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STUDY ON HIGH GAIN CIRCULAR WAVEGUIDE ARRAY ANTENNA WITH METAMATERIAL STRUCTURE

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Abstract—A new method to improve the gain of circular waveguide array antenna with metamaterial structure is presented. The electromagnetic characteristics of metamaterial and circular waveguide antenna with metamaterial structure are studied by using numerical simulation method, which are also compared with those of the conventional circular waveguide antenna. The simulation and experimental results show that this method is effective and metamaterial structure can realize congregating the radiation energy, so the gain of the antenna increases while the side lobe level decreases.

1. INTRODUCTION

In the late 1960s, Veselago [1] studied the electrodynamics of substances with simultaneously negative values of dielectric permittivity (ε) and magnetic permeability (μ). Although not present in nature, interesting properties were theoretically predicted for these substances, such as the reversal of the Snell law, Doppler Effect, Cherenkov radiation and build prefect lenses. Metamaterials have been extensively studied in the recent years, in the framework of microwave applications. Several works [2–4] have been aimed towards the improvement of the performances of antennas in the microwave range of frequencies. It is noted in [5, 6] that some principal properties of waves propagating in materials with negative permittivity and negative permeability are considered and high directivity can be obtained from conventional antenna using metamaterials. Some slotted antennas with metamaterials are studied in [7, 8].

In this paper, we present a new design of a high gain circular waveguide array antenna using metamaterial structure. The properties of metamaterial structure and the radiation characteristics of the array antennas are investigated by numerical method. The simulation results are given using Ansoft HFSS 3-D simulator which is based on the finite element method (FEM). Our studies demonstrate that the metamaterial structure can realize an effective refraction index which approximates zero and congregate the radiation energy. Moreover, a great improvement of gain can be obtained by using metamaterial structure on the array antenna in comparison with the conventional one.

2. PRINCIPAL CHARACTERISTICS OF METAMATERIAL STRUCTURE

The metamaterial, which is studied in this paper, is composed of copper grids with a square lattice whose period is equal to a mm (in the x-axis and y-axis directions). The grids' spacing in the z-axis direction is H mm, and side length of the square holes in the copper grids is $(a - r)$ mm. the structure of the metamaterial is shown in Fig. 1.

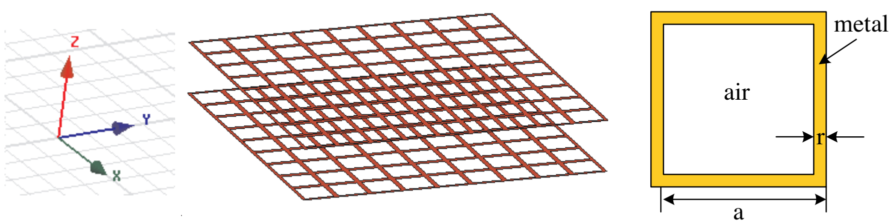


Figure 1. Structure of the proposed metamaterial.

When the period of the square lattices is less than microwave wavelength, this structure can be seen as a metal thin-wire array. This metamaterial structure has a characteristic response to electromagnetic radiation due to the plasma resonance of the electron gas. Theoretical and experimental researches have shown that such arrays of continuous thin wires are characterized by a plasma frequency [6]. Both approximate analytical theory and rigorous homogenization theory show that the equivalent permittivity has a behavior governed by a plasma frequency in the microwave domain:

$$\varepsilon_{eff}(\omega) = 1 - \omega_p^2/\omega^2 \tag{1}$$

where ω_p is the plasma frequency and ω the frequency of the electromagnetic wave. The equivalent permittivity is negative when the frequency is below ω_p, which has been widely discussed and applied in microwave domain [9], but other properties of this metamaterial structure have seldom been discussed: the permittivity can be positive and less than one when microwave frequency is just above the plasma frequency ($\omega \geq \omega_p$). That is to say, the permittivity can be less than one, eventually approximately zero. According to solid-state physical theory, the plasma frequency of metal thin-wire array can be defined as:

$$\omega_p^2 = \frac{n_{eff} e^2}{\varepsilon_0 m_{eff}} \tag{2}$$

where n_{eff} is the effective electron density, m_{eff} the effective mass of the electrons and e the electron charge. The average electron density of metamaterial structure is reduced in respect that only part of the space is filled by metal.

$$n_{eff} = n\frac{\pi r^2}{a^2} \tag{3}$$

Where n is the density of electrons in the wires, r is the radius of the wire and is the cell side of the square lattice on which the wires are arranged. At the same time, we note that, according to classical mechanics, any current flows, a strong magnetic field generates around the wire, and an enhancement of the effective mass of the electrons is caused by magnetic effects. Where m_{eff} is the new effective mass of the electrons given by

$$m_{eff} = \frac{\mu_0 e^2 \pi r^2 n}{2\pi} \ln(a/r) \tag{4}$$

From the classical formula for the plasma frequency of thin-wire structures

$$\omega_p^2 = \frac{n_{eff} e^2}{\varepsilon_0 m_{eff}} = \frac{n\frac{\pi r^2}{a^2} e^2}{\varepsilon_0 \frac{u_0 e^2 \pi r^2 n}{2\pi}} = \frac{2\pi}{\varepsilon_0 \mu_0 a^2 \ln(a/r)} = \frac{2\pi c_0^2}{a^2 \ln(a/r)} \tag{5}$$

where c_0 is the velocity of light in free space. According to this special metamaterial structure, formula (5) can be revised and defined as:

$$\omega_p^2 = \frac{n_{eff} e^2}{\varepsilon_0 m_{eff}} = \frac{\pi c_0^2}{KaH \ln(aH/rt)} \tag{6}$$

where K is the revised coefficient, $K = 3 \sim 5$, here K is 3. This metamaterial structure, which is satisfied with the microwave plasma frequency, can be designed easily according to [6]. The Snell-Decartes laws imply that the refractive index can be defined as $n = \sqrt{\mu_r \varepsilon_r}$, with the conclusion of [1] when microwave frequency is just above and close to plasma frequency, this structure has a very low refractive index within microwave plasma frequency. If the refractive index of the metamaterial is very small, then the emitted field is concentrated around the normal of the slab. This is summarized in Fig. 2. The E-field distributions in free space without and with metamaterial structure are shown in Figs. 3a and 3b, respectively.

We compare the different E-field distributions in Fig. 3 and find that, when electromagnetic wave propagates in free space, the electric

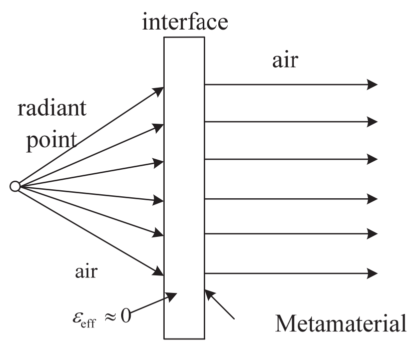


Figure 2. Geometrical interpretation of the emission of a source inside a slab of metamaterial whose refractive index approximates zero.

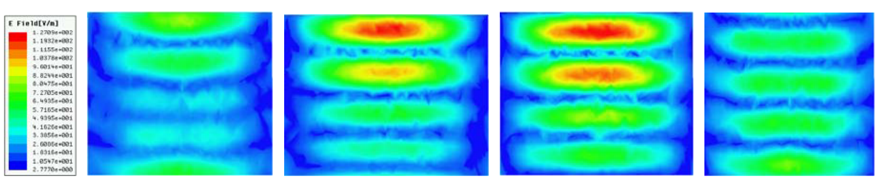


Figure 3a. E-field distribution in free space without metamaterial structure.

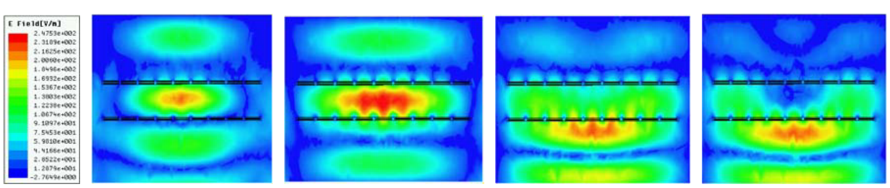


Figure 3b. E-field distribution in free space with metamaterial structure.

field is enhanced by using metamaterial structure. Making use of this extraordinary property of the metamaterial structure, we apply it to the antenna in order to focusing the incident fields radiated from the antenna. We can reduce the unit number of array antenna for the same gain, which has important significance to miniaturization design of array antenna.

3. SIMULATION AND NUMERICAL RESULTS

3.1. The Circular Waveguide Antenna

Based on the general process of antenna design, the structure of the circular waveguide antenna is shown in Fig. 4a. The circular waveguide antenna whose driven element is coaxial probe has been designed to work at 12 GHz. The diameter of circular waveguide is 20 mm and the length is 26.5 mm. The distance from the coaxial probe to the bottom of antenna is 9.25 mm. The length of coaxial probe is 6.25 mm,and the size of metal ground is 60 mm × 60 mm.

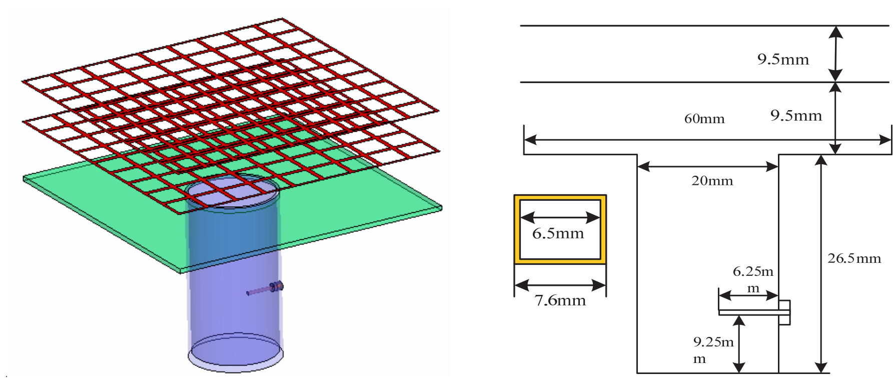


Figure 4a. Circular waveguide antenna with metamaterial structure.

The metamaterial structure is composed of very thin copper grids with square lattices whose period is equal to 7.6 mm, and side length of square holes in the copper grids is 6.5 mm. The spacing between two layers in the z-axis direction is 9.5 mm and each layer is composed of 9 × 9 cells, the total length of edge is 68.4 mm. The metamaterial structure is located at 9.5 mm from the antenna aperture.

The simulation results of PEC and metamaterial structures are shown in Fig. 4b. The gain of antenna with metamaterial structure increases from the original 9.053 dB to 17.34 dB, which is improved observably.

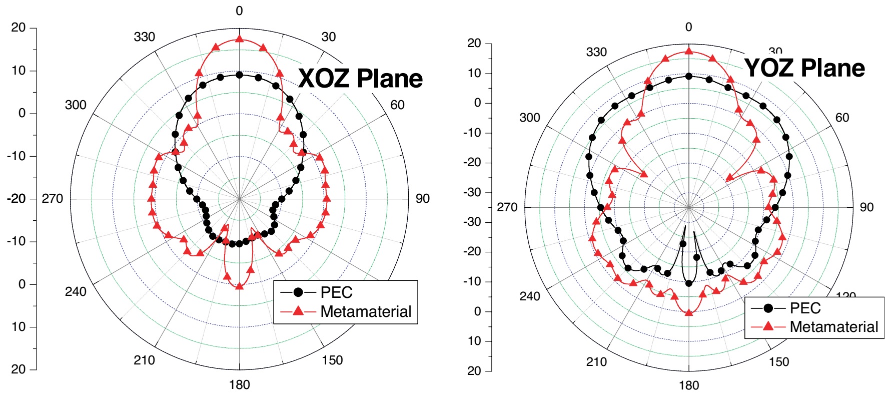


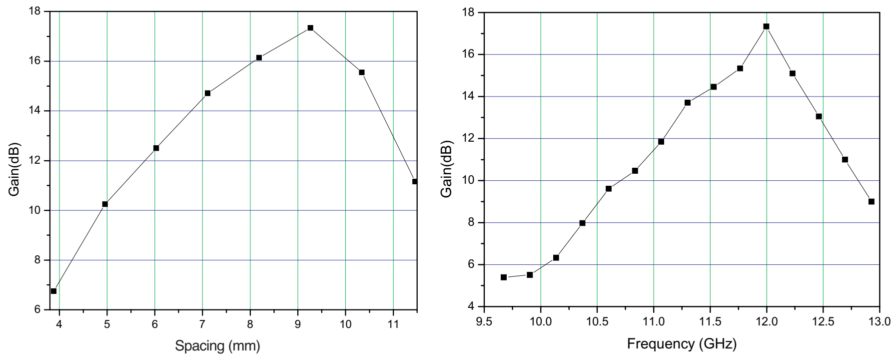
Figure 4b. Comparison of the radiation patterns.

In theory, the maximum directivity of an aperture antenna is $D_{\max} = 4\pi A/\lambda_0^2$, and the maximum gain $G_{\max} = kD_{\max}$, k is the efficiency. It is assumed $k = 1$, then it is approximate to take $G_{\max}(\text{dB}) = 10 * \log(4\pi A/\lambda_0^2)$, where $A = 60\,\text{mm} \times 60\,\text{mm}$, $\lambda_0 = c_0/f_0 = 25\,\text{mm}$, so the theoretical maximum value of the antenna gain is $G_{\max}(\text{dB}) = 18.6\,\text{dB}$. The gain of the circular waveguide aperture antenna with metamaterial structure is already very close to the theoretical maximum value of antenna with the same size and operating frequency.

As the foundation of the antenna design, it is necessary to analyze the effect of the spacing between two layers of matematerial structure, the curve of the gain which is changed with the spacing between two layers is shown in Fig. 5(a), while the curve of gain with different operating frequency is shown in Fig. 5(b). We can conclude that: only when the antenna works within the design frequency range can it get a more theoretical gain.

3.2. The Circular Waveguide Antenna Array

The arrays of circular waveguide antenna have found wide application in communication and radar domain. A conventional method to improve the gain of antenna is to use the array form. While in this paper, we propose a more effective method by using the array structure combining with metamaterial-mantled technology.



(a) (b)

Figure 5. (a) Gain of antenna with different spacing between two layers, (b) Gain of antenna with different operating frequency.

3.2.1. Two-element Array

A model of antenna array with two parallel elements using metamaterial structure is shown in Fig. 6a. The dimension of the element in array is the same as in the single circular waveguide antenna, and the distance of the two element centers is 42 mm. Two layers of metamaterial structure are placed, each layer of the metamaterial structure is composed of 15 × 15 cells with the total size is 68.4 mm × 114 mm, and the first layer is placed at 9.5 mm above the array antenna aperture. The spacing between two layers in the z-axis direction is also 9.5 mm. The simulation results are shown in Fig. 6b.

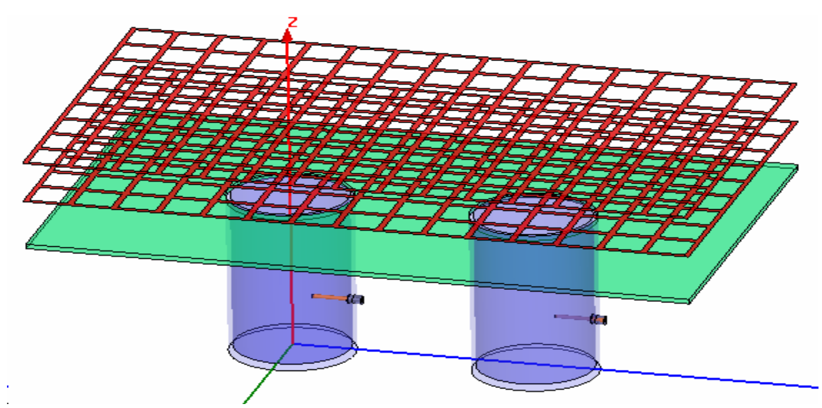


Figure 6a. Model of the two-element array.

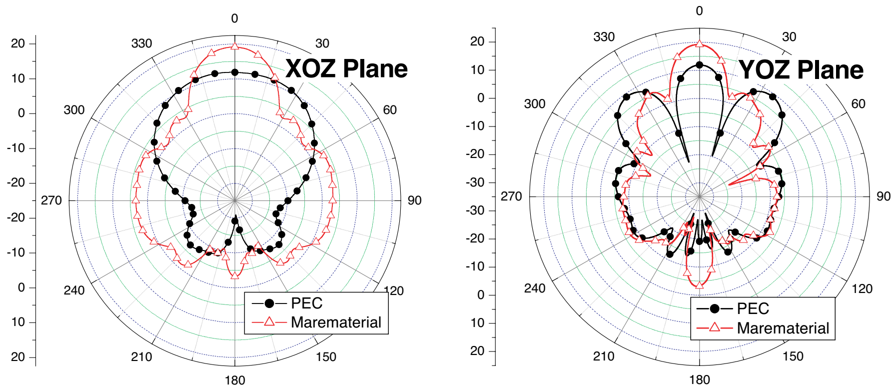


Figure 6b. Radiation patterns of the two-element array.

3.2.2. Four-element Array

Two cases of the four-element array with 1 × 4 form and 2 × 2 form are studied. The radiation patterns of the antenna array with matematerial structure are simulated and compared with the conventional antenna array.

In the case of the 1 × 4 array, the dimension of the element is the same as the single circular waveguide antenna, and the distance of the two element centers is 42 mm. The metamaterial structure is composed of 9 × 25 cells, Its total size is 68.4 mm × 200 mm with the first layer placed at 9.5 mm above the array antenna aperture. This model of four-element array with metamaterial structure is shown in Fig. 7a and its simulation results are shown in Fig. 7b.

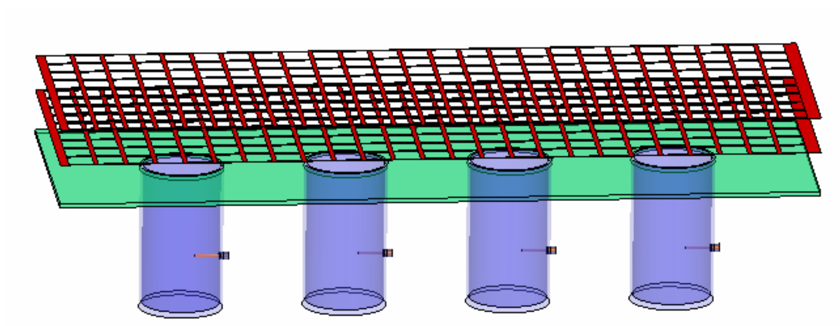


Figure 7a. Model of the 1 × 4 antenna array.

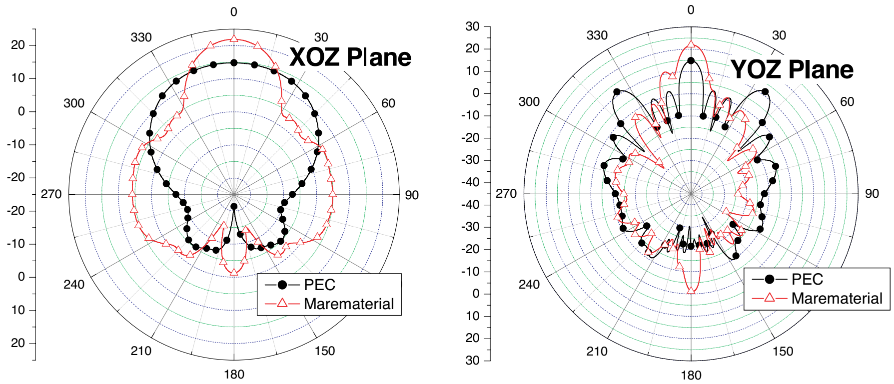


Figure 7b. Radiation patterns of the 1 × 4 antenna array.

The model of the 2 × 2 array antenna with metamaterial structure is shown in Fig. 8a.The dimension of the element is the same as the single circular waveguide antenna, and the distance of the two element centers is 42 mm. Each layer of the metamaterial structure is composed of 15 × 15 cells, and total size is 114 mm × 114 mm. Its simulation results are shown in Fig. 8b.

From the simulation results we can see that, the gain of two-element antenna array increases from the original 11.92 dB to 19.15 dB, while that of four-element antenna array is improved from 14.76 dB to 21.85 dB for 1 × 4 form and from 14.65 dB to 21.67 dB for 2 × 2 form, respectively. Generally speaking, the gains of the circular waveguide array antenna with metamaterial structure have an about 7 dB addition in comparison with those of conventional antenna. We believe that the improvement owns to metamaterial structure used on circular waveguide array antenna which can congregate the radiation energy.

In order to testify the simulation results, a circular waveguide antenna with metamaterial structure is fabricated and measured. Fig. 9(a) and (b) show the photographs of the PEC antenna and antenna with matematirial, respectively. Fig. 10 shows the measured radiation patterns of the circular waveguide antenna with matematirial structure and the conventional antenna which works at 12 GHz.

Compared with the PEC antenna, the gain of antenna with metamaterial structure has a 5.3 dB addition which is about 3 dB less than that of simulation result. It is believed that this difference is mainly caused by the errors of experiment. At the same time, the side lobe decreases obviously while the back lobe increases due to the

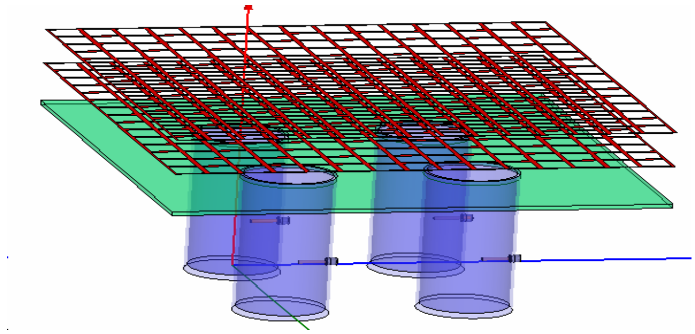


Figure 8a. Model of the 2 × 2 antenna array.

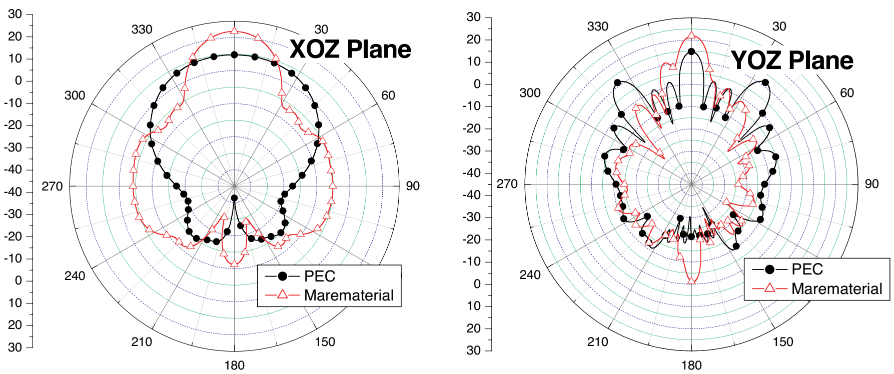
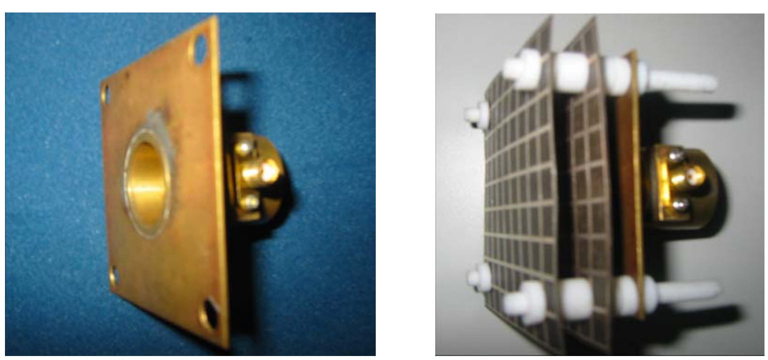


Figure 8b. Radiation patterns of the 2 × 2 antenna array.



(a) (b)

Figure 9. (a) Photograph of the PEC antenna, (b) Photograph of the antenna with metamatirial.

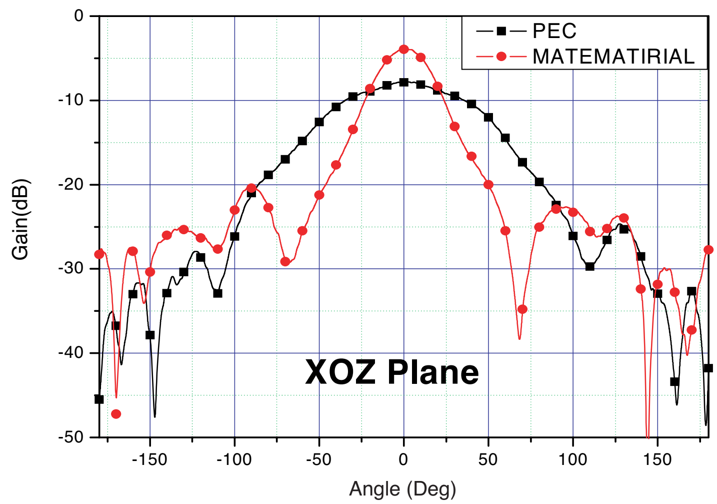


Figure 10a. Measured radiation patterns of the circular waveguide antenna (XOZ plane).

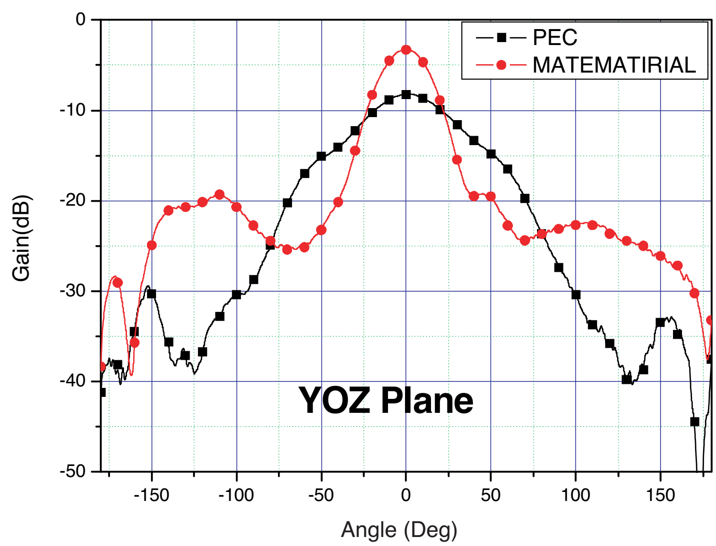


Figure 10b. Measured radiation patterns of the circular waveguide antenna (YOZ plane).

reflection effect of the metamaterial. The measurement results validate that, it is effectual to raise the gain of the circular waveguide antenna by using metamaterial structure.

4. CONCLUSIONS

The principle characteristic of the proposed metamaterial structure is studied, then the radiation characteristic of a circular waveguide antenna array with metamaterial structure is simulated using numerical method. The simulation results, which validate the theoretical analysis, show an about 7 dB addition in the antenna array gain in comparison with the conventional antenna array, so the radiation characteristics of antenna array with metamaterial structure are remarkably improved, finally the practicability of this method is illustrated with an example of single circular waveguide antenna. It is also expected that the metamaterial structure can be applied in various antennas to improve their radiation performance.

REFERENCES

1. Veselago, V. G., "The electrodynamics of substances with simultaneously negative values of ε and μ," *Soviet Physics USPEKI*, Vol. 10, No. 4, 509–514, 1968.
2. Smith, D. R., W. J. Padilla, D. C. Vier, et al., "Composite medium with simultaneously negative permeability and permittivity," *Physical Review Letters*, Vol. 84, No. 18, 4184–4187, 2000.
3. Enoch, S., G. Tayeb, P. Sabouroux, and P. Vincont, "A metamaterial for directive emission," *Physical Review Letters*, Vol. 89, No. 21, 213902:1-4, 2002.
4. Pendry, J. B., "Negative refraction males a prefect lens," *Physical Review Letters*, Vol. 85, No. 21, 3966–3969, 2000.
5. Lindell, L. V., S. A. Tretyakov, K. I. Nikoskinen, and S. Ilvonen, "BW media — media with negative paraments, capable of supporting backward waves," *Microwave Opt. Tech. Lett.*, Vol. 31, No. 2, 129–133, 2001.
6. Ziolkowski, R. W. and E. Heyman, "Wave propagation in media having negative permittivity and permeability," *Phys. Rev. E*, Vol. 64, No. 5, 056625:1-15, 2001.
7. Hamid, A.-K., "Study of lossy effects on the characteristics of axially slotted circular or elliptical cylindrical antennas coated with metamaterials," *Microwaves, Antennas and Propagation, IEE Proceedings*, 485–490, Dec. 2005.

8. Hamid, A.-K., "Axially slotted antenna on a circular or elliptic cylinder coated with metamaterials," *Progress In Electromagnetic Research*, PIER 51, 329–341, 2005.
9. The'venot, M., C. Cheype, A. Reineix, and B. Jecko, *IEEE Trans. Microwave Theory Tech.*, Vol. 47, 2115, 1999.