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Partially Excited Antenna Array for Near-Field Patterned Focusing

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Abstract—In this letter, a near-field focusing method for generating patterned focusing is studied. A partially excited planar array antenna is proposed for patterned focusing, which effectively suppresses the sidelobes of the focusing pattern. The phase of the array antenna is adjusted by a digital phase shifter. A prototype was made and tested to verify the effectiveness of the method. Both the full planar array and the partially excited array realize the "✦" focus pattern, and the partially excited array effectively reduces the sidelobes. The experimental results show that the method can achieve focusing in any area. This study can provide a reference for wireless energy transfer and microwave hyperthermia.

1. INTRODUCTION

Today, near-field focusing antennas are widely used in many applications, such as microwave imaging [1, 2], wireless energy transfer (WPT) [3, 4], microwave hyperthermia [5], and radio frequency identification (RFID) [6, 7]. For a traditional dielectric lens antenna, the incident waves from different positions of the lens arrive at the focal point in the same phase to achieve near-field focusing [8]. However, dielectric lens has the disadvantages of large volume and high profile. An improved method is Fresnel zone plate, which filters out electromagnetic waves with the required phase through annular metal strip and transmits them through the annular gap to achieve focusing [9]. Compared with the traditional dielectric lens, it has the advantages of simple structure and low cost, but the disadvantages of this method are low efficiency and narrow bandwidth. Later, reflectarrays and transmitarrays were proposed to modulate the incident wave from feed into in-phase distribution, achieving near-field focusing. However, they require an additional feed antenna which makes the overall profile relatively high [10, 11].

In recent years, planar array antennas have become popular for generating near-field focusing since they have the characteristics of low profile, high efficiency and flexibility [12–14]. However, they usually only concentrated on point focusing. Metasurface antennas were proposed to achieve both single and multi-focal points [15, 16]. However, even multi-foci focusing is far from meeting the practical needs because in some special occasions, it is necessary to concentrate the electromagnetic (EM) wave energy in a special area, and the EM energy in other areas should be reduced as much as possible. Therefore, the near-field shaped focusing is proposed. In [17], a reflective metasurface was designed to realize the focusing in some special patterns. However, this method can generate high sidelobes in the non-focusing area, resulting in an unclear focusing pattern and poor focusing effect. Therefore, how to achieve shaped focusing and reduce sidelobes at the same time needs to be resolved immediately. In this paper, we propose a design method of array antenna to generate low sidelobe near-field shaped focusing. By analyzing the magnitude distribution of the antenna array aperture, the antenna elements whose magnitude values are in the minimum range can be selected. This means that these elements contribute

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very little to the focusing pattern, which can lead to high sidelobes around the focal pattern. Next, these selected elements are disabled in the array antenna. Simulation and measurement both show that the partially excited antenna array can effectively suppress sidelobes of the near-field focusing pattern.

In this letter, patterned focusing is studied using a partially excited array which is constructed by the feeding part of antenna elements on the planar array. It can suppress the sidelobe of 8×8 full planar array focusing pattern. In this paper, an 8×8 antenna array is proposed to generate a "✦" focusing pattern by modulating the antenna array aperture phase with a digital phase shifter. When designing a partially excited array, the amplitude distribution of a planar array is firstly calculated, and only the antenna elements with larger amplitude values are excited. In this case, the sidelobes of the focusing pattern are suppressed. The work of this paper is organized as follows. In Section 2, the theory of patterned focusing is studied. In Section 3, the physical fabrication and method verification are carried out; the patterned focusing is realized; and the sidelobes of the pattern are suppressed by partially excited array. Section 4 is the conclusion of this letter.

2. PATTERNED FOCUSING ARRAY ANTENNA

For the near-field point focusing, the main principle is that by adjusting the excitation of the antenna array radiation unit, the in-phase superposition of energy is formed on the spatial characteristic position, and finally the focusing effect in the radiation near-field area is realized. In previous work, the principle of point focusing has been analyzed in detail [18]. However, if you want to focus the energy of the antenna array in a specific area, a single focus is far from enough. The principle of forming a special pattern is that multiple focal points work together. The principle is shown in Figure 1(a). The antenna array of $M \times M$ is located in the XOY plane, and the focal plane is located in the $X'O'Y'$ plane. For simpler analysis, the focal plane is divided into $N \times N$ grids, each with the spacing of d. At this time, the shaped pattern is also divided into grids, and when a shaped focus is desired, the ideal field distribution on the planar antenna array is the superposition of the aperture electric fields associated with the grid. As shown in Figure 1(a), the focal area is the blue area in the figure. After dividing the focal plane into a grid, red represents the position of the focal point. At this time, the ideal electric field on the antenna array is the sum of spherical waves generated by multiple foci, which can be expressed as:

$$\overrightarrow{E}\left(\overrightarrow{r_{ij}}\right) = \sum_{k=1}^{N}\sum_{m=1}^{N} \frac{A_{km}\exp\left[jk_0\left(\overrightarrow{r_{ij}} - \overrightarrow{r_{km}}\right)\right]}{\left|\overrightarrow{r_{ij}} - \overrightarrow{r_{km}}\right|} \tag{1}$$

where k_0 is the propagation constant in vacuum. A_{pm} and $\overrightarrow{r_{km}}$ are the magnitude and location of the kmth grid on the focal plane. $\overrightarrow{r_{ij}}$ is the location of ijth antenna element of the planar array.

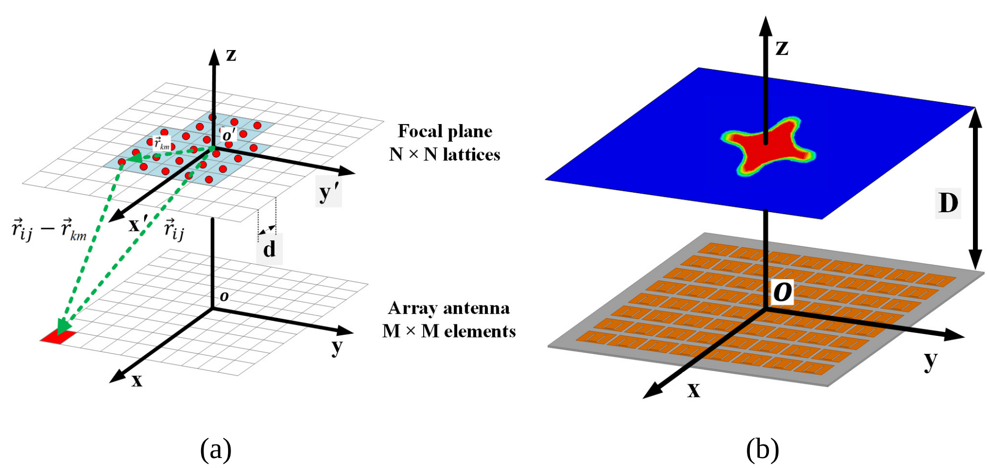


Figure 1. (a) Schematic diagram of near-field pattern focusing. (b) Near field focus shaping pattern.

As shown in Figure 1(b), we set the focusing pattern as "✦", and the distance from the antenna array to the focal plane is $D = 0.1\,\text{m}$. The operating frequency of the antenna array is 10 GHz, and the unit spacing is 15 mm. The amplitude and phase of the antenna array are calculated by Equation (1), as shown in Figures 2(a) and 2(b). Using the aperture distribution of the antenna array, only the modulation of the phase and the simultaneous modulations of the amplitude and phase are simulated, respectively, and the results are shown in Figures 2(c) and 2(d). It can be clearly seen that the focusing pattern formed by only phase modulation has obvious sidelobes, and the focusing pattern with simultaneous amplitude and phase modulation is very good.

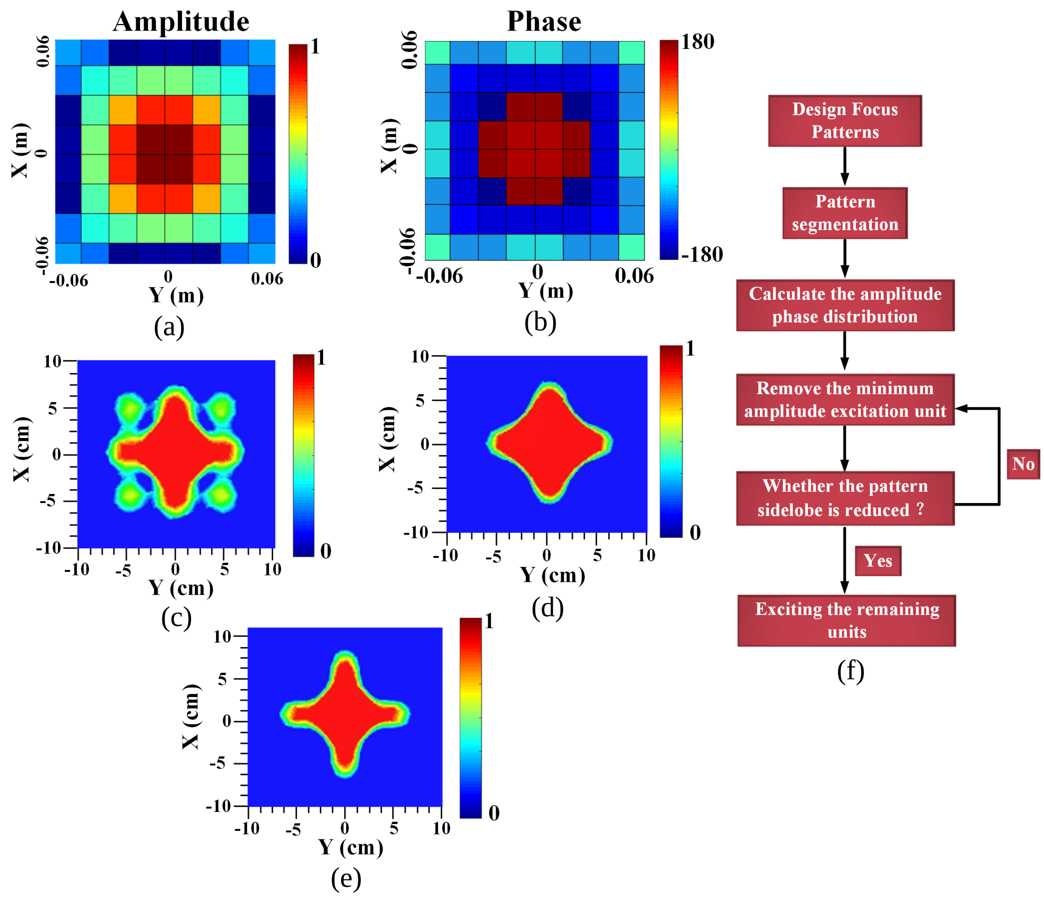
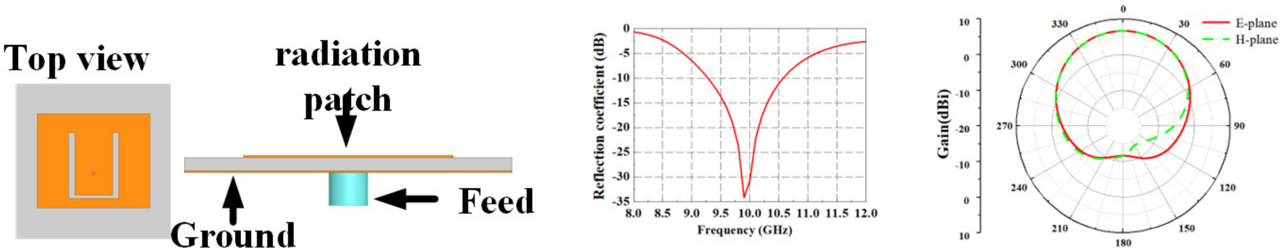


Figure 2. Calculated (a) amplitude and (b) phase distributions of the planar array for generating focusing "✦" shape. Simulated focusing performances of square shape with (c) only modulating phase and (d) both amplitude and phase modulations. (e) Simulating the focusing performance after partially excited antenna arrays. (f) The flowchart of design procedure.

From Figure 2(a) we can see that the amplitude distribution of the antenna array is uniform. In addition, since the amplitude values of some elements contribute very little to the focusing pattern, it can cause high sidelobes around the focusing pattern. Under this condition, when these units are disabled, we can construct a partially excited array, and the simulated pattern is shown in Figure 2(e). We can observe that the sidelobes of the focusing pattern are greatly reduced. Therefore, this method can be used to reduce sidelobes only through phase control.

The flowchart of design procedure is shown in Figure 2(f). Firstly, when the desired focusing pattern is designed, the pattern is divided into multiple focal points. The phase and amplitude distributions of the antenna array aperture are calculated using Equation (1). Since the amplitude values of some elements are small less than $-10\,\text{dBW}$, which means that these elements contribute very little to the focusing pattern, it can cause high sidelobes around the focusing pattern. Under this condition, we can construct a partial excitation array antenna by disabling these elements. When the element with the smallest amplitude is disabled, we can observe whether the sidelobes of focusing pattern are reduced, then repeat the above process, and finally achieve the purpose of reducing the sidelobes of the focusing pattern.

This letter adopts a simple and low-cost microstrip antenna unit. The structure of the antenna unit is shown in Figure 3(a) in which the radiation patch is a U-shaped slot, and the dielectric plate is F4B ($\varepsilon_r = 3.55$ and $\tan\delta = 0.002$) with thickness of 2 mm. The return loss and radiation patterns of the antenna elements are shown in Figures 3(b) and 3(c). This U-slot based antenna element has broadband feature and wide radiation pattern which is suitable for near-field focusing.

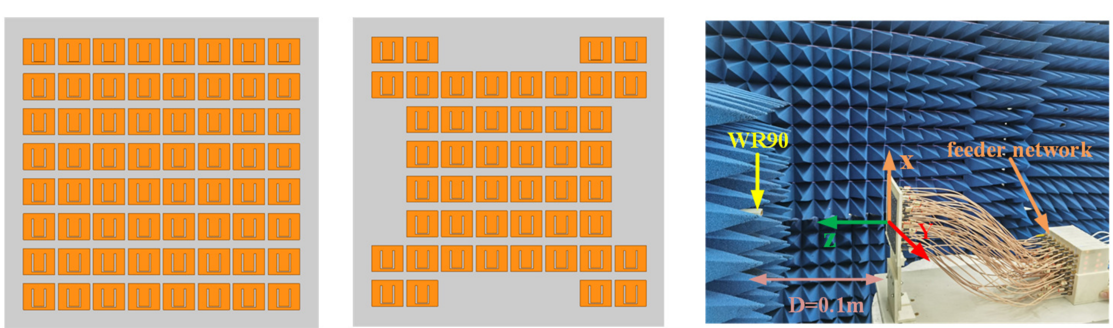


(a) (b) (c)

Figure 3. (a) Structure of the U-slot antenna element. (b) Return loss, (c) E-plane and H-plane radiation patterns of the E-slot microstrip antenna element.

3. EXPERIMENTAL VERIFICATION

In order to further verify the theoretical analysis method proposed in this paper, a planar antenna array with the size of 120 mm × 120 mm is fabricated. The topology of 8×8 full planar array antenna and the partially excited array antenna are shown in Figures 4(a) and 4(b), respectively. A 3D printed polylactic acid (PLA) material structure is used to hold its antenna array. First, the antenna elements are fed through the power divider which is used to split the RF energy input, and the phase of each output in the power divider is controlled by a digital phase shifter chip (Qorvo TGP2109-SM). The measurement configuration is shown in Figure 4(c). The operating frequency of the measurement system is set as 10 GHz; the sampling plane is 0.1 m away from the array antenna under test; and the size of the sampling surface is 0.1 m × 0.1 m. On the sampling plane, an open waveguide probe (WR90) is used for measuring the magnitude of E-field. The required phase-shift value for each unit is adjusted through a computer-controlled phase-shifting network.



(a) (b) (c)

Figure 4. Topology of (a) 8×8 full planar array antenna and (b) partially excited array antenna. (c) Measurement configuration.

Using the planar near-field scanning technique, the normalized electric field distributions of the patterns formed by the planar array and partially excited array can be measured, as shown in Figures 5(a) and 5(b), respectively. It can be seen that both the planar array and partially excited array can generate the desired "✦" pattern. However, the pattern generated by the planar array has sidelobes around the focused shape. However, the sidelobes can be effectively suppressed when a certain number of antenna elements are disabled (i.e., partially excited array). We can see that there is a little difference between the measured results and simulated ones which may be caused by phase error of the digital phase shifter and environmental noise. Nevertheless, the measurement results are basically consistent with the simulation ones. This verifies the effectiveness of the method proposed in this paper. The method can flexibly focus energy in an arbitrary shaped area; therefore, it can provide a reference for wireless energy transmission and radio frequency identification in the future.

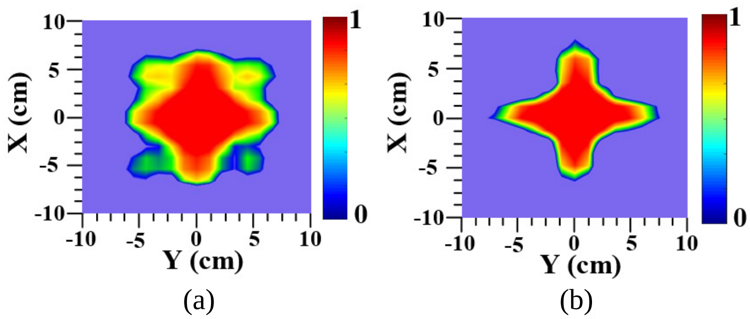


Figure 5. Focusing performances of the shaped pattern generated by (a) full planar array antenna and (b) partially excited array antenna.

4. CONCLUSION

In this letter, we propose a patterned focusing method for planar array antennas. After calculating the amplitude distribution of the planar array, only the antenna elements with larger amplitude are excited, and then the partially excited array formed can effectively reduce the sidelobes of the focusing pattern. A prototype of the array was fabricated and measured. The measurement results show that both the full planar array and the partially excited array realize the "✦" focus mode, and the partially excited array can effectively reduce the sidelobes. The proposed approach is so effective that it can also be used to design array antennas based on metamaterial surfaces [19]. Near-field shape-focusing technology can be widely used in microwave hyperthermia and wireless power transmission.

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