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Design of 2D Metal Photonic Crystal Array of Directional Radiation in Microwave Band

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Abstract—A 2D metal photonic crystal structure with a rectangular lattice is designed for directed wave propagation in the microwave frequency band. The dispersion curve of EPC is computed for designing the directed period array. In order to favor the computing, the rectangular period array is studied, which is different from the reference that is designed in optical range and uses the dielectric rods and hexagonal structure to compose the period array. The computed dispersion curves are combined with the theory of finite thick period array for obtaining the directed wave propagation structure. The influence of the number of metal rods on the antenna directionality is investigated, and the simulation results are compared and analyzed. It is found that when the number of transverse metal rods increases, the directionality of the antenna is enhanced, and the radiant power of the sidelobe radiation can be reduced. Based on the simulation results, the actual 2D metal photonic crystal array is constructed for the measurement validation. According to measurement results, the antenna located in the center of the array can get good directionality at 3.1 GHz.

1. INTRODUCTION

With the continuous development of communication system, the research of antenna directional radiation has great significance and practical application value. Electromagnetic wave directional propagation can enhance the signal coverage in a particular direction and can also have a protective isolation. It can be applied in a communication system with long distance, small coverage, high target density and high frequency utilization environment. Photonic crystal is a structure in which two or more materials are periodically arranged in space. In recent years, the research and application of photonic crystals have become more and more extensive. It has also been widely applied in the microwave frequency range. Scholars have carried out a series of research on the application of photonic crystal principle to improve the antenna performance of microwave range such as photonic crystal microstrip antenna, photonic crystal resonator, photonic crystal waveguide, and photonic crystal filter [1–5]. A way to enhance the directivity of an emitting device is proposed in the optical range. It is composed of dielectric material rods, and triangle units are used to form the periodic structure, to achieve directional radiation in the optical band [6]. However, in the microwave frequency range, most of photonic crystals are made of metal materials. From the energy band theory, the energy band structure of metal photonic crystals is also different from that of dielectric photonic crystal.

In this paper, a 2D metal photonic crystal array is designed for the directed wave propagation, and the finite metal rods with rectangular units are used to form the periodic structure. It is different from the dielectric photonic crystals with a triangular lattice as in [6], and the directional radiation can be achieved in the microwave frequency band. According to the Bloch Theorem and Energy Band theory of photonic crystals, the inherent characteristics of the photonic crystal are applied to make the antenna in the center of the array produce a good direction and enhance the effective utilization

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of radiation power. The numerical calculation method is used to model and simulate the 2D metal photonic crystal. Due to the difference between the dispersion diagram of the metal photonic crystal and the medium photonic crystal, the constant-frequency dispersion curve is analyzed. We have made a comparative analysis of the variables that affect the direction of the antenna in the metal photonic crystal. By optimizing the design, the antenna obtains better directionality at the frequency of 3.1 GHz with the most suitable number of metal rods. After that, we design the actual photonic crystal array and carry out the experimental measurement. The measurement and simulation results are compared and analyzed, which are basically the same. The antenna located in the center of the array can get good directionality at 3.1 GHz. This design is innovative in the microwave frequency band. The array made of metal has a simple structure and low cost, and it can be widely used in mobile communication systems, to achieve low-power directional radiation and long-distance communication.

2. DESIGN PRINCIPLE

From the Bloch theorem, in the infinite periodic structure, there are two invariant and independent translations vectors $\mathbf{d} = d\mathbf{e}_x$ and $\Delta = \Delta_x\mathbf{e}_x - \Delta_y\mathbf{e}_y$, and we denote the related components of the total field with $U(x, y)$. The Bloch theorem shows that each component $U_k(\mathbf{r})$ of an electromagnetic wave propagating in the crystal can be expressed as:

$$U_k(\mathbf{r}) = \exp(i\mathbf{k}\cdot\mathbf{r})V(\mathbf{r}) \tag{1}$$

$\mathbf{k}$ is the Bloch wave vector, and $V(r)$ is a periodic function:

$$V(\mathbf{r} + p\mathbf{d} + q\Delta) = V(\mathbf{r}), \quad \text{for all integers}\, p \,\text{and}\, q \tag{2}$$

For Bloch modes, any $p\mathbf{d} + q\Delta$ produces only a phase shift:

$$U_k(\mathbf{r} + p\mathbf{d} + q\Delta) = \exp(i\mathbf{k}\cdot(p\mathbf{d} + q\Delta))U_k(\mathbf{r}) \tag{3}$$

In the usual sense of the Bloch theorem, since we consider the actual bounded solution, the Bloch wave vector $\mathbf{k}$ is real.

Now we consider a crystal with finite thickness $Ny = 3$ (see Fig. 1):

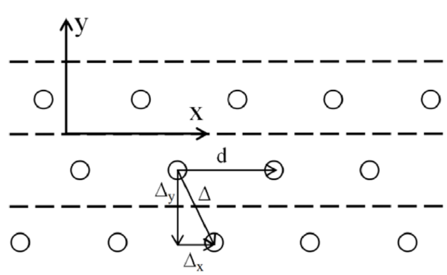

Figure 1. Photonic crystals with finite thickness.

We assume that the structure is infinite along the X direction and is illuminated by a plane wave:

$$U_{in}(x, y) = \exp(i\alpha x - i\beta y) \tag{4}$$

The total field $U\alpha(x, y)$ is a pseudo-periodic function with a pseudo-periodic coefficient α:

$$U_\alpha(x + d, y) = \exp(i\alpha d)U_\alpha(x, y) \tag{5}$$

In this case, the relationship between the Bloch wave vector propagating in the infinite photonic crystal and the pseudo-periodic coefficient α can be found. From Equations (1) and (5), we can obtain:

$$k_x = \alpha \tag{6}$$

In order to introduce the second translation vector Δy, we use the operator T that can transform any function:

$$Tf(x, y) = f(x + \Delta_x, y - \Delta_y) \tag{7}$$

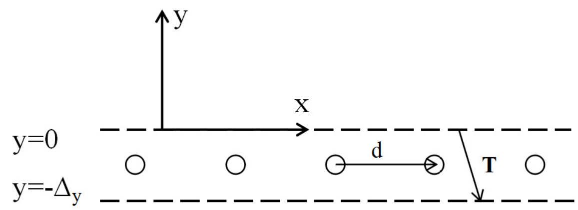

Figure 2. A single layer extracted from the photonic crystal.

The model in Figure 2 has a layer of the photonic crystal array. The T operator can be represented by a $\mathbf{T}$ matrix. We consider the eigenvectors of the T-matrix, with the eigenvalues μ:

$$\mathbf{T}U_\mu = \mu U_\mu \tag{8}$$

When $|\mu| = 1$, then:

$$U_\mu(x + \Delta_x, y - \Delta_y) = \exp(iarg(\mu))U_\mu(x, y) \tag{9}$$

From Equations (3) and (9):

$$ky = (kx\Delta x - \arg(\mu))/\Delta y \tag{10}$$

When $|\mu| \neq 1$, the restriction to the region $(-\Delta_y \leq y \leq 0)$ of U_μ associated with the eigenvector cannot be a Bloch solution with real vector $\mathbf{k}$.

Equations (6) and (10) point out the connection between the finite photonic crystal and the Bloch solution of the infinite structure. Consequently, for a given value of α, there are two different possibilities for the spectrum of the transfer matrix T. The detailed explanation is given in [7].

In any case, the field in the finite structure can never be reduced to a combination of Bloch waves with real Bloch wave vector of the infinite structure. The methods that rely upon this assumption can probably give accurate results in some circumstances, but their results should be carefully checked with the help of rigorous methods [8–10]. The same remark holds for the conclusions directly obtained from dispersion diagrams of Bloch waves. However, the dispersion diagrams are valuable for the prediction and understanding of the complex properties of photonic crystals.

Now we come back to the case of the crystal with finite thickness. Our purpose is to design an array so that the radiation source can radiate in a certain direction. It is assumed that the energy propagates in the Y direction. We assume that this array is excited by an arbitrary incident electromagnetic field, and the associated field components can be written as Fourier integrals:

$$U(x, y) = \int_{-\infty}^{+\infty} \hat{U}(\alpha, y) \exp(i\alpha x) d\alpha \tag{11}$$

By splitting the integration interval $[-\infty, +\infty]$ in subintervals $[(n - \frac{1}{2})\frac{2\pi}{d}, (n + \frac{1}{2})\frac{2\pi}{d}]$ simple change of variable leads to the other expression:

$$U(x, y) = \int_{-\pi/d}^{\pi/d} U\alpha(x, y) d\alpha \tag{12}$$

where the integrand:

$$U\alpha(x, y) = \sum_{m=-\infty}^{+\infty} \hat{U}\left(\alpha + m\frac{2\pi}{d}, y\right) \exp\left(i\left(\alpha + m\frac{2\pi}{d}\right)x\right) \tag{13}$$

is a pseudo-periodic function of x with pseudo-periodicity coefficient α. Consequently, the study of the general field $u(x, y)$ is reduced to the study of its pseudo-periodic components $U_\alpha(x, y)$ for all values of α in the first Brillouin zone $[-\pi/d,\ \pi/d]$ of the x-periodic problem.

This means that the radiation field propagating in any homogeneous medium outside the crystal can be written as the sum of the plane waves, and the plane wave with significant amplitude should

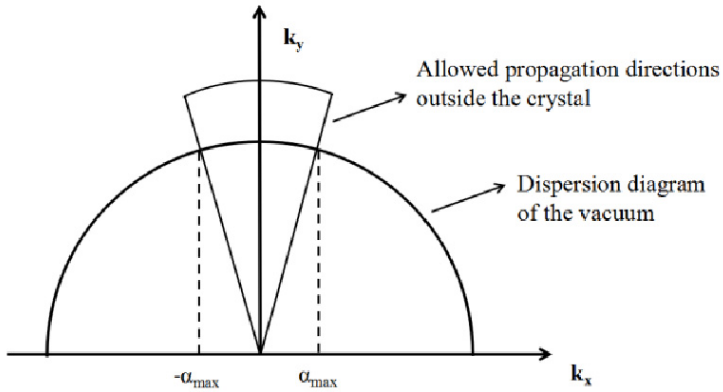

Figure 3. The Bloch modes which can be propagated in the finite thickness photonic crystal.

correspond to the smaller value of α, $\alpha \in [-\alpha_{\max}, \alpha_{\max}]$. Then, according to Equation (6), the allowed Bloch mode of the photonic crystal should be located in the region $k_x \in [-\alpha_{\max}, \alpha_{\max}]$. If this medium is free space, the dispersion curve is a circle defined by $kx^2 + ky^2 = k_0^2$, and the value of $\alpha_{\max}$ is determined by the angle range in the Y direction. We want to design the structure of the metal photonic crystal so that its curve of constant-frequency dispersion diagram of the Bloch modes is located in the region in Fig. 3.

3. SIMULATION RESULTS AND ANALYSIS

Based on the theoretical analysis, the influence of the number of metal rods on the antenna directionality is explored. The metal photonic crystal array is shown in Fig. 4, consisting of $Nx \times Ny$ metal rods. The rectangular lattice is used in the xoy plane to form the periodic structure. The length of metal rods in the z direction is much larger than the radius r, which can be approximated as infinite long metal rods. The lattice constants in the X and Y directions are $d_x = 33.33\,\text{mm}$, $d_y = 16.67\,\text{mm}$, $r = 0.75\,\text{mm}$. (A rectangle is chosen rather than a square as a cell lattice due to the desire to change the original periodic structure of the Y direction. The square lattice is compressed longitudinally, and the dispersion curves are also changed so that the antenna can radiate energy directional in the Y direction). The black area ($k_x \in [0, \frac{\pi}{dx}]$, $k_y \in [0, \frac{\pi}{dy}]$) in Fig. 5 is the First Brillouin Zone of the metal photonic crystal:

Fig. 6 shows a 3D dispersion diagram of the metal photonic crystal; Fig. 7 shows the constant-frequency dispersion curves (contour lines of the 3D dispersion diagram in Fig. 6). From Fig. 7, it can be seen that the curve is in a smaller region ($k_x \in [-\alpha_{\max}, \alpha_{\max}]$), when the frequency is close to the cutoff frequency of this Bloch mode. Here we take the case of $f = 3.28\,\text{GHz}$ as an example in Fig. 8.

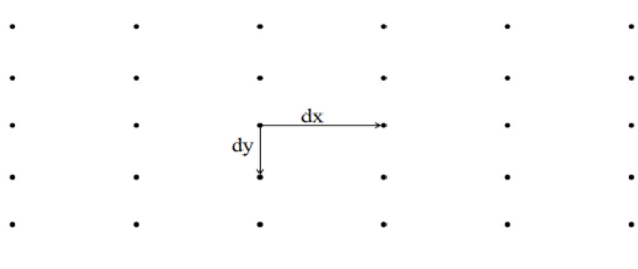

Figure 4. Metal photonic crystal.

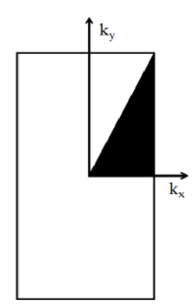

Figure 5. The First Brillouin Zone of the metal photonic crystal with the rectangular lattice.

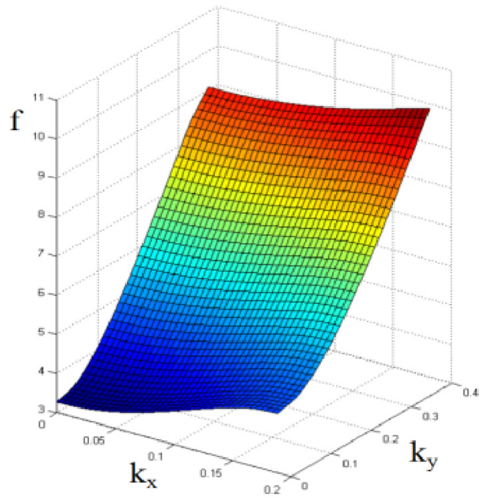

Figure 6. 3D dispersion diagram of the metal photonic crystal.

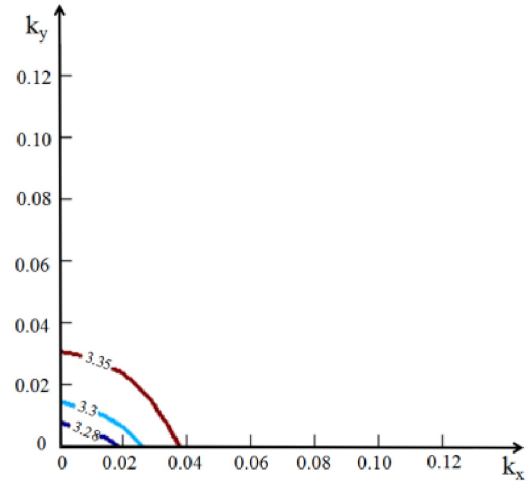

Figure 7. Constant-frequency dispersion curves.

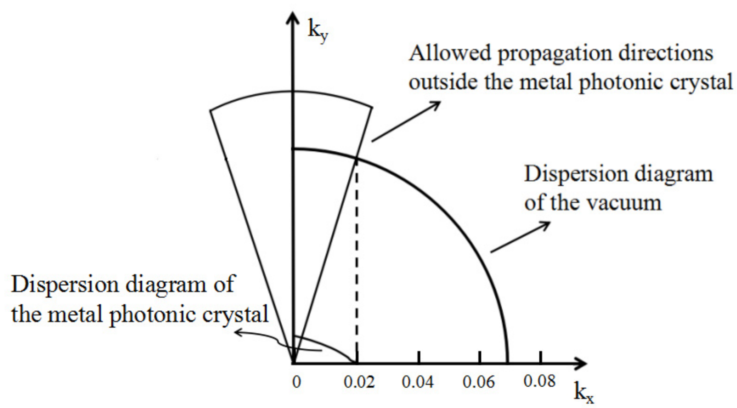

Figure 8. Constant-frequency dispersion diagram of the photonic crystal at the frequency of 3.28 GHz.

According to the above theoretical and some analysis of the simulation results, the finite array model is built and simulated at the frequency of 3.1 GHz. In order to investigate the effect of Nx, Ny and frequency on the antenna directionality, we first analyze the case of $Nx = Ny$. We simulate it respectively when $Nx = Ny = 6$ and $Nx = Ny = 8$, at the frequency of 3.1 GHz:

It can be seen that when $Nx = Ny = 6$, the antenna in the array already has a certain directionality in the Y direction, but it is not ideal as the sidelobe in the X direction is nearly -10 dB. From Fig. 9 and Fig. 10 we can draw the following conclusions that with the increase of array size, the directionality of the Y direction is obviously enhanced, and the sidelobe in the X direction is decreased.

According to the previous theoretical analysis, we can increase the size of array in the X direction to approximate the equivalent infinite condition in the X direction, to reduce sidelobes in the X direction. We keep $Ny = 8$ unchanged, increase Nx from 8 to 10.

It can be seen from Fig. 11 that when we increase Nx from 8 to 10, the sidelobe in the X direction can be effectively reduced. From Fig. 10 and Fig. 11 we can draw a conclusion that when we keep Ny unchanged and increase Nx, the sidelobe in the X direction can be reduced to enhance the directionality of Y direction.

If we increase Nx continuously, the change of the directionality pattern will not be obvious compared to the case of $Nx = 10$ and $Ny = 8$. From the simulation results, we can see that the array, which consists of only 80 metal rods, is able to get good directionality. Two-dimensional electric field distribution of the array at the frequency of 3.1 GHz is given in Fig. 12.

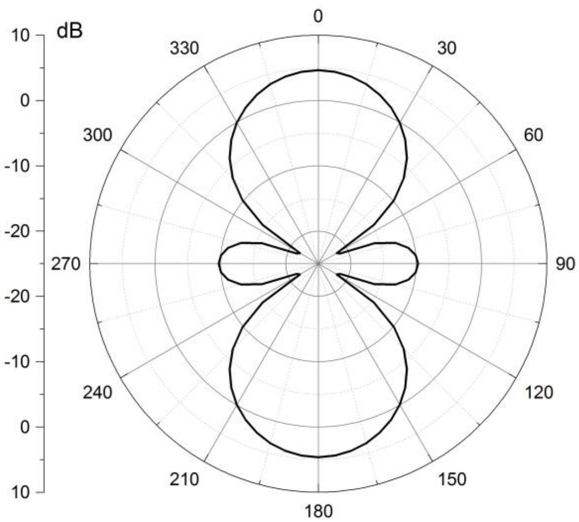

Figure 9. The directionality pattern with $Nx = Ny = 6$.

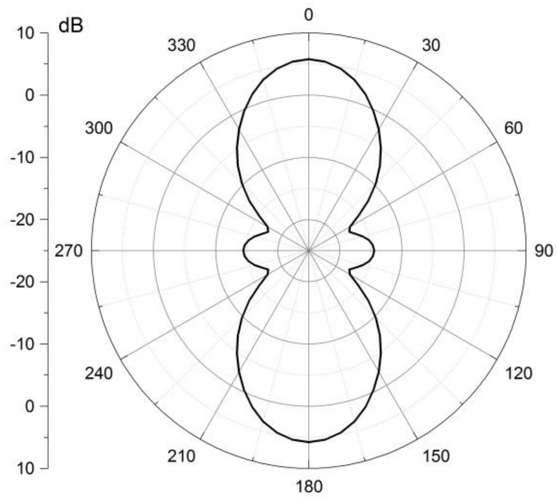

Figure 10. The directionality pattern with $Nx = Ny = 8$.

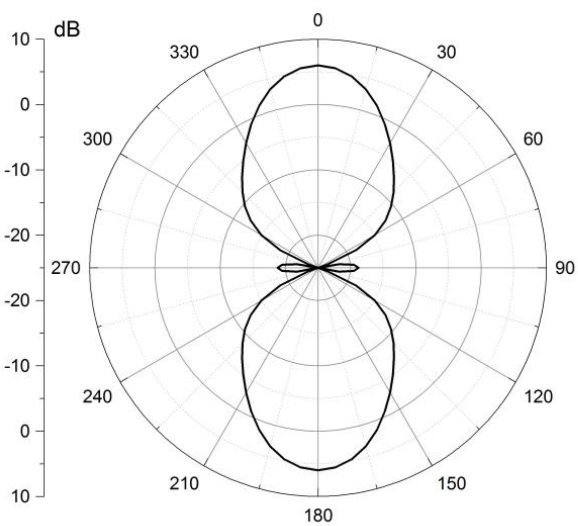

Figure 11. The directionality pattern with $Nx = 10$, $Ny = 8$.

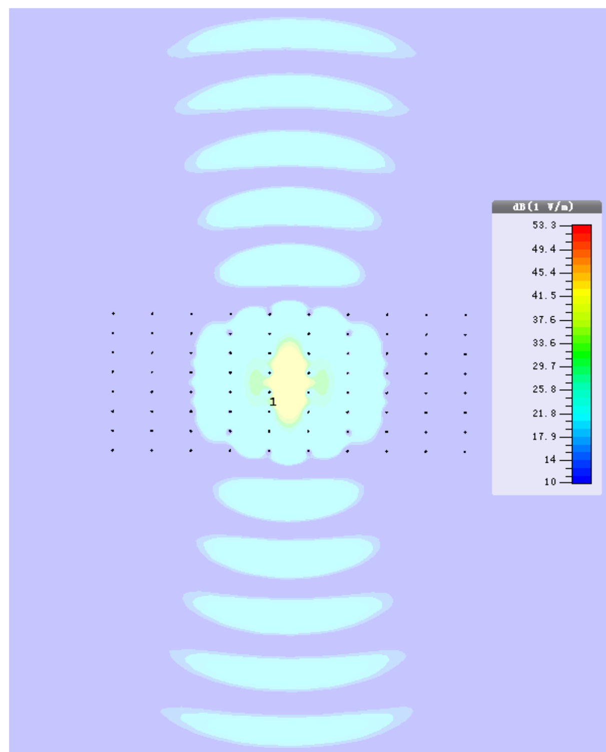

Figure 12. Two-dimensional electric field distribution of the array at the frequency of 3.1 GHz.

4. EXPERIMENT MEASUREMENT

Based on the previous simulation results, we design the actual metal photonic crystal array for measurement. As shown in Fig. 13 and Fig. 14, the array is similar to the simulation model, composed of 80 cylindrical copper rods having a length of 20 mm and radius of 0.75 mm (X-direction 10 columns,

Figure 13. The X direction view of the array.

Figure 14. The Y direction view of the array.

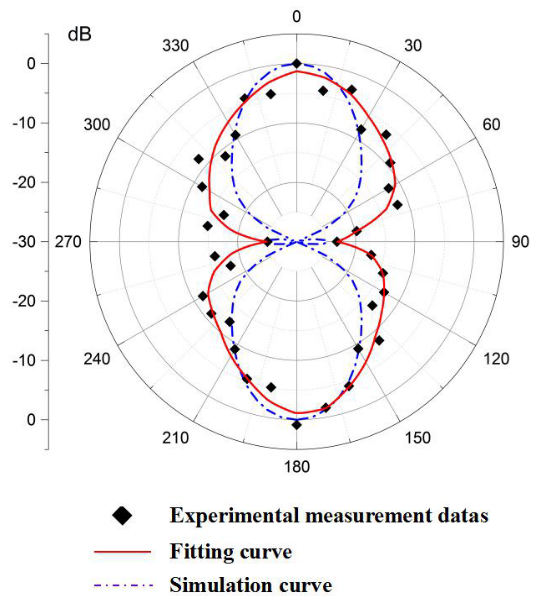

Figure 15. The comparison of measured results and simulated results.

Y-direction 8 columns), X-direction pitch of 33.33 mm, Y-direction pitch of 16.67 mm.

We use a foam plate with a dielectric constant close to the air dielectric constant to fix the metal rod and affix metal copper foil on the top of the foam board above and below the bottom of the foam board to get the ideal conductor surface. According to the principle of mirroring, the length of the copper rod in the Z direction can be equivalent to infinity. We use the 3.1 GHz dipole antenna as a transmitting antenna, inserted from the top of the array into the array and fixed. The rectangular waveguide antenna is used to receive the power of the dipole antenna radiated from the array, because the rectangular waveguide antenna can receive the power of the antenna in a particular direction and can reduce the experimental error.

We place the rectangular waveguide antenna in the far-field area of the array, and the distance between the rectangular waveguide antenna and the transmitting antenna is about 2 m. When measuring, we fix the rectangular waveguide antenna and fix the center point of the array as the center of a circle. We will rotate the array 10 degrees each time and a total of 36 power value data are recorded after a lap. We do not select too many experimental test points to measure, because according to the previous simulation results, the experimental data points are sufficient as long as they can reflect the directionality of the array. We compare the experimental results with the simulated ones after normalization, as shown in Fig. 15.

The radiation patterns in polar coordinate system of experimental measurement and simulation results are given in Fig. 15. The black dots are the result of the experiment; the red curve is the fitting curve of the experimental data; the blue dotted line is the simulation result. It can be seen that in the actual measurement, the array makes the dipole antenna located at its center obtain directionality, and the difference of the radiation power between X and Y directions can reach more than 20 dB. However, there is a certain error in the directionality between simulation and actual measurement results. The half-power radiation angle is slightly larger than that of the simulation results. The small sidelobes in X direction fails to be detected due to the restriction of the experimental conditions. In general, though the directionality of the dipole antenna is not as good as the simulation results, the structure can make the antenna radiate power directionally in the Y direction.

5. CONCLUSION

In this paper, a metal photonic crystal array with rectangular lattices made of finite number of metal rods is designed. It is different from the dielectric photonic crystals with triangular lattices. We analyze the dispersion curves with the Bloch theory and establish the simulation model of the array. Then, the influences of Nx and Ny values on the directivity are investigated and compared. By optimizing the simulated results, we can make the antenna located in the center of array obtain a good directionality at 3.1 GHz. After that, we design an actual photonic crystal array and carry out the experimental measurement. The measurement and simulation results are compared and analyzed, and they are basically the same. The antenna located in the center of the array can get good directionality at 3.1 GHz. The design of the metal photonic crystal improves the effective utilization of radiation power and makes the antenna get better directionality. It can be used for long-distance mobile communication.

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