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Compact Broadband End-Fire Antenna with Metamaterial Transmission Line

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Abstract—A broadband end-fire antenna loaded with magneto-electro-dielectric metamaterial (MED-MTM) is presented in this paper. Based on a planar printed structure, many periodic structures are investigated in antenna design. The metal patch is embedded with a C-shaped complementary split-ring resonator (CSRR) array, and many cross slots are etched on the ground plane. The zeroth-order resonance (ZOR) and first-order resonance (FOR) can be excited. As a result of electromagnetic coupling effect, the C-shaped patch and ground plane compose metamaterial transmission line (MTL). For potential applications, the broadband and end-fire antenna can work with a 53.5% (3.81–6.59 GHz) impedance bandwidth. The proposed antenna achieves size reduction, gain improvement and bandwidth enhancement.

1. INTRODUCTION

Planar microstrip antennas with compatible electrical and physical characteristics have received much attention for antenna design. Many novel electromagnetic metamaterials (MTMs), with the advantages of smaller physical size and higher gain, have aroused great impetus [1, 2]. Many left-handed metamaterials with simultaneous negative permittivity and permeability have been attained [3]. A metamaterial patch antenna with a wide bandwidth and compact size is reported [4]. Based on a planar magneto-electro-dielectric waveguided metamaterials and a magnetic embedded Hilbert-line, a compact broadband patch antenna is analyzed [5]. Metamaterials with simultaneously right-handed and left-handed properties can afford two adjacent resonant modes to enhance bandwidth. A wideband left-handed metamaterial antenna based on an aperture-coupled grid-slotted feeding mode is investigated in [6]. A slot antenna using a grounded metamaterial slab is presented for directivity enhancement with a grounded negative permittivity metamaterial [7]. A compact dual-band metamaterial inspired antenna using series resonant mode is presented in [8]. The antenna comprises two annular ring resonators to excite higher order modes.

Very little work can utilize left-handed metamaterials to realize end-fire with broadband and compact size. The left-handed metamaterials provide a convenient way to the radiation direction of antenna. In this paper, a compact broadband and end-fire antenna employing novel metamaterial transmission lines (MTLs) is proposed. The patch embedded with an epsilon-negative CSRR array acts as the main radiator, and many cross slots are periodically etched on a ground plane. Because of using an asymmetric C-shaped configuration, two modes can be excited. Without additional feeding part, the antenna can be end-fire in a very wide frequency band. This paper provides a new method for metamaterial antenna miniaturization, end-fire bandwidth enhancement, and high gain. The CSRR array is etched in the radiation patch, and many strip gaps are etched in the ground periodically. Due to the coupling between the CSRR array and the ground, a composite right/left-handed (CRLH) transmission line antenna is achieved.

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2. ANTENNA THEORY AND DESIGN

2.1. Theory of MTL

According to the Babinet complementary principle, the complementary electromagnetic problem is a dual problem, and the electromagnetic field distribution meets the duality principle. CSRR is the complementary structure of SRR. The periodic aperture array is etched in the ground under the CSRR. Smith points out that the equivalent dielectric constant and equivalent permeability can be negative in some frequency band [9]. The SRR array can excite magnetic resonance. The CSRR array patch and periodic aperture array ground can excite subwavelength dielectric resonance. The electric field of adjacent sheet metals in the ground can provide the equivalent capacitance of an LC resonance circuit. The coupling between CSRR metal strips and the periodic aperture array in ground can provide equivalent inductance. When the dielectric substrate is selected, the performance of CRLH transmission line structure can be optimized by adjusting the equivalent capacitance and equivalent inductance. It has been discovered that etching periodic aperture array on the ground of a traditional patch antenna aperture can constitute a planar metamaterial dielectric substrate. The novel substrate can affect equivalent medium parameters of the normal medium plate, decrease the quality factor of the antenna, decrease the size of the patch antenna, and improve the bandwidth at the same time.

The magnetoelectric coupling between cells and the periodic structures with multi-band left-handed characteristic can induce backward wave. The C-shaped metal patch loaded with many periodic subwavelength structures and cross-slotted ground plane are adopted to realize a CRLH transmission line, which can excite both backward and forward waves. The ZOR and FOR are excited, which are merged into a broadband. The transmission characteristics can be analyzed by a left-handed and right-handed equivalent circuit model. The equivalent circuit model is shown as in Fig. 1. A shunt LC resonant tank (C_R and L_L) consists of a C-shaped patch, and a series LC resonant tank (C_L and L_R) consists of cross-slotted ground.

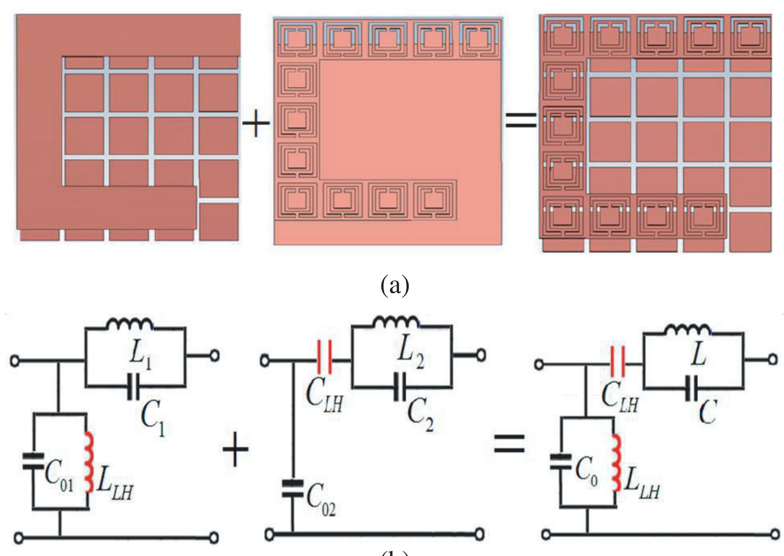


Figure 1. Equivalent circuit model of the MTL. (a) Configuration. (b) The relative equivalent circuit.

As shown in Fig. 1, the coupling between the cross-slotted ground and C-shaped patch introduces additional parallel inductance, which constitutes a parallel resonant circuit. The CSRR cell is determined by geometrical parameters ($4.0 \times 4.0\,\text{mm}^2$) and split width (0.3 mm). The series CSRR array determines the permeability μ_{eff}, and the shunt 8×6 square metallic unit cells determine the permittivity ε_{eff}. The material permeability and permittivity can be manipulated by the geometrical parameters of the CSRR and split.

The effective permittivity ε_{eff} and permeability μ_{eff} of the metamaterial TLs are obtained as

$$\begin{aligned}\varepsilon_{eff} &= C_R - \frac{1}{\omega^2 L_L} \\ \mu_{eff} &= L_R - \frac{1}{\omega^2 C_L}\end{aligned} \tag{1}$$

The quality factor of the metamaterial antenna can be calculated as

$$Q = \omega \frac{W_m}{W_{loss}} = \frac{\pi\omega}{4Gh\eta_{eff}} = \frac{\pi\omega\sqrt{\varepsilon_{eff}}}{4Gh\eta_0\sqrt{\mu_{eff}}} \tag{2}$$

W_m is the average stored energy, W_{loss} the loss energy, and G the radiation conductance. It is generally known that antenna bandwidth is inversely proportional to quality factor. According to the effective medium theory, by controlling the effective permittivity ε_{eff} and permeability μ_{eff}, a broadband antenna can be achieved.

By applying Bloch-Floquet theorem, the dual-mode resonance of the MTLs can be obtained. Regardless of the loss, an important dispersion relation is calculated using [10]:

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

The CRLH resonant modes can be obtained by:

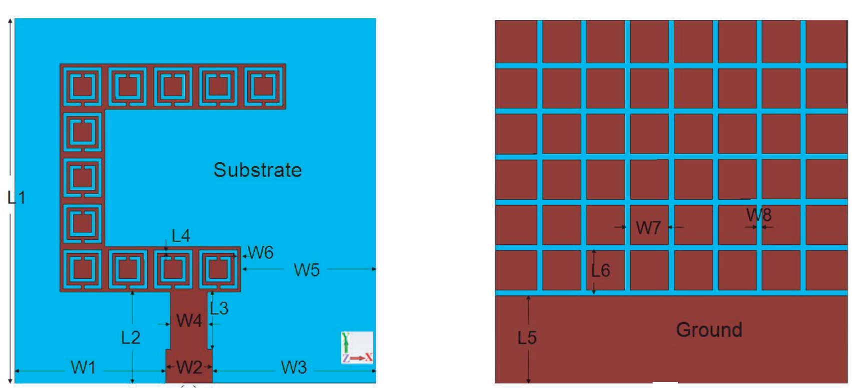
$$\beta_n = n\pi/l \quad n = 0,\ \pm 1,\ \cdots,\ \pm(N-1) \tag{4}$$

where β is the phase constant of the electromagnetic wave, Δx the differential length, and l the overall physical length of the resonator for the oped-ended boundary condition. When $n = 0$ and $n = 1$, the ZOR and FOR can be excited simultaneously. The ZOR and FOR are merged into a broadband.

The coupling between SRR array etched on the radiation patch and the cross-slotted ground introduces an additional series capacitor, which constitutes a series resonance circuit. The C-shaped CSRR patch and the periodic cross-slotted ground constitute a CRLH transmission line resonant circuit, which can induce a backward wave. By the phase compensation of the subwavelength resonant cavity of the CRLH transmission line, a zeroth-order resonator independent of the size of the resonator can be realized. The dual-mode resonances can be explained as the magnetoelectric coupling by the periodic cascading unit [11]. The electromagnetic coupling effect between the C-shaped patch and the cross-slotted ground can extend the bandwidth of this MTL antenna.

2.2. Antenna Design

As shown in Fig. 2, the antenna is composed of an upper C-shaped metal patch and a lower ground plane. An epsilon-negative SRR array is embedded in the metal patch, which is printed on the top of an F4B-2 substrate with a dielectric constant of 2.65, loss tangent 0.001, and thickness of 1.5 mm.



(a) (b)

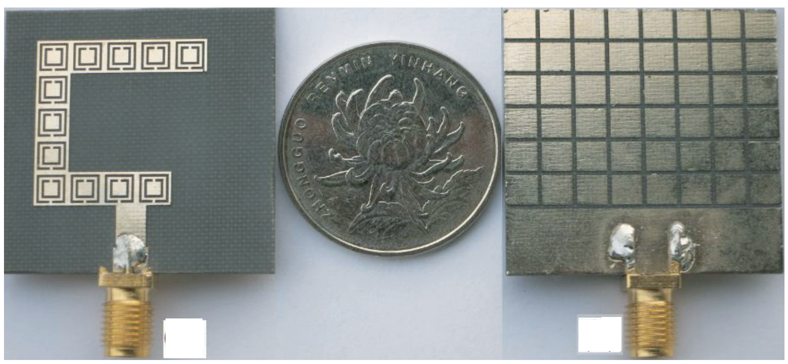
Figure 2. Configuration of antenna. (a) Top view. (b) Bottom view.

Table 1. Dimensions of the proposed antenna (unit: mm).

W_1	W_2	W_3	W_4	W_5	W_6	W_7
13.35	4.1	14.55	3.3	16.0	0.3	3.5
W_8	L_1	L_2	L_3	L_4	L_5	L_6
0.3	32.0	8.0	3.8	5.0	8.0	4.0

As shown in Table 1, the main dimensions are used as reference. The size of the periodic sheet metals is much smaller than the wavelength. The prototype of the MTL antenna is shown in Fig. 3.

Many periodic cross slots are etched on the ground plane. By applying the planar metamaterial structures on the C-shaped patch and ground plane, the end-fire antenna with excellent performance is realized. The left-handed metamaterial characteristic has been demonstrated in [12]. The optimized width of the microstrip feed line is fixed for 50-Ω characteristic impedance from 3.81 to 6.59 GHz. Due to the advantage of the MED-MTM, it is easy to manufacture a end-fire antenna with low profile, wide bandwidth, high gain, and good radiation efficiency.



(a) (b)

Figure 3. Photograph of the fabricated antenna. (a) Top view. (b) Bottom view.

3. SIMULATION AND EXPERIMENTAL RESULTS

The ZOR and FOR are excited, which are merged into a broadband directly. The broadband end-fire antenna has been numerically studied using CST Microwave Studio simulation tool and experimentally validated.

By alerting W_1 and fixing other parameters, Fig. 4 shows simulated reflection coefficients characteristics of the proposed antenna. The resonant frequency increases as the value of W_1 varies from 12.75 mm to 13.95 mm. The feeder position is comprehensively optimized to achieve an end-fire radiation with good impedance matching condition.

It can be seen from Fig. 5(a) that the resonant frequency is shifted down slightly as the length of L_2 changes from 7.0 mm to 9.0 mm. When L_2 is 8.0 mm, the proposed antenna has the widest impedance bandwidth.

Figure 6 illustrates the simulated and measured reflection coefficients of the proposed antenna. The simulated −10 dB impedance bandwidth is as much as 2.62 GHz (3.74–6.36 GHz). It is seen that the MTL antenna offers wideband behavior with 51.9% fractional bandwidth. The reflection coefficient of the fabricated antenna is measured through a network analyzer Agilent E8361A. The measured −10 dB impedance bandwidth is 53.5% (3.81–6.59 GHz) covering the bands of fixed satellite (3.40–4.80 GHz). The slight upward shift of the band may result from the fabrication, measurement environment, and actual dielectric constant of the substrate. Due to the ZOR and FOR modes excited by a C-shaped

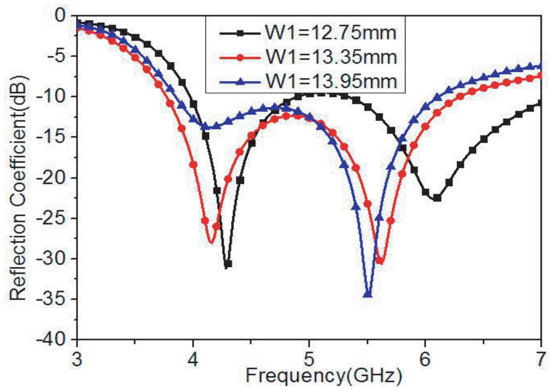


Figure 4. Simulated reflection coefficients curves of the proposed antenna with different W_1.

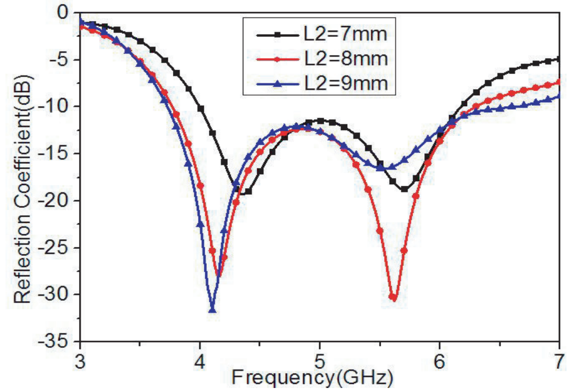


Figure 5. Simulated reflection coefficients curves of the proposed antenna with different L_2.

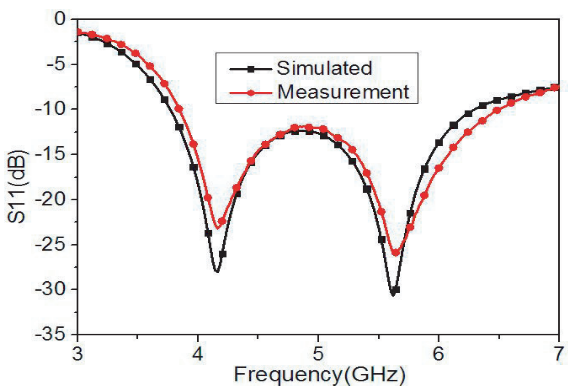


Figure 6. Simulated and measured reflection coefficients characteristics curves.

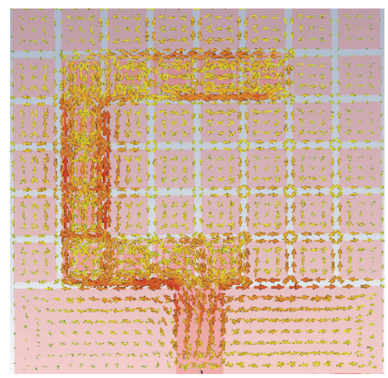


Figure 7. Simulated surface current distributions of the proposed antenna at 4.6 GHz.

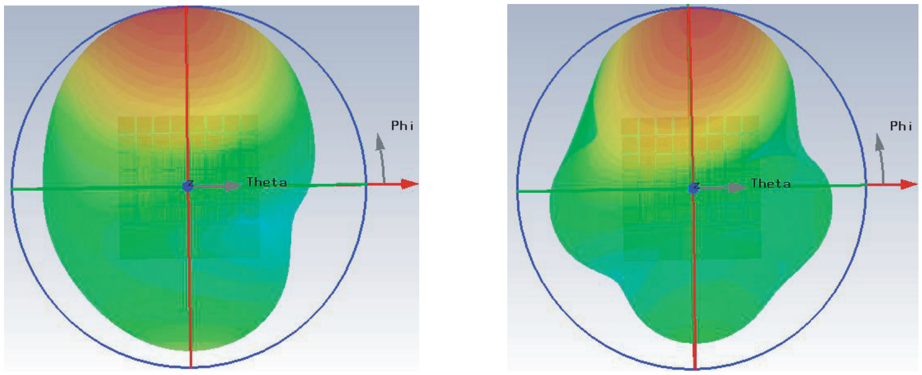
metal patch and the periodic cross slots on ground planes, the bandwidth of the MTL antenna is greatly extended.

As shown in Fig. 7, the surface current distributions can be observed. Due to the asymmetrical C-shaped metal patch, the balance of surface current distribution is broken. Two quasi-dipole resonant modes are achieved. As a result, the C-shaped metal patch and cross-slotted ground planes make a better impedance match for broadband.

In general, the main radiation direction of the conventional antenna is in the normal direction of the patch. However, the radiation direction of the CRLH antenna is end-fire. The effect of the size on the end-fire antenna performance is studied. In the case of co-polarization, the radiated energy is mainly focused around the Y-direction in the YZ-plane. The dominant surface wave along the E-plane is launched in the cross-slotted grounded substrate. As shown in Fig. 8, the main radiation direction is in horizontal direction rather than vertical direction of the traditional patch antenna. The radiation along the patch end-fire direction is significantly enhanced.

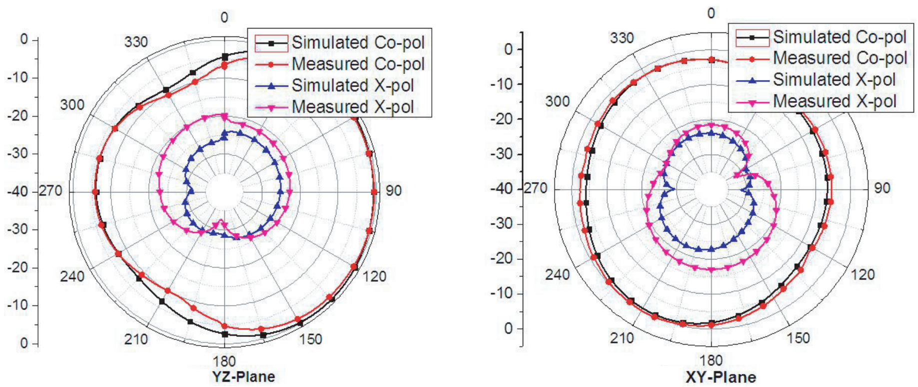
At the resonant frequency of 4.12 GHz utilized in the fixed satellite systems, the measured and simulated patterns of the proposed antenna in two principal planes are seen in Fig. 9 and Fig. 10, namely the XZ-plane and YZ-plane. It can be shown that the measured patterns are in good coincidence with simulated results. The proposed antenna exhibits a stable end-fire radiation pattern. In the YZ-plane, the radiation pattern is a quasi-omnidirectional pattern.

The measured and simulated peak gains variation with frequency are seen in Fig. 11. It is observed that the simulated gains change from 5.64 dBi to 7.48 dBi. Due to the energy losses of the actual material and measurement environment, the measured gains are a little less than the simulated results. The gain



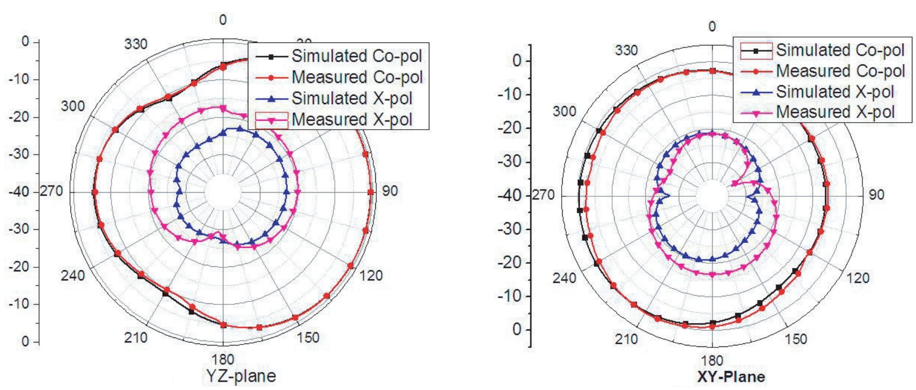
(a) (b)

Figure 8. Simulated 3D radiation patterns of the proposed antenna at (a) 4.12 GHz, (b) 5.60 GHz.



(a) (b)

Figure 9. Radiation patterns of the proposed antenna at 4.12 GHz. (a) YZ-plane. (b) XZ-plane.



(a) (b)

Figure 10. Radiation patterns of the proposed antenna at 5.60 GHz. (a) YZ-plane. (b) XZ-plane.

of the compact MTL antenna is very high compared with those conventional antennas. The radiation efficiency varies from 76.2% to 91.1% in the working band.

The performance of the compact broadband antenna is compared with those of the metamaterial antennas [4, 6, 13], as shown in Table 2, where λ_0 is the operating wavelength in free space. The end-fire planar antenna provides smaller size, higher gain, and significant enhanced bandwidth.

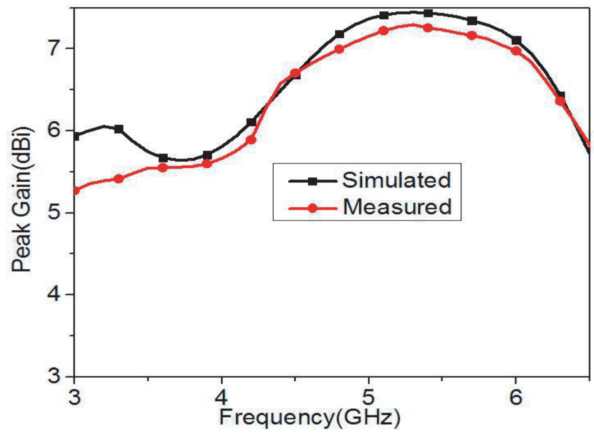


Figure 11. The measured and simulated antenna peak gains of the antenna.

Table 2. Comparison of this work and other previous metamaterial antennas.

	Frequency (GHz)	Substrate size (MM^2)	Overall size	Bandwidth
This work	5.20	32×32	$0.55\lambda_0 \times 0.55\lambda_0$	53.5%
[4]	7.15	32×28	$0.76\lambda_0 \times 0.67\lambda_0$	40.6%
[6]	5.27	60×60	$1.05\lambda_0 \times 1.05\lambda_0$	27.7%
[13]	5.47	60×60	$1.09\lambda_0 \times 1.09\lambda_0$	25.4%

4. CONCLUSION

In this letter, by exciting two ZOR and FOR modes, a novel compact broadband end-fire antenna has been proposed and demonstrated. An epsilon-negative CSRR array and cross-slotted ground plane are employed to increase the bandwidth for small physical size. A new bandwidth extension technique is proposed. Compared with the recently-reported metamaterial antennas, the proposed MTL antenna has a wider bandwidth, higher gain, and smaller size. The fractional impedance bandwidth is 53.5%. The maximum gain is 7.48 dBi. The compact broadband antenna shows a stable end-fire radiation performance in the working band, which is suitable for applications in wireless mobile communication systems such as RFID, WiFi, and fixed satellite.

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