Vol 18 No 1, January 2009
1674-1056/2009/18(01)/0174-05

Chinese Physics B

© 2009 Chin. Phys. Soc.
and IOP Publishing Ltd

The research of high-directive anisotropic magnetic metamaterial antenna loaded with frequency-selective surface*

Sun Yong-Zhi(孙永志)†, Ran Li-Xin(冉立新),
Peng Liang(彭 亮), Wang Wei-Guang(王伟光),
Li Ting(李 庭), Zhao Xu(赵 旭), and Chen Qiu-Lin(陈秋林)

No.8511 Research Institute of China, Aerospace Science Industry Corp., Nanjing 210007, *China*

(Received 10 January 2008; revised manuscript received 7 June 2008)

This paper uses a Computer Simulation Technology microwave studio to simulate the performance of a new high-directivity anisotropic magnetic metamaterial antenna loaded with a frequency-selective surface. Frequency-selective surface with cross-dipole element has a great effect on the directivity, radiation pattern, and gain of such an antenna. The experimental results show that frequency-selective surface (FSS) significantly improve the radiation performance of anisotropic magnetic metamaterial antenna. For example, as a single anisotropic magnetic metamaterial antenna, half power beam width is 4 degrees in the H planes, and the gain of this antenna is 19.5 dBi at 10 GHz, achieving a 2.1 degree increment in half power beam width, and a 7.3 dB gain increment by loading with the FSS reflector. The simulating results are consistent with our experimental results.

Keywords: anisotropic magnetic metamaterial, high-directivity antenna, frequency-selective surface
PACC: 4110H

1. Introduction

During the last years, there has been a lot of interest in high-directivity antenna in the microwave and millimetre region.[1,2] The one of major applications of this type antenna is the passive direction-of-arrival location and direction measurement of satellite and radar system. To achieve high directional radiation, traditional antenna utilizes large antenna size, for instance, the high-directivity paraboloid antenna with large aperture, large size antenna array. The disadvantages of the traditional high directivity antenna, i.e. paraboloid antenna, are large size, accurate design and fabrication, and thus cost too much. In recent years, metamaterial antennas become a hot research in antenna field. Due to the backward wave property of metamaterial,[3] the physical dimensions of the microstrip antenna have been significantly reduced.[4−7] The refractive indices of metamaterial can be controlled by the external voltage applied on the varactor diode,[8] and the mini-scanning controllable antenna can be designed. From the gain and half power beam width, and size, the high-directivity metamaterial antenna have unique advantages.[9−11] There are few reports on the improvement of performance of the high-directivity metamaterial antenna. Li *et al*[12] used a high impedance surface and an electrically responded surface to make a clipole highly directive, and 3dB angular width is less than 30°.

Frequency selective surface (FSS) has been extensively investigated in the last two decades. FSS is periodic arrays of conducting elements and exhibits total reflection or transmission at the resonance frequency.[13−15] Due to its unique characteristics, FSS is widely used in the area of the high-directivity antenna, greatly increasing the gain and directivity of the antenna.[16−18] As the FSS structure acts as an efficient reflector that redirects most of the wasted energy from the undesired direction to the desired direction without interfering with the metamaterial antenna return loss performance, this paper uses the FSS structure with double-square-loop element to improve performance of high-directivity anisotropic

*Project supported by the National Natural Science Foundation of China (Grant No 60371010).
†Corresponding author. E-mail: nanshen01@126.com

magnetic metamaterial antenna.

2. A new high-directive anisotropic magnetic metamaterial antenna using FSS

2.1. FSS structure

This paper designs the FSS structure with cross-dipole element, as shown in Fig.1.

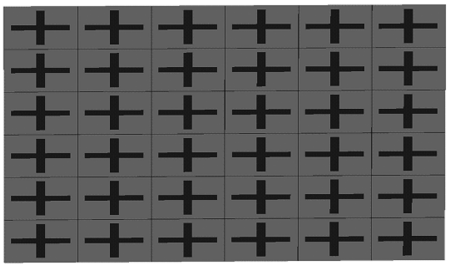


Fig.1. The FSS structure with cross-dipole element.

The simulated transmission property of the FSS is shown in Fig.2. Figure 2 shows that the electromagnetic wave is totally reflected at the 10 GHz.

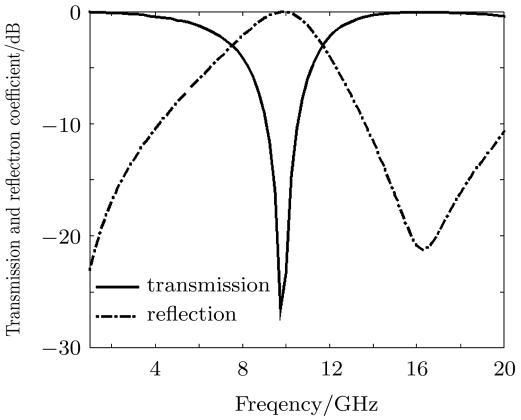


Fig.2. Transmission and reflection coefficient of the FSS.

2.2. An anisotropic magnetic metamaterial

The metamaterial is assumed to have a constant effective permittivity with $\varepsilon_{\mathrm{r}} = 1$, while the effective permeability is anisotropic. The dispersion relation of the effective anisotropic permeability is described by Drude model. Drude model has the following formulation:

$$\mu_{\mathrm{r}} = \mu_{\mathrm{r}}(\infty) - \frac{\omega_{\mathrm{p}}^2}{\omega(\omega + \mathrm{i}\gamma)}. \tag{1}$$

To construct this anisotropic magnetic metamaterial, whose effective permeability is a tensor expressed as $\bar{\bar{\boldsymbol{\mu}}}_{\mathrm{r}} = \mathrm{diag}(\mu_{rx}, \mu_{ry}, \mu_{rz})$, the effective permeability in different direction is chosen as $\mu_{rx} = \mu_{rz} = 1 - \dfrac{\omega_{\mathrm{p1}}^2}{\omega(\omega + \mathrm{i}\gamma_1)}$ and $\mu_{ry} = 10 - \dfrac{\omega_{\mathrm{p1}}^2}{\omega(\omega + \mathrm{i}\gamma_1)}$ with $\omega_{\mathrm{p1}} = 2\pi \cdot (10 \times 10^9)(\mathrm{rad/s})$ and $\gamma_1 = \pi(\mathrm{rad/s})$. At the plasma frequency of 10GHz, the effective permeability can be calculated as: $\bar{\bar{\boldsymbol{\mu}}}_{\mathrm{r}} \approx \mathrm{diag}(\mathrm{i}\alpha, 9 + \mathrm{i}\alpha, \mathrm{i}\alpha)$. Meanwhile from the calculated numerical results, the imaginary part of the anisotropic permeability is almost to be zero, i.e. $\alpha \ll 1$, so this material can be treated as a low loss anisotropic magnetic metamaterial and $\bar{\bar{\boldsymbol{\mu}}}_{\mathrm{r}} \approx \mathrm{diag}(0, 9, 0)$.

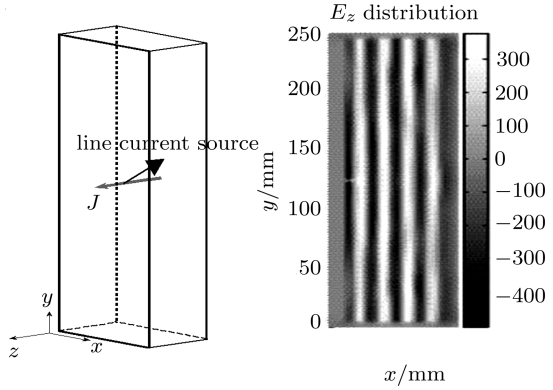
Assume that z-polarized electromagnetic wave propagates inside this material, if the operation frequency is smaller than the plasma frequency (10 GHz) of this dispersive media, the dispersion relation of a transverse-electric (TE) wave is derived as a parabolic curvature (see above derivation) for $\mu_{ry} < 0$, while the dispersion exhibits an elliptical curvature when the operation frequency is above 10 GHz. The dispersion relation of the low loss dispersive media can be written as:

$$\frac{k_x^2}{\mu_{ry}} + \frac{k_y^2}{\mu_{rx}} = k_0^2. \tag{2}$$

Around 10 GHz, due to the fact that $\mu_{ry} \gg \mu_{rx}$, the asymptote slope of the parabolic dispersion curve and the shorter axis of the elliptical dispersion curve should be very small. The wave number of the TE wave propagation in two directions are $k_x \approx 3k_0$ and $k_y \approx 0$ with k_0 is the wave number in free space. Thus, the radiated TE wave inside the metamaterial will exhibit special properties. In the y-direction, the radiated wave will have a large wavelength and a large phase velocity, while in the x-direction, the radiated wave will have a small wavelength and a small phase velocity, so the radiated wave inside the metamaterial will can be treated as a quasi-plane wave. Because of the finite dimension of the anisotropic metamaterial, the electromagnetic wave radiated inside the metamaterial will suffer the boundary between metamaterial and free space. At the boundary, the phase match condition will force the omnidirectional wave inside the metamaterial to propagate along x-direction after the metamaterial-air as previous analysis.

2.3. Simulated results of high-directive metamaterial antenna using FSS

In our CST simulation, the dimensions of the metamaterial bulk are 45 mm, 250 mm and 20 mm in the different x, y and z directions, as shown in Fig.3(a). A 20 mm long line current source is placed inside the media with its axis along z-direction. For the anisotropic magnetic dispersive property of the media, this metamaterial bulk will only influence the radiation direction of the z-polarized wave. In the calculation, we choose the boundaries in x and y directions to be perfect matched layers, but a periodic boundary condition is used in z direction.



(a) the dimensions of the metamaterial bulk (b) the electric field distribution

Fig.3. The electric field distribution inside the metamaterial bulk media.

From CST simulation, the electric field distribution inside the bulk media is shown in Fig.3(b). As predicted, the radiated wave inside the media is a quasi-plane wave around 10 GHz, which is determined by the intrinsic dispersion of the bulk media. In the x-direction, the bulk has a boundary paralleling to y-axis with air. The electric field is almost uniformly distributed on this boundary, which will cause a strong radiation along the x-direction in free space. While in the y-direction, the bulk has a boundary paralleling to x-axis with air. The electric field has a wave-like distribution on this boundary, which will degrade the radiation in y-direction in free space. We simulate the radiation pattern of this kind metamaterial bulk antenna in $-x$ and $+x$ direction, the result is shown in Fig.4.

From the radiation pattern of this kind metamaterial bulk antenna, half power beam width (HPBW) is 5.6 degrees, and the main lobe has a peak of 12.4 dBi.

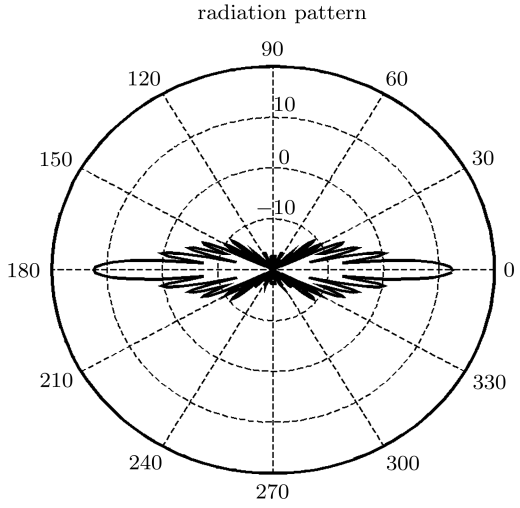


Fig.4. The radiation pattern of anisotropic magnetic metamaterial antenna in $-x$ and $+x$ direction.

To increase the gain of this antenna, the FSS is placed behind the bulk antenna, a distance of 2.5 mm from line current source in the x direction, and the line source is placed at the bulk edge, as shown Fig.5. In this case, the antenna will radiate power in only one direction (x-direction), we find that the application of the FSS does improve the radiation pattern, as the simulated results, in Fig.6.

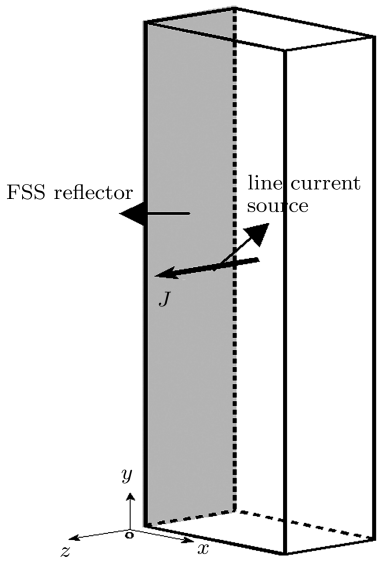


Fig.5. Anisotropic magnetic metamaterial antenna loaded with FSS.

From the simulated result in Fig.6, the directivity of the antenna is higher than the previous one, HPBW

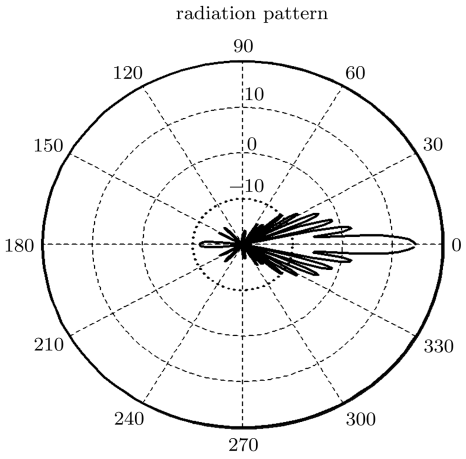
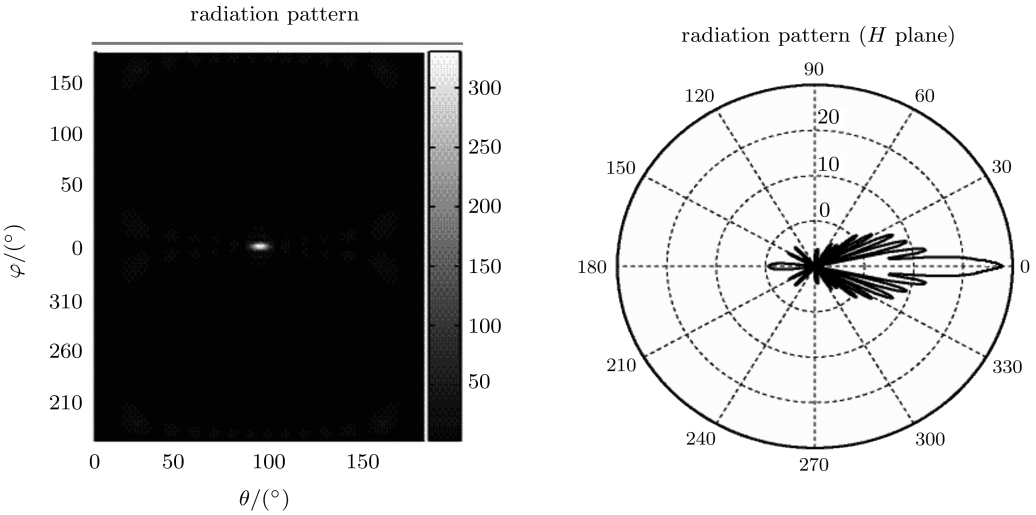


Fig.6. The radiation pattern of antenna in x direction.

is 3.2 degree, achieving a 2.4 degree increment, while the gain is 20dBi, a 7.6 dB increment is achieved by the FSS reflector.

To realize the high directivity in space, we use antenna array in the z-direction to improve the directivity and gain the antenna loaded with FSS. We repeat the single antenna in z-direction with 8 periods, the radiation pattern of the antenna array is evaluated by adding the radiation patterns with different radiation origins, as shown in Fig.7.

Our calculated results show that the radiation pattern has a 4.1 degree HPBW in the H-plane. The antenna gain of this antenna array is 29.3 dBi.



(a) radiation patte ns in three dimensional space

(b) radiation patterns in H-plane

Fig.7. The radiation pattern of the antenna array loaded with FSS.

3. Experimental results

Experimental setup of single anisotropic magnetic metamaterial antenna loaded with FSS and antenna array is respectively shown in Fig.8 and Fig.9.

The radiation patterns of single anisotropic magnetic metamaterial antenna and antenna array with and without FSS are measured. Table 1 is the experimental results of the antenna radiation patterns.

From the experimental results in Table 1, whether single antenna or array antenna, the FSS structure greatly improves performance of anisotropic magnetic metamaterial antenna. Our experimental results are consistent with the simulating results.

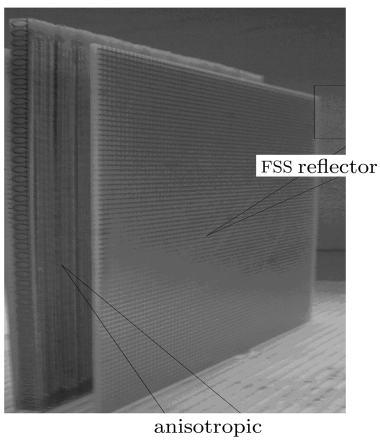


Fig.8. Experimental setup of single anisotropic magnetic metamaterial antenna loaded with FSS.

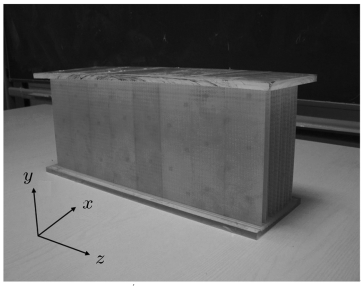


Fig.9. Experimental setup of the metamaterial antenna array.

Table 1. Experimental results of the antenna.

metamaterial antenna	FSS	HPBW/(°)	Gain/dBi
single antenna	without	6.1	12.2
	with	4	19.5
antenna array	without	6.4	22.1
	with	4.3	29

4. Conclusion

This paper uses the FSS structure to improve performance of high-directivity anisotropic magnetic metamaterial antenna. Whether single antenna or array antenna, the FSS structure greatly improves performance of metamaterial antenna. For single anisotropic magnetic metamaterial antenna, the simulated result shows that HPBW is 3.2 degree, achieving a 2.4 degree increment, while the gain is 20dBi, a 7.6 dB increment is achieved by the FSS reflector, at 10 GHz. The simulating results are consistent with our experimental results.

References

[1] Borja C, Font G and Blanch S 2000 *Electron. Lett.* **36** 778
[2] Hung T P and Ching-Kuang C T 2001 *Asia-Pacific Microwave Conference Proceedings, APMC* **2** p962
[3] Meng F Y, Wu Q and Wu J 2006 *Acta Phys. Sin.* **55** 2200 (in Chinese)
[4] Wu M F, Meng F Y, Wu Q and Wu J 2006 *Acta Phys. Sin.* **55** 5790 (in Chinese)
[5] Wu M F, Meng F Y, Wu Q and Wu J 2006 *Acta Phys. Sin.* **55** 6368 (in Chinese)
[6] Yang R, Xie Y J, Wang P and Yang T M 2007 *Acta Phys. Sin.* **56** 4504 (in Chinese)
[7] Wu M F, Meng F Y, Fu J H, Wu Q and Wu J 2008 *Acta Phys. Sin.* **57** 822 (in Chinese)
[8] Wang S L, Zhang Y W, He L, Li H Q and Chen H 2006 *Acta Phys. Sin.* **55** 226 (in Chinese)
[9] Bonefacic D, Hrabar S and Vakan D K 2006 *Microwave and Optical Technology Letters* **48** 2581
[10] Weng Z B, Wang N B, Jiao Y C and Zhang F S 2007 *Microwave and Optical Technology Letters* **49** 456
[11] Lee Y J, Park W S, Yeo J and Mittra R 2006 *Electromagnetics* **26** 203
[12] Li H Q, Qin Y Q, Wei Z Y, Chen H, Zhang Y W, Zhou L and Chan C T 2004 *4th Int. Conf. Microwave and Millimeter Wave Technology ICMMT* p480
[13] Romeu J and Rahmat-Samii Y 2000 *IEEE Trans. Antennas and Propagation* **48** 1097
[14] Gianvittorio J and Romeu P J 2003 *IEEE Trans. Antennas and Propagation* **51** 3088
[15] Jose K A, Sha Y, Varadan V K and Neo C P 2002 *IEEE Trans. on Antennas and Propagation Society, AP-S Int. Symposium* (Digest) **2** 576
[16] Ju L Y, Junho Y, Raj M and Sang P W 2004 *Microwave and Optical Technology Letters* **43** 462
[17] Ge Z C, Zhang W X, Liu Z G and Gu Y Y 2006 *Microwave and Optical Technology Letters* **48** 1272
[18] Guerin N, Hafner C, Cui X and Vahldieck R 2005 *Asia-Pacific Microwave Conference Proc. APMC* l.1 p1606213