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A Circular Aperture Array Configuration with a Small Antenna Radius

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SUMMARY In this paper, small sized arrays with a few elements are investigated. The antenna diameter is assumed to be less than $3\lambda_o$. The focus of this paper is to compare the gain characteristics of a triangle arrangement with these of a uniform arrangement. The method of moments is used to calculating the gain characteristics. It is shown that the triangle arrangement is not always sufficient to obtain maximum gain for a small-sized antenna with only a few elements. Also, the type of antenna element used greatly influences the required number of elements and the element configuration.

key words: *array configuration, uniform arrangement, patch antennas helical antennas*

1. Introduction

Recently, the demand for small-sized array antennas is increasing [1], [2]. For example, the satellites for the Inmarsat system employ high gain spot beam antenna to reduce the size of the antenna for ship earth station.

In an array antenna, gain and sidelobe characteristics are very important factors. Array antennas for mobile communications system have a small number of elements. These array antennas are categorized into relatively small array antennas. In such a small array antenna, the gain characteristics are the main factor for designing the array antenna rather than the sidelobe characteristics [3].

It is well known that the antenna gain increases in proportion to the inter element spacing, which is less than one wavelength. For a uniformly arranged linear array, it is reported that approximately 0.9 wavelength is the optimum spacing [4]. According to this result, the spacing is also suitable for planar array antennas whose elements have rectangular arrangement, triangle arrangement, or circular arrangement.

For a large array antenna, it is common knowledge that a triangle arrangement [5] is almost the best arrangement to obtain maximum gain with a minimum number of elements. In a practical design, the triangle arrangement can not be used because the array spacing is restricted by antenna size. Hence, a reduction of elements that keeps the antenna gain high is important. In addition, from the mass-production point of view, it is preferable to reduce the number of elements to reduce the cost.

In this paper, small sized array configurations with only a few elements are investigated. We especially focus on the antenna gain characteristics. The Antenna diame-ter is chosen near $3\lambda_o$, where λ_o is the wavelength at the operational center frequency, 1.6 GHz.

In Sect. 2, a uniform array configuration is defined as a fundamental configuration with an antenna diameter of $3\lambda_o$. In Sect. 3, the antenna characteristics of uniform array configurations are investigated in detail using the method of moments. In Sect. 4, a prototype antenna is fabricated and tested. The measured and calculated results are presented.

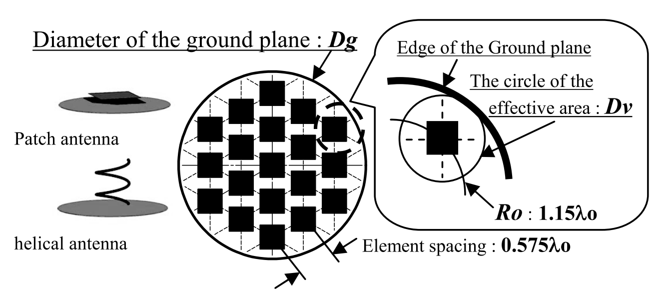
2. Array Antenna Configuration

In this section, the array configuration is investigated for a small-sized array antenna. To compare the antenna characteristics against the triangle arrangement, a uniform arrangement is examined as one example of a non-triangle arrangement.

In this paper, isotropic elements, circular-polarized patch antennas, and axial mode helical antennas are used as array elements. The latter two antennas are assumed to be low profile and three-dimensional as depicted in Fig. 1(a). Our purpose is to clarify the uniformly arranged suitable array configuration with a ground plane size of $3\lambda_o$ in diameter.

2.1 Triangle Array Configuration

Figure 1(b) shows the triangle array configuration on the cir-



(a) Antenna element. (b) Element arrangement.

Fig. 1 Triangle arrangement array antenna.

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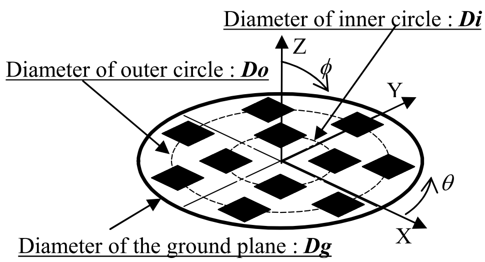


Fig. 2 Uniform arrangement as the fundamental array configuration and its coordinate system.

cular ground plane of $3\lambda_o$ in diameter. In this figure, the elements of the array are illustrated as square patches and are arranged with triangle lattices. The distance between elements on the lattices are all identical and are fixed at $0.575\lambda_o$.

Generally, the size of the antenna can not be decided only by the arrangement of the elements in the array. Since the size of the ground plane may change even though the array configuration is fixed. We determine the triangle array configuration considering the following points. When an element of an array antenna is located at the edge of the ground plane, the gain of the element deteriorates. This means that the element requires a certain area. To take into the account this phenomenon, the concept of the effective antenna area [6] is introduced. We assume that the effective area is a circle. The center of the circle coincides with the center of the antenna element. Also we assume that the diameter of the circle D_v is $0.7\lambda_o$ [7]. As a result, the radius of the element located at the farthest point from the center of the ground plane, R_o is $1.15\lambda_o$.

2.2 Uniform Array Configuration

Figure 2 shows a typical example of the uniform arrangement. In this figure, the elements of the array are illustrated as square patches and arranged in concentric circles. Because the spacings between elements on the same circle are identical, we call it as Uniform array configuration in this paper.

In this arrangement, there are two parameters to be determined: the number of the elements in each circle and the diameter of each circle.

The fundamental array configuration is derived from the following procedures.

1) The diameter D_g of an imaginary ground plane is defined. In our case, D_g is $3\lambda_o$. Then, the diameter of outer circle D_o is determined from the following equation.

$$D_g = D_o + D_v \tag{1}$$

where D_v is a diameter of the effective area of an antenna element.

2) The diameter D_i of the inner circle is determined so as to enlarge the spacing between the outer elements, and also to enlarge the inner elements, that is $(D_o - D_i)/2$. The diameter D_i is desirable as large as possible, then the following relationships are derived from these two restrictions.

$$D_i = 0.5D_o \tag{2}$$

3) The last step is to determine the number of elements n on the each circle. The spacing L between adjacent elements on the same circle is given by the following equation which we call a polygonal.

$$L = 0.5 \times D_x \sqrt{2\{1 - \cos(2\pi/n)\}} \tag{3}$$

Usually the spacing between adjacent elements is chosen to be less than one wavelength so as to avoid grating lobes. Then, the Eq. (3) is restricted by the following equation, where D_x is D_o or D_i.

$$D_x < \frac{2\lambda_o}{\sqrt{2\{1 - \cos(2\pi/n)\}}} \tag{4}$$

From Eq. (1) through (4), the fundamental array parameters are determined. The parameters are summarized in Table 1. The derived array configuration is shown in Fig. 2.

Table 1 Array parameters.

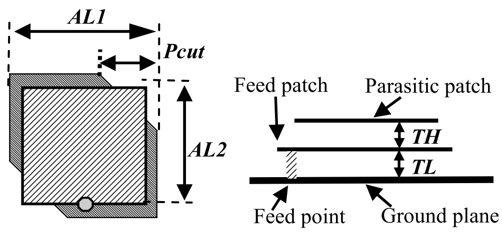
The diameter of ground plane: Dg	3λo
The diameter of the virtual effective antenna area: Dv	0.7λo
The diameter of the inner circle: Di	1.15λo
The diameter of the outer circle: Do	2.3λo
The number of elements arranged on the inner circle: Ni	4
The number of elements arranged on the outer circle: No	7

3. Characteristics of a Uniform Arrangement Array Antenna

As described in the previous subsection, the array elements are on two concentric circles. The elements on each circle are affected by mutual coupling. The mutual coupling between elements usually degrades the array characteristics such as antenna gain and radiation pattern. In the previous subsection, the mutual coupling is not considered. To evaluate the array performance including the effects of mutual coupling, the method of moments is employed.

In this section, the gain characteristics of the triangle arrangement are compared with those of the uniform arrangement for a small-sized array antenna. As sample elements, isotropic, patch and helical antennas are used.

As depicted in Fig. 2, the array elements are on two circles. The elements on each circle have different characteristics due to the number of elements and the diameter of the circle. Therefore, the elements on the inner circle are decided first under the condition that there are no elements on the outer circle. After that, the number of elements for the outer circle is determined.



(a) Top view. (b) Side view.

Fig. 3 Configuration of patch antenna.

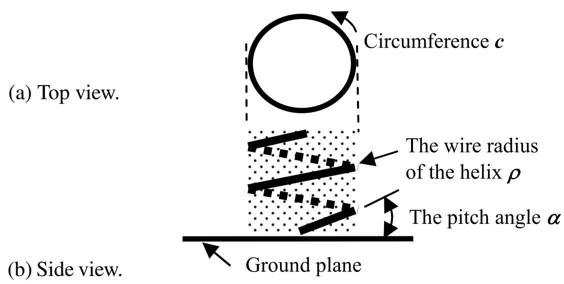


Fig. 4 Configuration of helical antenna.

Table 2 Parameters of the helical antenna.

The pitch angle: α [deg.]	12.5
The circumference of the helical antenna: c [λo]	1.0
The number of turns	2
The wire radius of the helical antenna: ρ [mm]	2.5

3.1 The Circularly Polarized Patch Antenna [8]

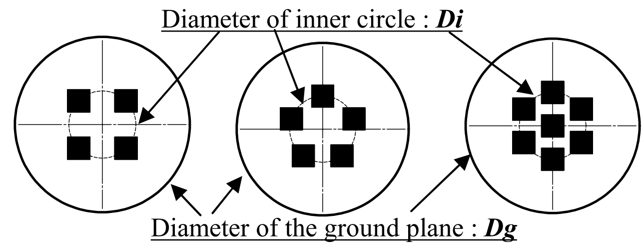
Figure 3 shows the geometry of the circularly polarized patch antenna [8] used in this array simulation. The antenna consists of three parts: a ground plane, a lower antenna element and an upper antenna element. The lower element has a hexagonal shape with long sideways, and is fed at the position of the usual feed point of a square microstrip antenna. The upper element has a square shape, and the center of the element coincides with that of the lower element.

3.2 The Helical Antenna [9], [10]

Figure 4 shows the structure of the helical antenna. The antenna parameters are the pitch angle α, the helical circumference c, the wire radius ρ and the number of turns n. The helical antenna is placed on the finite size ground plane of $3\lambda_o$ in diameter. A wire grid method is used to analyze the antenna characteristics. The parameters used in this paper are listed in Table 2.

3.3 Gain Characteristics vs. the Number of Elements

Firstly, the antenna gain characteristics of the inner circle arrays are investigated. For the inner circle, three types of array configurations, shown in Fig. 5, are considered, that



(a) 4-element. (b) 5-element. (c) 7-element.

Fig. 5 Array configurations of inner circle.

is 4-element uniform array with a square lattice, 5-element uniform array with a pentagonal lattice, and 7-element triangle array with triangle lattices. The reason why the 7-element array is considered is that 7-element is required to constitute the triangle array in the same circle. In this paper, matched gain described below is used as term "Gain," which compensated with loss due to mismatch.

$$G_m = G_o + L_m$$
$$L_m = 0.25(1 + VS)^2/VS,$$

where G_m denotes the matched gain, G_o denotes commonly used gain, L_m denotes loss due to mismatch and VS denotes Voltage Standing Wave Ratio (VSWR).

The mutual coupling is also considered for the patch array and helical array cases, but not considered for the isotropic case. The results for the isotropic case are derived using array factor formulations.

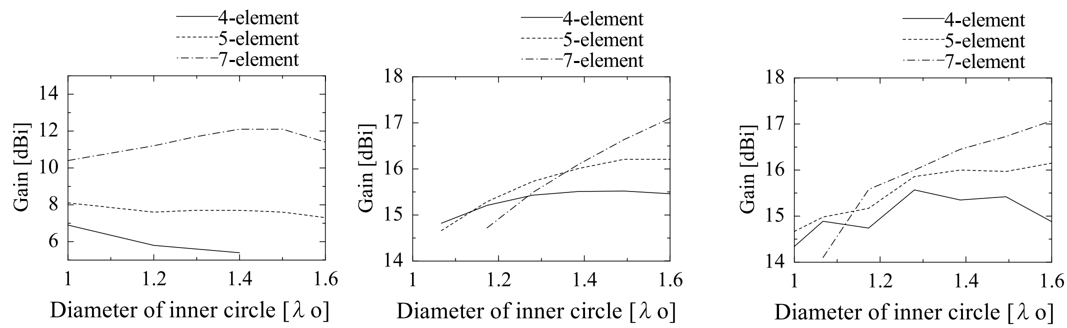
The gain characteristics of the isotropic array antennas are shown in Fig. 6(a). In this case, the diameter of the inner circle is varied from $1.0\lambda_o$ to $1.6\lambda_o$. It is found that as the element number increases, the gain also increases. Therefore, the triangle array is on the adequate configuration for this array.

In comparison with the isotropic element, the same arrangements are also investigated for the microstrip and the helical antenna as element antenna. The reason why microstrip and helix are chosen as the element antenna is that these are one of the typical antenna of three dimensional and flat antennas.

Figure 6(b) shows the calculated result of the gain of the patch array. When the diameter of the inner circle is less than $1.15\lambda_o$, the 4-element array has higher gain than that of the other arrangements. On the other hand, when the diameter of the inner circle is between $1.15\lambda_o$ and $1.35\lambda_o$, the gain of 5-element array is a higher than that of the others. From Table 1, the diameter of the inner circle, $1.15\lambda_o$ is suitable for the ground plane with $3.0\lambda_o$, Therefore, a 4-element uniform array is adequate for this case.

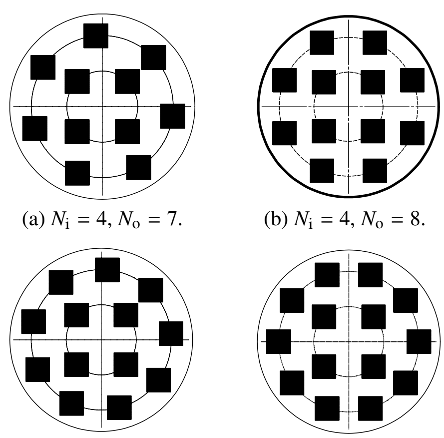
The gain characteristics of the helical array antenna are also shown in Fig. 6(c). Although slight fluctuation are seen, which is a feature of helical antenna, the gain characteristics of the helical array are almost the same as those of the patch array. Hence the uniform array is adequate.

Next, we investigate the gain characteristics of the array antenna that includes the outer circle elements. The ar-



(a) Isotropic array case. (b) Patch array case. (c) Helical array case.

Fig. 6 Gain characteristics vs. diameter of inner circle for isotropic element.



(a) $N_\mathrm{i} = 4, N_\mathrm{o} = 7$. (b) $N_\mathrm{i} = 4, N_\mathrm{o} = 8$.

(c) $N_\mathrm{i} = 4, N_\mathrm{o} = 9$. (d) $N_\mathrm{i} = 4, N_\mathrm{o} = 10$.

Fig. 7 Uniform arrangement array antennas. N_i and N_o denote number of element.

Table 3 Gain characteristics vs. number of elements on outer circle.

Number of elements	Gain of patch	Gain of helical
7	18.90	18.50
8	19.18	18.66
9	19.16	19.13
10	19.17	18.99

ray configurations are shown in Fig. 7.

The patch antenna and the helical antenna are used as the antenna elements. From the previous result, the number of elements on the inner circle is fixed at 4, and the diameter of the inner circle is also fixed at $1.15\lambda_\mathrm{o}$. The number of elements on the outer circle is increased from 7 to 10.

Table 3 summarizes the gain characteristics of the patch array and the helical array. In the case of the patch array, the gain does not increase when the number of elements is greater than 8 elements. On the other hand, in the helical array, the maximum gain is obtained when the number of elements is 9. These array configurations are shown in Fig. 7(b) and (c).

In Sect. 2, we show that 4-element array for the inner circle and 7-element array for the outer circle are adequate for the fundamental configuration of an array antenna with a diameter of $3\lambda_\mathrm{o}$. However, the effect of the mutual coupling which depends on the element type such as patch or helical antenna, is not considered in this calculation. Therefore, the suitable number of elements is changed in the above results.

3.4 Gain Characteristics vs. GND Diameter

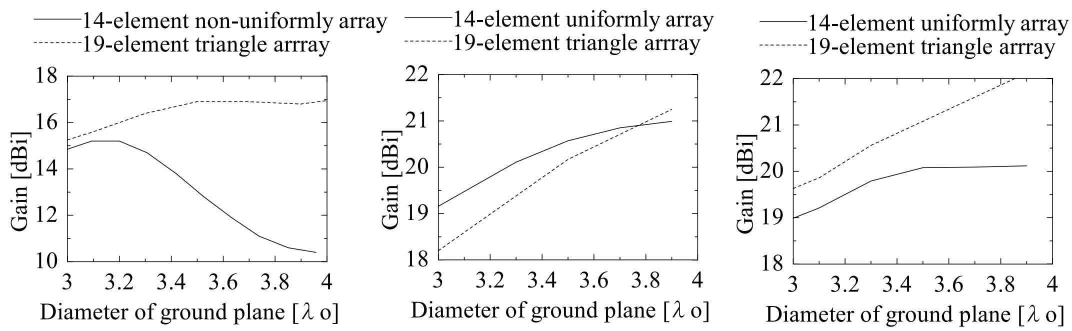
In this subsection, the gain characteristics of whole array configuration are described. The element number of the uniform array is set at 14, despite the result of 12 elements obtained in Sect. 3. The antenna gain of 14-element uniform arrangement shown in Fig. 7(d) is compared with the 19-element triangle arrangement shown in Fig. 1. In this case the diameter of the ground plane is varied from $3\lambda_\mathrm{o}$ to $4\lambda_\mathrm{o}$. It is noted that the element spacing increases as the ground plane size increases keeping the equations described in Sect. 2.

The gain characteristics of isotropic array are shown in Fig. 8(a). The gain of the 19-element triangle array increases until the diameter of the ground plane is $3.5\lambda_\mathrm{o}$, and the gain is almost saturated over $3.5\lambda_\mathrm{o}$. The gain of the 14-element uniform array decreases for ground plane diameters greater than $3.1\lambda_\mathrm{o}$. Comparing these gain characteristics, the triangle array with isotropic 19-elements is superior to the uniform array with 14-elements.

On the other hand, in the patch array, the gain of the 14-element uniform array is greater than the gain of the 19-element triangle array when the diameter of the ground plane is less than $3.7\lambda_\mathrm{o}$ as shown in Fig. 8(b). Particularly, the gain of the uniform array is approximately 1 dB higher for the $3\lambda_\mathrm{o}$ diameter than that of triangle array.

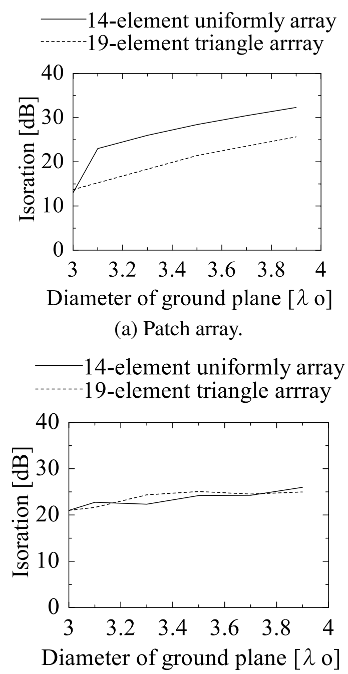
Figure 8(c) shows the gain characteristics of the helical array. In this case, the distinctive difference of the gain depending on the array configuration can not be observed, except the difference of the array elements number.

To clarify these gain characteristics, isolation between elements is calculated using the method of moments. Figure 9(a) shows the worst case of the isolation between elements of the patch array. The antenna parameters are the same as those of the results in Fig. 8. The isolation of the 14-element patch antenna is larger than that of the 19-element patch antenna. This is apparent since considering the array configuration shown in Fig. 10, the 19-element patch array



(a) Isotropic array case. (b) Patch array case. (c) Helical array case.

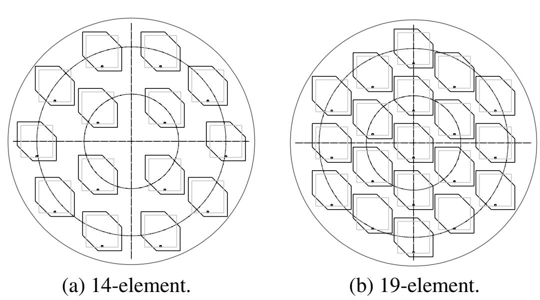
Fig. 8 Gain characteristics vs. ground plane.



(a) Patch array.

(b) Helical array.

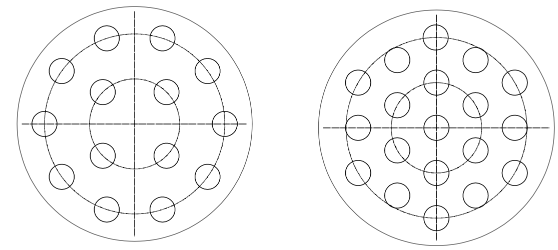
Fig. 9 Isolation between element antennas.



(a) 14-element. (b) 19-element.

Fig. 10 Patch array configurations.

suffers strong mutual coupling, which causes the gain reduction. Figure 9(b) also shows the worst case of the isolation between elements of the helical array case. In this case, the isolation of the 14-element helical array is almost the same as that of 19-element helical array. This means that the antenna gain is decided by the number of elements in array antenna, because the elements in the helical array case are arranged sparsely as shown in Fig. 11. Therefore, the gain of the 19-element array is higher than that of the 14-element array. These are the reasons why a higher gain is obtained with the 19-element helical array and with the 14-element patch array.



(a) 14-element. (b) 19-element.

Fig. 11 Helical array configurations.

As a result, it is found that the triangle arrangement is not necessarily acceptable to obtain a maximum gain for small-sized antenna arrays with only a few of elements, and that the antenna element greatly influence to the gain of the array antenna. Also, the element type affects the configuration of array and the number of elements.

3.5 Frequency Response of Gain and Axial Ratio

Frequency responses of the gain and axial ratio are compared between the uniform arrangement in Fig. 7(d) and the triangle arrangement in Fig. 1. In these considerations, the patch antenna is used as the element antenna. The diameter of the ground plane is fixed at $3\lambda_o$.

The frequency responses of the gain for the patch array are shown in Fig. 12. The trend of the gain response of the 14-element uniform array is similar to that of the 19-element triangle array. The difference of the gain depends on the number of elements.

The frequency responses of the axial ratio are shown in Fig. 13. Comparing the axial ratio of both array configurations, the axial ratio of the 19-element array is worse than that of the 14-element array because the mutual coupling in the 19-element array is stronger than that of the 14-element due to the element spacing of the 19-element array being smaller than that of the 14-element array. Therefore, for the axial ratio characteristics, the 14-element uniform array is superior to the 19-element triangle array.

3.6 Radiation Patterns

The radiation patterns of the 14-element uniform array are compared with those of the 19-element triangle array. Figure 14 shows the simulated radiation patterns in the planes, $\phi = 0^o$, $\phi = 45^o$ and $\phi = 90^o$, respectively. The frequency, f_o, is 1.6 GHz.

In these figures, the first sidelobe levels of the 14-element uniform array are approximately 4 dBi, while those of the 19-element triangle array are approximately −1 dBi.

The second sidelobe levels of the 14-element uniform array is −8 dBi at the worst, while that of the 19-element triangle array is −10 dBi at worst case. Considering the worst case of the sidelobe level, remarkable discrepancy can not be realized.

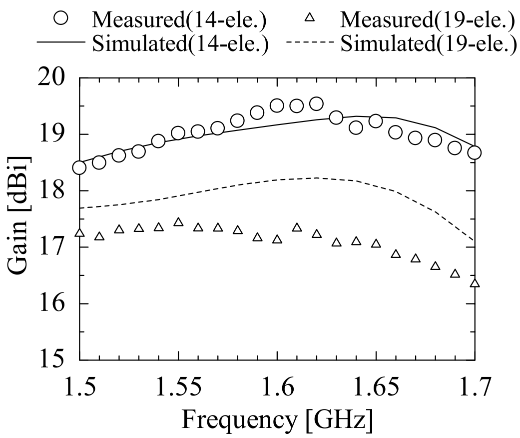


Fig. 12 Frequency responses of antenna gain.

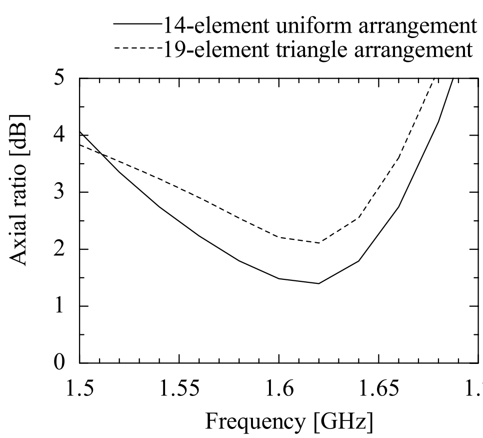


Fig. 13 Frequency responses of axial ratio.

4. Experimental Results

Based on the above investigations, the prototype antenna was fabricated and tested. The photograph of the fabricated antenna is shown in Fig. 15. The antenna parameters are slightly modified to improve the axial ratio shown in Fig. 13.

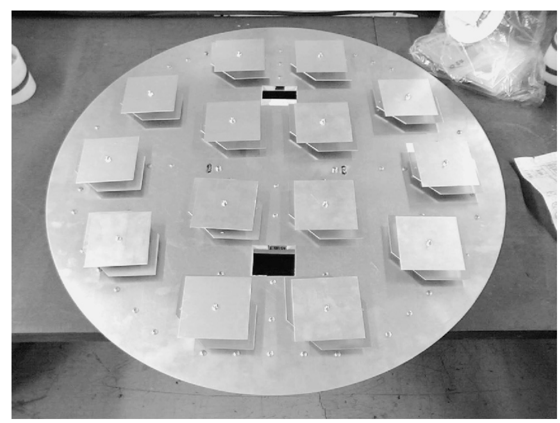
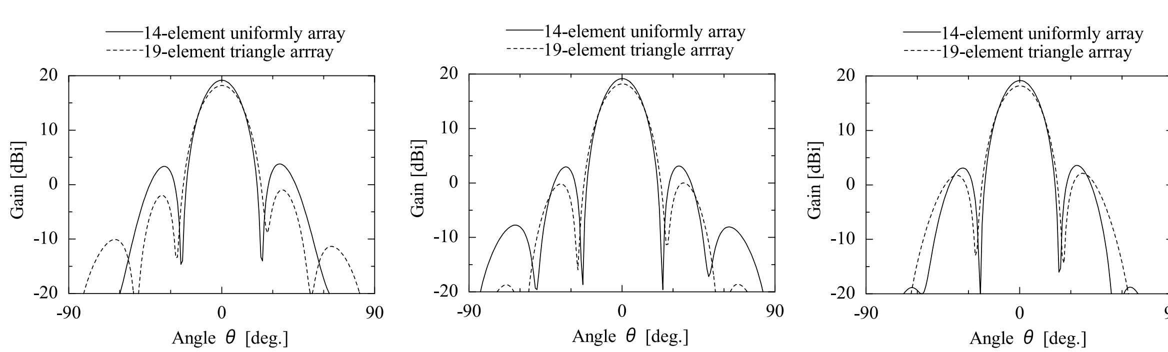


Fig. 15 Photograph of fabricated antenna.

Table 4 Fabricated array parameters.

The diameter of ground plane: Dg	3λo
The diameter of the effective antenna area: Dv	0.7λo
The diameter of the inner circle: Di	0.94λo
The diameter of the outer circle: Do	2.27λo
The Number of elements arranged on the inner circle: Ni	4
The Number of elements arranged on the inner circle: No	10

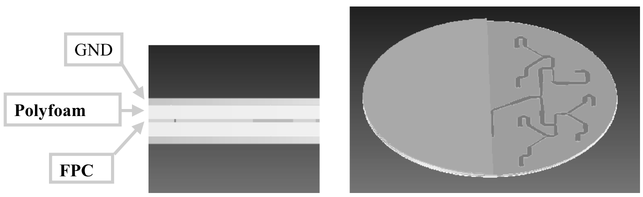


(a) $\phi = 0$ deg. plane. (b) $\phi = 45$ deg. plane. (c) $\phi = 90$ deg. plane.

Fig. 14 Simulated radiation patterns. Element number: $N_i = 4$, $N_o = 10$.

The detailed parameters are listed in the Table 4.

Figure 17(a) shows the measured VSWR of the fabricated antenna. Because the antenna is an array antenna, VSWR is measured at the input port (feed point) of the array. The feed network of the array is shown in Fig. 16. In this case, each element is excited by equal amplitude and cophase. The frequency response is nearly flat and the VSWR less than 2 is within the range from 1.5 GHz to 1.667 GHz. This VSWR value corresponds to approximately 0.5 dB loss of the antenna gain.

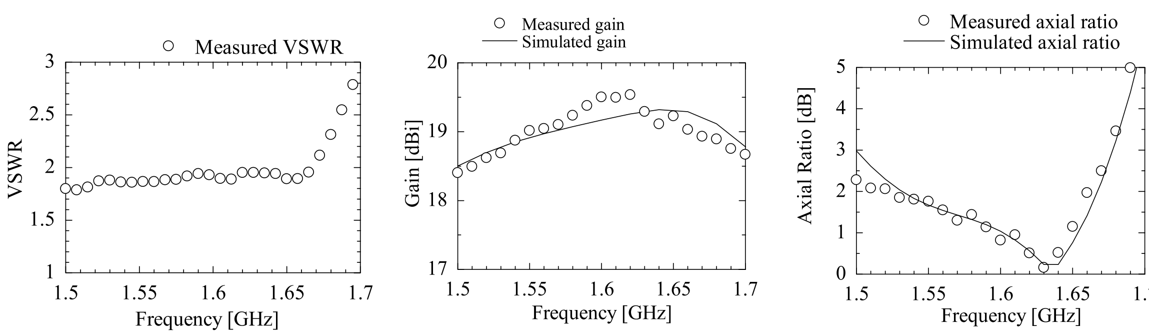


(a) Side view. (b) Perspective view.

Fig. 16 Fabricated feed network.

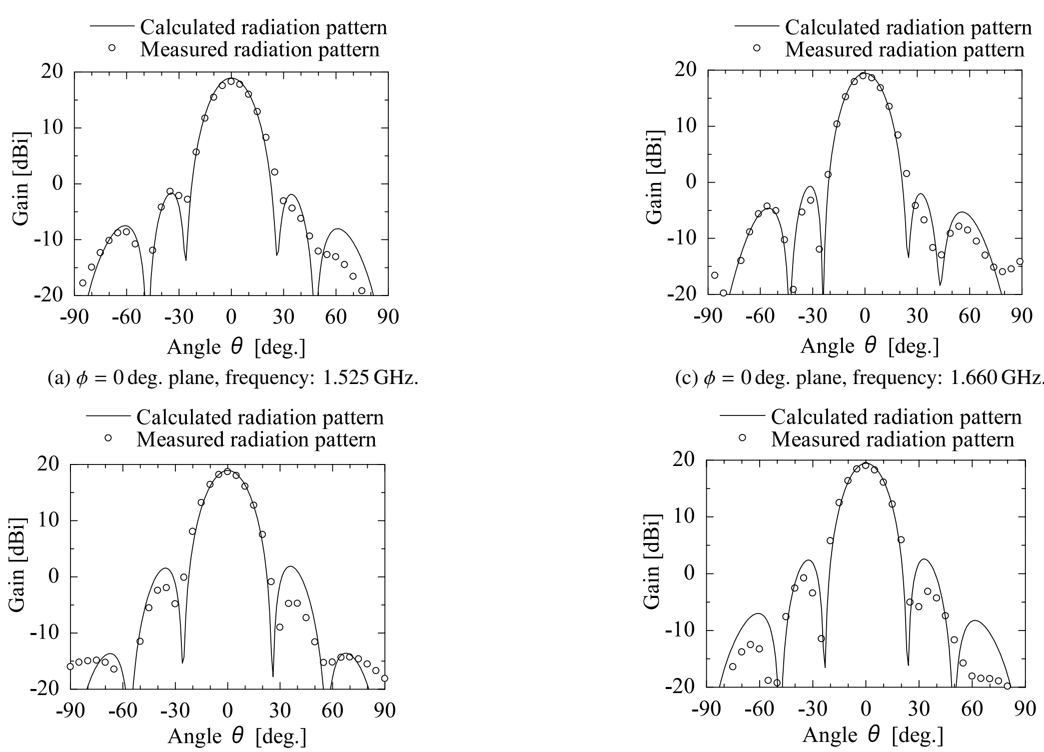
In Fig. 17(b), plotted points show the measured antenna gain and the solid line shows the simulated antenna gain. The measured gain is compensated with the loss due to the mismatch in addition to the feeding network loss. The measured gain is almost same as the simulated gain, except some ripples in the measured data. The measured gain at f_o = 1.6 GHz is 19.5 dBi.

In Fig. 17(c), plotted points show the measured axial ratio and the solid line shows the simulated axial ratio. The measured data coincide with the simulated one. The mea-



(a) VSWR. (b) Antenna gain. (c) Axial ratio.

Fig. 17 Frequency responses of fabricated antenna.



(a) ϕ = 0 deg. plane, frequency: 1.525 GHz. (c) ϕ = 0 deg. plane, frequency: 1.660 GHz.
(b) ϕ = 45 deg. plane, frequency: 1.525 GHz. (d) ϕ = 45 deg. plane, frequency: 1.660 GHz.

Fig. 18 Calculated and measured radiation patterns.

sured axial ratio less than 2 dB is obtained over a 8.8% bandwidth.

The measured radiation patterns are shown in Fig. 18 and compared with those of the simulated ones. In Fig. 18(a) and (b), the radiation patterns are measured at 1.525 GHz and Fig. 18(c) and (d) at 1.66 GHz. The measured radiation patterns are in good agreement with the calculated radiation patterns.

5. Conclusion

An antenna with small sized array configurations of $3\lambda_o$ diameter was investigated. Uniform arrangement with identical spacing of each element on two concentric circles is proposed. The effect of the element numbers and the element type were examined for the antenna gain characteristics. The method of moments is employed for the simulation.

The 14-element uniform arrangement patch array antenna is fabricated and tested to confirm the calculated results. Good agreement between the calculated data and measured one are seen.

As a result, it is found that the triangle arrangement is not necessarily applicable to obtain maximum gain for a small sized array antenna with only a few element. Also, it is found that the antenna element type has a large influence on the number of elements and the configuration of the array antennas.

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