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Enhancement of gain and directivity for microstrip antenna using negative permeability metamaterial

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ABSTRACT

A method to improve the gain and directivity of the patch antenna using permeability negative metamaterial (MTM) cells is proposed. Composing of dual-layer symmetry single ring resonator pair (D-SSRRP) embedded on both sides of the dielectric layer, the MTM cell is easy to integrate with a patch antenna and can be used as an insulator to reflect surface waves based on the μ-negative characteristic. By inserting the D-SSRRP-loaded MTM cells with different dimensions around the conventional patch antenna, a dual-band antenna with high gain and narrow beamwidth is designed, which operates at 5.2 GHz and 6.75 GHz for WLAN. As a result, both the numerical and experimental results illustrate that the μ-negative D-SSRRP-loaded MTM antenna achieves a good radiation performance: at both working frequencies, the antenna gain has increased at least 2.2 dB and the half-power beam width (HPBW) decreased around 20° compared with that of the conventional microstrip patch antenna.

1. Introduction

In recent years, great interests have been focused on microstrip patch antennas in wireless communication field due to their small volume, low profile and easy fabrication. However, conventional microstrip patch antenna suffers from low radiation gain and narrow bandwidth. Now, electromagnetic (EM) metamaterials (MTMs) have become a field of intense research activities with remarkable achievements and have been widely applied to design functional devices and to improve the performances of conventional microwave devices [1–4]. More importantly, MTMs have considerably enriched the area of antennas, especially for the antennas with unique behaviors that conventional ones hardly exhibit, such as enhanced gain and directivity, wider bandwidth and also multifrequency property [5–20]. For example, low or zero index metamaterials (LIM/ZIM), based on the transformation optics theory, are designed to enhance the directivity of the microstrip antennas [5–8]. However, the bandwidth of the LIM/ZIM is always narrow. Primary antennas are engineered with a significant directivity enhancement using the gradient-refractive-index MTMs [9]. However, the fabrication process of the antenna is complex. Antenna array is an efficient method to achieve higher radiation gain, while the added feeding networks are always difficult to design and the antenna size is always electrically large [10]. Single negative MTMs (SNMs) have also been used to improve the antenna performances, such as mitigating the mutual coupling between closely placed antennas [13–19] and enhancing the antenna directivity. However, these antennas operate at only a narrow band. Consequently, it is still a sharp challenge to engineer multi-band microstrip patch antenna with good directivity.

In this article, the goal is to provide an improved strategy not only to address the dual-band or multi-band issue but also to obtain good antenna performance such as high gain and narrow beamwidth. In Section 2, to provide a better understanding of the characteristic of the proposed D-SSRRP MTM, the circuit model and characterization of the MTM element are researched in depth. In Section 3, a μ-negative D-SSRRP-loaded MTM antenna is comprehensively studied by comparing several different configurations with conventional coaxial-fed patch antenna. For experimental demonstration, two prototypes of the MTM antenna and conventional antenna are eventually fabricated and measured, and the results are shown in Section 4. Finally, a conclusion of the whole paper is made. The μ-negative D-SSRRP-loaded MTM antenna with good performances of high gain and directivity predicts promising applications in mobile and wireless local area network (WLANs) systems.

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2. Design and characterization of a μ-negative D-SSRRP-loaded MTMs

As we all know, DNMs are made up of periodic elements to obtain the abnormal behaviors such as anti-parallel phase and group velocities, negative-refractive-index and backward-wave propagation. SNMs also consist of periodic elements to realize negative permittivity (ε) or negative permeability (μ). For example, the split-ring resonators (SRRs) are used to obtain the negative permeability, and its counterpart CSRRs are able to generate an electric response. It is obvious that the electromagnetic wave cannot propagate in SNMs for the negative ε or μ. Thus, SNMs can be used as EM insulators. The surface wave can be suppressed and more energy will be radiated along the broadside direction when the SNMs are used in microstrip patch antenna. To validate the effectiveness of the method, we design a dualband patch antenna with enhanced radiation gain.

In order to obtain single negative behavior and also to cooperate with the microstrip patch antenna smoothly and efficiently, we propose the structure of dual-layer symmetry single ring resonator pair (D-SSRRP). Fig. 1(a) depicts the schematic of the proposed D-SSRRP and the setup process of simulation. As is shown, the proposed cell can be illustrated as a sandwich of conductor–insulator–conductor. The symmetry single ring resonator pair (SSRRP) consists of a pair of identical SRR cells with their splits symmetrically located in the center part of the two SRRs, and is loaded on both sides of the substrate. Thus the middle substrate layer is used to support the D-SSRRP. The structure is easy to fabricate because it is compatible with available printed circuit board (PCB) technique. Similar to the circuit model of the transmission line, the equivalent circuit of the proposed D-SSRRP is shown in Fig. 1(b), where *Ls* models the line inductance of the D-SSRRP which is affected by the parameters *a*, *b* and *k*, *Cg* models the gap capacitance which is decided by *d*, *C* represents the coupling between the upper and lower SSRRP which is described by means of a parallel resonant tank *Lp* and *Cp*. Compared with SSRRP, larger values of *Ls* is expected for the proposed D-SSRRP which results from the longer current path. Thus a miniaturization is realized. Fig. 1(c) shows the setup process of the simulation, the D-SSRRP-loaded MTM is illuminated by a dominant transverse electric and magnetic (TEM) plane wave with wave vector along *x*-direction, and the E-field is along the *y*-direction. The perfect electric conductor (PEC) and perfect magnetic conductor (PMC) boundary conditions are set in the front-back faces and the up-down faces of the box, which is used to mimic an infinite array.

For characterization, the F4B substrate with a thickness of 1.5 mm and a dielectric constant of 2.65 is applied in all designs including the following conventional patch antenna and the D-SSRRP-loaded MTM antenna. The proposed D-SSRRP-loaded MTMs are analyzed by the commercial full-wave finite element method (FEM) EM field simulator Ansoft HFSS. For further research, the permeability and permittivity is retrieved by the chen method [21,22].

Aiming at acquiring a systematic characterization and give a guideline in the upcoming MTM antenna design, several conditions are considered and simulated, such as different parameters, different polarizations, number of the cells along the propagation direction and the influence of the periodic of the proposed D-SSRRP cell. Fig. 2 shows the results of the scatting parameters under different conditions and the retrieved constitutive EM parameters against frequency. As shown in Fig. 2(a), it is obvious that the resonant frequency (f_0) can be tuned by geometrical dimensions. It is observed that the transmission dip reduces when the parameters (a and b) increase. And the band-gaps are identified from transmission dips that are observed obviously in all three cases. Referring to Fig. 2(b), as the number of cells increase from one to three in the propagation direction, the bandwidth identified by the isolation better than 20 dB is increased from 0.48 GHz to 1.95 GHz. The resultant wider isolation bandwidth is induced by the coupling effect generated between adjacent cells. The coupling enhances when more cells are cascaded [4]. Further analysis indicates that f_0 is insensitive except for a slight shift upward when different polarization directions are adopted in the simulation. According to Fig. 2(c), when the dimensions of the D-SSRRP are fixed, the EM response of the MTM cell are almost identical, which indicates that the periodicity has a negligible effect on the insulating response. The material parameters are retrieved for the D-SSRRP with the geometrical dimensions $a = b = 4.5$ mm. A negative permeability generates at the vicinity of the aforementioned transmission dips in Fig. 2(d), which accounts for the magnetic resonance response generated. There is also a strong electric anti-resonance generated by the bounded refractive index of the structure. Moreover, the EM performance of the proposed structure is almost consistent for one layer or multilayers. And one layer is chosen to reduce the thickness of the substrate for the upcoming antenna design. Antenna with multiplayer MTMs is also simulated for comparison. To gain a better understanding of the principle of the proposed D-SSRRP cell, the theoretical dispersion curve is calculated using HFSS. The top and bottom are assigned as perfectly matched layers and the four boundaries along x- and y-direction are assigned as master/slave boundary for the eigenmode analysis. It is obvious that a consistent coincidence is observed between Figs. 2(a) and 3. A further inspection indicates that a bandgap is clearly shown in the region of 4.33–5.56 GHz.

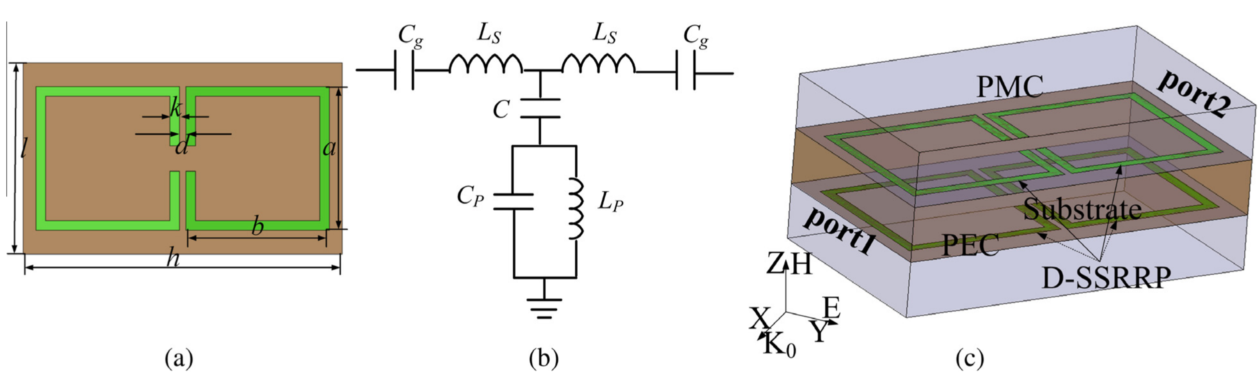

Fig. 1. Topology of the proposed D-SSRRP cell. (a) Top-and-bottom view as well as the illustration of geometrical dimensions; (b) circuit model; (c) perspective view and the simulation setup. The final parameters of the proposed D-SSRRP cell are $h = 10$ mm, $l = 6$ mm, $a = b = 4.5$ mm, $d = 0.2$ mm, $k = 0.3$ mm.