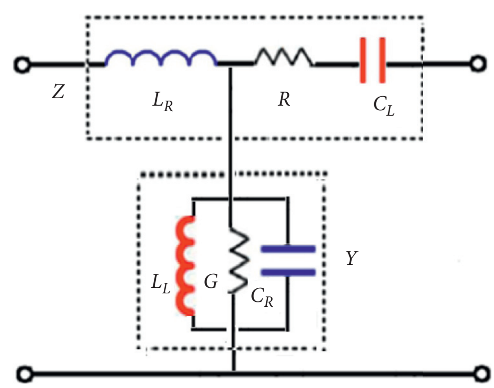


Figure 2: Equivalent circuit model of the CRLH-TL.

which can simultaneously excite backward and forward waves. Microwave metamaterial TLs with left-handed and right-handed characteristics provide both positive and negative phase-shift constants. The right-handed shunt capacitor C_R is owing to the coupling between the main radiator and ground. The right-handed series inductance L_R is due to a rectangular patch. The interdigital capacitor on the patch is the series left-handed capacitor C_L. The microstrip line between the interdigital capacitor and the ground plane is the left-handed shunt inductance L_L.

Through the equivalent circuit of the CRLH transmission line, the principles of subwavelength resonance and bandwidth expansion are analyzed to solve the problems of large size and complex feeding of circularly polarized antenna.

Equivalent impedance is calculated as

$$Z = j\omega L_R + 1/j\omega C_L. \quad (1)$$

Equivalent admittance is calculated as

$$Y = j\omega C_R + 1/j\omega L_L. \quad (2)$$

The equivalent circuit model of the CRLH transmission line is analyzed by the periodic boundary condition and Bloch Floquet theorem. In order to simplify the calculation and ignore the loss, the dispersion relation of CRLH-TL is

$$\cos(\beta\Delta x) = 1 + \frac{1}{2}\left(\frac{L_R}{L_L} + \frac{C_R}{C_L} - \omega^2 L_R C_R - \frac{1}{\omega^2 L_L C_L}\right). \quad (3)$$

The bandwidth of CRLH-TL resonance is mainly determined by the left-hand shunt inductance L_L and the right-hand shunt capacitance C_R. The fractional bandwidth is [15]

$$FBW = G\sqrt{L_L/C_R}, \quad (4)$$

where G is the shunt conductance of the CRLH-TL. The special coplanar waveguide structure is provided with a small shunt capacitance. The short-circuit microstrip line can increase the left-hand shunt inductance, which improves the impedance bandwidth of the CRLH-TL antenna.

3. Simulation and Experimental Results

A fabricated prototype for the CRLH CP antenna is shown in Figure 3. The CRLH-TL has the characteristics of phase compensation, larger bandwidth, and lower loss. When the other parameters of the antenna remain unchanged, the interdigital distance of interdigital capacitance is reduced; that is, the value of C_L is changed to achieve the purpose of reducing the electrical size of the antenna. The resonant frequency of the antenna is reduced accordingly. The capacitance and inductance of CRLH-TL can be realized by independent components or microstrip lines. The CP antenna is simulated by the Ansoft HFSS version 16.

The S scattering matrix is obtained by using the transmission line matrix. The dispersion diagram of the CRLH-TL is plotted using the equation

$$\cos(\beta\Delta x) = \frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{21}}. \quad (5)$$

The dispersion diagram characteristic of the proposed CRLH-TL antenna is shown in Figure 4. The ZOR occurs at 4.23 GHz, where the value of $\beta\Delta x = 0$. The right-handed region and the left-handed region can be separated by ZOR. The left-handed region with a negative phase velocity is the distinctive characteristic of the CRLH-TL. The ZOR frequency has an infinite wavelength. The antenna can be designed particularly compact.

Different from the previous zeroth-order resonance CP antenna, the CRLH-TL structure can excite multifrequency resonance, and the antenna can radiate multiorder circularly polarized waves at the same time. Theoretical and experimental results show that the resonant frequency, bandwidth, radiation efficiency, size, and circular polarization of the

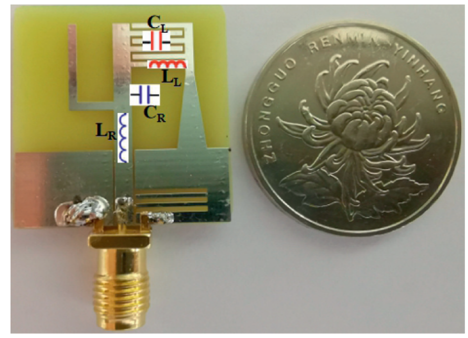


Figure 3: Photograph of the fabricated antenna with corresponding lumped elements.

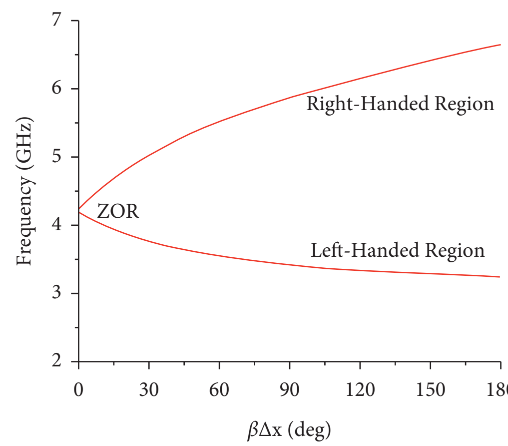


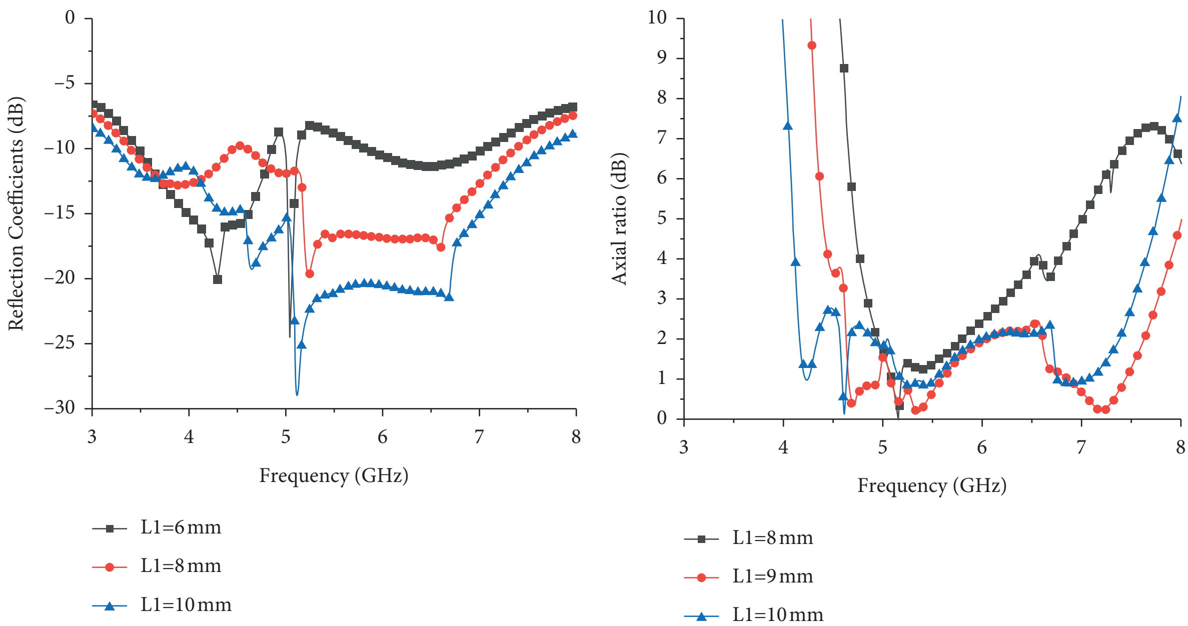
Figure 4: Dispersion diagram characteristic of the proposed CRLH-TL antenna.

CRLH-TL antenna are controllable. When the other parameters of the antenna remain unchanged, the scanning parameter optimization analysis shows the relationship between interdigital capacitance structure and antenna bandwidth.

Figure 5 describes the simulated reflection coefficient and axial ratio characteristics. The axial ratio bandwidth and center resonant frequency of the antenna are greatly affected by the different antenna lengths. With the decrease of L1, the high-frequency band appears slow blue-shifted. When L1 is 10 mm, the axial ratio bandwidth overlapped in the impedance bandwidth is the widest.

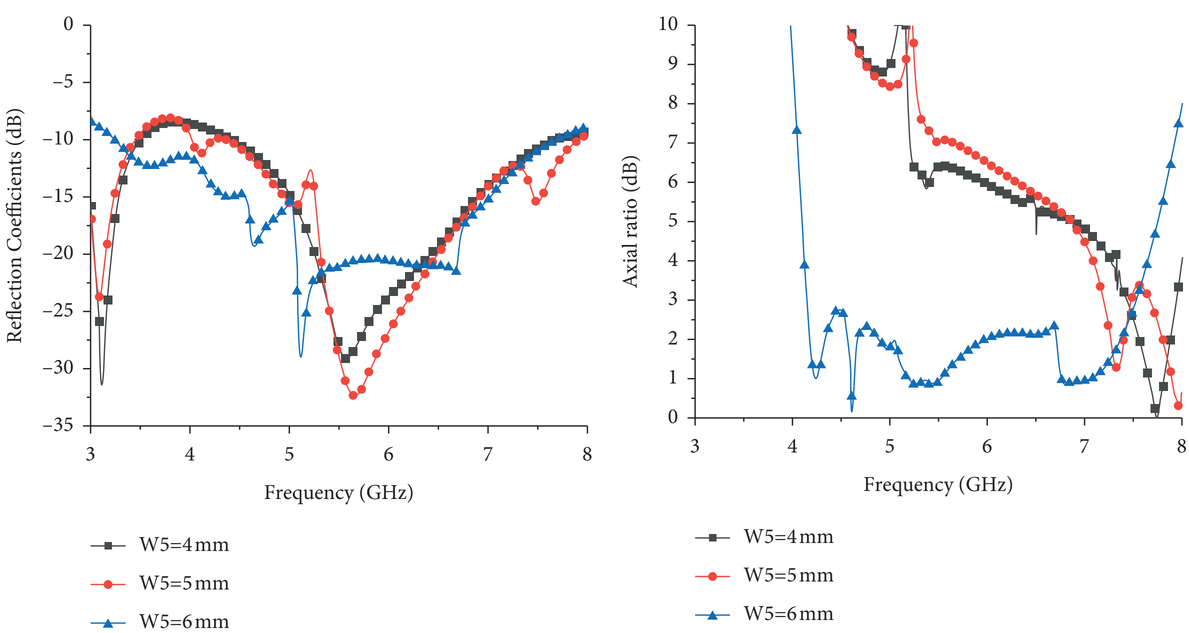
In Figure 6, it is noted that the simulated reflection coefficient and axial ratio characteristics with different widths of W5 has a great influence on the bandwidth. The value of the impedance and AR bandwidth deteriorates when W5 is reduced.

The physical dimensions of this CRLH CP antenna are 25 mm ∗ 24 mm ∗ 1 mm. The S_{11} responses of the fabricated CP antenna are measured by a network analyzer Agilent E8361 A. Figure 7 indicates that the measured 10 dB impedance bandwidth is 79.5% (3.31–7.68 GHz), and the simulated impedance bandwidth is 81.2% (3.24–7.67 GHz). The measured 3 dB AR bandwidth is 56.2% (4.29–7.64 GHz), and the simulated 3 dB AR bandwidth is 58.1% (4.14–7.53 GHz).



(a) (b)

Figure 5: Parametric study for the proposed antenna with different L1: (a) reflection coefficients and (b) AR.



(a) (b)

Figure 6: Parametric study for the proposed antenna with different widths of W5: (a) reflection coefficients and (b) AR.

Figure 8 shows the measured normalized radiation patterns of the proposed CRLH CP antenna at 5.50 GHz. In two principal planes, the polarization of the CP antenna is a left-hand circular polarization (LHCP) wave.

Figure 9 shows the surface current distributions at $\omega t = 0^\circ (90^\circ)$ and $\omega t = 180^\circ (270^\circ)$. When $\omega t = 0^\circ$, the predominant radiating currents are in 90° direction. When $\omega t = 90^\circ$, the predominant radiating currents are in 180° direction. The dominant surface currents turn in a clockwise direction toward the $+z$-direction. With equal magnitude and 90° phased difference, two linearly polarized modes can excite circularly polarized waves. From the figure, the current distribution at 180° and 270° are opposite phases, but has same amplitude as 0° and 90°. Two orthogonal modes are excited with 90° phase differences. Along the feed network, using the

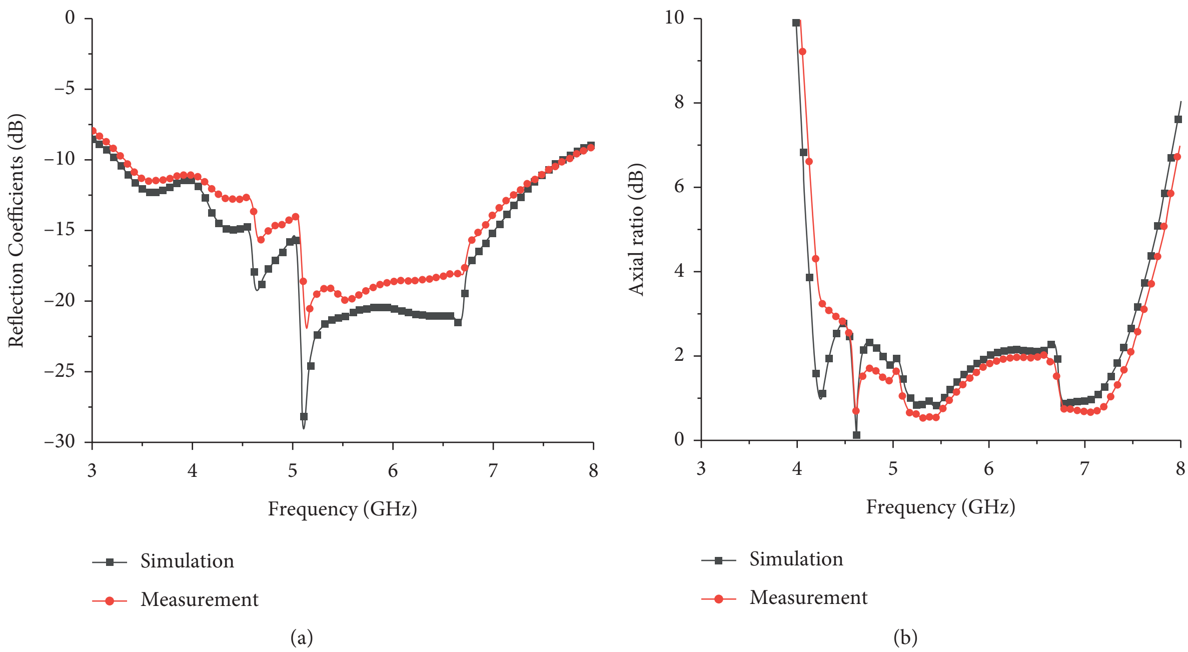


Figure 7: Simulated and measured reflection coefficients and AR versus frequency for the CP antenna: (a) reflection coefficients and (b) AR.

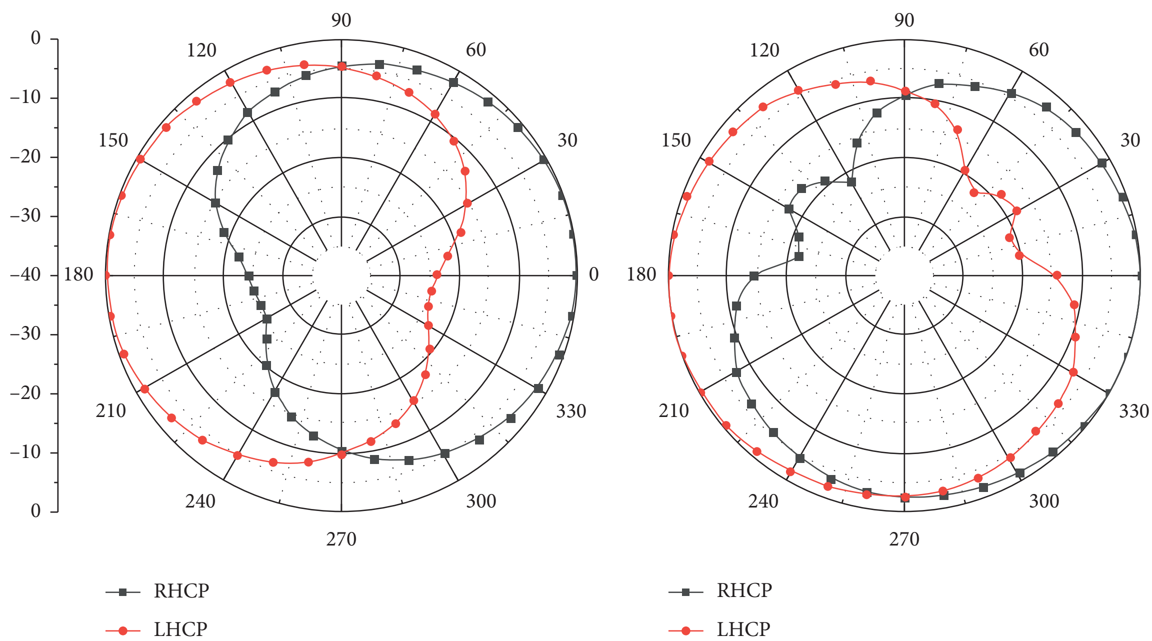


Figure 8: Measured radiation performance of the CP antenna at 5.50 GHz: (a) XZ-planes; (b) YZ-planes.

asymmetric structure of the interdigital capacitor and microstrip ground structure, two quasi-monopole resonant modes are excited alternately. The balance of the surface current distribution is broken, which is equivalent to introducing phase perturbation to excite circularly polarized waves.

In order to improve the impedance bandwidth and 3 dB AR bandwidth, the CRLH-TL structure between the floor and the chip excites multiorder resonance. Using a single-layer asymmetric structure, a compact circularly polarized antenna with wide bandwidth is realized.

Figure 10 shows the measured radiation gain of the proposed CP antenna. The measured peak gain is 2.53 dB at 6.0 GHz. The measurement radiation efficiency is better than 83% over the working frequency range.

The antennas' circularly polarized performances compared to the recently reported various metamaterial antennas are listed in Table 2. The CRLH CP antenna achieves a

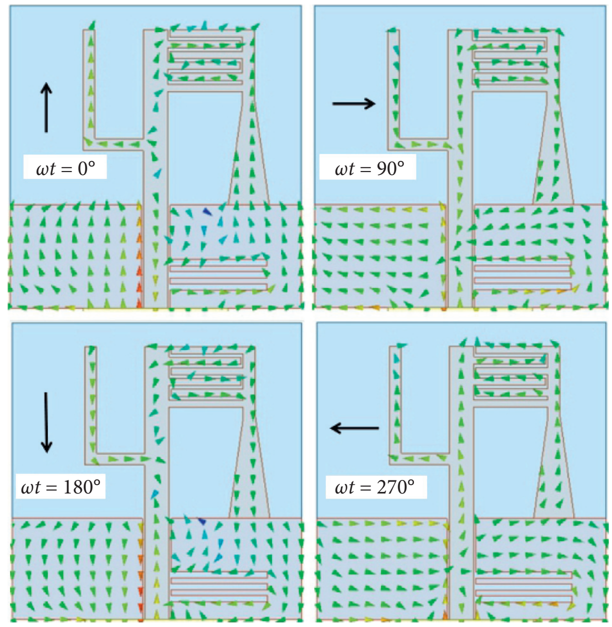


FIGURE 9: Simulated surface current distributions of the CRLH CP antenna at 5.50 GHz at four phases.

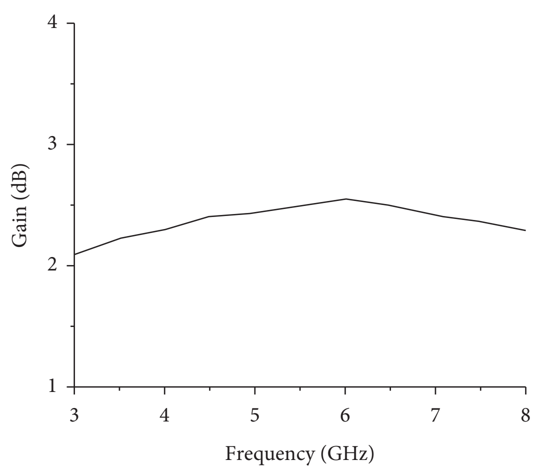


FIGURE 10: Measured antenna radiation gain in $+Z$ direction.

TABLE 2: Comparison between various metamaterial antennas.

	Overall antenna size	Impedance bandwidth (%)	AR bandwidth (%)	Gain (dB)
This work	25 mm ∗ 24 mm	79.5	56.2	2.53
[6]	43.5 mm ∗ 43.5 mm	4.7	1.9	2.0
[7]	31 mm ∗ 31 mm	4.6	1.46	0.96
[8]	24.8 mm ∗ 22 mm	6.58	0.7	−1.1
[13]	50 mm ∗ 50 mm	14.1	2.5	2.95
[14]	20 mm ∗ 20 mm	10.86	2.54	2.02

notable enhancement in its impedance bandwidth, AR bandwidth, and gain.

4. Conclusion

A circularly polarized antenna plays an important role in radar, satellite communication, GPS positioning system, radio frequency identification (RFID), and various mobile communication systems. In order to realize circular polarization, two orthogonal resonant modes are obtained by a single feed. This method has a simple structure and no complicated power divider and phase-shift circuit. In various wireless communication systems, single-fed microstrip circularly polarized antenna is a common RF terminal device for transmitting and receiving signals because of its low profile, simple design, and low cost. The 10 dB impedance bandwidth can achieve 79.5%, and the 3 dB AR bandwidth is 56.2%. The compact CRLH-TL simple antenna structure shows practical CP performance in the frequency bands of 4.29–7.64 GHz, which cover various wireless mobile broadband communications systems and navigational systems.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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References

[1] C. Caloz and T. Itoh, *Application of the Transmission Line Theory of Left-Handed (LH) Materials to the Realization of a Microstrip "LH Line*, pp. 412–415, IEEE Antennas and Propagation Society International Symposium, San Antonio, 2002.

[2] M. A. Antoniades and G. V. Eleftheriades, "Multiband compact printed dipole antennas using NRI-TL metamaterial loading," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 12, pp. 5613–5626, 2012.

[3] H. M. Lee, "A compact zeroth-order resonant antenna employing novel composite right/left-handed transmission-line unit-cells structure," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 1377–1380, 2011.

[4] T. Kumar and A. R. Harish, "Broadband circularly polarized printed slot-monopole antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 1531–1534, 2013.

[5] C.-J. Wang and K.-L. Hsiao, "CPW-fed monopole antenna for multiple system integration," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 2, pp. 1007–1011, 2014.

[6] H.-X. Xu, G.-M. Wang, J.-G. Liang, M. Q. Qi, and X. Gao, "Compact circularly polarized antennas combining meta-surfaces and strong space-filling meta-resonators," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 7, pp. 3442–3450, 2013.

[7] Y. D. Yuandan Dong, H. Toyao, and T. Itoh, "Compact circularly-polarized patch antenna loaded with metamaterial structures," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 11, pp. 4329–4333, 2011.

[8] C. Zhou, G. Wang, Y. Wang, B. Zong, and J. Ma, "CPW-fed dual-band linearly and circularly polarized antenna employing novel composite right/left-handed transmission-line," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 1073–1076, 2013.

[9] J. M. Kovitz, J. H. Choi, and Y. Rahmat-Samii, "Supporting wide-band circular polarization: CRLH networks for high-performance CP antenna arrays," *IEEE Microwave Magazine*, vol. 18, no. 5, pp. 91–104, 2017.

[10] S.-T. Ko, B.-C. Park, and J.-H. Lee, "Dual-band circularly polarized patch antenna with first positive and negative modes," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 1165–1168, 2013.

[11] B.-C. Park and J.-H. Lee, "Omnidirectional circularly polarized antenna utilizing zeroth-order resonance of epsilon negative transmission line," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 7, pp. 2717–2721, 2011.

[12] Z. Wang and Y. Dong, "Miniaturized RFID reader antennas based on CRLH negative order resonance," *IEEE Transactions on Antennas and Propagation*, vol. 68, pp. 83–696, 2020.

[13] Z. Wang, Y. Dong, and T. Itoh, "Miniaturized wideband CP antenna based on Metaresonator and CRLH-TLs for 5G new radio applications," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 1, pp. 74–83, 2021.

[14] M. Ameen and R. K. Chaudhary, "Metamaterial-based circularly polarised antenna employing ENG-TL with enhanced bandwidth for WLAN applications," *Electronics Letters*, vol. 54, no. 20, pp. 1152–1154, 2018.

[15] T. Jang, J. Choi, and S. Lim, "Compact coplanar waveguide (CPW)-fed zeroth-order resonant antennas with extended bandwidth and high efficiency on vialess single layer," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 2, pp. 363–372, 2011.