A Compact Dual-Mode Metamaterial-Based Loop Antenna for Pattern Diversity

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***Abstract*—This letter presents a novel design of compact dual-port dual-mode metamaterial-based loop antenna for pattern diversity. The proposed metamaterial-based loop antenna consists of a loop based on periodically loaded capacitive arc strips and two independent ports with feeding networks. Similar to mu-zero resonance (MZR) antennas, the periodically loaded capacitive loop antenna proposed in this letter allows current along the loop to remain in phase and uniform. By making use of a hybrid feed network, the even and odd modes of the proposed metamaterial-based loop antenna are exploited so that its pattern diversity is achieved effectively. The theory of operation and performances of the proposed antenna are demonstrated in both a full-wave simulation and in the experiments.**

***Index Terms*—Even mode, loop antenna, odd mode, pattern diversity, reconfigurable pattern.**

I. Introduction

DURING the last several years, along with the fairly rapid development of wireless communications, the indoor and urban wireless access points have been increasing. In such environments, severe multipath propagation may occur. This propagation phenomenon affects the signal-to-noise ratio (SNR) and introduces signal distortion. To diminish the vulnerability of wireless access points against the destructive interference of multipath radio waves, diversity techniques can be applied [1], [2]. There are several diversity techniques such as spatial diversity, polarization diversity, and radiation pattern diversity. Spatial diversity uses two or more antennas separated in space for reception or transmission. Spatial diversity for wireless access points requires wide antenna spacing for proper operation. Polarization diversity can compensate for polarization losses due to multipath effects [3]. Pattern diversity can also compensate for the signal reception from different channels by changing the radiation pattern.

To change the radiation pattern, two major techniques, pattern reconfigurability and multiantennas, have been employed. There are many methods to obtain reconfigurable patterns, such as varators, p-i-n diodes, and radio frequency microelectromechancial systems (RF-MEMS) switches [4]–[6]. Similar to phased array, a radiation pattern can be changed by controlling amplitude and phase, as in [7]–[9]. However, these methods are not enough to achieve the required efficiency of the antenna. By using multiantennas, the pattern can be easily changed [8]. However, when using this method, a relatively large area must be occupied by the antennas.

Recently, studies on left-handed metamaterials (LHMs) based on periodic structures for microwave applications have progressed rapidly to enhance antenna performances. LHMs have many unique properties such as supporting a fundamental backward wave (opposite group and phase velocities) and zero propagation constant ($\beta = 0$) with nonzero group velocity at the zeroth-order resonance (ZOR). LMHs with dimensions smaller than the guided wavelength have attracted considerable attention in view of minimizing the size of antennas [10], [11]. In our previous work [12], using the theory of zeroth-order resonance, we have provided a novel design for several arc-shaped strips that make up the loop antenna to obtain the horizontally polarized omnidirectional radiation pattern.

In this letter, we proposed a novel compact dual-mode metamaterial antenna for pattern diversity. By making use of a hybrid feed network, the even and odd modes of the proposed metamaterial-based loop antenna are exploited with pattern and polarization diversities. Moreover, it has a simple structure and a compact size, provides low-cost fabrication, and still shows good performance.

II. Proposed Antenna Design—Theory of Operation

A. Proposed Antenna Structure

The proposed antenna in microstrip technology with a single-layer substrate is shown in Fig. 1, with dimensions in Table I. Its material parameters are relative permittivity of 2.65, loss tangent of 0.002, and thickness of h. The proposed antenna consists of a loop based on periodically loaded capacitive arc strips and

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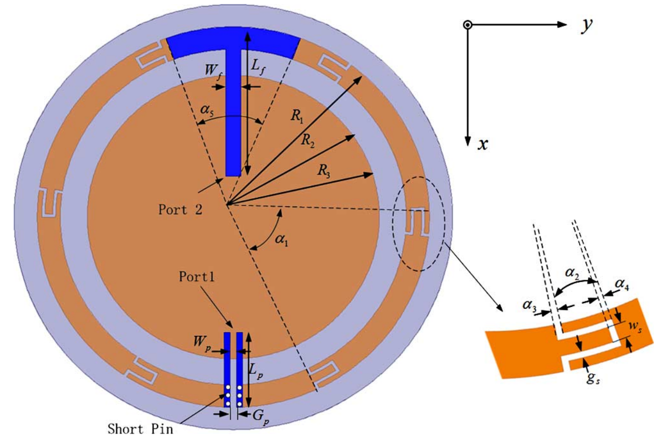

Fig. 1. Geometry of the proposed dual-port dual-mode metamaterial-based loop antenna.

TABLE I
DIMENSIONS OF THE PROPOSED ANTENNA (UNIT: MILLIMETERS)

R_1	R_2	R_3	α_1	α_2	α_3	α_4	α_5
25.5	22.5	19	59	1	8	1	40
L_p	L_f	W_p	W_f	G_p	w_s	g_s	h
10	20	0.8	2	0.8	1	0.4	0.5

two independent ports with a hybrid feeding network. Periodical capacitive loading is realized by adding interlaced coupling lines at the end of each arc strip's line section. These interlaced coupling lines periodically introduce series capacitance to the loop, which provides a very small phase correction between the adjacent sections so that the current that flows along the loop is kept in phase and uniform even though the perimeter of the loop is comparable to the operating wavelength. The in-phase current distribution of the proposed metamaterial-based loop antenna is similar to that of mu-zero resonance (MZR) antennas [13], which is also implemented by the series capacitance of a unit cell.

B. Even-Odd Mode Analysis

The loop based on periodically loaded capacitive arc strips and the circle ground of the proposed antenna can be considered as an uneven transmission line (TL) with distributed radiation characteristics. To determine the dispersion relation and resonances of the proposed structure, the resonance resistances are neglected, but without affecting the resonance characteristic. Therefore, the corresponding equivalent transmission line's circuit model and equivalent lumped-element circuit model are shown in Fig. 2. In Fig. 2(a), every section of the arc strip and ground is represented by the characteristic impedance, Z_0, and the electrical length, θ. The coupling of the interdigital slot between the arc strips is represented by the series interdigital capacitor, C_L. When one port is excited, the other port and its feed network are represented by the series capacitor C_P, which is in the center of the circuit model. For the electrical length, θ, when it is small, the short arc strip sections can be further replaced by their equivalent series inductance, L_R, and parallel capacitor, C_R, as shown in Fig. 2(b). Because of the series interdigital capacitor, C_L, the well-known composite right/left-handed

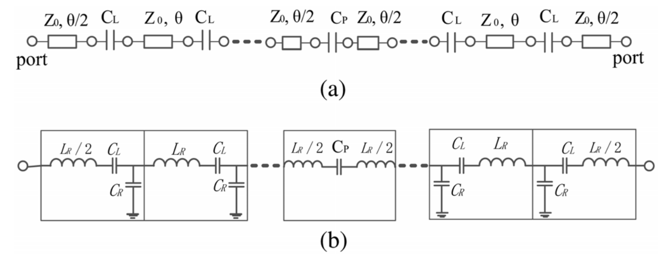

Fig. 2. (a) Corresponding equivalent TL circuit model of the proposed antenna. (b) Corresponding equivalent lumped-element circuit model.

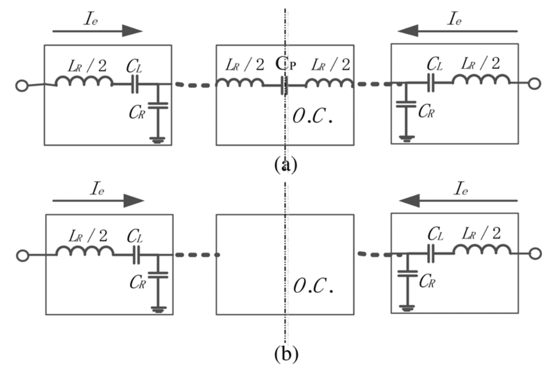

Fig. 3. (a) Imposing the even-mode excitation. (b) Simplified lumped element circuit with the O. C. boundary condition at the center.

(CRLH) transmission line is constructed, which has been analyzed in detail in [14] and [15], thus theory analysis has been omitted in this letter.

Thanks to the structural symmetry of the proposed antenna as shown in Fig. 1, its properties can be analyzed by decomposing the currents on the loop strip into a superposition of an even mode (I_e) and an odd mode (I_o) when port 1 and port 2 are being excited, respectively.

Fig. 3 shows the equivalent circuit model in the case of even mode. The coupling current from the T-shaped feeding strip to the loop was decomposed two opposite directions. Due to the symmetry of the proposed antenna, the currents are equal and in phase. We found that no current will flow through the coupling capacitor C_P at the center. Then, the current at the center of the loop is zero, and we can regard the center of the loop as the open-circuit boundary condition, as shown in Fig. 3(a). For this reason, the further simplified circuit model can be obtained as shown in Fig. 3(b). The capacitor C_P can be directly removed from the model.

In the case of odd mode, the excitation at port 1 can be decomposed to two equal amplitudes but in opposite phase. Due to the symmetry of the structure, the short-circuit boundary condition can be considered at the center of the loop where port 2 is placed, as shown in Fig. 4(a). Thus, we can further obtain two identical decoupled circuits with equal but opposite excitations, as shown in Fig. 4(b).

To clarify the design concept, the current distributions are shown in Fig. 5. In Fig. 5(a), when port 2 is excited, the current null occurs at port 1. The currents are opposite in both sides of the ports. In Fig. 5(b), when port 1 is excited, the currents on the loop are approximately of equal amplitude and in phase.

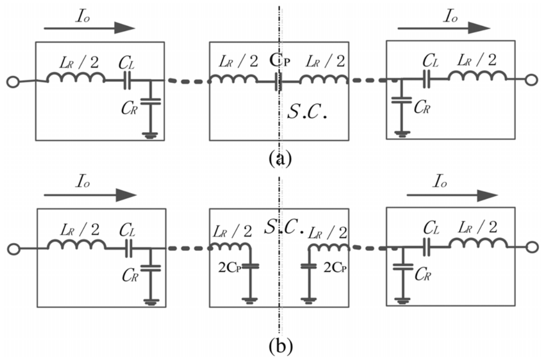

Fig. 4. (a) Imposing the odd-mode excitation. (b) Simplified lumped element circuit with the S. C. boundary condition at the center.

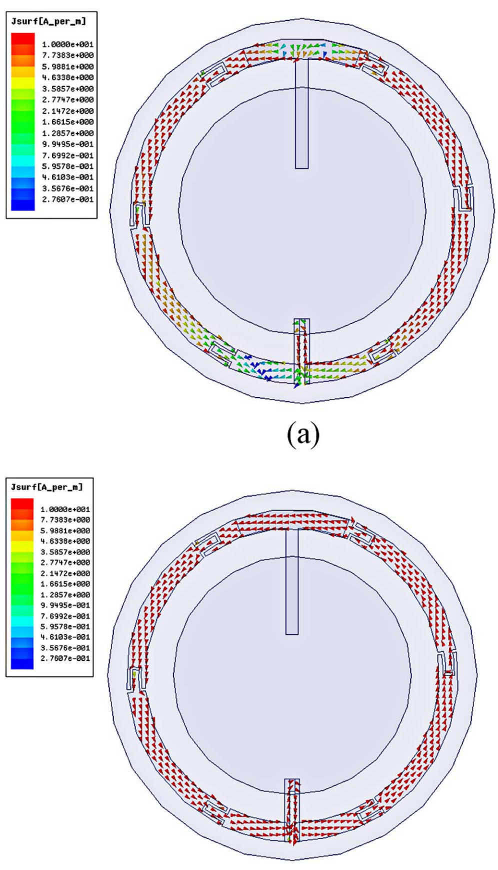

Fig. 5. Simulated current distribution along the loop. (a) Even mode when be excited at port 2. (b) Odd mode when be excited at port 1.

III. Simulation and Measurement Results

To obtain good impedance matching at the same frequency range and to minimize the antenna's dimensions, the antenna parameters have been optimized by using ANSYS High Frequency Structure Simulator (HFSS).

To verify experimentally the validity of the above analysis and simulation results, a prototype antenna was fabricated as shown in Fig. 6.The top and bottom views are shown.

Fig. 7 shows the simulated and measured results of return loss of the two ports that support the even mode and odd mode. For the odd mode, which can be excited at port 1, the measured 10-dB bandwidth is ranged from 2.38 to 2.52 GHz (5.8%), while the simulated one is ranged from 2.33 to 2.52 GHz (8.1%). For the even mode, which can be excited at port 2, the measured 10-dB bandwidth is range from 2.38 to 2.72 GHz (14.2%), while the simulated one ranges from 2.40 to 2.53 GHz (5.4%). The two modes share the same frequency band from 2.40 to 2.52 GHz (5%). The measured data of return losses of the three ports are in good agreement with the simulated results. The discrepancy between the simulated and measured results might be caused by the manufacturing and measuring tolerance.

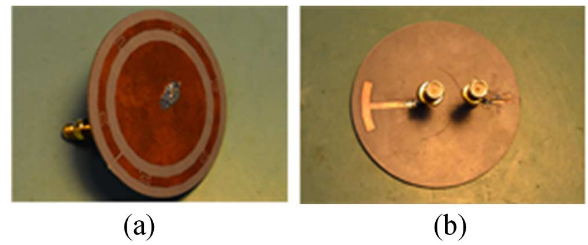

Fig. 6. Prototype of the proposed antenna: (a) top view and (b) bottom view.

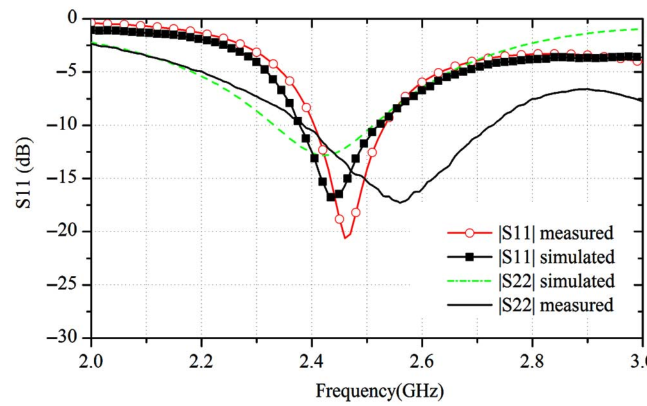

Fig. 7. Measured and simulated return loss of each port.

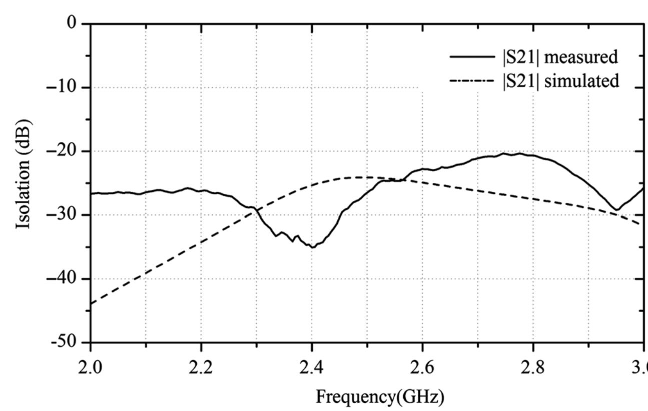

Fig. 8. Measured and simulated isolation between two ports.

Fig. 8 shows the simulated and measured results of the isolation between ports 1 and 2. The isolation between two ports is better than 25 dB in the impedance bandwidth. In general, the measured data agree with the simulated result. The reason for the high isolation between the two ports can be explained by the analysis in the above section. When port 2 was excited, the even mode current was distributed on the loop. The current

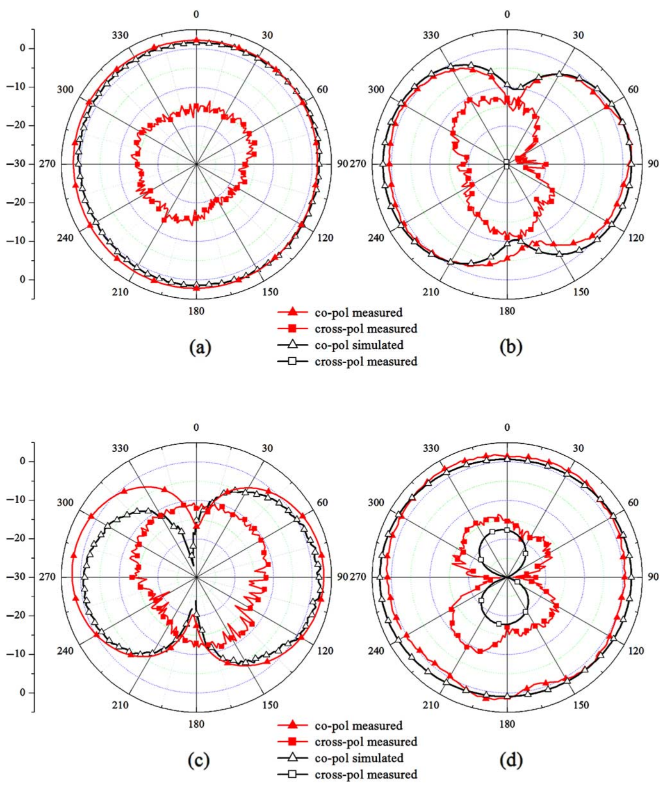

Fig. 9. Measured and simulated gain patterns of the proposed antenna. (a) Port 1, xy-plane. (b) Port 1, yz-plane. (c) Port 2, xy-plane. (d) Port 2, yz-plane.

was zero on the location of port 1, and then no current flowed in port 1. When port 1 was excited, the odd/even mode current was distributed on the loop. The voltage on the location of port 2 was identical to port 1, so no current flowed in port 2, and then the isolation became high between the two ports.

The measured and the simulated radiation patterns at 2.44 GHz are shown in Fig. 9. Note that when the radiation pattern is measured for exciting each port, we must ensure that the other ports are matched with 50-Ω loads. Good agreement between the simulated and the measured results is obtained. For port 1, the good magnetic dipole-like horizontally polarized omnidirectional pattern in the xy-plane was obtained for the odd-mode radiation, which is shown in Fig. 9(a). The 8-shaped radiation pattern in the yz-plane for the odd mode is also shown in Fig. 7(b). For port 2, the good omnidirectional pattern in the yz-plane was obtained for the even-mode radiation, which is shown in Fig. 7(d). The radiation pattern in the xy-plane for the even mode is shown in Fig. 7(c). The measured gains for the two modes are also shown in Fig. 9. For port 1, the gain is 2.1 dB, and the max radiation plane is xy-plane. For port 2, the max radiation plane is yz-plane, and the gain is 2.3 dB. The simulated cross polarizations are better than -20 dB for the two situations, but due to the scales in Fig. 9, the patterns of the simulation cross polarizations in Fig. 9 are not able to seen except in Fig. 9(d). The measured cross polarizations are better than -15 dB for the two situations. There is some discrepancy between the radiation patterns of the cross polarization, which caused the test cable and the loop strip plane to be unparalleled to the test polarization.

IV. Conclusion

In this letter, a compact dual-mode metamaterial loop antenna for pattern diversity has been successfully presented. By making use of a hybrid feed network, the even mode with magnetic dipole-like horizontally polarized omnidirectional radiation patterns and the odd-mode radiation pattern could be excited at the same frequency range. Therefore, gain pattern diversity was compensated by the even and odd modes, respectively. The two modes share the same frequency band from 2.40 to 2.52 GHz (5%). The high isolation, which is better than -25 dB, was obtained due to the features of the currents on the loop with even and odd modes being excited. With the proposed antenna, additional features such as low profile and reduced space can be obtained, and the capacity by which pattern diversity can be exploited becomes suitable for WLAN application.

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