Design of a metamaterial-based high-directivity antenna

Shiquan Zhang*
Foundation Department, Engineering University of PAP, Xi’an, China

*Corresponding author e-mail: zsquany@163.com

Abstract. Two layer lattice-type metamaterial unit is loaded above a microstrip antenna, gathering electromagnetic wave by using the zero refraction index effect. The \( \pi \) -type metamaterial unit is etched on a substrate, and the band gap is wore out for restraining the backward wave. Simulation tests are carried out to two methods, respectively. Finally two methods are combined for designing a high directivity antenna, and the effects of the distance between the covering layer and the antenna are discussed. Comparing the simulated and the real test results, we verified the method and the theory. We can see that the gain of the newly-designed microstrip antenna has achieved by 8.94dB and the directivity factor gained an relative increase of by 49.08%.

1. Introduction
Microstrip antenna, as a typical microwave antenna, has been widely applied in various of electrical engineering areas because of its merits such as compact size and easiness to assemble. However, its dismerits of disatisfied directivity and high loss hinde its aplications. With increasing requirements for antenna performance by varied elecrtical devices, the demand for high-gain-high-directivity microstrip antenna has attracted the attentions of many reserchers. Traditional optimization methods cannot overcome the interactive restraint among the physical size, bandwidth and gain, etc. Hence, after metamaterials were discovered in 2001, improvement of antenna performance based on metamaterials has become the one of the fashionable topic of studies [1,2,3]. Usually A covering layer with zero refraction index is etched above the antenna to prduce the high gain and high directivity to some extent. Yet, fewer works deal with the use of combination of two methods above to analyze antenna performance. In this paper, metamaterials are printed in both the covering layer and the base board in a traditional antenna. Detailed analysis is made on the antenna covering layers with influential parameters. The result shows that both the gain and the directivity of this kind of antenna have been obviously increaseed in comparison with traditional microstrip antenna.

2. Antenna design
The concrete requirements are set at first, then unit structure is designed and parameters are adjusted to meet the corresponding demands. Through numerical analysis and simulation testing , we choose FR4 with a dielectric constant \( \varepsilon_r = 4.4 \) and to be the base board of the antenna, seting the thickness \( h=1.6\text{mm} \). A type of coaxial feed microstrip antenna with a central working frequency of is designed. The size of the base board is 48mm×40mm and that of the antenna radiation patch is 16mm×10.8mm . The coaxial feeding point is 2.7 mm away from the center of the patch ,that is L=2.7mm. We use 50\( \Omega \) coaxial feed model for the antenna.
2.1. Metamaterial Unit Design

Fig. 1(a) and Fig. 1(b) shows the lattice-type (Type I) and π-type (Type II) metamaterial unit structures, respectively, which are designed in this paper. Their size parameters are: \( L_x = 8 \text{mm}, L_1 = 7.5 \text{mm}, w = 6 \text{mm}, L_y = 8 \text{mm} \) for unit of Type I and \( L_x = 8 \text{mm}, L_y = 8 \text{mm}, w = 2.8 \text{mm}, b = 0.4 \text{mm}, L_1 = 7.5 \text{mm}, L_2 = 7.5 \text{mm}, a = 0.4 \text{mm} \) for unit of Type II.

![Image of Unit Type I and Type II](image_url)

**Figure 1.** Metamaterial unit structures

Six metamaterial units of Type I are laid and plated on the substrate, with a thickness of 1.6mm as the covering layer of the antenna. HFSS software is used for the simulation analysis. See Fig. 2(a) for S parameter. Smith method is applied to obtain the data shown in Fig. 2(b) to acquire the effective refraction index of the surface layer in Fig. 2(b) [4,5]. We can see from Fig. 2(b) that the refraction rate of the surface layer at the frequency of 6GHz approaches to zero, which conforms to the design requirements.

![Image of S parameter and Refraction rate](image_url)

**Figure 2.** Unit parameter of Type I

Type II metamaterial is laid around the antenna substrate. Fig. 3 shows the S parameter after simulation. It can be seen from the figure that the peak value of the transmission curve of the baseboard is \(-24.5\text{dB}\) at the frequency of 6GHz. It can be seen that this kind of structure can be used to restrain the backward wave of the antenna and it meets the needs of the designed antenna.

![Image of Transmission curve of metamaterial substrate](image_url)

**Figure 3.** Transmission curve of metamaterial substrate

2.2. Metamaterial-based Antenna Design

Type II metamaterials unit is periodically plated on the antenna baseboard around the patch to obtain the antenna showed in Fig. 4(a), while the . Then covering layer of Type I is supported by foam and put right above the microstrip antenna. The distance between the lower layer and the antenna is equal to half of the wavelength. The distance between the two layers is set to \( b = 5 \text{mm} \). The designed antenna structure is shown in Fig. 4(b).
The return loss of the original antenna, the metamaterial-based antenna with and the antenna designed by simulation and real antenna experiments are shown in Fig. 5. From the the figure, compared with the original antenna, we can see that the return loss of the antenna deteriorates after metamaterials is loaded. The reason is that weak loss of the metamaterial itself occurs at the central frequency.

Fig. 6 and Fig. 7 show the gain of the antenna. It can be seen from the gain of the figures that metamaterials-loaded antenna get an obvious increase at angle of about ±10°, infering that the metamaterials substrate can effectively suppress the backward wave. Due to the incompletely covering of metamaterials sidelobe appears in antenna directivity figure. The antenna gain reaches 8.94 dB, appearing an increase of over 3 dB compared with the original antenna.

Fig. 8 shows the antenna’s directivity factor. From the figure we can see that the directivity factor of the antenna with metamaterials appears an increase of 49.08% compared with the traditional antenna.

Figure 4. High-directivity antenna prototype

Figure 5. Return loss of the antenna

Figure 6. Antenna gain chart
2.3. Discussion of Parameters of the Covering Layer

In the design process, we need to adjust the geometric size of the metamaterials unit so that it matches the central working frequency of the antenna. Besides, the loading of the covering layer above the antenna, space between the covering layer and the antenna and space between covering layers are all important parameters affecting the antenna performance.

**Fig. 9** Influences of changes in the distance between the covering Layer and antenna over return loss of the Antenna
According to Fig. 9, changes in the distance between the antenna covering layer and the antenna bring about small deviation in the central frequency of the antenna; the greater the distance between the covering layer and the antenna, the weaker the near field impact on the antenna. Accordingly, the return loss of the antenna decreases as the distance between the covering layer and the antenna increases. It can be known from Fig. 10 that the distance between the antenna covering layer and the antenna doesn’t have great impact on the radiation main lobe of the antenna. While the total radiation energy of the antenna is fixed, changes in the distance between the antenna covering layer and the antenna influence the energy distribution on the back lobe and sidelobe because the electromagnetic wave of the antenna radiation produces certain reflection when it meets the covering layer. The reflection waves form a looping-in between the space between the antenna covering layer and the substrate, which leads to amplified back lobe of the antenna.

3. Conclusion
Two different metamaterial units, the lattice-type and $\pi$-type metamaterials units, are loaded on the same microstrip antenna. The typical feature of zero refraction index of metamaterials and the band gap feature are applied to design the antenna covering layer, which suppress the surface wave of the substrate from the direct radiation of electromagnetic wave and reduce the back wave energy loss of the antenna. It is realized that both the antenna directivity factor and the gain are increased, with the antenna performance being significantly enhanced.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (Grant No.61072034), the National Natural Science Foundation of China (Grant No.51302318), the National Natural Science Foundation of China (Grant No.11547050), Natural Science Foundation of Shaanxi Provence(Grant No. 2016JM1027) and the Basic Research Project of Engineering University of PAP (Grant No.WJY201404).

References
[1] LIU Y H, ZHAO X P. Investigation of anisotropic negative permeability medium cover for patch antenna[J]. IET Microwaves, Antennas and Propagation, 2008. 7(2) , pp. 737-744.
[2] LIU Y H, ZHAO X P. Enhanced patch antenna performances using dendritic structure metamaterials[J]. Microwave and Optical Technology Letters, 2009, 51(7) , pp. 1732-1738.
[3] TANG H F, ZHAO X P. Center-fed circular epsilon-negative zeroth-order resonator antenna[J]. Microwave and Optical Technology Letters, 2009, 51(10), pp. 2423-2428.
[4] D. R. Smith and S. Schultz. Determination of effective permittivity and permeability of metamaterials from reflection and transmission coefficients[J], 2002. Phy. Rev B, 65, 195104.
[5] D.R. Smith, J.B. Pendry, and M.C.K. Wiltshire, Metamaterials and negative refractive index[J], Science 305 , 2004. pp. 788–792.