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Improved patch antenna performance by using a metamaterial cover*

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Abstract: A new patch antenna system with a metamaterial cover is presented in this paper. The impedance, radiation pattern, and directivity of such an antenna are studied. A performance comparison between the conventional patch antenna and the new metamaterial patch antenna is given. The results show that the directivity of the metamaterial patch antenna is significantly improved. The effect of the metamaterial cover's layer numbers on the radiation pattern of the patch antenna is also studied.

Key words: Directivity, Metamaterial, Patch antenna
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INTRODUCTION

Metamaterials are periodic metallic structures exhibiting unique properties not existing in natural materials. They are also called backward wave materials, double negative materials, or left-handed materials (LHM) in particular, in which the vectors ***E***, ***H*** and ***k*** form a left-handed system. Since the idea proposed by Veselago (1968), metamaterials have attracted great interest in the last years (Smith *et al*., 2000; Pendry, 2000; Smith and Kroll, 2000; Shelby *et al*., 2001). The applications of such a material have been widely spread in many fields, such as imaging lenses (Chen *et al*., 2004), planar microwave circuits (Grbic and Eleftheriades, 2003), etc.

A metamaterial structure composed of copper grids with a square lattice was given by Enoch *et al*.(2002). It was validated that the radiated electromagnetic waves in the media can be congregated in a narrow rectangle area. When applied to a monopole antenna as a ground plane, this structure can greatly improve the directivity of the antenna. Different kinds of covers have been used to improve the performance of the antennas. A superstrate cover is used to effectively enhance the gain of a cavity-backed slot (CBS) antenna (Tan *et al*., 2005), and Photonic Bandgap (PBG) covers can significantly increase the directivity of patch antennas (Thèvenot *et al*., 1999; Qiu and He, 2001; Zhu *et al*., 2003; Jaffre *et al*., 2003). In this paper we present a new design of patch antenna system, in which a metamaterial structure is introduced as the cover of the antenna. A periodic metallic structure is designed and the band structure is calculated. The electromagnetic waves in the media are congregated in a small solid angle around the normal if the working frequency is selected properly. The impedance, radiation pattern, and directivity of the new patch antenna are studied by full-wave simulations (Ansoft HFSS 9.0), combined with boundary treatment of the perfectly matched layer (PML) (Berenger, 1996). The effects of the cover layer numbers on the performance of the antenna are also analyzed.

DESIGN AND RESULTS

The schematic of the new patch antenna system is shown in Fig.1. It is composed of a patch antenna

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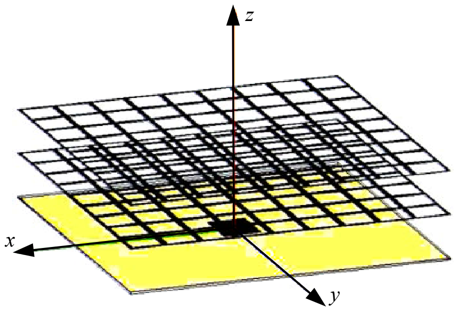


Fig.1 Schematic of the metamaterial patch antenna

with a new cover made up of two metamaterial layers with the same structure. The metamaterial structure is chosen to be similar to (Enoch *et al*., 2002) and is composed of copper grids with a square lattice whose period is 35.4 mm (in the *x*-axis and *y*-axis directions), with the edge of the copper grids' square holes being 30.22 mm.

The space of the grids in the *z*-axis direction is chosen to be 43 mm, and the band structure of the metamaterial is calculated. The phase differences between the two boundary surfaces which are vertical to *x*-, *y*- and *z*-axis are set to be Phase 1, Phase 2 and Phase 3, respectively. The values of Phase 1 and Phase 2 used in simulation are indicated in Fig.2a and the calculated band structure of the metameterial with different values of Phase 3 is shown in Figs.2b, 2c and 2d, respectively. From Fig.2 we can see that the electromagnetic waves in the media can only propagate along a small solid angle around the normal axis (the *z*-axis) at about the frequency of 2.585 GHz. So the operating frequency of the conventional patch antenna is selected at 2.585 GHz. The dielectric constant of the substrate is ε_r=2.2. The patch of the antenna is rectangular with 45.9 mm width and 36.8 mm length, and the thickness of the substrate is 2 mm. The size of the substrate is the same as that of the cover. Each metamaterial layer consists of 9×9 units, so the size of the substrate and the cover is 318.6 mm×318.6 mm. The distance between the substrate and the first layer is chosen to be 43 mm, which is the same as the

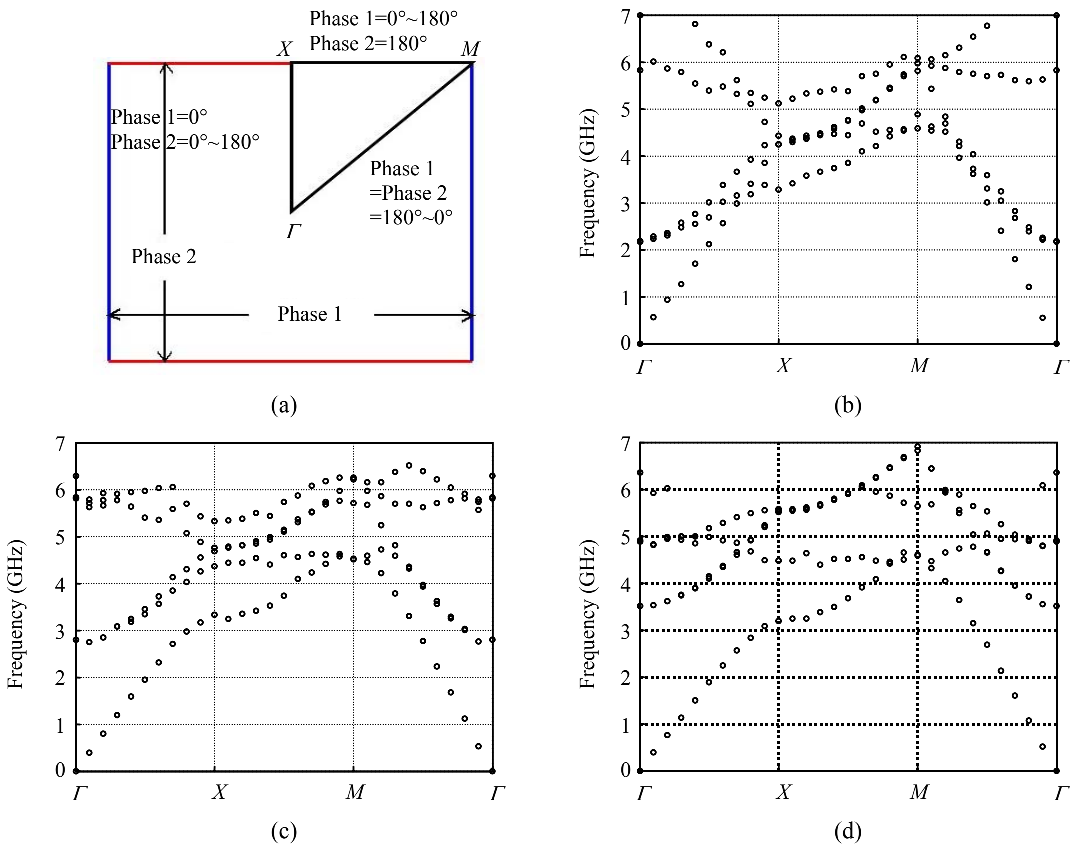


Fig.2 The square lattice (a) and the band structure of the metameterial when (b) Phase 3=0; (c) Phase 3=π/2; (d) Phase 3=π

distance between the two layers.

The input return loss (S_{11}) of the metamaterial patch antenna and the conventional patch antenna is shown in Fig.3, showing that the operating frequency of the patch antenna shifts slightly to 2.57 GHz in the presence of the metamaterial cover. The radiation patterns, distribution of Poynting vector and the directivities are compared at the resonant frequency of each type of the antennas.

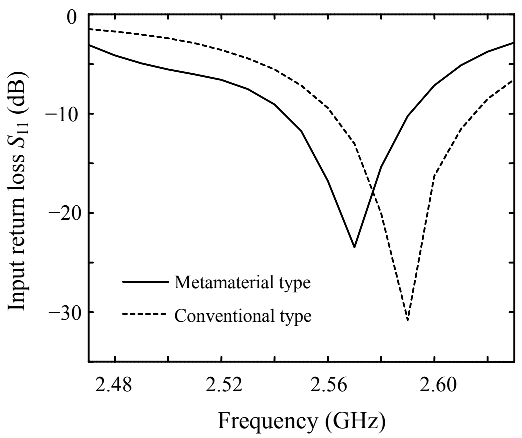
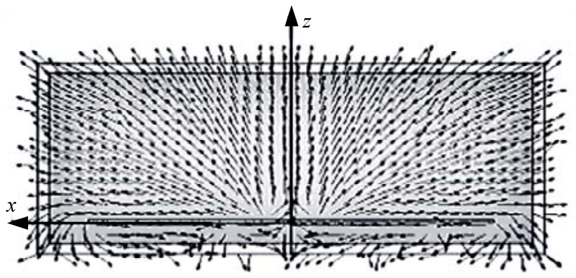


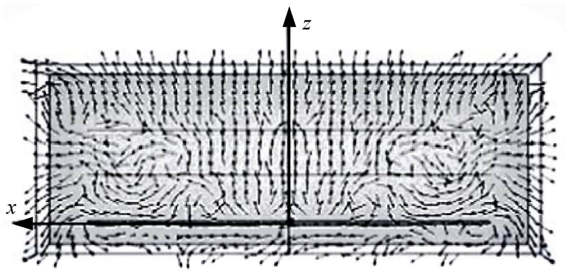
Fig.3 Input return loss (S_{11}) for the conventional patch antenna and the metamaterial patch antenna

Fig.4 is the distribution of Poynting vector in the *E*-plane (*x*-*z* plane) for the cases of the conventional patch antenna (Fig.4a) and the metamaterial patch antenna (Fig.4b). It can be seen clearly that the directions of the Poynting vector point close to the *z*-axis obviously when electromagnetic waves propagate through the metamaterial cover. This demonstrates the congregation effect of the metamaterial on the radiation of the electromagnetic waves, which is analogous to the focus effect of convex lens on the propagation of light waves actually. It can also be seen that there are still some electromagnetic waves leaking out from the boundary of the metamaterial cover of finite size. A larger cover is needed to reduce the amount of leaked waves which can be done by enlarging the antenna volume.

The metamaterial cover can not only congregate the radiation remarkably when electromagnetic waves propagate through the two layers, but also can make the waves radiate more consistently. Fig.5 shows the distribution of the magnetic field on the surface of the cover of the first layer (Fig.5a) and the second



(a)



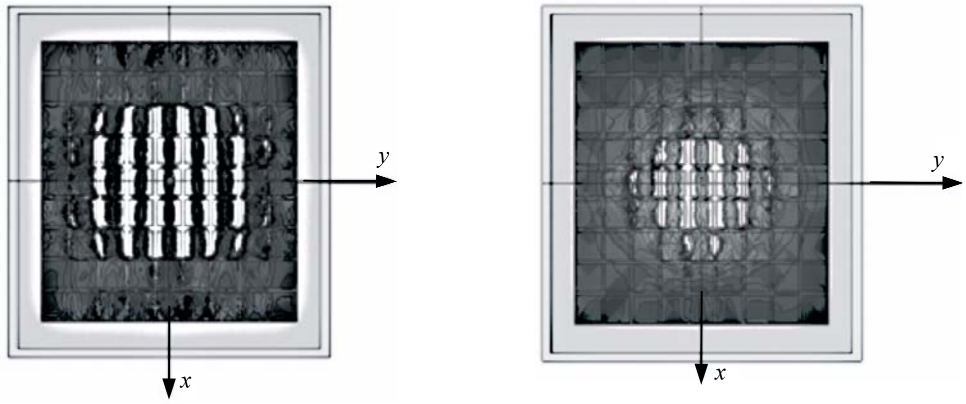
(b)

Fig.4 Distribution of Poynting vector in the *E*-plane (*x*-*z* plane). (a) The conventional patch antenna; (b) The metamaterial patch antenna

layer (Fig.5b) from the substrate upward. We can see obviously that the distribution of the magnetic field on the surface is quite uniform, which makes the cover act as an aperture antenna, and that the magnetic field on the second layer is more congregated to the *z*-axis and more regular than that of the first layer.

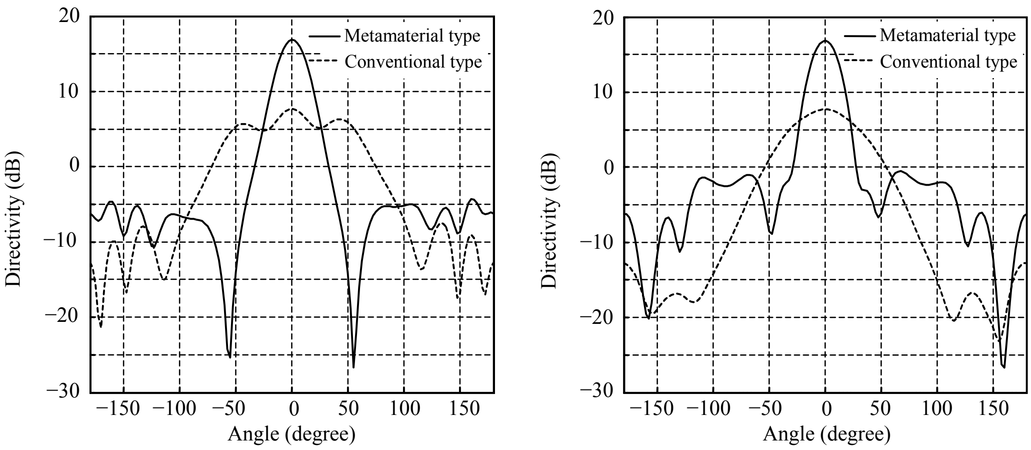
Fig.6 shows the radiation patterns for the conventional patch antenna and the metamaterial patch antenna on the *E*-plane (Fig.6a) and the *H*-plane (Fig.6b). It is shown that there is a 10 dB improvement in the forward direction in the *E*-plane. And the beam becomes less divergent. Almost the same results can be obtained from the *H*-plane. The metamaterial cover can increase the directivity from 7.7 dB (of the conventional patch antenna) to 16.84 dB. Theoretically the aperture antenna's maximal directivity is $D_{max}= 4\pi A/\lambda_0^2$. Since the area of the aperture is A=318.6 mm×318.6 mm, and $\lambda=c_0/f_0$=116.7 mm, so one has D_{max}=19.72 dB. The directivity of the designed patch antenna with the metamaterial cover is very close to the maximum directivity (19.72 dB) physically possible for this size of antenna.

The effect of the layer numbers of the metamaterial cover on the radiation pattern of the antenna is studied. Fig.7 shows 3D radiation pattern for the



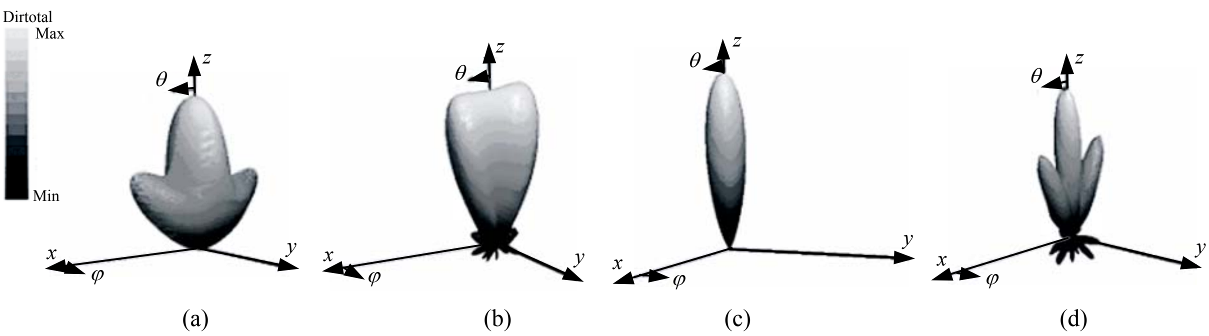
(a) (b)

Fig.5 Distribution of the magnetic field on the surface of the metamaterial cover
(a) The first layer; (b) The second layer (from the substrate upward)



(a) (b)

Fig.6 Radiation patterns of the conventional patch antenna and the metamaterial patch antenna
(a) *E*-plane; (b) *H*-plane



(a) (b) (c) (d)

Fig.7 Radiation pattern in sphere coordinates. (a) Conventional patch antenna; (b) One cover layer patch antenna; (c) Two cover layers patch antenna; (d) Three cover layers patch antenna

conventional patch antenna and the metamaterial antennas with different layer numbers of the cover. From this figure we can see that the main lobe of the radiation pattern becomes sharper as the layer numbers of the cover increased. This indicates that the congregation effect of the metamaterial cover is intensified with the increase of the layer numbers. When the layer numbers are increased from two to three, the side lobe becomes very sharp in addition (Figs.7c and 7d). This will result in the decrease of the antenna's directivity. So the layer numbers of the metamaterial cover should be carefully chosen. For a case of too few layer numbers of the metameterial cover, the function of the cover could not be exerted adequately, and for a case of too many layer numbers of the cover, the radiation of the electromagnetic waves at the boundary of the cover will be intensified; these two cases will both weaken the performance of the antenna by decreasing the directivity.

CONCLUSION

A new patch antenna system with a metamaterial cover has been designed. The impedance, distribution of Poynting vector, radiation pattern, and directivity of such an antenna were presented. The numerical results showed that the directivity of the patch antenna was significantly improved. The new metamaterial patch antenna can increase the directivity up to 16.84 dB, which is very close to the maximum directivity (19.72 dB) physically possible for this size of antenna. The effect of the layer numbers of the cover on the performance of the antenna was also studied. Experimental work on this new type patch antenna is under study.

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