Metamaterials-based High-gain Antenna with Wide Viewing Angle

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Abstract— Metamaterials (MMs) refer to a class of artificially engineered structures comprised of electric/magnetic resonant building blocks much smaller than the operating wavelength. The extraordinary electromagnetic responses of MMs, not available for naturally occurring materials, have attracted intensive investigations on the underlying physics as well as related applications. In recent years, MMs-based antennas are widely studied and proved to have great potential in improving the radiation performance. In this paper, a MMs-based Febry-Perot cavity antenna with wide viewing angle is proposed about 14 GHz. The antenna consists of a high-impedance surface which works as an artificial magnetic conductor (AMC) at resonance frequency and a partially reflective surface (PRS). The AMC loading contributes to the low-profile and high-gain property of the antenna, as the AMC ground plane gives a near-zero phase shift in contrast to conventional metal sheet ground plane. The lateral size of the antenna is only about $3\lambda \times 0.6\lambda$; and the thickness is about $\lambda/5$. Metal walls surrounding the limited aperture are introduced to prevent the leakage of cavity mode and improve the radiation pattern, which also protects the antenna from external electromagnetic environment. The MMs-based high-gain antenna has a broad beam width in H-plane, which may be applied in ETC and RFID system.

1. INTRODUCTION

Metamaterials (MMs) [1, 2], a class of man-made materials constructed with artificial electromagnetic atoms/molecules, exhibit many nontrivial properties and novel functionalities, including negative refraction [3], subwavelength imaging [4], invisible cloaking [5–7], etc.. In recent years, MMs are proved to have great potential in antenna applications. They are utilized for antenna miniaturization [8, 9], side-lobe suppression [10], as well as achieving low-profile and high-gain antennas [11–15]. In 1999, D. F. Sievenpiper et al. proposed a subwavelength metal-dielectric-metal structure which can provide zero reflection phase shift at resonance frequencies [16]. It does not change phase of the electric field, but reverses that of the magnetic field, which works as a magnetic mirror and is usually referred to as artificial magnetic conductor (AMC) [17]. AMC loading in a Febry-Perot (F-P) cavity antenna helps significantly reduce the thickness of the antenna while maintaining high directivity [18, 19]. The cavity thickness can be reduced to $\lambda/60$ or even thinner [20].

In this paper, we focus on the design of a F-P cavity antenna with wide viewing angle. The maximum realized gain is 10.9 dB at 14.1 GHz in simulation. And it has a broad beam width of 76° in H-plane for spatial coverage, which may be applied in ETC and RFID system. The proposed antenna is fabricated with printed circuit board (PCB) technique and measured in the microwave chamber. The experimental results are in well agreement with simulations.

2. STRUCTURE DESIGN AND SIMULATIONS

The proposed antenna is schematically shown in Fig. 1. It is comprised of an AMC sheet and a partially reflective surface (PRS), and is fully filled with dielectric substrate. The feeding dipole antenna is centered in the cavity with a length of 18 mm. The AMC sheet has a thickness of $h_1 = 1.6$ mm. Its upper surface is presented in Fig. 1(b). The square patch array has a period of $p = 3.5$ mm and a width of $a = 2.9$ mm. The PRS as shown in Fig. 1(c) shares the same period with the patch array. The wire width is $w = 0.2$ mm. The cavity has a thickness of $h_2 = 3.2$ mm, giving rise to a whole antenna thickness of $h_1 + h_2 = 4.8$ mm, about $\lambda/5$ at 14.1 GHz. The substrate has a dielectric constant of $\varepsilon_r = 2.2$ with a loss tangent of $\tan\delta = 0.0009$. The antenna has 20 periods in x-direction and 4 periods in y-direction, giving rise to a lateral size of 70 mm × 14 mm, about $3\lambda \times 0.6\lambda$. The antenna is surrounded by four metal sheets to suppress mode leakage and improve the directivity of the radiation pattern. As the antenna has a relatively small aperture and strong field concentration, the metal walls also protect the cavity mode from external electromagnetic environment.

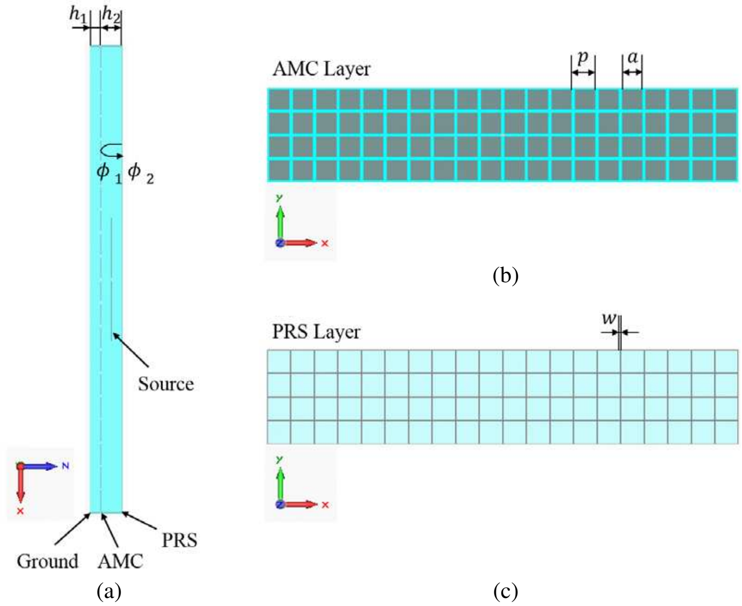


Figure 1: (a) Schematic of the proposed antenna. (b) The AMC layer. (c) The PRS layer.

The cavity mode is excited when the resonant condition is satisfied,

$$-4\pi f n h_2/c_0 + \phi_1 + \phi_2 = 2m\pi \quad (m = 0, \pm 1, \pm 2, \ldots),$$

where f is the operating frequency, c_0 is the light velocity in vacuum, n is the refractive index of the dielectric filling the cavity, h_2 is the cavity thickness [see Fig. 1(a)]. While the PRS gives a phase shift of $\phi_2 \approx \pi$ as metals and high-index dielectric surfaces with $n > 1$, the AMC sheet can provide a phase shift of ϕ_1 which changes from π to $-\pi$ and crosses through zero at the resonance frequency. This property of AMC facilitates the reduction in cavity thickness.

We perform FDTD simulations to determine the property of the antenna system. The cavity mode is excited around 14 GHz, exhibiting high directivity. Fig. 2 presents the radiation pattern in E-plane and H-plane at 14.1 GHz where the realized gain reaches a maximum of 10.9 dB. It can be seen that the proposed antenna has a narrow beam width of 14° in E-plane, while the beam width in H-plane is broad (about 76°), forming a fan-like radiation pattern.

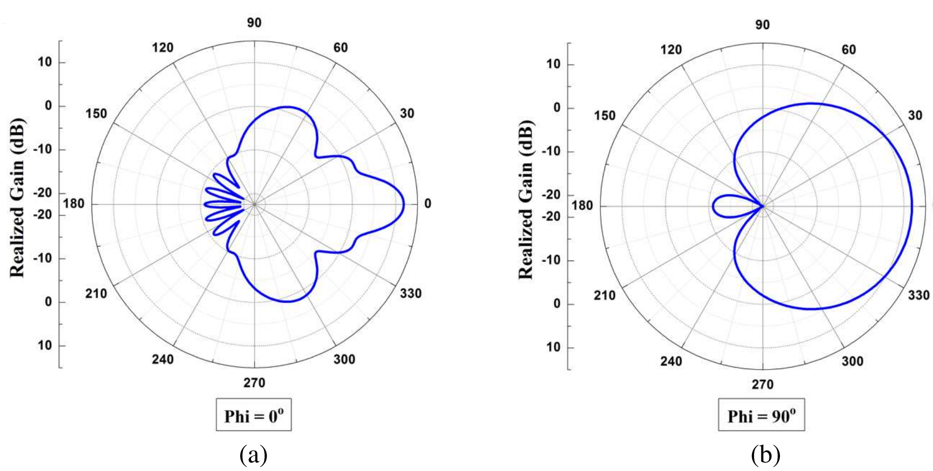


Figure 2: Numerically calculated gain of the antenna in (a) E-plane and (b) H-plane.

3. MEASUREMENTS AND RESULTS

The antenna is fabricated by three pieces of 1.575-mm thick Taconic TLY-5 substrate. A mesh array is etched onto the first layer, working as the PRS. The second layer is an additional dielectric spacer. And the third layer forms the AMC sheet, with a square patch array etched on one side and a ground plane on the other side. Then the three PCBs are assembled in order. Fig. 3 shows the photos of the antenna before and after assembling. The dipole source is fixed between the first and the second layer and fed by a 50 Ω coaxial cable. The whole antenna is surrounded by electro-conductive films as modeled in the simulation.

Measurements of the fabricated antenna are taken in the microwave chamber with a directive horn antennas working at 12.4–18 GHz with a gain factor of 24 dB. The antenna is positioned on a rotary table in the chamber. The rotary table, driven by a computer, provides a finest angular resolution of 0.1°. The far-field pattern is normalized to the gain of standard horn antenna. Fig. 4 shows the radiation pattern in E-plane and H-plane at 14.5 GHz. The half-power bandwidths are

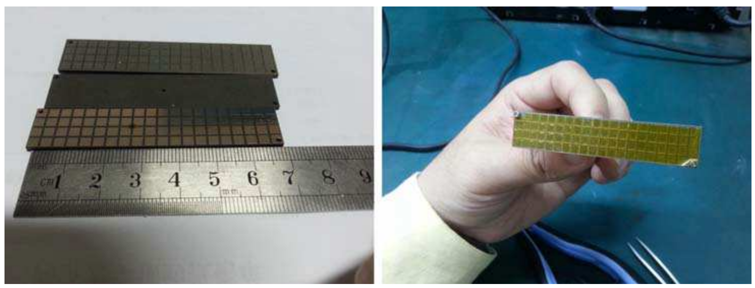
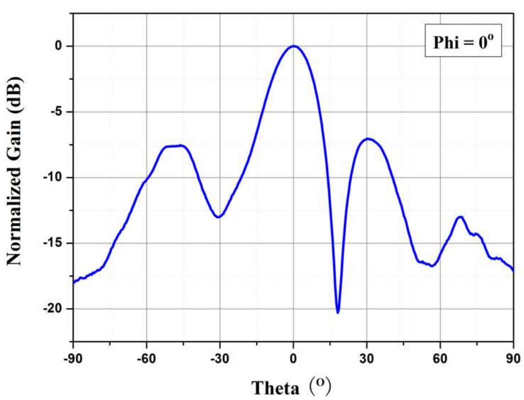
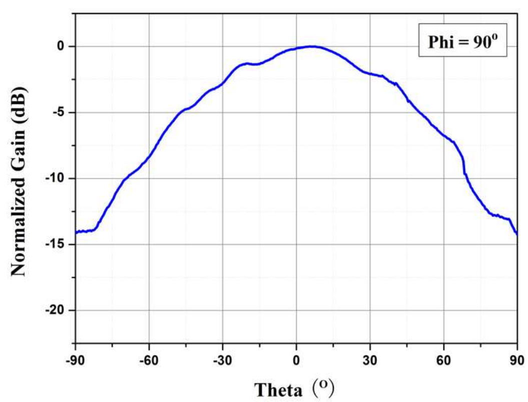


Figure 3: Photos of the fabricated antenna.

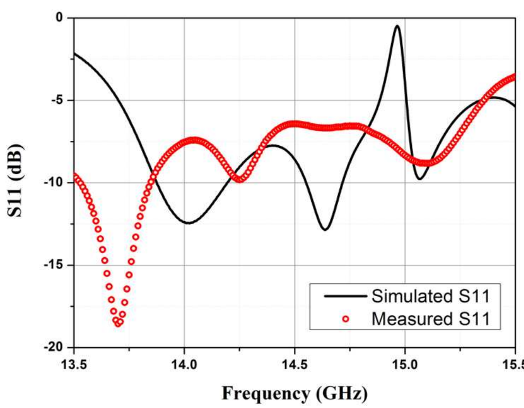


(a)

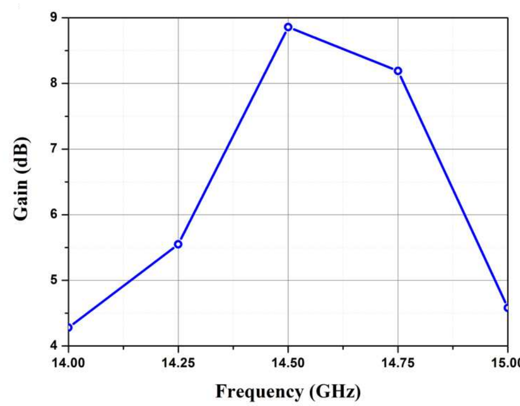


(b)

Figure 4: Measured radiation pattern in (a) E-plane and (b) H-plane.



(a)



(b)

Figure 5: (a) Simulated and measured return loss S_{11}. (b) Measured gain of the antenna.

18° in E-plane and 73° in H-plane, which are in good agreement with the simulation as shown in Fig. 3. Fig. 5(a) presents the simulated and measured return loss S_{11} as a function of frequency. It shows that the return loss is below -6 dB at the working frequency 14.5 GHz, which implies that the cavity mode is well matched to the dipole excitation. The measured gain of the antenna is plotted in Fig. 5(b). It can be seen that there is a peak of 8.9 dB near 14.5 GHz, which indicates the existence of a resonance mode.

4. CONCLUSION

A metamaterials-based high-gain antenna with wide viewing angle is modeled and fabricated. The antenna working around 14 GHz has a overall volume of $70\,\text{mm} \times 14\,\text{mm} \times 4.8\,\text{mm}$. It has a narrow beam width in E-plane, while the beam width in H-plane is broad, forming a fan-like radiation pattern. It is a compact and low-profile design, which has great potential in related applications.

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