Compact Circularly Polarized Patch Antenna Using a Composite Right/Left-Handed Transmission Line Unit-Cell

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Abstract. *A compact circularly polarized (CP) patch antenna using a composite right/left-handed (CRLH) transmission line (TL) unit-cell is proposed. The CRLH TL unit-cell includes a complementary split ring resonator (CSRR) for shunt inductance and a gap loaded with a circular-shaped slot for series capacitance. The CSRR can decrease the TM_{10} mode resonance frequency, thus reducing the electrical size of the proposed antenna. In addition, the asymmetry of the CSRR brings about the TM_{01} mode, which can be combined with the TM_{10} mode by changing the slot radius. The combination of these two orthogonal modes with 90° phase shift makes the proposed antenna provide a CP property. The experimental results show that the proposed antenna has a wider axial ratio bandwidth and a smaller electrical size than the conventional corner-truncated square patch antenna and the reported compact CP patch antennas. Moreover, the proposed antenna is designed without impedance transformer, 90° phase shift, dual feed and ground via.*

Keywords

Circular polarization, compact patch antenna, composite right/left-handed transmission line, complementary split ring resonator, circular-shaped slot.

1. Introduction

In recent years, researches on metamaterials for microwave applications have grown rapidly with the verification of left-handed metamaterials. Especially, the transmission line approach of left-handed metamaterials has led to the realization of the composite right/left-handed (CRLH) transmission line (TL) which includes left-handed and right-handed attributes. A large number of CRLH microwave components have been developed, including many radiated-wave devices [1-4]. The rich dispersion relation of the CRLH TL provides these antennas with some unique features. For instance, the CRLH leaky-wave antennas developed with various techniques exhibit a full-space beam steering capability [5], [6]. The designed resonant-type antennas offer an alternative solution for antenna miniaturization [7], [8]. Since these compact antennas excite a single mode at a discrete frequency, they can only exhibit linearly polarized patterns.

Compact circularly polarized (CP) patch antennas have been desirable for the modern satellite communication systems owing to their numerous advantages such as low profile, light weight, and better weather penetration than the linearly polarized counterparts. Actually, researchers have introduced several methods to reduce the size of a conventional half-wave CP patch antenna. They included using high dielectric substrate, embedding a single cross-shaped slot [9], utilizing four asymmetric slits [10], etc. Although using high dielectric substrate can reduce the antenna size significantly, the axial ratio (AR) bandwidth (AR ≤ 3 dB) is extremely small. The antenna in [9] has a size reduction of around 10% as compared with the conventional corner-truncated square patch antenna and an AR bandwidth of 0.7%. In [10], the electrical size of the antenna is about $0.454\lambda_g \times 0.454\lambda_g$. However, its AR bandwidth is also small (0.5%).

In this paper, a compact CP patch antenna using a CRLH TL unit-cell is presented. In order to impose CRLH properties on a patch antenna, the antenna includes a complementary split ring resonator (CSRR) for shunt inductance and a gap loaded with a circular-shaped slot for series capacitance. Owing to the CSRR and the circular-shaped slot, the patch antenna has provided a CP property. In addition, the CSRR is used to reduce the antenna's size [11]. The proposed antenna has an experimental return loss bandwidth of 16.08%, an experimental AR bandwidth of 1.52% and an electrical size of $0.389\lambda_g \times 0.389\lambda_g$. These performances are better than those of the conventional corner-truncated square patch antenna and the reported compact CP patch antennas in [9], [10], [12-16]. Moreover, the proposed antenna is designed without impedance transformer, 90° phase shift, dual feed and ground via.

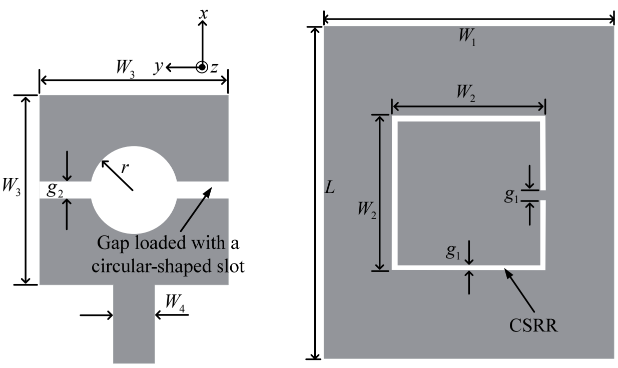
2. Antenna Structure

The geometry of the proposed antenna is shown in Fig. 1. In order to construct a single planar CRLH TL unit-cell in the antenna, a CSRR is etched on the ground plane for shunt admittance, and a gap loaded with a circular-shaped slot is inserted into the patch for series capacitance. The entire structure is synthesized on the substrate with a relative permittivity of 2.2 and a thickness of 1.5 mm. The dimensions of the proposed antenna are: $W_1 = 35$ mm, $W_2 = 18.4$ mm, $W_3 = 22$ mm, $W_4 = 4.6$ mm, $L = 40$ mm, $g_1 = 0.2$ mm, $g_2 = 2$ mm, $r = 5.1$ mm. The equivalent circuit model of the CRLH TL unit-cell is shown in Fig. 2. The CSRR is represented as a shunt LC resonant tank (L_C and C_C), while the patch with a gap loaded with a circular-shaped slot is represented as a series LC circuit (L and C_g). In addition, the capacitance C accounts for the capacitance between the patch and the ground plane. From the equivalent circuit model, the dispersion relation can be written as:

$$\cos(\beta d) = 1 + \frac{(\omega^2/\omega_C^{\ 2} - 1)(\omega^2/\omega_R^{\ 2} - C/C_g)}{2(1 - \omega^2/\omega_z^{\ 2})} \qquad (1)$$

where $\omega_R = 1/\sqrt{LC}$, $\omega_C = 1/\sqrt{L_C C_C}$, $\omega_Z = 1/\sqrt{L_C(C + C_C)}$.

The resonance frequencies of the proposed CRLH TL unit-cell can be derived from the dispersion relation in (1). The 0 mode resonance, where $\beta d = 0$, occurs at ω_C. At the 0 mode resonance, the phase constant (β) becomes zero and infinite wavelength propagation is allowed. However, since the bandwidth of the 0 mode resonance is extremely narrow, it is not practical to use in an antenna application. The +1 mode resonance (ω_1) arises where $\beta d = +\pi$. For simplicity, the detailed expression of ω_1 is not presented. According to [17], a decrease in series capacitance (C_g) will give rise to the increase in the +1 resonance frequency.



(a) (b)

Fig. 1. Geometry of the proposed antenna: (a) top view, (b) bottom view.

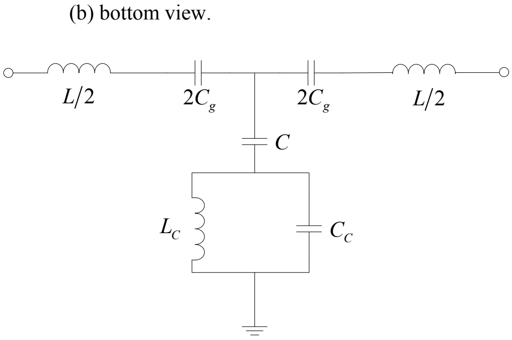


Fig. 2. Equivalent circuit model of the CRLH TL unit-cell.

3. Simulation and Discussion

Fig. 3 depicts the simulated return loss characteristic of the proposed structure when the slot radius is 3 mm ($r = 3$ mm). It is observed that a unique resonance mode (3.8 GHz) is generated besides the 0 mode (1.6 GHz) and +1 mode (3.34 GHz). This is because of the asymmetry of the CSRR along the x-axis, which induces y-oriented currents on the patch. The simulated electric field distributions of the proposed structure ($r = 3$ mm) at the +1 mode and at the unique mode are illustrated in Fig. 4(a) and (b), respectively.

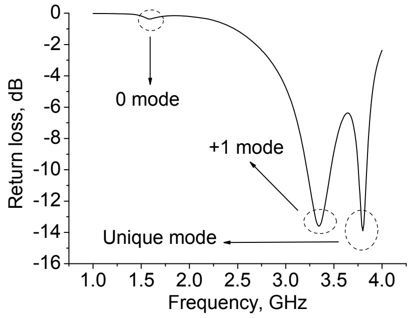
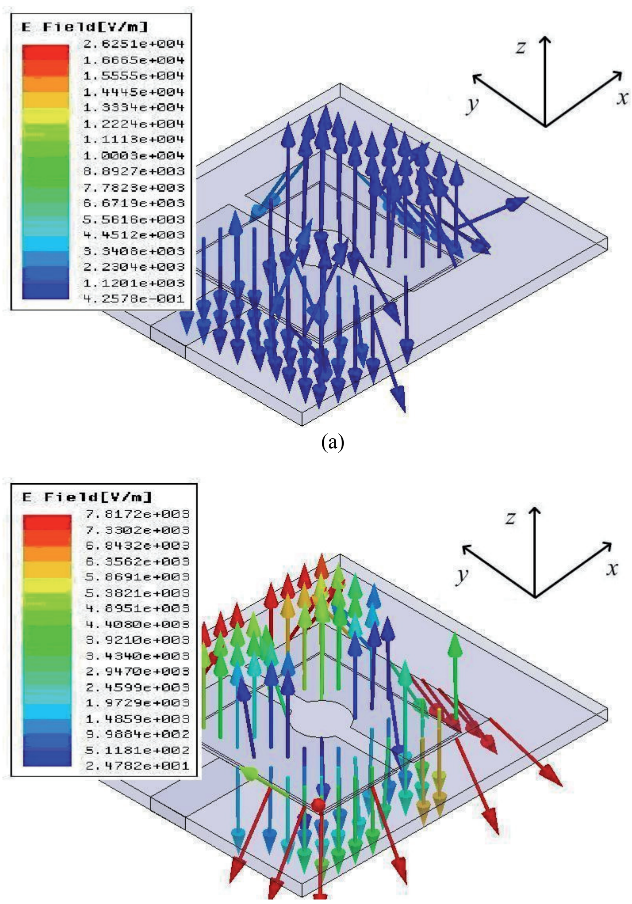


Fig. 3. Simulated return loss of the proposed structure ($r = 3$ mm).



(b)

Fig. 4. Simulated electric field distributions on the patch ($r = 3$ mm): (a) +1 mode (3.34 GHz), (b) unique mode (3.8 GHz).

As shown in Fig. 4, the +1 mode oriented along the x-direction is the TM_{10} mode, and the unique radiation mode is the TM_{01} mode. Therefore the two radiation modes are orthogonal to each other in the proposed structure.

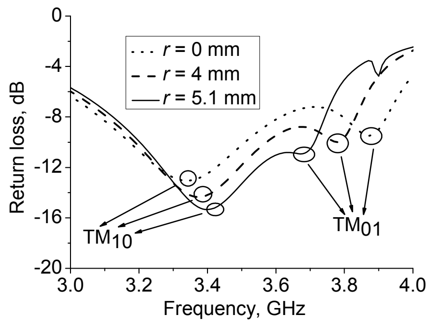


Fig. 5. Simulated return loss properties of the proposed structure for various slot radiuses.

Fig. 5 shows the simulated return loss properties of the proposed structure for various slot radiuses (0 mm to 5.1 mm). The TM_{10} mode resonance frequency increases as the slot radius increases. This is because the increase of r provides the decreased series capacitance. However, owing to the lengthened currents on the patch, an increase in r results in a decrease in the TM_{01} mode resonance frequency. The operating frequency of the TM_{01} mode can approach and combine with that of the TM_{10} mode when r is 5.1 mm.

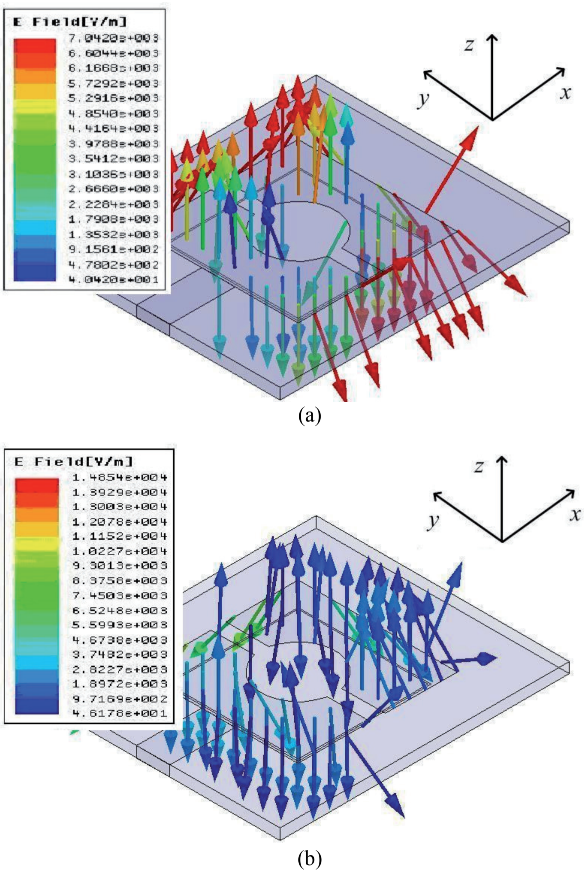


Fig. 6. Simulated electric field distributions on the patch (r = 5.1 mm) at 3.677 GHz when the input phase are 0° (a) and -90° (b).

Fig. 6 depicts the simulated electric field distributions on the patch (r = 5.1 mm) at 3.677 GHz for different input signal phases (0° and -90°). In Fig. 6(a), when the input signal phase is 0°, the TM_{01} mode dominates the antenna radiation. On the contrary, when the input signal phase is -90°, the TM_{10} mode dominates as shown in Fig. 6(b). Therefore, these two orthogonal modes can provide a CP property at 3.677 GHz when r is 5.1 mm.

4. Experimental Results

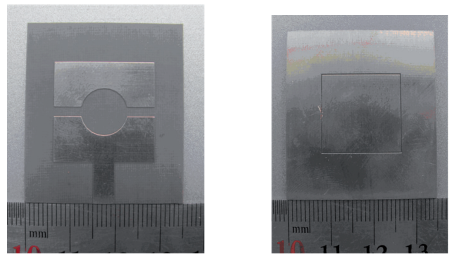


Fig. 7. The prototype of the proposed antenna.

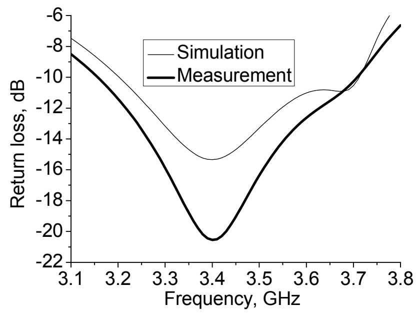


Fig. 8. Simulated and experimental return losses of the proposed antenna.

The proposed antenna (r = 5.1 mm) is fabricated and measured. Its prototype is shown in Fig. 7. The simulated and experimental return losses are shown in Fig. 8. The experimental data are in good agreement with those of the simulation. The experimental return loss bandwidth is 16.08% (3.156-3.708 GHz). Fig. 9 depicts the simulated and experimental broadside AR characteristics of the proposed antenna. It is observed that the antenna has an experimental AR bandwidth of 1.52% (3.649-3.705 GHz). The electrical size of the patch is only $0.389\lambda_g \times 0.389\lambda_g$ (22 mm × 22 mm) at 3.677 GHz. The performances of the proposed antenna are compared with those of the conventional corner-truncated square patch antenna and the reported compact CP patch antennas [9], [10], [12-16] in Tab. 1. Although the proposed antenna provides further size reduction, it exhibits wider AR bandwidth than the reference antennas.

In addition, Fig. 10 shows the experimental normalized radiation patterns of the proposed antenna at 3.677 GHz. The front radiation of the antenna is left-hand circular polarization (LHCP) while the back one is right-hand circular polarization (RHCP). Moreover, this antenna has an experimental peak gain of 4.43 dBi at 3.677 GHz.

	Electrical size (λ_g)	AR bandwidth (%)
Proposed antenna	0.389×0.389	1.52
The conventional corner-truncated square patch antenna	0.5×0.5	1.45
[9]	0.428×0.428	0.7
[10]	0.454×0.454	0.5
[12]	0.473×0.473	1.4
[13]	0.429×0.429	0.84
[14]	0.426×0.426	1.3
[15]	0.408×0.408	0.86
[16]	0.414×0.414	0.8

Tab. 1. Comparison of antenna performances.

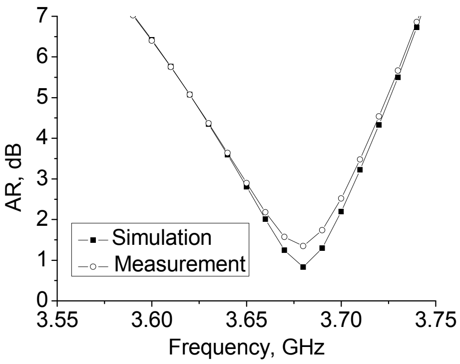


Fig. 9. Simulated and experimental broadside AR characteristics of the proposed antenna.

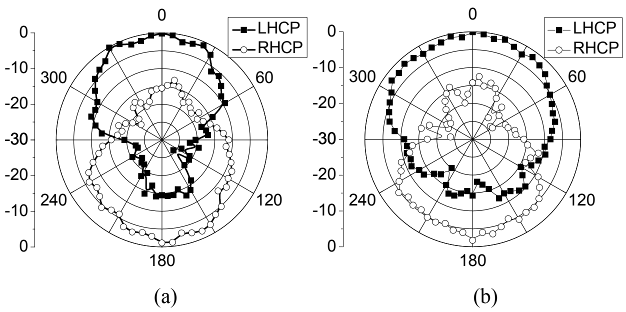


Fig. 10. Experimental normalized radiation patterns of the proposed antenna at 3.677 GHz: (a) the x-z plane, (b) the y-z plane.

5. Conclusion

In this article, a compact CP patch antenna using a CRLH TL unit-cell is proposed. The proposed antenna includes a CSRR for shunt inductance and a gap loaded with a circular-shaped slot for series capacitance. By using the CSRR, the antenna has a smaller electrical size compared with a conventional half-wave patch antenna. In addition, the asymmetry of the CSRR generates a unique radiation mode (TM_{01} mode), which can be combined with the normal TM_{10} mode by changing the slot radius. The combination of these two orthogonal modes with 90° phase shift makes the proposed antenna provide a CP property. The experimental results show that the proposed antenna has advantages of simplicity, small size, wide bandwidth, low-profile, easy fabrication and integration with other circuits. It has potential applications in modern wireless communication system.

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