Progress In Electromagnetics Research Letters, Vol. 107, 33–38, 2022

Near-Field Shaped Focusing with Planar U-Slot Antenna Array of Amplitude and Phase Regulation

Yingjun Li, Shixing Yu*, and Na Kou

Abstract—In this paper, we present a planar array for near-field shaped focusing. A near-field synthesis method for forming a special pattern on the focal plane is investigated. The phase and amplitude of the array are adjusted by digital phase shifters and attenuators. Prototypes are fabricated and measured to verify the effectiveness of this method. Near-field shaped focusing performances with square and triangular patterns are realized respectively. The experimental results show that the method can focus the electric field to a designated area clearly. Our work can provide a reference for applications such as microwave hyperthermia and wireless power transfer.

1. INTRODUCTION

Near-field focusing antennas can be used to focus electromagnetic energy to any point in the near-field region like lenses. They are widely applied in various scenarios, such as wireless power transfer (WPT) [1], industrial inspection [2], and microwave imaging [3]. Near-field focusing can be realized by adjusting the phase distribution of the antenna aperture, where the phase is superimposed in the same direction at the focus. There are many types of antennas to carry out the near-field focusing with a single focus or multiple foci, such as dielectric lens, Fresnel zone plate lens, leaky-wave antenna, metasurface, and phased array.

Traditionally, dielectric lens antenna can concentrate the electric field from the feed source. It can be easily designed by the geometrical optics method; however, it is bulky and heavy [4]. To deal with the shortcoming of dielectric lens, Fresnel zone plate lens antenna is brought forward, which is composed of a single-layer printed circuit board [5]. It can screen out the electromagnetic waves transmitting through the annular gaps with the required phase, with superposition in-phase at the focus. Unfortunately, Fresnel zone plate lens antennas are of low efficiency and narrow bandwidth. However, the aforementioned near-field focusing antennas require additional feed sources, which will be of large profile sizes overall. For near-field focusing antenna with low profile, a common type is leaky-wave antenna [6], which introduces structural abrupt changes at appropriate positions on transmission routes. With appropriate leaky-wave radiation, electric fields at different positions can be superimposed in-phase at the focus. However, leaky wave antennas have the disadvantage of low efficiency. With the excellent performance for flexibly regulating the aperture phase distribution, metasurfaces can easily realize near-field focusing with high efficiency. In [7], a design of near-field focusing metasurface is proposed to flexibly generate a single focus and multiple foci.

In some specific occasions like classical conformal radiation therapy (CCRT), focused energy in some ideal area is required where single focus or multi-foci cannot satisfy the demand. Therefore, in [8], a dual-polarized reflectarray is realized by orthogonally arranged tri-dipoles, which can generate different near-field patterns in the horizontal and vertical polarizations, respectively. Although phase modulation

Received 23 August 2022, Accepted 11 October 2022, Scheduled 18 October 2022
* Corresponding author: Shixing Yu (sxyu1@gzu.edu.cn).
The authors are with the Key Laboratory of Micro-Nano-Electronics and Software Technology of Guizhou Province, College of Big Data and Information Engineering, Guizhou University, Guiyang 550025, China.

can be easily and flexibly realized, it is difficult to implement amplitude modulation by metasurfaces. With low profile and high efficiency, planar array antennas have always been the most popular way to achieve near-field focusing [9–13]. Compared with aforementioned near-field focusing methods, planar array antennas own a powerful feed network to flexibly control the phase and amplitude excitations. In previous literatures, planar array antennas were usually used to achieve point focusing. Studies show that better results can be achieved through both phase and amplitude modulations at the same time, but most works only concentrate on the phase modulation. In applications like microwave hyperthermia and wireless power transfer, electromagnetic energy is expected to deliver to the designated area, and in the meantime, the electric field on other areas needs to be controlled as small as possible at the same time.

This letter proposes a planar array antenna of 8×8 units for near-field shaped focusing, by controlling the phase and amplitude excitations through phase-shifters and attenuators. This work is organized as follows. In Section 2, we discuss the theory for near-field focusing on the specified area by planar antenna array. In Section 3, we design an array with 64 U-slot antenna elements to verify the proposed method. Simulated results are consistent with the theoretical ones. Further experimental results show that a triangular and a square shaped focusing patterns are recognized on the focal plane. Section 4 concludes this work.

2. SHAPED FOCUSING ARRAY ANTENNA

The principle of forming a single focus of the antenna array has been presented in our earlier work [14]. Specifically, the spatial delay is compensated by phase shift of each antenna element, and the in-phase superposition is achieved at the focus position. However, when we want to generate a shaped focusing pattern, multiple foci are required to generate, as shown in Figure 1(a). The planar array antenna with $M \times M$ elements is located on the XOY plane, and the focal area forming the special pattern is located on the $X'O'Y'$ plane. Firstly, the specific focus pattern is divided into $N \times N$ grids, each of which corresponds to a focus point, and the distance between the grids is d. When one wants to form a shaped-focusing pattern, the desired field distribution on the planar antenna array is the superposition of the aperture electric fields associated with meshed grids. For example, when the desired focus pattern is a square area which is presented by the green area in Figure 1(a), firstly, we need to divide the green area into $N \times N$ grids. Each grid shown in the red position of Figure 1(a) represents the focus position. Then, the ideal electric field on a planar antenna array is the sum of the spherical waves generated by the multiple focal points which can be expressed as [8]:

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

where k_0 is the propagation constant in vacuum. A_{pm} is the amplitude of the shaped pattern on the pm-th lattice of the focal plane. $\overrightarrow{r_{pm}}$ is the location of the pm-th grid on the focal plane. $\overrightarrow{r_{ij}}$ is the location of the ij-th antenna element of the planar array.

To illustrate the principle of shaped focusing, we set the focused shape as a square pattern, as shown in Figure 1(b). The distance from the aperture to the focal plane is $D = 0.35\,\text{m}$. Firstly, the focal plane pattern is divided into 8×8 grids with spacing $d = 60\,\text{mm}$, which is approximately a half wavelength at 2.4 GHz. Then we can calculate the aperture distribution of the antenna array by Eq. (1). The required amplitude and phase distributions of planar array are shown in Figures 2(a) and (b), respectively, and the actual values are shown in Table 1. Based on the calculated aperture distributions, we can simulate the near-field focusing performance when the planar array is of only phase modulation and that is of both amplitude and phase modulations, as shown in Figures 2(c) and (d), respectively. It can be seen that when only the phase compensation for planar array is introduced, the focused square shape is relatively blurry, and the energy is not concentrated in the center of the shape. However, when both the amplitude and phase excitations are introduced, a relatively clear square shape can be observed on the focal plane, and the energy is more concentrated on the focused square pattern than Figure 2(c).

Furthermore, we also use an example of triangle focusing shape to verify the effectiveness of shaped focusing. Figure 3(a) and (b) are the ideal excitation distributions of planar array for generating triangle focusing shape, and the actual values are shown in Table 2. When only phase modulation of planar

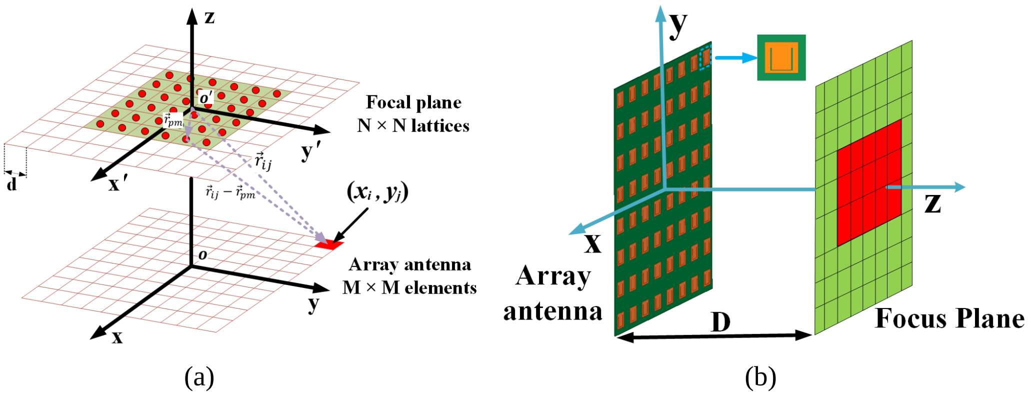


Figure 1. (a) Near-field shaped focusing. (b) Configuration of shaped-focusing using planar antenna arrays.

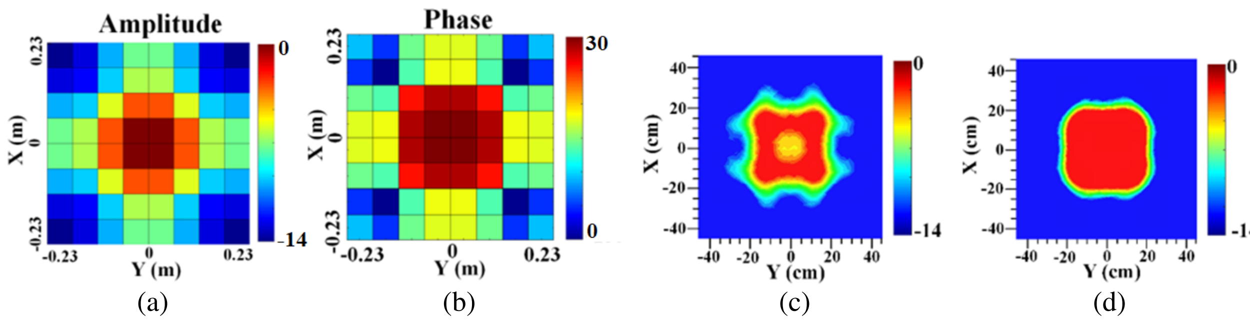


Figure 2. Square shaped focus. (a) Antenna array amplitude distribution. (b) Antenna array phase distribution. (c) Simulation of the focal plane energy distribution for only modulating the phase. (d) Simulated focal plane energy distribution of modulated phase and amplitude.

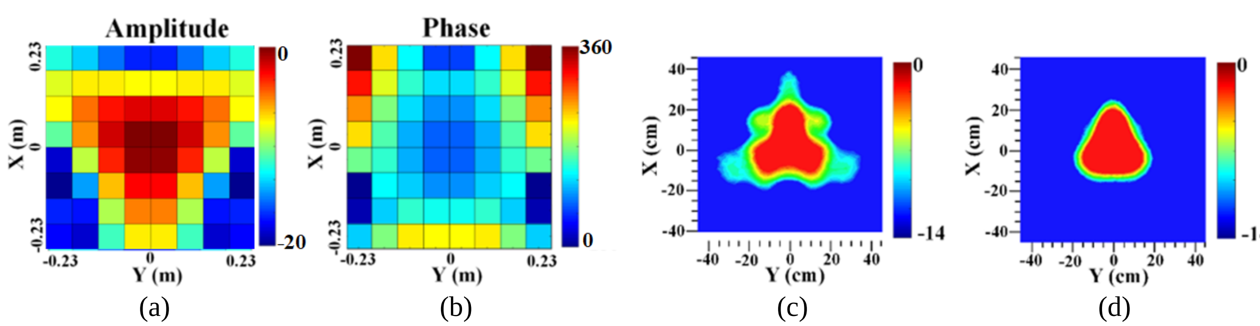


Figure 3. Triangle shaped focus. (a) Antenna array amplitude distribution. (b) Antenna array phase distribution. (c) Simulation of the focal plane energy distribution for only modulating the phase. (d) Simulated focal plane energy distribution of modulated phase and amplitude.

array is performed, the E-field distribution of focusing plane is shown in Figure 3(c). The triangle-shaped focusing performance of planar array antenna with both phase and amplitude modulations is presented in Figure 3(d). We can also see that the focused triangle shape of Figure 3(d) is clearer and more concentrated than that of Figure 3(c). Hence, both phase and amplitude need to modulate to obtain good shaped-focusing pattern.

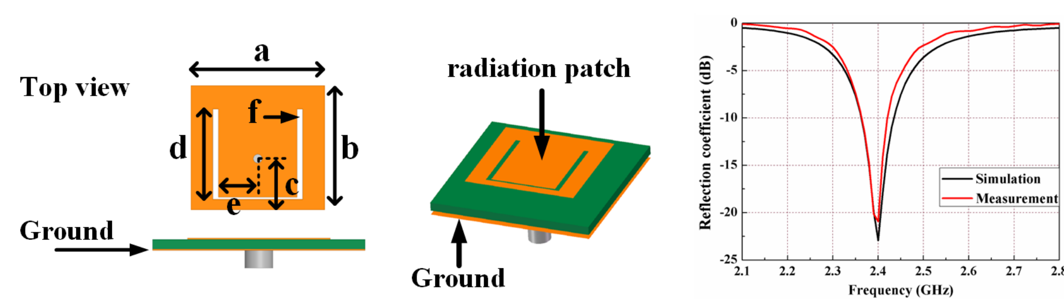
In this work, a microstrip patch antenna with low cost is selected as the antenna element for planar array, as shown in Figure 4(a). The radiation patch is a U-shaped slot supported by the dielectric plate

Table 1. Phase and amplitude distributions of square shaped focus.

Phase (degree)/Amplitude (dB)								
x_i, y_j	1	2	3	4	5	6	7	8
1	6.3/−13.7	2.8/−12.6	12.4/−9.8	15.8/−7.3	15.8/−7.3	12.4/−9.8	2.8/−12.6	6.3/−13.7
2	2.8/−12.6	0/−12.1	13.9/−9.1	17.9/−6.3	17.9/−6.3	13.9/−9.1	0/−12.1	2.8/−12.6
3	12.4/−9.8	13.9/−9.1	25.6/−5.5	27.3/−2.7	27.3/−2.7	25.6/−5.5	13.9/−9.1	12.4/−9.8
4	15.8/−7.3	17.9/−6.3	27.3/−2.7	28.3/0	28.3/0	27.3/−2.7	17.9/−6.3	15.8/−7.3
5	15.8/−7.3	17.9/−6.3	27.3/−2.7	28.3/0	28.3/0	27.3/−2.7	17.9/−6.3	15.8/−7.3
6	12.4/−9.8	13.9/−9.1	25.6/−5.5	27.3/−2.7	27.3/−2.7	25.6/−5.5	13.9/−9.1	12.4/−9.8
7	2.8/−12.6	0/−12.1	13.9/−9.1	17.9/−6.3	17.9/−6.3	13.9/−9.1	0/−12.1	2.8/−12.6
8	6.3/−13.7	2.8/−12.6	12.4/−9.8	15.8/−7.3	15.8/−7.3	12.4/−9.8	2.8/−12.6	6.3/−13.7

Table 2. Phase and amplitude distributions of triangle shaped focus.

Phase (degree)/Amplitude (dB)								
x_i, y_j	1	2	3	4	5	6	7	8
1	94.4/−10.5	54.7/−11.8	22.8/−13.7	2.2/−15.2	2.2/−15.2	22.8/−13.7	54.7/−11.8	94.4/−10.5
2	76.1/−7.2	44.7/−6.6	25.0/−6.5	15.9/−6.6	15.9/−6.6	25.0/−6.5	44.7/−6.6	76.1/−7.2
3	62.2/−6.7	33.3/−4.2	14.9/−2.6	6.1/−1.7	6.1/−1.7	14.9/−2.6	33.3/−4.2	62.2/−6.7
4	53.8/−9.3	27.6/−4.7	9.3/−1.6	0/0	0/0	9.3/−1.6	27.6/−4.7	53.8/−9.3
5	38.7/−15.9	26.5/−7.7	9.8/−2.8	0.4/−0.5	0.4/−0.5	9.8/−2.8	26.5/−7.7	38.7/−15.9
6	340.1/−19.0	22.9/−12.3	14.9/−5.4	6.8/−2.4	6.8/−2.4	14.9/−5.4	22.9/−12.3	340.1/19.0
7	339.6/−15.8	17.7/−15.4	26.2/−8.0	21.0/−4.6	21.0/−4.6	26.2/−8.0	17.7/−15.4	339.6/−15.8
8	11.7/−16	37.7/−16.5	51.5/−10.0	47.9/−6.5	47.9/−6.5	51.5/−10.0	37.7/−16.5	11.7/−16



(a) (b)

Figure 4. (a) Structural and size parameters of the U-slot antenna element. ($a = 31.4$ mm, $b = 29.2$ mm, $c = 12.85$ mm, $d = 23.6$ mm, $e = 9$ mm, $f = 1.3$ mm). (b) S_{11} Simulation and Measured.

of FR-4 with thickness of 2 mm, relative permittivity of 4.4, and loss tangent of 0.02. The return loss of the U-slot antenna is shown in Figure 4(b). This antenna element operates at 2.4 GHz and and can be used to verify near-field focusing performance.

3. EXPERIMENTAL

After theoretical analysis, in order to verify the feasibility of the method, an array antenna with the size of 460 mm × 460 mm is fabricated, as shown in Figure 5(a). This array is composed of 8 × 8 U-slot antenna elements, each of which is connected to a digital phase shifter (chip type: PE44820) and an attenuator network (chip type: HMC424ALP3E) to perform phase and amplitude modulations, respectively. The output port of the digital phase shifter is connected to the input port of attenuator, as shown in Figures 5(b)–(c). In addition, a single-chip microcomputer based system is designed to control the phase shifter and attenuator networks for generating desired phase and amplitude compensations to satisfy the ideal excitation of the antenna array.

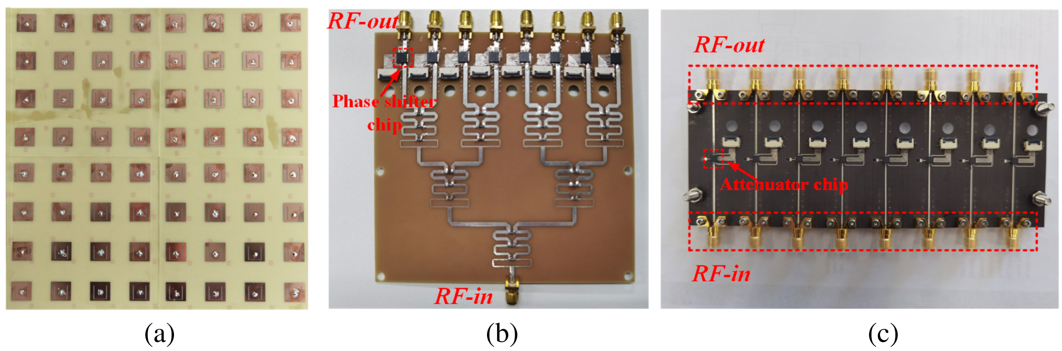


Figure 5. (a) Fabricated planar array antenna. (b) Digital phase shifter network and (c) attenuator network.

The near-field measurement system is shown in Figure 6(a). The operating frequency of the measurement system is 2.4 GHz, and a dipole antenna is used as the receiving antenna. The sampling plane is 0.35 m away from the antenna array with the size of 0.9 m × 0.9 m, and the scanning plane owns fixed sampling space of 10 mm. The normalized electric field distribution of the focal plane measured by the near-field plane scanning technique is shown in Figures 6(b)–(c). It can be seen that there are some differences between the measurement and simulation. This can be attributed to the installation errors and excitation errors of the phase shifter and attenuator. However, the antenna array can clearly focus the energy on the desired square/triangular shape, and the measured results are consistent with the simulated ones. Compared with the traditional single-focusing and multi-focusing techniques, the energy of the antenna array can be focused on an arbitrary area in this study. Therefore, it can be flexibly applied to the fields of wireless power transmission and radio frequency identification.

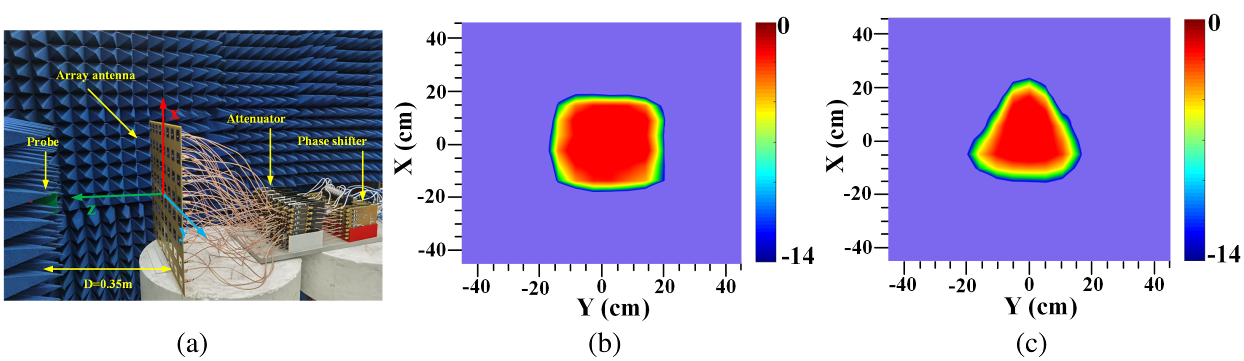


Figure 6. (a) Measurement configuration. Focusing performances of the (b) square shape and (c) triangular shape.

4. CONCLUSION

In this paper, we propose a shaped-focusing method using planar array antenna. Multi-focal formation is analyzed to form a special focusing shape. The amplitude and phase distributions of planar array can be calculated to generate arbitrary focusing shape. A prototype of planar array with both phase and amplitude modulations is fabricated and measured using near-field plane scanning technique. The measured results show that on the focal plane, clear square, and triangular focusing shapes can be obtained. The near-field shaped-focusing technique can be applied in the fields of wireless power transfer and microwave imaging.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China under Grant No. 61961006 and the Science and Technology Foundation of Guizhou Province under Grant No. QKHJC [2020]1Y257.

REFERENCES

1. Ayestarán, R., G. León, R. Pino, and P. Nepa, "Wireless power transfer through simultaneous near-field focusing and far-field synthesis," *IEEE Trans. Antennas Propag.*, Vol. 67, No. 8, 5623–5633, Aug. 2019.
2. Bogosanovic, M. and A. Williamson, "Microstrip antenna array with a beam focused in the near-field zone for application in noncontact microwave industrial inspection," *IEEE Trans. Instrum. Meas.*, Vol. 56, No. 6, 2186–2195, Dec. 2007.
3. Jouade, A., L. Ferro-Famil, S. Meric, O. Lafond, and L. Coq, "High resolution radar focusing using spectral estimation methods in wide-band and near-field configurations: Application to millimeter-wave near-range imaging," *Progress In Electromagnetics Research B*, Vol. 79, 45–64, 2017.
4. Shavit, R., T. Wells, and A. Cohen, "Forward-scattering analysis in a focused-beam system," *IEEE Trans. Antennas Propag.*, Vol. 46, No. 4, 563–569, Apr. 1998.
5. Karimkashi, S. and A. Kishk, "Focusing properties of Fresnel zone plate lens antennas in the near-field region," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 5, 1481–1487, May 2011.
6. Wu, Y., Y. Cheng, and Z. Huang, "Ka-band near-field-focused 2-D steering antenna array with a focused rotman lens," *IEEE Trans. Antennas Propag.*, Vol. 66, No. 10, 5204–5213, Oct. 2018.
7. Hao, H., S. Zheng, Y. Tang, and X. Ran, "Design of electromagnetic wave multi-type focusing based on 1-bit metasurface," *Progress In Electromagnetics Research M*, Vol. 105, 79–88, 2021.
8. Yu, S., N. Kou, Z. Ding, and Z. Zhang, "Design of dual-polarized reflectarray for near-field shaped focusing," *IEEE Antennas Wirel. Propag. Lett.*, Vol. 20, No. 5, 803–807, May 2021.
9. Karimkashi, S. and A. Kishk, "Focused microstrip array antenna using a Dolph-Chebyshev near-field design," *IEEE Trans. Antennas Propag.*, Vol. 57, No. 12, 3813–3820, Dec. 2009.
10. Li, P., S. Qu, S. Yang, Y. Liu, and Q. Xue, "Microstrip array antenna with 2-D steerable focus in near-field region," *IEEE Trans. Antennas Propag.*, Vol. 65, No. 9, 4607–4617, Sept. 2017.
11. Siragusa, R., P. Lemaitre-Auger, and S. Tedjini, "Tunable near-field focused circular phase-array antenna for 5.8-GHz RFID applications," *IEEE Antennas Wirel. Propag. Lett.*, Vol. 10, 33–36, 2011.
12. Tofigh, F., J. Nourinia, M. Azarmanesh, and K. Khazaei, "Near-field focused array microstrip planar antenna for medical applications," *IEEE Antennas Wirel. Propag. Lett.*, Vol. 13, 951–954, 2014.
13. Wu, Y., Y.Cheng, S. Yao, and Y. Fan, "Millimeter-wave near-field-focused full 2-D frequency scanning antenna array with height-modulated-ridge waveguide," *IEEE Trans. Antennas Propag.*, Vol. 69, No. 5, 2595–2604, May 2021.
14. Li, Y., S. Yu, N. Kou, Z. Ding, and Z. Zhang, "Cylindrical conformal array antenna for near field focusing," *Int. J. RF Microw. Comput.-Aided Eng.*, Vol. 32, No. 6, e23135, 2022.