Reconfigurable Array Designed for Directional EM Propagation using Energy Band Theory of Photonic Crystals

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Abstract **─** A type of reconfigurable array consisting of metal rods was designed for directional electromagnetic (EM) wave propagation at microwave frequency. By adding or removing a part of metal rods, the designed array can be reconfigured between a hexagonal-lattice array and a rectangular-lattice array. As a result, the directional radiation pattern can be changed. In this study, the method of designing metal photonic crystals array is proposed. Dispersion curves of Energy band theory of photonic crystals were computed and integrated with the theory of finite thickness periodic arrays. Measurement results are well consistent with the simulation results, suggesting that the antenna as a radiation source located in the center of the hexagonal-lattice array could reach good directionality at the designed frequency. When the array is transformed into the rectangular-lattice array by adding or removing a part of metal rods, the directional radiation pattern can be changed ±30 degrees at the same frequency.

Index Terms **─** Antennas, directional EM propagation, metal photonic crystals, reconfigurable array.

I. INTRODUCTION

In recent years, the researches and applications of photonic crystals in the microwave domains have become increasingly extensive, e.g., electromagnetic band gap (EBG) antenna [1], photonic crystal directional coupler switch [2], EBG waveguide [3] and EBG filter [4]. With the continuous development of the communication system, the research about the directional EM wave propagation comes to have great significance and practical application value. A periodic structure composed of dielectric material rods with triangle lattices is designed to improve the directivity of emitting devices at optical frequency [5]. But the directivity only vary by rotating the entire array. At microwave frequency, many photonic crystals are made of metal materials. In accordance with the Energy band theory, the dispersion curves of metal photonic crystals also differ from those of dielectric photonic crystals at optical frequency.

In this study, the method of designing metal photonic crystals array for directional EM propagation at microwave frequency was proposed, which is different from that of dielectric photonic crystals at optical frequency. The rough operating frequency range could be determined by the constant-frequency dispersion curves of metal photonic crystals. Subsequently, the optimal operating frequency could be found in the frequency range after the array was simulated. A type of reconfigurable metal array is designed for directional EM wave propagation at microwave frequency, and the directional radiation pattern can vary by changing the structure of the array rather than rotating the entire array, it is an innovative design. By adding or removing a part of metal rods, the designed array can be reconfigured between the hexagonal-lattice array and the rectangular-lattice array, so that the directional radiation pattern can be changed. In accordance with the Bloch Theorem and Energy band theory of photonic crystals, the constant-frequency dispersion curves of photonic crystals with rectangular lattices were analyzed, and Computer Simulation Technology (CST) were employed for modeling and simulations. Based on the simulation results, actual metal arrays were constructed for measurement validation. The measurement results were compared with the simulation results, and the analysis had a high degree of anastomosis. The antenna as a radiation source located in the center of the hexagonal-lattice array could reach the good directionality at 3.1GHz. The array could be transformed into a rectangular-lattice array by adding or removing a part of metal rods, so that the directional radiation pattern could vary by ±30 degrees at the same frequency.

II. DESIGN PRINCIPLE

A rectangular coordinate system (O,X,Y,Z) is used in this paper ,the unit vectors of the axes are $\boldsymbol{e_x}$, $\boldsymbol{e_y}$, and $\boldsymbol{e_z}$. Harmonic fields are expressed using a time dependence in $\exp(-i\omega t)$, with $\omega = 2\pi c/\lambda = ck_0$, c being the speed of light in vacuum, λ the wavelength and k_0 the wavenumber in vacuum. Two-dimensional photonic

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crystals are made with lossless materials (dielectric or perfectly conducting (PEC)) and invariant by translation along the z-axis.

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

$$U_k(\boldsymbol{r}) = exp(i\boldsymbol{k}\cdot\boldsymbol{r})V(\boldsymbol{r}). \quad (1)$$

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

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

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

$$U_k(\boldsymbol{r}+p\boldsymbol{d}+q\Delta)=exp(i\boldsymbol{k}\cdot(p\boldsymbol{d}+q\Delta))U_k(\boldsymbol{r}). \quad (3)$$

The Bloch wave vector $\boldsymbol{k}$ is real in the usual sense of the Bloch theorem, because actual bounded solutions are considered. In all this paper, we keep this usual definition.

Now we consider a finite thickness crystal with a stake of Ny grids (Ny=3), as shown in Fig. 1.

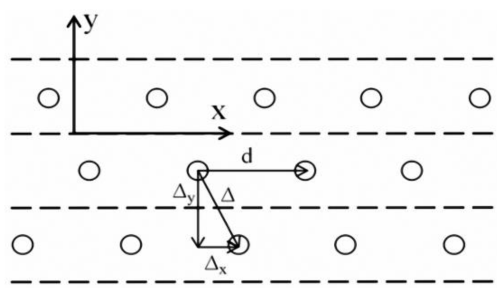

Fig. 1. Photonic crystals with finite thickness (Ny=3).

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

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

The total field Uα (x, y) is a pseudo-periodic function of x with a pseudo-periodic coefficient α:

$$U_\alpha(x+d, y) = exp(i\alpha d)U_\alpha(x, y). \quad (5)$$

Then, the relationship between the Bloch wave vector propagating in the infinite photonic crystal and the pseudo-periodic coefficient α can be found. The equations (3) and (5) can match together when:

$$k_x=\alpha. \quad (6)$$

In order to consider the second translation vector Δ, we relate Δ to a translation operator T which can transform any function f as flow:

$$Tf(x, y)=f(x+\Delta_x, y-\Delta_y). \quad (7)$$

The model in Fig. 2 is a layer of the photonic crystal array. The T operator can be represented by a **T** matrix. We consider an eigenvectors of the *T*-matrix, with the eigenvalues μ:

$$\mathbf{T}U_\mu=\mu U_\mu. \quad (8)$$

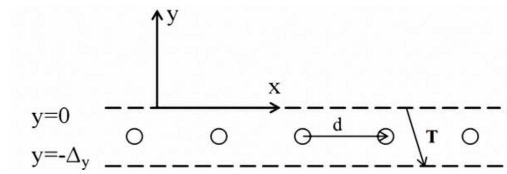

Fig. 2. A single layer extracted from the photonic crystal.

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

$$U_\mu(x+\Delta_x, y-\Delta_y) = exp(iarg(\mu))U_\mu(x, y). \quad (9)$$

From equations (3) and (9):

$$k_y = (k_x\Delta_x - arg(\mu)) / \Delta_y. \quad (10)$$

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 **k**.

Equations (6) and (10) indicate the relationship between the finite photonic crystal and the Bloch solution of the infinite structure. 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 the references [6].

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. However, for predicting and understanding the complex properties of photonic crystals, the analysis of dispersion diagrams are of great value. Methods based on this assumption may give accurate results in certain cases, but their results should be carefully examined by strict methods [7], [8].

Now, we consider the finite thickness crystal. We assume that this crystal is illuminated by an arbitrary incident electromagnetic field, and the associated field components can be written as a Fourier integral:

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

The integration interval $[-\infty, +\infty]$ could be split into subintervals $[(n+\frac{1}{2})\frac{2\pi}{d}, (n-\frac{1}{2})\frac{2\pi}{d}]$. Then, the expression could be changed into:

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

where the integrand:

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

is a pseudo-periodic function of x with pseudo-periodicity coefficient α. Consequently, we can simplify the study of the general field u(x, y) 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 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 vacuum, the dispersion curve is a circle defined by $k_x^2 + k_y^2 = k_0^2$, the value of α_{max} is determined by the angle range in the Y direction. Our purpose is to design an array so that the source of radiation can radiate energy in a certain direction. According to the previous principle, we want to design a metal photonic crystal and make a curve of constant-frequency dispersion diagram of the Bloch modes is located in a small region in Fig. 3. Then, the operating frequency of this photonic crystal array could be found, it is the frequency corresponding to the constant-frequency curve.

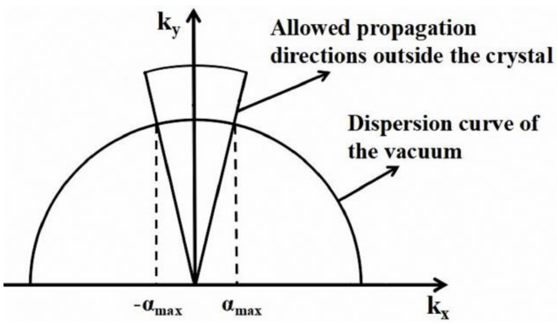

Fig. 3. The Bloch modes which can be propagated in the finite thickness photonic crystal.

III. ANALYSIS OF DISPERSION CURVES

Since experimental tests can be conveniently performed in our laboratory at 3.1GHz, we designed an appropriate structure of the array so that its working frequency is 3.1GHz. As shown in Fig. 4, it is a two-dimensional metal photonic crystal array with rectangular periodic lattices in the XOY plane. Our purpose was to embed a radiation source inside the array and to enforce the radiated field inside a small angular range centered around the normal, and the red point in the center of the array is the radiation source. The length of metal rods along the z-axis direction is infinite. The lattice constants were $d_x = 20\sqrt{3}$ mm, $d_y = 20$ mm, $r = 0.75$ mm. The model was built in the electromagnetic field simulation software CST. In the modeling process, the materials of all metal rods were PEC. The Eigenmode Solver was applied for the unit lattice simulation, and Frequency Domain Solver was employed for the entire array simulation.

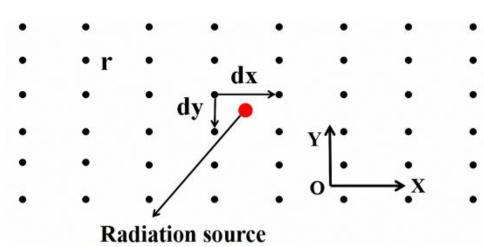

Fig. 4. Two-dimensional metal photonic crystal array with infinite periodic rectangular lattices

As shown in Fig. 5, the model in the left picture represents the rectangular lattice unit and Boundary condition setting in CST. The black area in the right picture ($k_x \in [0, \pi/d_x]$, $k_y \in [0, \pi/d_y]$) is a quarter of the First Brillouin Zone of the metal photonic crystal. Using the Eigenmode Solver of CST, the rectangular lattice unit could be simulated, and the Bloch mode corresponding to each point in the region could be calculated (100 points were calculated here). After the data was imported into MATLAB, the three-dimensional dispersion diagram of the array could be generated. Figure 6 gives the 3D dispersion diagram of a Bloch mode of the metal photonic crystal, the horizontal plane gives the Bloch wave vector k, and the vertical axis gives the frequency f.

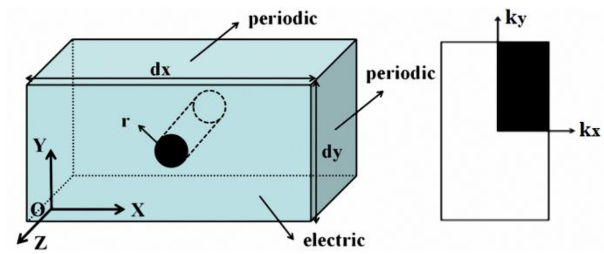

Fig. 5. The rectangular lattice unit and the First Brillouin Zone of the infinite metal photonic crystal.

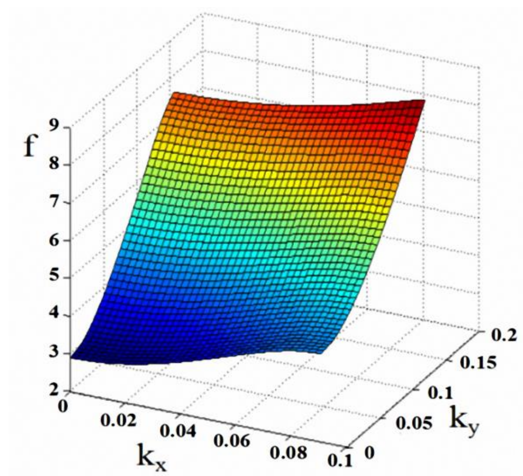

Fig. 6. 3D dispersion diagram of metal photonic crystal.

As shown in Fig. 7, the constant-frequency dispersion curves of the metal photonic crystal with rectangular lattices could help to determine the frequency of directional EM wave propagation. Three constant-frequency dispersion curves are presented in Fig. 7, which are all contour lines of the 3D dispersion diagram in Fig. 6. Only three representative curves were listed. The high frequency constant-frequency curves were not given in Fig. 7, because kx of them were not in a small region.

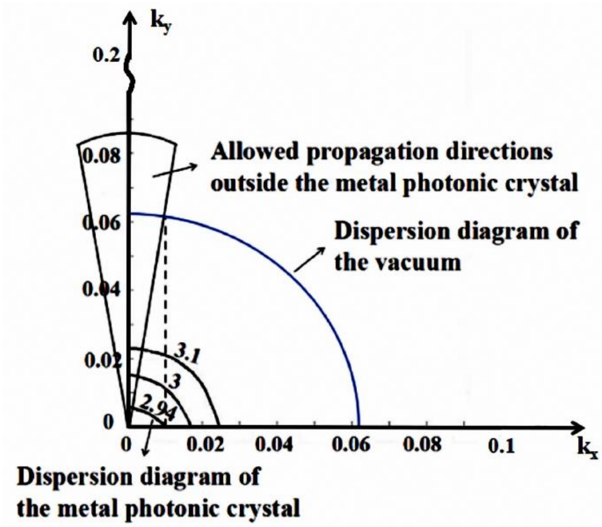

Fig. 7. The constant-frequency dispersion curves.

When the frequency was closer to the cut-off frequency f_0 of this Bloch mode, the constant-frequency dispersion curves would become smaller, and they would be located in a small region of $k_x \in [-\alpha_{max}, \alpha_{max}]$. This suggests that a finite thickness photonic crystal array with such lattice constants could propagate waves directionally in a small frequency band with f_0 as the center frequency. A detailed explanation was given in the reference [5]. We only simply identified an approximate frequency range capable of making the source radiate energy in a certain direction since the field in the finite structure could never be reduced to a combination of Bloch waves with real Bloch wave vector of the infinite structure. To determine the optimal operating frequency, the entire array must be simulated by CST.

IV. SIMULATION MODELS AND RESULTS

In accordance with the previous analysis, the metal photonic crystal array with such lattice constants could make waves propagate directionally in the direction along the short side of the array, and the optimal operating frequency was in the approximate frequency range identified from the constant-frequency dispersion curves. In our previous studies, we explored the impacts of the change of the number of metal rods and frequency on directionality [9]. Based on the previous work, in this study, we directly selected an appropriate number of metal rods and designed a lattice reconfigurable array, which could not only make the source radiate energy in a certain direction but also change the direction of the beam by changing the structure of the array.

As shown in Fig. 8, two same metal finite thickness rectangular-lattice arrays in the XOY plane are composed of 8×6 metal rods, with their horizontal axes intersecting at 60 degrees. The lattice constants were the same as those of the metal photonic crystals in Fig. 1. The length of metal rods in the Z direction was much larger than the radius, which could be approximated as infinite long metal rods. In accordance with the previous analysis, both of the two arrays could make waves propagate directionally in the direction along the short side of each array at a certain frequency as shown in Fig. 9, and the directional patterns of the top array and bottom array were symmetrical about the Y direction. Figure 12 gives the directional patterns of the top array in Fig. 8, at the frequencies of 2.9GHz, 3.1GHz and 3.2GHz, respectively. Here we gave the small frequency range (2.9-3.2GHz) based on the previous analysis of the constant-frequency curves, and in this frequency range we could find a frequency point allowing the new array with lattice reconstruction could make EM waves propagate directionally in the Y direction. Subsequently, the frequency was found as 3.1GHz.

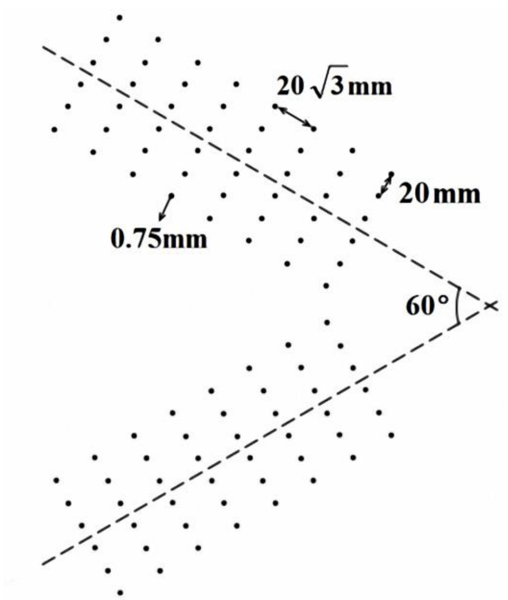

Fig. 8. Two finite thickness rectangular-lattice arrays crossed together at 60 degrees.

As shown in Fig. 10, the array in the red border consists of those two arrays in Fig. 8 crossed together with the angle of 60 degrees, and the crossed part forms a structure with hexagonal lattices. The cross array enabled EM waves from the radiation source to be propagated directionally in the Y direction. We only selected the array in the red box since the metal rods outside the red border would radiate energy in other directions and cause the appearance of excess sidelobes and affect the directionality.

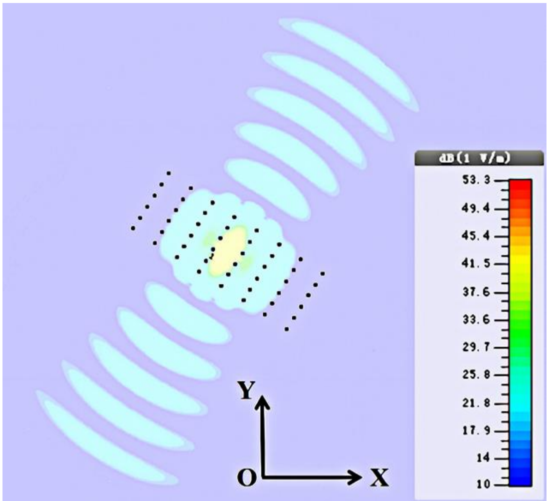

Fig. 9. The electric field distribution of the rectangular-lattice array at 3.1GHz.

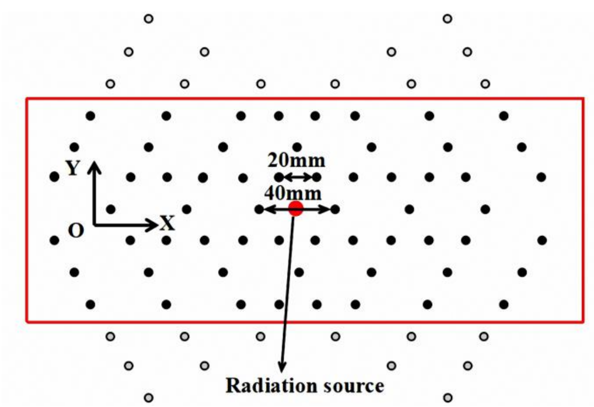

Fig. 10. The crossed part forms a finite thickness array with hexagonal lattices.

The models were simulated with the electromagnetic field simulation software CST. As shown in Fig. 11, the crossed array with hexagonal lattices can make the waves propagate directionally in the Y direction at 3.1GHz. The new crossed array with hexagonal lattices could propagate EM waves directionally in the Y direction since the two rectangular-lattice arrays were superimposed to form the new array with hexagonal lattices, their Bloch wave vectors are also superimposed on each other, and the X-direction components cancel each other.

It is noteworthy that the crossed array was not only composed of hexagonal lattices but of some defective ones. Yet by analyzing constant-frequency dispersion curves, it could be determined that a finite thickness metal array consisting of hexagonal lattices entirely could be designed for directional EM wave propagation at a different frequency by analyzing its constant-frequency dispersion curves. The hexagonal-lattice array could be transformed into either of the two rectangular-lattice arrays in Fig. 8 by adding or removing a part of metal rods, and Fig. 12 presents the directional patterns of the top array with rectangular lattices in Fig. 8, the direction of its main lobe was 30 degrees off the Y direction. Directional patterns of the top array and bottom array were symmetrical about the Y direction. Now we could determine that both the rectangular-lattice array and the hexagonal-lattice array could make EM waves propagate directionally at 3.1GHz, the directional radiation pattern could vary by ±30 degrees through the mutual transformation between the two kinds of array. Arrays of lattice structures which could be transformed were called reconfigurable array.

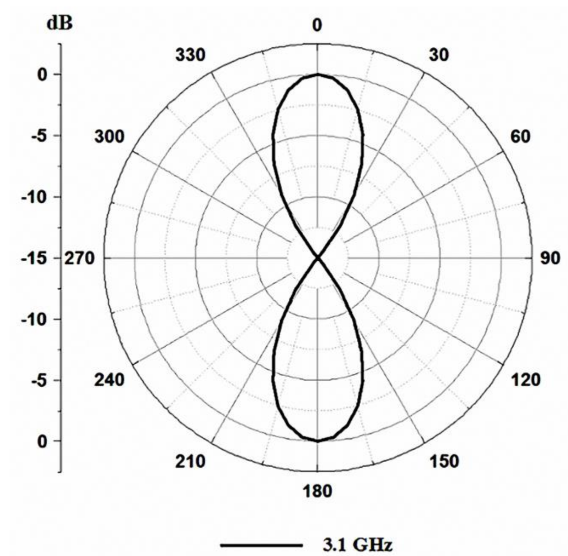

Fig. 11. Directional pattern of the hexagonal-lattice array.

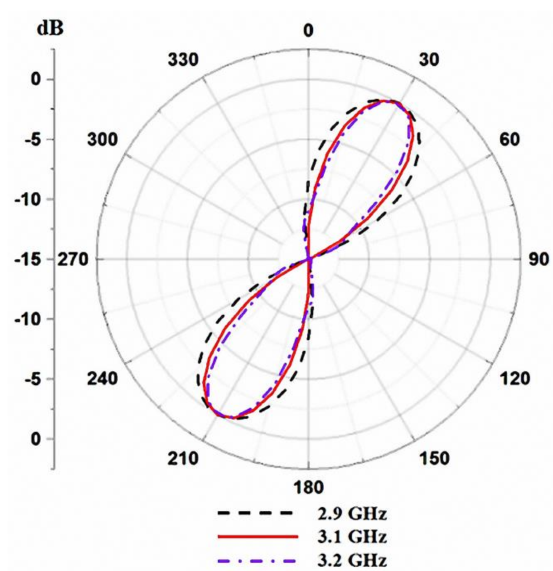

Fig. 12. Directional patterns of the top array in Fig. 8.

V. MEASUREMENT RESULTS

Based on the previous simulation models, actual arrays composed of copper rods were constructed for measurement validation at 3.1GHz. Different structures can also be designed to make it operate at the required frequency by the method in this paper. Considering the conditions of our laboratory, this frequency band is selected for experimental testing. Figure 13 shows the photographs of the hexagonal-lattice array and the rectangular-lattice array. Foam plates with a dielectric constant close to the air dielectric constant were used to fix copper rods. Copper foils were affixed on the upper surface of the top foam board and the lower surface of the bottom foam board to form the perfect electric conductor (PEC) surface. In accordance with the principle of Mirror Image, the length of copper rods in the Z direction could be approximately equal to infinite length.

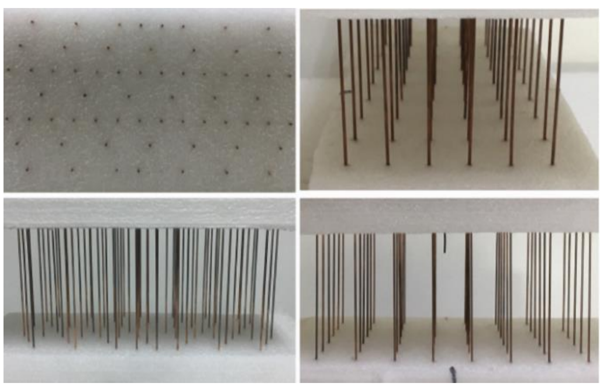

Fig. 13. Actual reconfigurable hexagonal-lattice array and rectangular-lattice array.

As shown in Fig. 14, a rectangular waveguide antenna (WR-284, 2.60-3.95GHz) is employed to receive the radiation power of the monopole antenna in the center of the array. The rectangular waveguide antenna is placed in the far-field area, and the distance between the rectangular waveguide antenna and the array is nearly 2m. Figure 15 shows the picture of the experimental measurement environment. A monopole antenna served as radiation source, inserted from the top of the array into the center of the array and fixed. When measuring, the rectangular waveguide antenna was fixed, and the center point of the array was fixed as the center of a circle. The measured array was rotated 10 degrees each time, and a total of 36 experimental data would be recorded after a lap. The measurement results were compared with the simulation results after normalization at 3.1GHz.

As shown in Fig. 16 and Fig. 17, the black dots were experimental data. The red curves were fitting curves of experimental data generated by the software ORIGIN. The blue dotted lines were simulation results. It could be seen that both of the two arrays could give the monopole antenna good directionality, and the differences between the gains in the two vertical directions of each array could reach more than 10 dB. The fitting curves are well consistent with the simulation curves, except that there were small sidelobes in the direction perpendicular to the main radiation direction of each array.

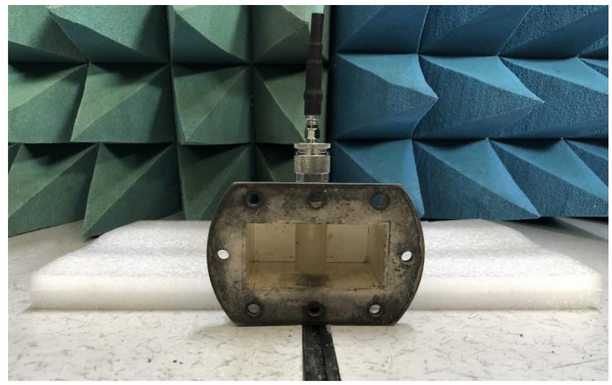

Fig. 14. The rectangular waveguide antenna.

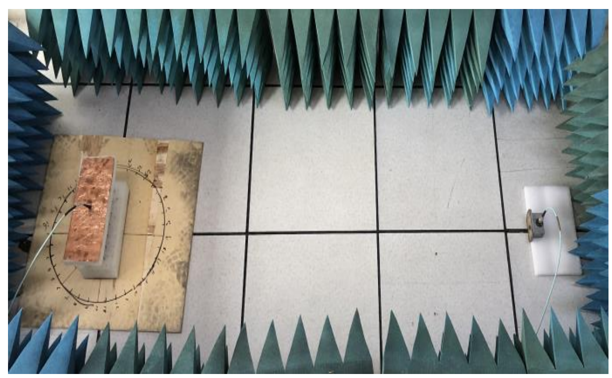

Fig. 15. Experimental measurement environment.

The experimental results suggest that the sidelobes of the rectangular-lattice array was smaller than those of the hexagonal-lattice array. This was because they have different lattice structures. Moreover, there were some defect lattices of hexagonal-lattice array, while the rectangular-lattice array completely consisted of rectangular lattices. Accordingly, the inhibitory effect of the former on sidelobes was weaker than that of the latter. Small variations of the sidelobes were allowed to achieve the reconfigurable properties of the array. Sidelobes could be reduced by increasing the number of metal rods of the arrays, specific methods were described in our previous paper [9]. In general, not only the two types of arrays could be employed for directional EM wave propagation at 3.1GHz, but also the directional radiation pattern could be changed through the mutual transformation between the two structures.

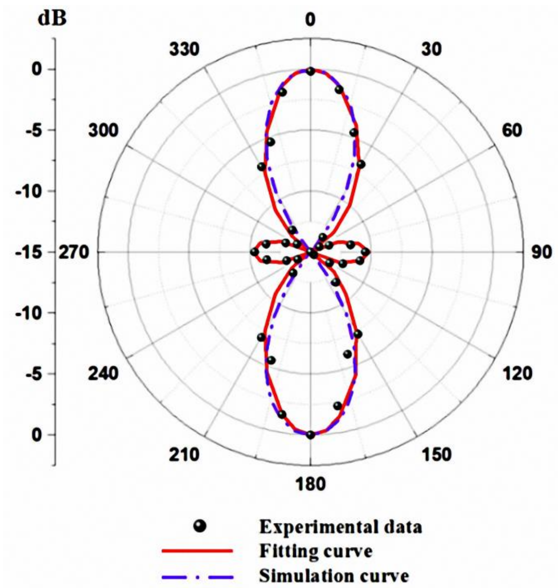

Fig. 16. The comparison of measurement results and simulation results of hexagonal-lattice array at 3.1GHz.

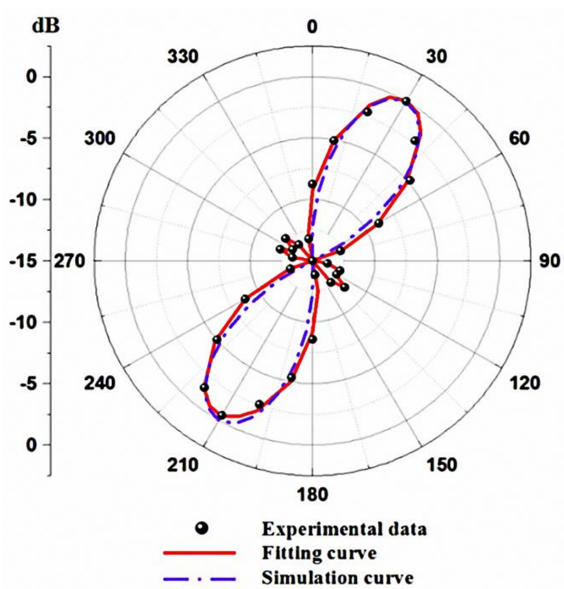

Fig. 17. The comparison of measurement results and simulation results of rectangular-lattice array at 3.1GHz.

VI. CONCLUSION

In this study, a type of reconfigurable array consisting of metal rods was designed for directional EM propagation at microwave frequency. The method of designing the metal array was proposed. Measurement results are well consistent with the simulation results, which shows that the antenna as a radiation source located in the center of the hexagonal-lattice array can get good directionality at the designed frequency. Meanwhile, the array can be reconfigured into a rectangular-lattice array by adding or removing a part of metal rods. And the directional radiation direction can vary by ±30 degrees at the same frequency. Different structures could also be designed to make it operate at required frequencies by the method in this paper.

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