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A new patch antenna with metamaterial cover*

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Abstract: A metamaterial was introduced into the cover of a patch antenna and its band structure was analyzed. The metamaterial cover with correct selection of the working frequency increases by 9.14 dB the patch antenna's directivity. The mechanism of metamaterial cover is completely different from that of a photonic bandgap cover. The mechanism of the metamaterial cover, the number of the cover's layers, and the distance between the layers, were analyzed in detail. The results showed that the metamaterial cover, which works like a lens, could effectively improve the patch antenna's directivity. The physical reasons for the improvement are also given.

Key words: Metamaterial, Patch antenna, FDTD, Plane wave expansion method
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INTRODUCTION

Investigation of metamaterials is currently one of the most active frontiers in engineering and physics. Metamaterials are also called backward-wave materials, double-negative materials, or left-handed materials. Left-handed materials were proposed by Veselago (1968). The applications of metamaterials are widely spread in many fields (Pendry, 2000; Grbic and Eleftheriades, 2003; Foteinopoulou *et al*., 2003), such as imaging apparatus, planar light wave circuits, optical wave-guides, antennas, etc.

Metamaterials have periodic structures. Photonic bandgap (PBG) materials, which also have periodic structures, have been used to improve antenna properties for more than 10 years. Many PBG antennas have been developed, such as PBG substrate antennas (Brown *et al*., 1993), PBG cover antennas (Thèvenot *et al*., 1999; Lin *et al*., 2004), MPBG resonant antennas (Lin *et al*., 2002).

When a PBG material is used as a patch antenna's cover, it is illuminated by the electromagnetic (EM) fields radiated from the patch antenna, and almost all of the dielectric elements of the cover are excited so that the field distribution on the cover surface is quite uniform. So the PBG cover is excited to serve as an aperture antenna, and the antenna's directivity is improved.

Metamaterials can also very efficiently improve antenna directivities. A metamaterial was introduced into the cover of a patch antenna in this paper. The metamaterial presented here is similar to that described in (Enoch *et al*., 2002). Its effective index is between 0 and 1. With correct selection of the working frequency, the metamaterial cover, whose mechanism is completely different from that of a PBG cover, increases by 9.14 dB the patch antenna's directivity.

The simulations of such a metamaterial-cover patch antenna were computed by the finite element method (Ansoft HFSS 9.0), in combination with boundary treatment of the perfectly matched layer (PML) (Berenger, 1996). Computations were run for enough steps to ensure that a steady result was achieved.

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DESIGN AND RESULTS

The metamaterial is composed of perfect conductor with a square lattice and whose period is equal to 35.4 mm (in the *x*-axis and *y*-axis directions). The grids' spacing in the *z*-axis direction is 43 mm. The edge of the square holes of the perfect conductor grids is 30.22 mm.

The metamaterial-cover patch antenna is composed of an ordinary patch antenna and two metamaterial layers each composed of 9×9 units (Fig.1).

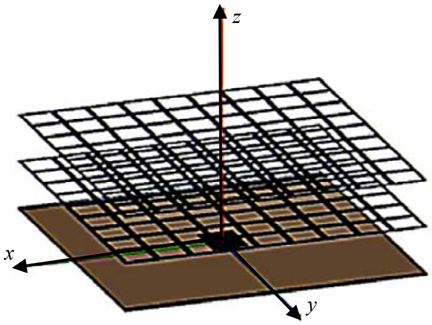


Fig.1 The structure of metamaterial-cover patch antenna

Given the structure of ordinary patch antenna and the structure of metamaterial layer, there are three key factors to adjust: the working frequency, the number of the layers and the distance between the layers (the grid's spacing in the *z*-axis direction).

The working frequency of ordinary patch antenna is to be 2.585 GHz. The substrate is 2 mm thick, and composed of medium with the relative dielectric coefficient equal to 2.2. The input mode is back-feed. The patch size is 36.8 mm×45.9 mm, and the feed which is a 1.2 mm diameter metal cylinder, 6.65 mm to the center of the patch along the *x*-axis direction.

Fig.2 compares S_{11} between ordinary patch antenna and metamaterial cover patch antenna. Obviously the working frequency moves to 2.57 GHz and the scope of impedance is not changed much. We observed and compared the chosen frequency of the two types of antenna.

As EM wave metamaterial has effect similar to that of congregation, we can see clearly through the arrow direction's changing process of Poynting vector from Fig.3, where the arrow indicates the direction of Poynting vector, not the magnitude of the vector. Figs.3a and 3c show the direction of Poynting vector in ***E***-plane (*x*-*z* plane) of each patch antenna respectively and Figs.3b and 3d respectively show the direction of Poynting vector in ***H***-plane (*y*-*z* plane) of each patch antenna. Obviously, the vector's direction points close to *z*-axis when EM wave threads through the metamaterial. This shows that the metamaterial has congregating effect on the EM wave's transmission direction, and is similar to the congregation effect which convex lens to the radiation of light-wave.

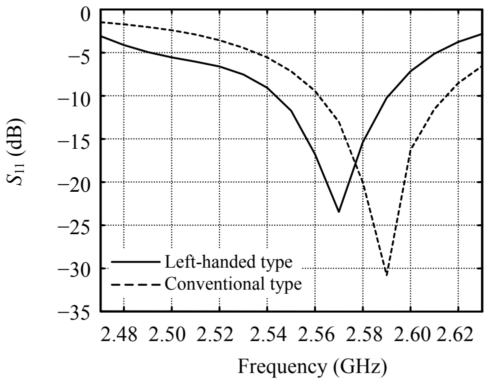
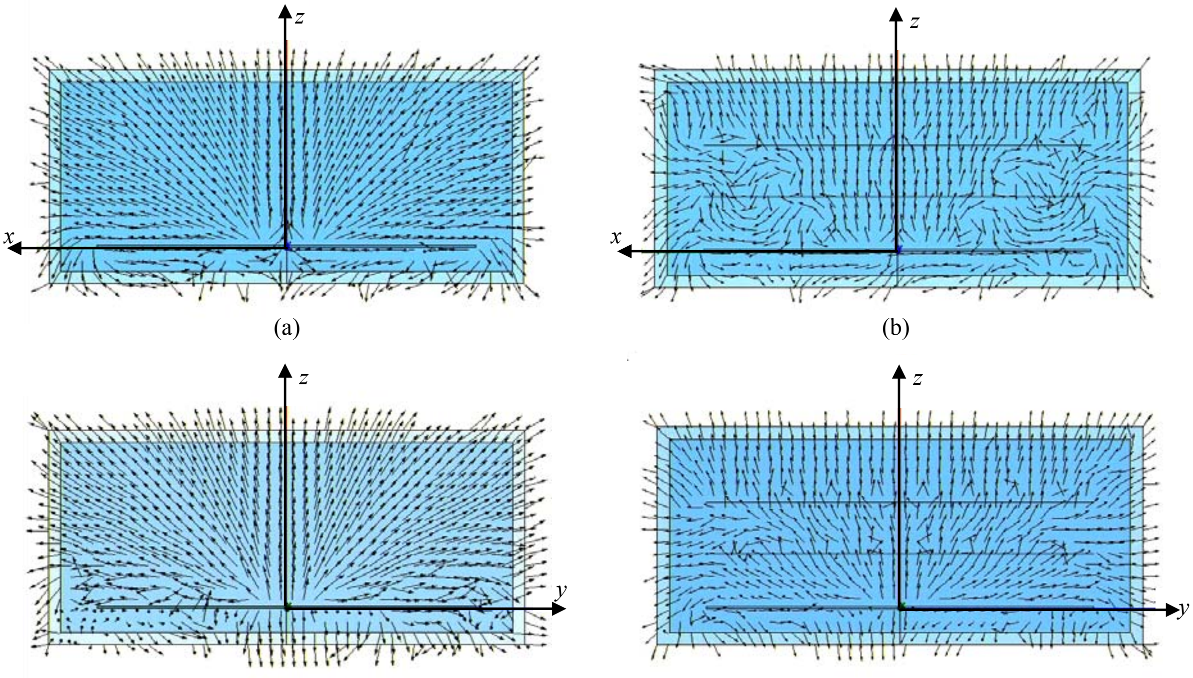


Fig.2 S_{11} of conventional type and metamaterial type patch antenna

Fig.3 shows that there are still some EM waves leaking into the edge of the metamaterial cover. In order to reduce the leak as effectively as possible, larger metamaterial cover should be used. At the same time, to make the congregation effect of metamaterial to the EM wave direction more evident, more layers of metamaterial are needed in the cover. Under ideal conditions, the larger the cover size of the metamaterial, the better; the more the layers, the better. But under actual conditions, we must use the least space resource to obtain the best functions of the antenna, the resource performance of which must be as high as possible. So the size and layer number of the metamaterial cover need be adjusted accordingly.

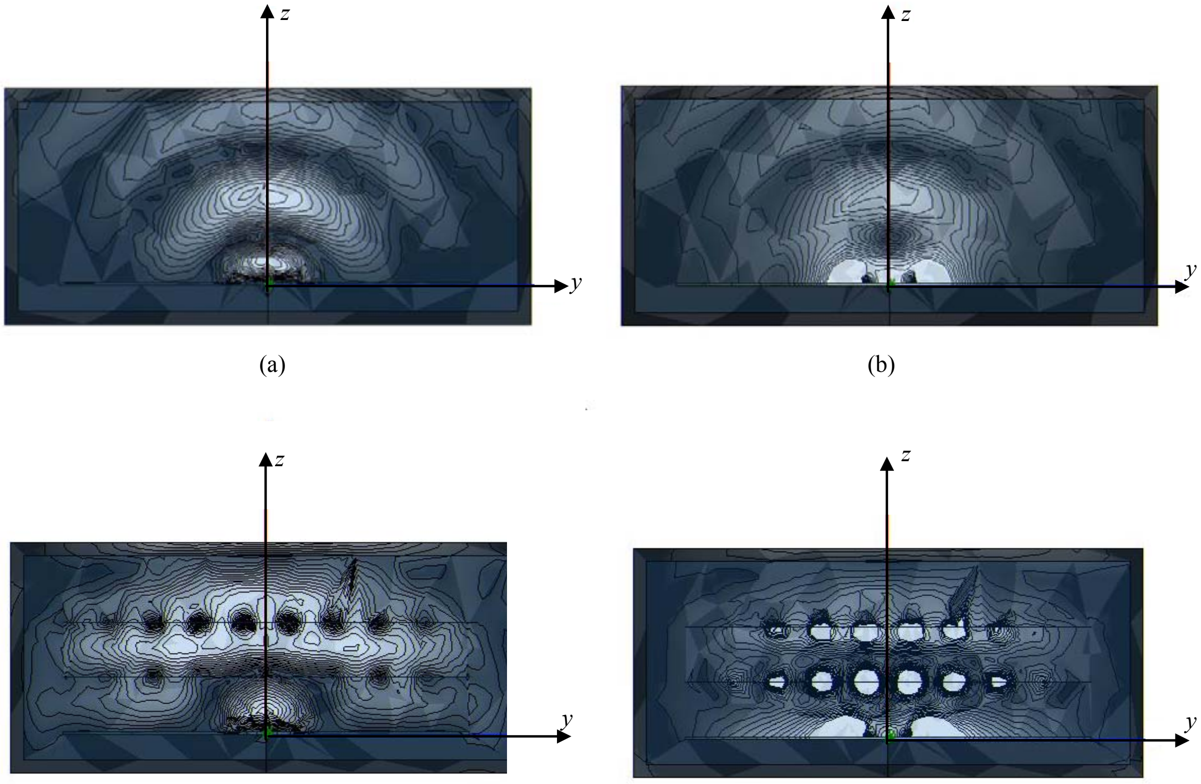
Figs.4a and 4b are ***H***-plane intensity distribution of ordinary patch antenna in electric field and magnetic field respectively; while Figs.4c and 4d are ***H***-plane intensity distribution of metamaterial cover patch antenna in electric field and magnetic field respectively. Comparison of those two groups of figures clearly shows that the main lobe of the ordinary patch antenna has a large distribution angle; this means its directivity is bad. And the main lobe of the patch antenna with metamaterial cover points toward the *z*-axis direction; it means its directivity is better.



(a) (b)

(c) (d)

Fig.3 Distribution of Poynting vector in *E*-plane: (a) ordinary patch antenna; (b) metamaterial cover patch antenna and in *H*-plane: (c) ordinary patch antenna; (d) metamaterial cover patch antenna



(a) (b)

(c) (d)

Fig.4 *H*-plane intensity distribution of ordinary patch antenna: (a) electric field; (b) magnetic field and *H*-plane intensity distribution of metamaterial cover patch antenna: (c) electric field; (d) magnetic field

This also shows that metamaterial has remarkable effect on the congregation of the radiation energy.

Figs.5a~5d are the far field directivity three-dimensional patterns of ordinary patch antenna, 1 layer, 2 layers and 3 layers of patch antenna with metamaterial cover respectively. By comparison, we can see that with addition of layer, the main lobe becomes sharper, indicating that the congregation effect is intensified gradually to radiation direction.

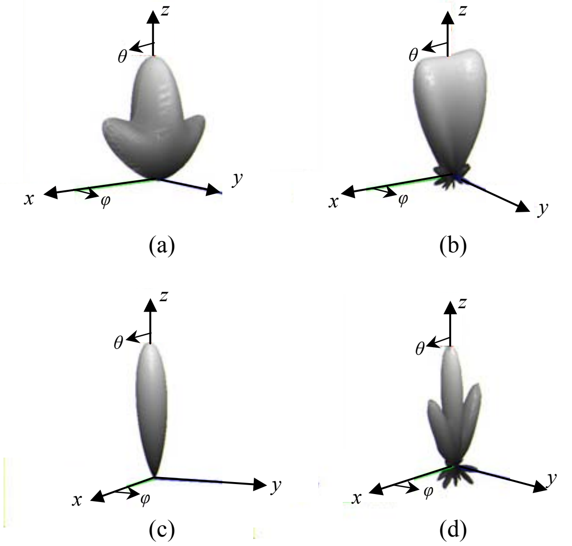


Fig.5 Radiation patterns in spherical coordinates. (a) Ordinary patch antenna; (b) One cover layer patch antenna; (c) Two cover layers patch antenna; (d) Three cover layers patch antenna

But, when added layers were increased from two to three, the EM wave reaching the cover's edge is very strong. So the side lobe is as strong in directivity as the main lobe. This indicates that the radiation wave at the boundary has become the main holdback affecting the antenna's directivity of increasing intensiveness.

As its effective index is between 0 and 1, not below 0, the EM wave radiation angle shrunk gradually (Fig.6 and Fig.7). The three layers cover limits the various directivity lobes to the cover's boundary as the EM wave diffuses toward the cover. Moreover when the layer number is 1, the characteristics of the cover are weak, so the coupling of EM energy and cover is not strong enough and more energy reflects to the boundary via the space between cover and substrate, which brings about very strong scattering. Therefore there are many miscellaneous lobes in Fig.5b. When we design patch antenna with metamaterial cover, we should consider the following two

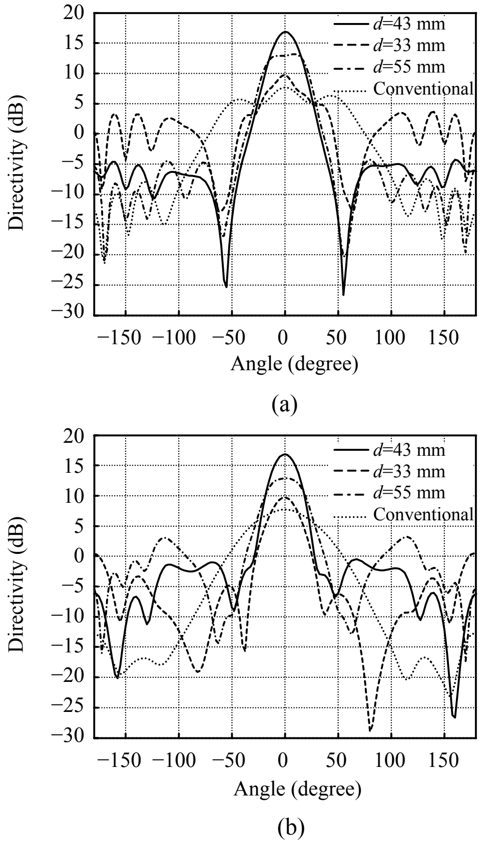


Fig.6 Radiation patterns of metamaterial-cover patch antenna under different distances of gaps and ordinary patch antenna. The abscissa represents angle between the normal of the cover and the radiation direction. (a) *E*-plane; (b) *H*-plane

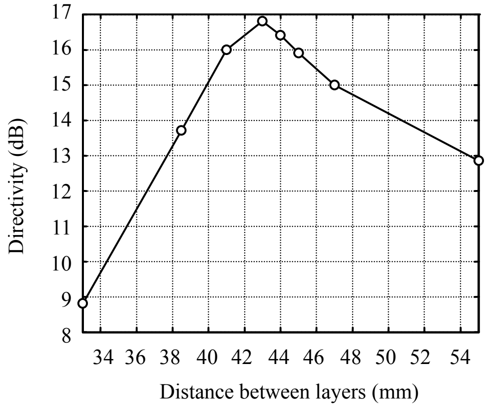


Fig.7 Radiation directivity of metamaterial-cover patch antenna change with different distances between layers

aspects synthetically: cover size and layer number.

After selecting the working frequency (2.57 GHz) and the structure and size of the cover, and fixing the layer number at two, we analyze the effect of layers' gap on the patch antenna.

Results of detailed analysis on the radiation pattern of ***E***-plane and ***H***-plane of the patch antenna when the distance *d* between layers is 33 mm, 43 mm and 55 mm are shown in Figs.6a and 6b respectively.

Comparison of the width of the main lobe in the radiation pattern under those three distances showed clearly that when *d* was 33 mm, the width *w* between ***E***-plane and ***H***-plane of the main lobe was the biggest; when *d* was 55 mm, *w* was smaller than that when *d* was 33 mm, and a little bigger than that when *d* was 43 mm, and when *d* was 43 mm, the radiations of the ***E***-plane and ***H***-plane were the most consistent.

Through the analysis we know that, when *d* was 43 mm, the back lobe of the ***E***-plane and ***H***-plane were the most symmetric; when the gap was increased or reduced, the scope of the front lobe reduced, that of the back lobe increased, then a serious unbalance appeared.

From comparison between the radiation direction figures under those three different distances, we know that under condition of optimum layer number of the metamaterial cover, appropriate working frequency of certain structure and proper size of patch antenna cover, the distance between the metamaterial layers of the antenna patch cover has great effect on the main and back lobe radiation patterns of the patch antenna.

So, for metamaterial cover with certain structure and size, there exists the problem of choosing the layer number and distance between the layers. Fig.7 shows that radiation directivity of patch antenna with metamaterial cover changes with different distances between layers.

From a survey of the near field's EM wave of two patch antennas, we know the processing mechanism of the EM field distribution of the patch antenna with metamaterial cover. The radiation main lobe of the metamaterial-cover patch antenna is very sharp. When the directivity increases strongly, the side lobe will decrease sharply, the back lobe of the antenna radiation (mainly the range less than −90° and higher than +90° in the figure of the radiation direction) will expand a little. There are two ways to improve the pattern, the first one is to enlarge the size of the cover but this will decrease the resource performance of the antenna; the other way is to adopt PBG or PMC substrate. This is a feasible scheme and worthy of deep research.

The ordinary patch antenna's directivity is 7.7 dB; after adding metamaterial, the patch antenna's directivity is increased to 16.84 dB. Theoretically, the maximum directivity of an aperture antenna is

$$D_{\max}=4\pi A/\lambda_0^2\,, \tag{1}$$

where,

$$A=l^2=318.6\text{ mm}\times318.6\text{ mm}, \tag{2}$$

$$\lambda=c_0/f_0=116.7\text{ mm}, \tag{3}$$

so $D_{\max}$=19.72 dB.

The directivity of the patch antenna with metamaterial designed by us has almost approached the theoretical limit of the antenna with the same size and the same working frequency.

CONCLUSION

In this work based on the results of Fresnel Institute, a periodic metamaterial structure was designed. By selecting the working frequency, its effective index is between 0 and 1. The radiation characteristics of the near and far field were investigated. An effective metamaterial cover for the patch antenna was designed and details about selecting the number and the distance of the cover's layers are given in the text.

Compared with photonic bandgap (PBG) materials, metamaterial is simpler to process and lighter in weight. Applying metamaterial to patch antenna is an important development of new high-directivity patch antenna.

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