

# Design of a Feed Array Antenna to Obtain a Uniform Near-Field Distribution on a Virtual Surface Placed within a Specified Wavelength

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**Abstract:** This paper proposes a novel feed array antenna to achieve a uniform electric field distribution in the near-field region for feeding a large-aperture antenna. The feed antenna has a  $4 \times 4$  rectangular array configuration to obtain uniform near-field distribution on a virtual target surface. Each element of the array consists of a Vivaldi radiator and parasitic rings, and these two components have different radiating modes. In particular, the near-field pattern of the parasitic rings can be varied by adjusting their radii. Thus, the required near-field distribution on the virtual target surface can be achieved by optimizing the radii of the parasitic rings. To further enhance the uniformity of the electric field, the input phase of each Vivaldi radiator is adjusted by applying different transmission line lengths to the Vivaldi radiators depending on their positions in the array. To verify the feasibility of the proposed antenna, the electric field distributions are measured in an electromagnetic anechoic chamber. The results demonstrate that the proposed feed array antenna can achieve uniform near-field distribution with an average of 1.7 dB and a deviation of 6.8 dB on the virtual target surface placed within half a wavelength from the antenna aperture.

**Keywords:** feed array antenna; parasitic rings; uniform near-field; Vivaldi radiators



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## 1. Introduction

Feed antennas are typically employed to operate various electrical large-aperture antennas, such as dielectric lens antennas, frequency selective surfaces, and metasurface transmissive arrays [1–9]. The feed antennas make it possible to generate a desired electric field distribution over the surface of a large-aperture antenna, enabling a high gain and beam steering while maintaining low design complexity and manufacturing costs [10–12]. In general, patch antennas [13], horn antennas [14], and log-periodic dipole antennas [15] are used as feed antennas. However, these feed antennas are often mounted in the far-field region several wavelengths away from a large-aperture surface, which poses the problem of increasing the overall volume of the antenna system. To resolve this problem, research has been conducted on near-field feed antennas that can be placed within a specific wavelength from the large-aperture antenna [16,17]. In the near-field region, since it is difficult to generate a uniform electric field distribution using a single-element feed antenna, studies on array feed antennas including multiple elements have recently been conducted [18–20]. In particular, array feed antennas are competitive for near-field feeding because they can adjust the amplitude and phase of each element to achieve more uniform field generation in the near-field region.

In this paper, we propose a novel feed array antenna to achieve a uniform electric field distribution in the near-field region for feeding a large-aperture antenna. The feed antenna has a  $4 \times 4$  rectangular array configuration to obtain uniform near-field distribution on a virtual target surface. The virtual target surface was set as a flat surface with dimensions

of  $200 \times 200 \text{ mm}^2$ . The size of the virtual surface can be flexibly determined to suit the requirements of the specific application. Each element of the array consists of a Vivaldi radiator and parasitic rings, where the parasitic rings are placed on top of the Vivaldi radiators. The Vivaldi radiator and the parasitic rings have different radiating modes, and, in particular, the near-field pattern of the parasitic rings can be varied by adjusting their radii. Thus, the required near-field distribution on the virtual target surface can be achieved by optimizing the radii of the parasitic rings. To further improve the uniformity of the field distribution, the input phase of each Vivaldi radiator is adjusted by applying different transmission line lengths to the Vivaldi radiators depending on their positions in the array. This configuration can easily control the phase distribution in the array without the use of a complex phase shifter. Then, three variables such as array spacing, an input phase for each element, and a separation distance between the feed array and the virtual target surface are optimized using the genetic algorithm (GA) [21]. Herein, the cost function of the GA is determined by considering both the average and the deviation of the near-electric field distribution on the virtual target surface. The feed array antennas with the optimum design variables are then fabricated, and the electric field distribution is measured on a target surface using a near-field scanner. The results demonstrate that the feed array with the optimum array configuration and parasitic rings can obtain uniform near-field distribution with an average of 1.7 dB and a deviation of 6.8 dB on the virtual target surface placed within half a wavelength from the antenna aperture.

## 2. Design of the Proposed Feed Array

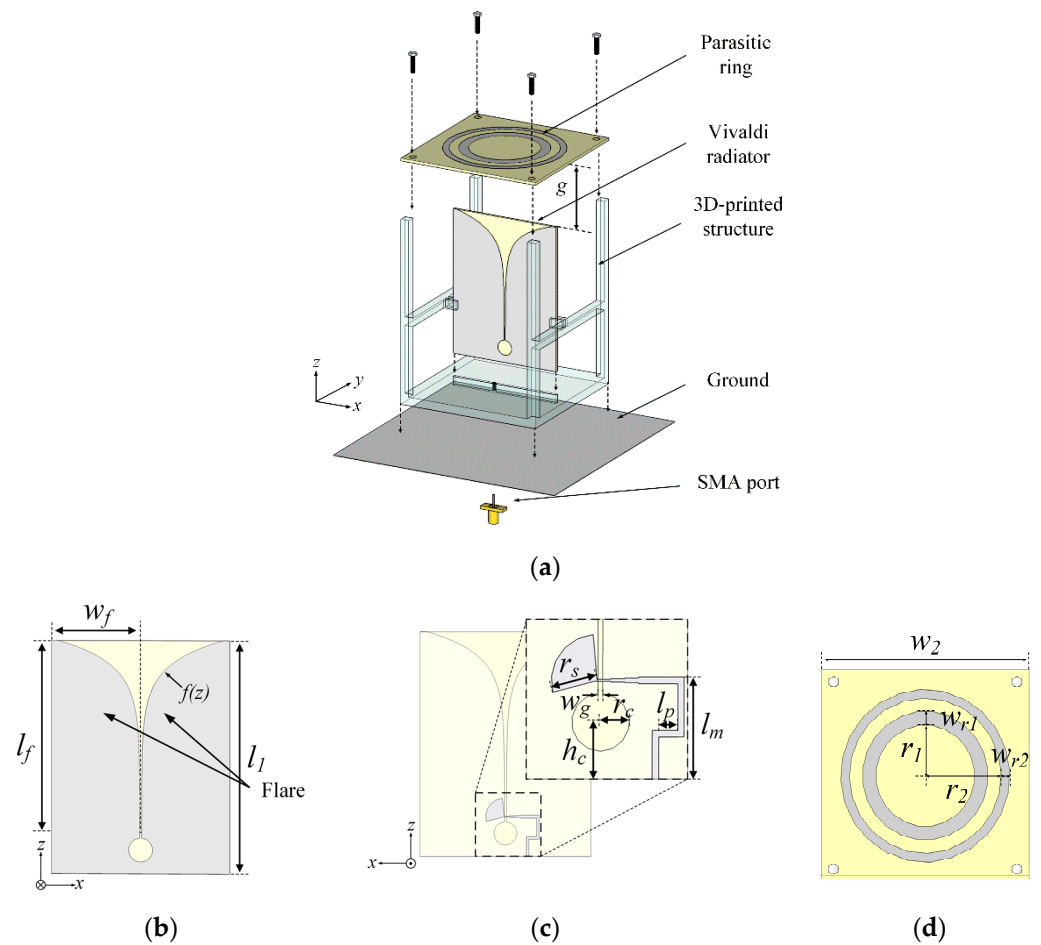
### 2.1. Single-Element Design

Figure 1 presents the geometry of a single element of the proposed feed array for feeding a large-aperture antenna. To obtain a uniform electric field distribution in the near-field region on a virtual target surface, the proposed element consists of a Vivaldi radiator and the parasitic rings. The parasitic rings are placed on top of the Vivaldi radiators, and the gap between the Vivaldi radiator and the parasitic rings is  $g$ , as shown in Figure 1a. The Vivaldi radiator is directly connected to the SMA connector, and the parasitic rings are coupled-fed from the Vivaldi radiator. The Vivaldi radiator and the parasitic rings have different radiating modes, and, in particular, the near-field pattern of the parasitic rings can be varied by adjusting their radii. The Vivaldi radiator and parasitic rings are stably fixed to the ground plane with a resin support structure. This resin structure is fabricated using the stereo lithography apparatus (SLA) 3D printing method. The Vivaldi radiator has two flares and a coupled-fed structure, and they are printed on an FR-4 substrate ( $\epsilon_r = 4.6$ ,  $\tan\delta = 0.018$ , thickness = 1.6 mm). The width and length of the flares are  $w_f$  and  $l_f$ , respectively, as shown in Figure 1b. The curvature of the inner flares is determined using the function  $f(z)$  to achieve broadband characteristics as follows [22,23]:

$$f(z) = a \times e^{k(z-(l_1-l_f))} \quad (1)$$

$$k = \frac{1}{l_f} \ln\left(\frac{1}{a}(w_f - w_g) + 1\right) \quad (2)$$

where  $w_g$  is the gap between the two flares, and  $a$  is the coefficient of the exponential curve line. On the opposite side of the flares, a microstrip line with a radial stub is printed to feed the antenna through the electromagnetic coupling. The Vivaldi radiator has a circular cavity with a radius of  $r_c$ , which is located at a distance  $h_c$  from the ground surface to further improve the antenna bandwidth, as shown in Figure 1c [23]. The parasitic rings consist of inner and outer rings, and the radii of these two rings are  $r_1$  and  $r_2$ , respectively, as shown in Figure 1d. The required near-field distribution on the virtual target surface can be achieved by optimizing the radii of the parasitic rings. The design parameters of the proposed single element have been optimized using a CST Studio Suite 2020 EM simulator [24], and they are listed in Table 1. In addition, the simulation settings are shown in Table 2.



**Figure 1.** Geometry of the single element. (a) Isometric view. (b) Front view of the Vivaldi radiator. (c) Back view of the Vivaldi radiator. (d) Top view of the parasitic rings.

**Table 1.** Parameters of the proposed single element.

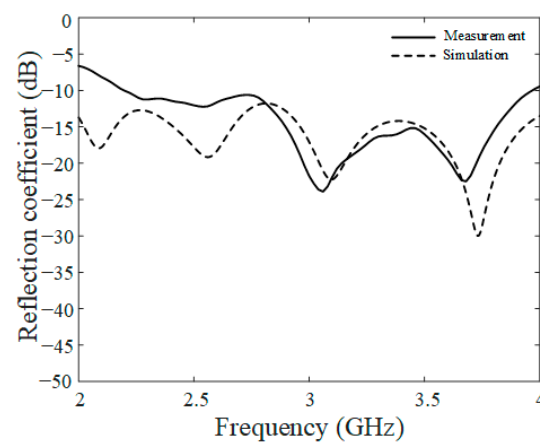
| Parameters              | Values   |
|-------------------------|----------|
| $g$                     | 24 mm    |
| $w_f$                   | 32.15 mm |
| $w_2$                   | 85 mm    |
| $w_{r1}$                | 2 mm     |
| $l_1$                   | 85 mm    |
| $l_f$                   | 69.5 mm  |
| $r_1$                   | 12 mm    |
| $r_2$                   | 15 mm    |
| $r_c$                   | 4.4 mm   |
| $r_s$                   | 7 mm     |
| $h_c$                   | 8.65 mm  |
| $l_m$                   | 15.5 mm  |
| $t$                     | 1.6 mm   |
| $a$                     | 0.01     |
| $w_g$                   | 0.7 mm   |
| $l_p$ (Central element) | 0 mm     |
| $l_p$ (Outer element)   | 1.8 mm   |

Figure 2 shows the reflection coefficient of the single element of the proposed feed array antenna. The Vivaldi radiator has the advantage of easily achieving broadband characteristics, which exhibits a matching bandwidth of 1.78 GHz (2.21 GHz to 3.99 GHz,  $|\Gamma|_{\text{dB}} < -10$  dB) with a fractional bandwidth of 59%. In addition, the average reflection

coefficient in the operating frequency band is  $-18$  dB. There are some discrepancies between the simulated and measured reflection coefficients due to manufacturing and assembly tolerances during the antenna fabrication process. In particular, a connection point with soldering between the transmission line and SMA connector in the Vivaldi radiator is very sensitive to the antenna's performance. However, the tendency of the measurement is in agreement with the simulated result. The bore-sight gain and HPBW of the single element are  $5.91$  dBi and  $78^\circ$ , respectively, and the radiation efficiency is  $85\%$ .

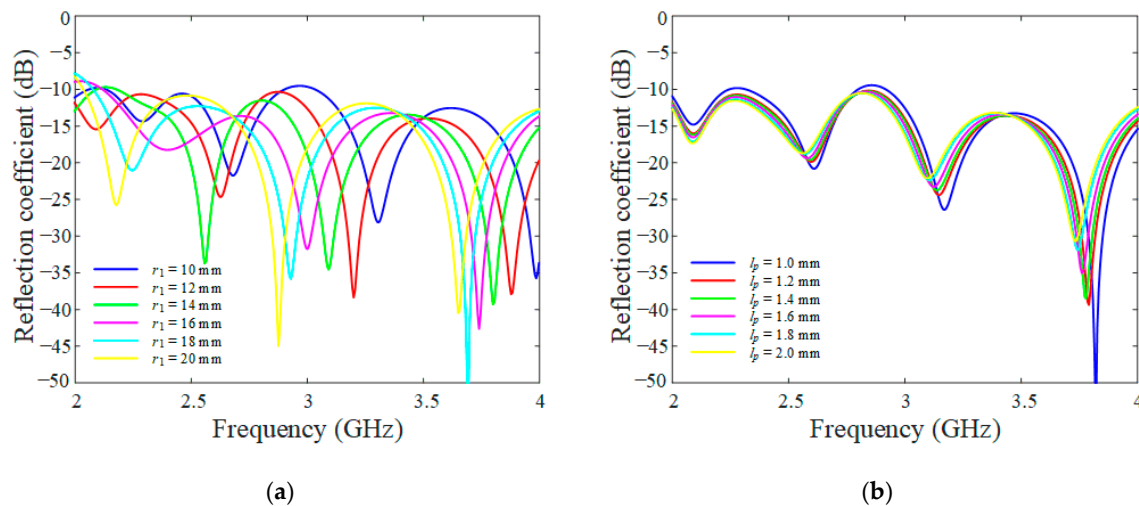
**Table 2.** CST simulation environment.

| Parameters          | Values             |
|---------------------|--------------------|
| Solver type         | Time domain solver |
| Mesh type           | Hexahedral mesh    |
| Mesh size           | $1/15 \lambda$     |
| Boundary condition  | Open boundary      |
| Analysis time range | 0 to 9 ns          |



**Figure 2.** Reflection coefficients of the proposed single element.

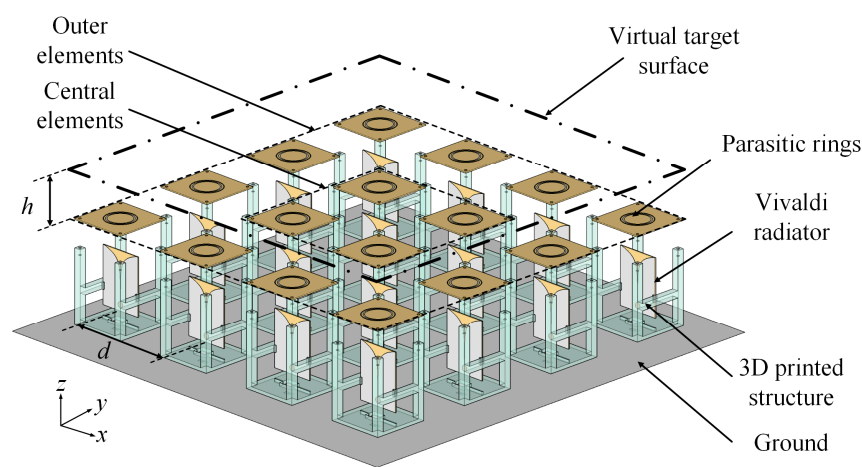
Figure 3 provides the reflection coefficients according to the radius of the parasitic rings ( $r_1$ ) and transmission line lengths ( $l_p$ ). In Figure 3a,  $r_1$  varies from  $10$  mm to  $20$  mm with intervals of  $2$  mm, and in Figure 3b,  $l_p$  varies from  $1$  mm to  $2$  mm with intervals of  $0.2$  mm. As can be seen, the reflection coefficient is more sensitive to changes in  $r_1$ , while the  $l_p$  has little effect on the reflection coefficient.



**Figure 3.** Reflection coefficients of the proposed single element according to  $r_1$  (a) and  $l_p$  (b).

## 2.2. $4 \times 4$ Feed Array Design

Figure 4 illustrates the configuration of the proposed feed array for feeding a large-aperture antenna. The feed system has 16 elements with a  $4 \times 4$  rectangular array configuration to obtain the uniform near-field distribution on a virtual target surface. The array spacing in this configuration is  $d$ , and the separation distance between the feed array antenna and the virtual target surface is  $h$ . The area of this virtual target surface is assumed to be  $200 \times 200 \text{ mm}^2$ . The input phase of each Vivaldi radiator is adjusted by applying different transmission line lengths to the Vivaldi radiators depending on their positions in the array. For example, the transmission line length of the central Vivaldi radiator is shorter than that of the Vivaldi radiator placed on the outside of the array. This configuration can easily control the input phase distribution in the array without the use of a complex phase shifter. The input phase delay of the outer element compared to that of the central element is expressed as  $\phi_{edge}$ .

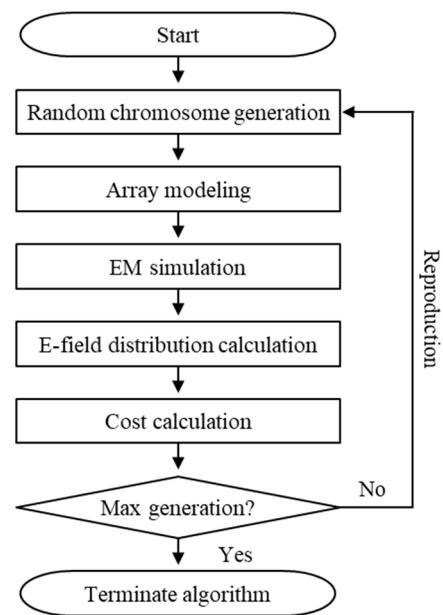


**Figure 4.** Geometry of the proposed feed array antenna.

Figure 5 shows the flowchart of the GA to optimize the array design parameters such as the array spacing ( $d$ ), the input phase delay of the outer element ( $\phi_{edge}$ ), and the separation distance between the feed array and the virtual target surface ( $h$ ). In this optimization process, we focused on optimizing only the variables for the array configuration to reduce the time and resources required for optimization. To find the optimum design parameters, a random chromosome is created, and the decoded values from the chromosome are then applied to the design parameters of the feed array model. Next, the array antenna model with these design parameters is simulated using the CST Studio Suite EM simulator to calculate the electric field distribution on a virtual target surface. The cost function for the GA is defined as follows:

$$Cost = \alpha(E_{ave}) + \beta(E_{dev}) \quad (3)$$

where  $E_{ave}$  is the average value of the electric field distribution used to evaluate the uniformity of the electric field distribution. However, since  $E_{ave}$  alone is not suitable for finding the null point of the electric field, we observed not only the average but also the deviation  $E_{dev}$  of the electric field.  $E_{dev}$  is determined by the deviation between the maximum and minimum values of this electric field distribution. Therefore, the cost function is defined as the summation of  $E_{ave}$  and  $E_{dev}$  of the electric field distribution.  $\alpha$  and  $\beta$  denote the weightings of these two parameters, respectively, and these weights can be adjusted according to the application. In our study, these weights are set to  $\alpha = 0.7$  and  $\beta = 0.3$ . Consequently, the optimum design parameters for the feed array antenna are determined at a minimum cost in the GA, which means that the proposed antenna has the field distribution closest to the uniform distribution on the virtual target surface. The GA parameters, such as the crossover ratio, mutation ratio, number of populations, and number of generations, are listed in Table 3.

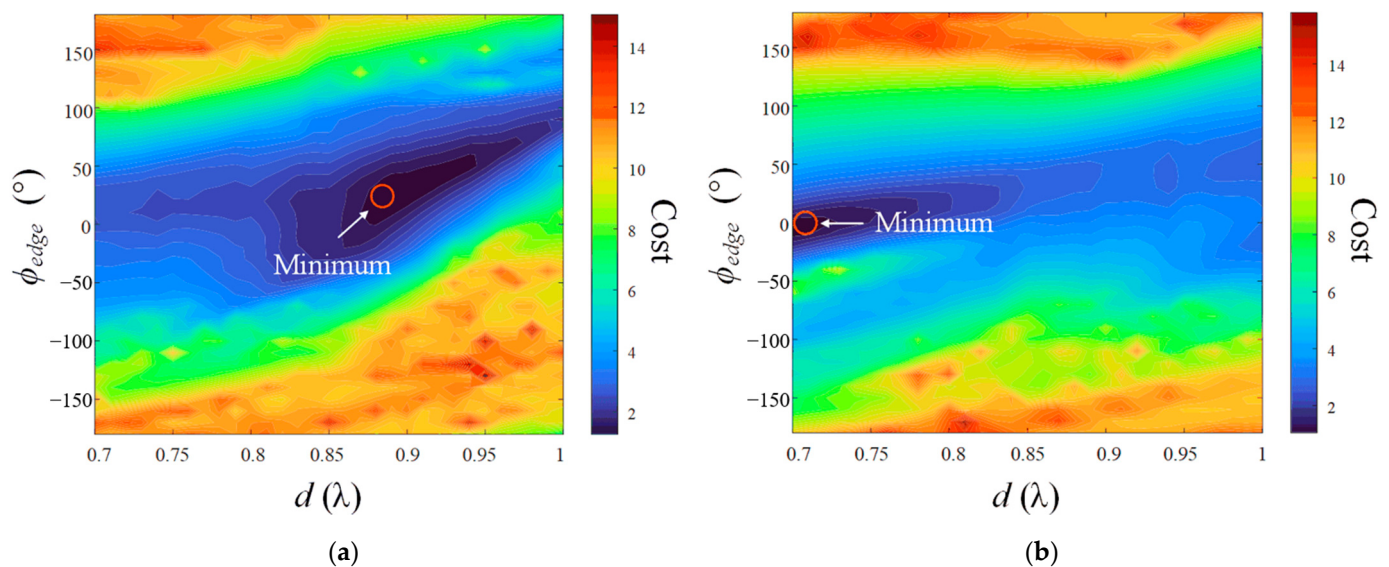


**Figure 5.** Flowchart of the GA algorithm.

**Table 3.** Parameters of GA set up.

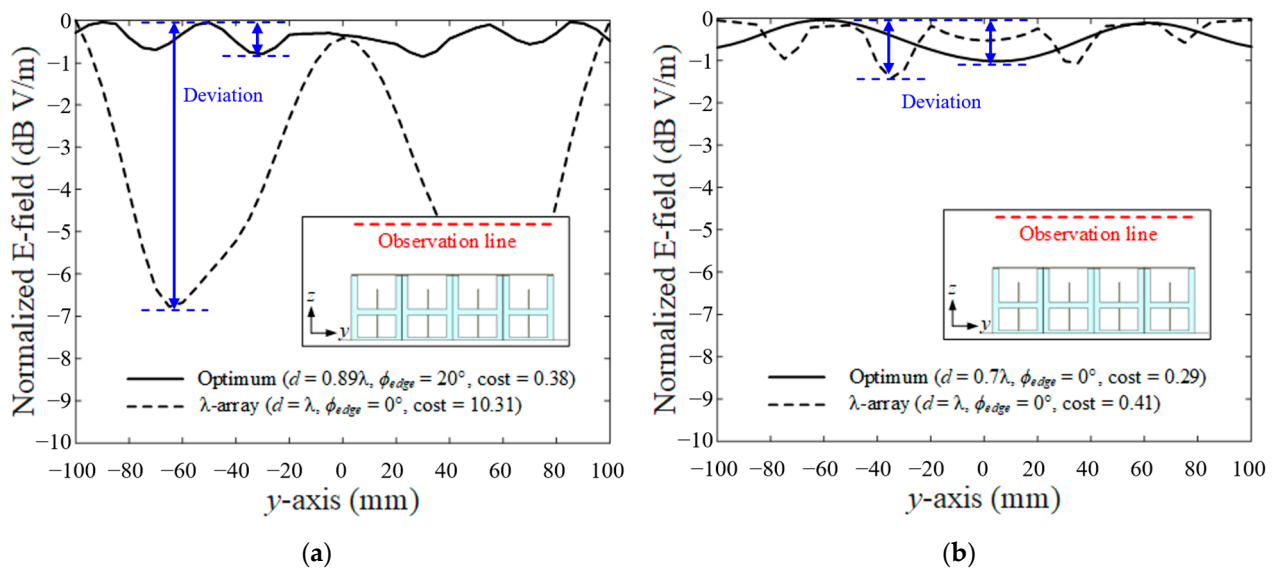
| Parameters      | Values |
|-----------------|--------|
| Crossover ratio | 0.8    |
| Mutation ratio  | 0.1    |
| Populations     | 30     |
| Generations     | 30     |

Figure 6 presents the variation in the cost value according to the array spacing ( $d$ ) and the input phase delay ( $\phi_{edge}$ ) at 3.05 GHz. As can be seen in Figure 6a, when the separation distance between the feed array antenna and the virtual target surface ( $h$ ) is  $0.4\lambda$ , the minimum cost value is observed at  $d = 0.89\lambda$  and  $\phi_{edge} = 20^\circ$ . On the other hand, when  $h$  is  $0.6\lambda$ , the minimum cost value is indicated at  $d = 0.7\lambda$  and  $\phi_{edge} = 0^\circ$ , as shown in Figure 6b.



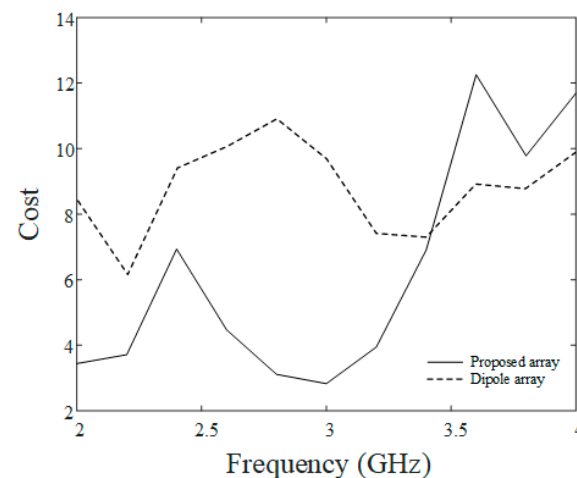
**Figure 6.** Cost variation according to  $d$  and  $\phi_{edge}$ . (a)  $h = 0.4\lambda$ . (b)  $h = 0.6\lambda$ .

Figure 7 represents the normalized electric field distribution of the feed array antenna at 3.05 GHz. In this analysis, the electric field distribution is observed along a straight line ( $x = 0$  and  $-100 \text{ mm} < y < 100 \text{ mm}$ ) by varying the height ( $h$ ). The optimized near-field distribution with design parameters of  $h = 0.4\lambda$ ,  $d = 0.89\lambda$ , and  $\phi_{edge} = 20^\circ$  are compared with the near-field field when  $h = 0.4\lambda$ ,  $d = 1\lambda$ , and  $\phi_{edge} = 0^\circ$ . The optimized array has a more uniform field distribution (cost = 0.38) than the other (cost = 10.31), as shown in Figure 7a. When  $h$  is  $0.6\lambda$ , the optimized array ( $d = 0.7\lambda$  and  $\phi_{edge} = 0^\circ$ ) has a field distribution closest to the uniform (cost = 0.29), as shown in Figure 7b.



**Figure 7.** Normalized electric field distribution of the feed array antenna. (a)  $h = 0.4\lambda$ . (b)  $h = 0.6\lambda$ .

Figure 8 shows the simulated cost variation according to the operating frequency. The solid line and dashed line indicate the cost variations of the proposed antenna and the half-wave dipole array, respectively. The results show that the proposed antenna can obtain a more uniform field distribution compared to the conventional half-wave dipole array. In particular, the near-field of the proposed antenna becomes closest to a uniform distribution from 2.6 GHz to 3.3 GHz with a cost of less than 5.

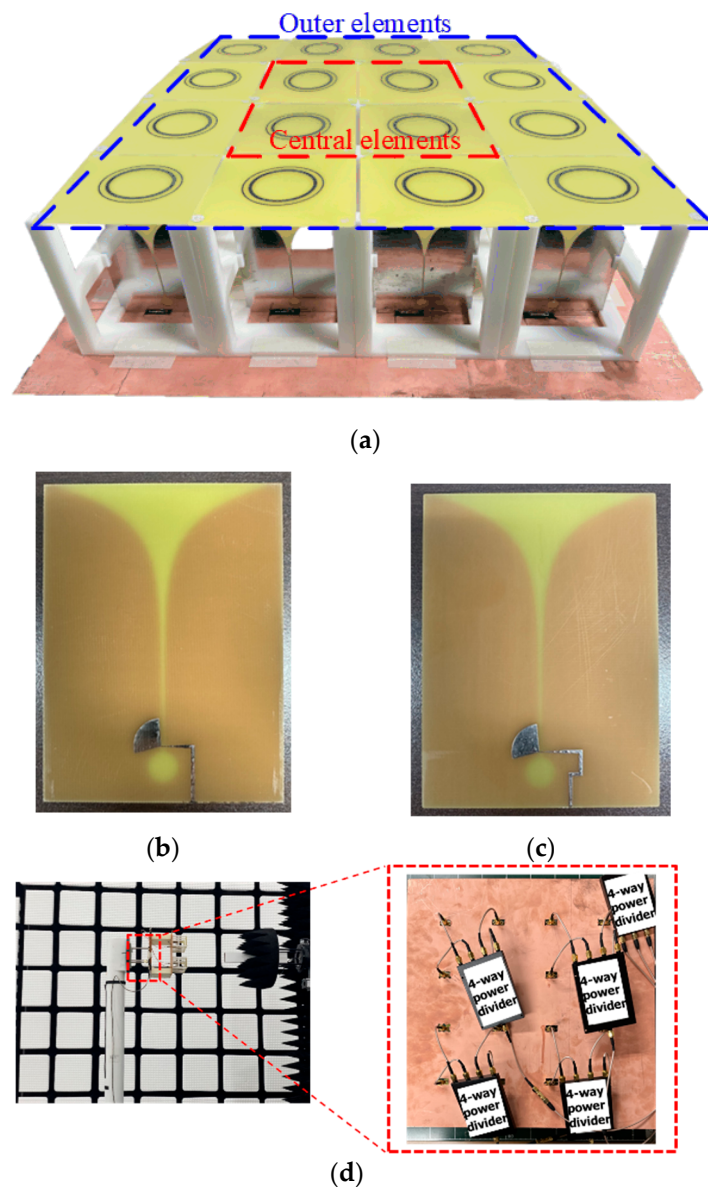


**Figure 8.** Cost variation according to operating frequency.

### 3. Fabrication and Measurement of the Proposed Feed Array Antenna

Figure 9 shows the photographs of the proposed feed array antenna. As can be seen in Figure 9a, the fabricated feed array antenna has 16 elements, and the optimum array

design parameters obtained using the GA are applied to the proposed array antenna. To adjust the input phase of each element, the different transmission line lengths are used for the central and outer elements of the array, as shown in Figure 9b,c. The near-field distribution of the proposed feed array antenna is measured in a full anechoic chamber. The dimensions of this chamber are  $10 \times 10 \times 10 \text{ m}^3$ . A simple waveguide antenna is used as a probe to scan the aperture of the antenna being measured after antenna calibration based on the three-antenna method [25]. Herein, a resolution of the measured near-field data is 0.01 m. SMA connectors are mounted on the bottom face of the ground plane of the array, and all SMA connectors are connected to the network analyzer using five four-way power dividers, as shown in Figure 9d. The array parameters of the proposed feed array antenna are listed in Table 4.



**Figure 9.** Photographs of the proposed feed array antenna. (a) The  $4 \times 4$  feed array antenna. (b) Vivaldi radiator of the central elements. (c) Vivaldi radiator of the outer elements. (d) Measurement setup.

**Table 4.** Parameters of proposed feed array antenna.

| Parameters    | Values       |
|---------------|--------------|
| $d$           | 85.4 mm      |
| $h$           | 30.2 mm      |
| $\phi_{edge}$ | $24.3^\circ$ |

Figure 10 illustrates the normalized electric field distribution of the proposed feed array by measurement and simulation at 3.05 GHz. The electric field distributions are observed to be 30.2 mm ( $0.3\lambda$ ) above the aperture of the feed array antenna. The average and deviation of the measured electric field are 1.7 dB and 6.8 dB (cost = 3.2), respectively. This is in good agreement with the simulated results, which are an average of 1.3 dB and a deviation of 6.9 dB (cost = 2.9). The results demonstrate that the feed array with the optimum array configuration and the parasitic rings can obtain uniform electric field distribution in the near-field region.

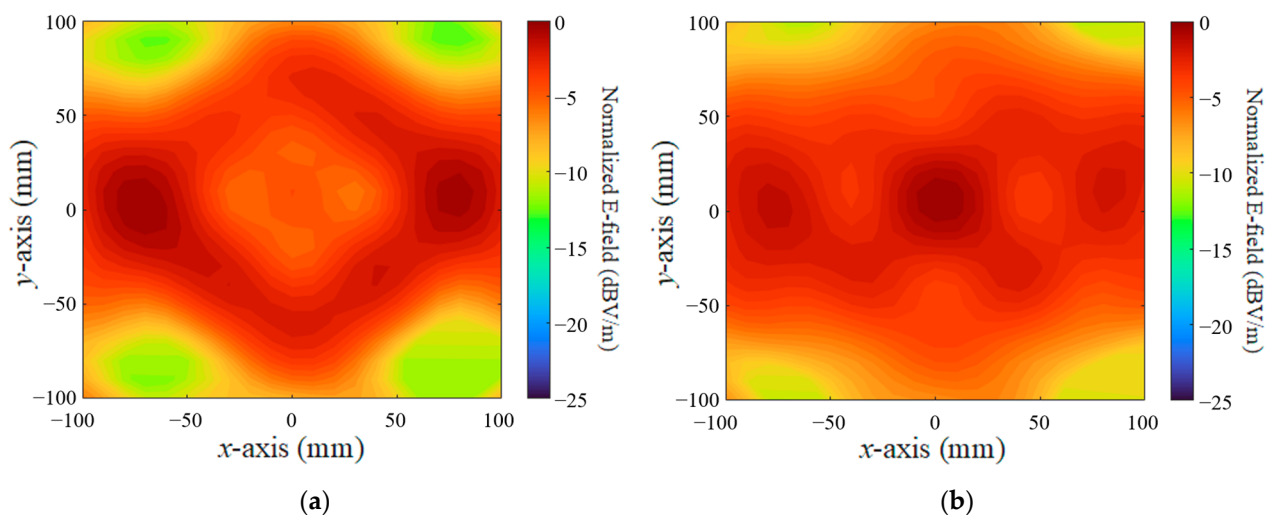
**Figure 10.** Electric field distribution of the proposed feed array. (a) Measurement. (b) Simulation.

Table 5 provides the comparisons with other feeders. As can be seen in this table, the feeders in [13,14] are used the single element, which has an advantage of low structural complexity. However, these feed antennas are often mounted in the far-field region, increasing the overall volume of the antenna system. The feeder in [16] is used the array configuration to enhance the uniformity of the near-field distribution. Then, the proposed antenna can achieve the required near-field distribution on the virtual target surface by optimizing the radii of the parasitic rings, transmission line length of each Vivaldi radiator (phase distribution), and array spacing.

**Table 5.** Comparisons with other feeders.

| Research  | Antenna Type  | Structural Complexity | Distance to the Aperture | Regions    |
|-----------|---------------|-----------------------|--------------------------|------------|
| [13]      | Single patch  | Low                   | $1.2 \lambda$            | Far-field  |
| [14]      | Single horn   | Low                   | $5.4 \lambda$            | Far-field  |
| [16]      | Slot array    | High                  | $0.1 \lambda$            | Near-field |
| This work | Vivaldi array | Medium                | $0.3 \lambda$            | Near-field |

#### 4. Conclusions

In this paper, we used a feed array antenna to achieve uniform electric field distribution in the near-field region for feeding a large-aperture antenna. Each element of the

array consisted of a Vivaldi radiator and parasitic rings, and it was possible to vary the near-field pattern of the parasitic rings by adjusting their radii. Thus, the required near-field distribution on a virtual target surface can be achieved by optimizing the radii of the parasitic rings. The reflection coefficient of a single element had a matching bandwidth of 1.78 GHz with a fractional bandwidth of 59%, and the average reflection coefficient in the operating frequency was  $-18$  dB. The uniformity of the electric field distribution in the near-field was evaluated by the cost, and this cost was determined by considering both the average and the deviation of the near-electric field distribution. The average and deviation of the proposed feed array were 1.7 dB and 6.8 dB (cost = 3.2), respectively. The result demonstrated that the feed array with the optimum array configuration and parasitic rings can obtain uniform near-field distribution on the virtual surface placed within half a wavelength from the antenna aperture. The proposed antenna can be employed to operate various electrical large-aperture antennas, such as dielectric lens antennas, frequency selective surfaces, and metasurface transmissive arrays. Therefore, we expect that the proposed feed array will be useful in practical applications such as radars, satellite communications, and medical systems [26,27]. On the other hand, the proposed antenna requires further studies to evaluate the antenna's durability.

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**Conflicts of Interest:** Author Doyoung Jang was employed by the company Hanwha Systems Company Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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