Experimental Study of Ninja Array Antenna Composed of Yagi-Uda Antennas

Keisuke Konno[1a)], Kohei Morita[2], Qiang Chen[1] and Qiaowei Yuan[3]

[1] *Department of Communications Engineering, Graduate School of Engineering, Tohoku University*
6-6-05, Aramaki Aza Aoba Aoba-ku Sendai-Shi Miyagi 980-8579, Japan
[2] *KDDI Corporation*
Garden Air Tower, 3-10-10, Iidabashi, Chiyoda-ku, Tokyo 102-8460, Japan
[3] *Sendai National College of Technology*
4-16-1, Ayashichuuou Aoba-ku Sendai-Shi Miyagi 989-3128, Japan

a) *konno@ecei.tohoku.ac.jp*

Abstract: Performance of a Ninja array antenna whose backscattering level is lower than that of conventional phased array antennas is demonstrated experimentally. A linear array antenna which is composed of non-identical Yagi-Uda monopole antenna elements is designed. Designed array is fabricated and its scattering/radiation performance is measured. The fabricated array shows low backscattering performance without losing its beam scanning capability.

Keywords: Ninja array antenna, phased array antenna, reflectarray
Classification: Antennas and propagation

References

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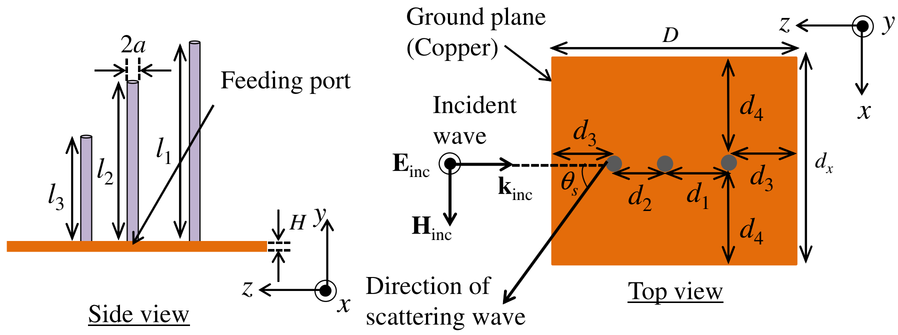
1 Introduction

Phased array antennas have been used for various applications, such as radar, communications, and microwave imaging [1]. The phased array antennas are often designed as periodic structures with identical elements and resultant backscattering level is high. High level of backscattering wave may result in interference problems to other electronic devices and should be suppressed as much as possible.

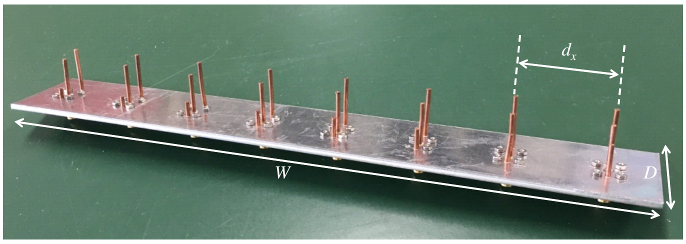
Various approaches have been proposed to reduce the backscattering of the phased array antennas. One of the effective approaches is to enclose or cover the phased array antennas using scatterers. So-called metasurface has been applied to reduce radar cross section (RCS) of the phased array antennas. Low RCS phased array antennas with metasurfaces have been proposed and their scattering/radiation performance have been demonstrated numerically and experimentally[2]-[4]. All of these metasurfaces have been designed so that their scattering field cancels out the scattering field of array antennas and ground planes. Although previous studies have focused not only on in-band RCS reduction but also on radiation performance, beam scanning capability of array antennas has not been discussed. One of the disadvantages of array antennas with metasurfaces is their complicated structure because metasurfaces must be mounted on array antennas as extra scatterers.

Recently, our group has proposed a low backscattering phased array antenna named as a Ninja array antenna [5], [6], where Ninja is a traditional covert agent who works stealthily in Japan. The Ninja array antenna is a low backscattering phased array antenna which is composed of non-identical elements. Although proposed Ninja array antennas are composed of dipole type elements, any kind of elements such as patch, loop and slot can be used as a non-identical array element. Owing to well-designed non-identical elements, scattering wave of the Ninja array antenna can be directed to non-specular direction. As a result, level of backscattering wave of the Ninja array antenna becomes low over its operating frequency band. One of the major advantages of the Ninja array antenna over array antennas with metasurfaces is its simple geometry because the Ninja array antenna has no extra scatterers. The other advantage is a degree of freedom on design of its scattering pattern while conventional metasurfaces mounted on array antennas have been designed so that their scattering field simply cancels out each other. Excitation method for each non-identical element which is based on an array element pattern has been presented. Numerical simulation was performed in order to demonstrate scattering performance and beam scanning capability of the Ninja array antenna. On the other hand, performance of the Ninja array antenna has not been demonstrated experimentally.

In this letter, low backscattering performance and beam scanning capability of a Ninja array antenna are demonstrated experimentally. A linear Ninja array antenna which is composed of non-identical Yagi-Uda monopole antenna elements is designed using method of moments (MoM) and is fabricated. Scattering/radiation pattern of the fabricated Ninja array antenna



(a) Geometry of a Yagi-Uda monopole antenna element with a finite ground plane.



(b) Fabricated prototype of a linear Ninja array antenna with eight Yagi-Uda monopole antenna elements.

Fig. 1. A Yagi-Uda antenna element and the fabricated prototype of Ninja array antenna.

are measured. It is clarified that the fabricated Ninja array antenna shows low backscattering performance without losing its beam scanning capability.

2 Design of the Ninja Array Antenna

A Yagi-Uda antenna element is used as an array element for a Ninja array antenna in this letter because scattering/radiation performance of the Ninja array antenna with the Yagi-Uda antenna element has been demonstrated numerically in our previous work [5]. Instead of a dipole-type Yagi-Uda antenna element used in reference [5], a monopole-type Yagi-Uda antenna element with a finite ground plane is used in this letter because no balanced to unbalanced transformer is necessary during measurement.

Geometry of a Yagi-Uda monopole antenna element with a finite ground plane is shown in Fig. 1(a). A feeding port is terminated with 50 Ω resistance during numerical simulation because the Ninja array antennas are not passive scatterers and work as phased array antennas. Operating frequency is f =4 GHz and a Ninja antenna is designed so that its scattering field is directed to $(\theta, \phi) = (\theta_s, \phi_s)$. A specific value $(\theta_s, \phi_s) = (20°, 0)$ is given here for design of an example of a Ninja array antenna. Dimensions of the Yagi-Uda monopole antenna element except for length of a director element (=l_3) are designed in advance of the numerical simulation; $l_1 = 23$ mm, $l_2 = 19$ mm, $a = 0.5$ mm, $H = 0.3$ mm, $d_1 = 10$ mm, $d_2 = 5$ mm, $d_3 = 15$ mm, $d_4 = 19$ mm, $d_x = 38$

mm, and $D = 45$ mm. The Yagi-Uda monopole element was illuminated by plane wave of normal incidence and phase of scattering field to (θ_s, ϕ_s) was obtained as a function of l_3. As a result of numerical simulation, linear phase variation over 250° was obtained when l_3 is from 5 mm to 19 mm.

Based on simulated phase of scattering field, a linear Ninja array antenna with eight Yagi-Uda antenna elements was designed and fabricated. Fabricated prototype of the linear Ninja array antenna is shown in Fig. 1(b). It should be noted that length of the director ($= l_3$) is non-identical for each array element in order to control phase of scattering field. Here, as an example, a director whose length is 5 mm is given to the leftmost antenna element shown in Fig. 1(b) and a Ninja array antenna is designed. For all the other antenna elements, length of their directors is given so that their scattering field is in-phase at (θ_s, ϕ_s). Starting from left side on Fig. 1(b), length of a director l_3 for each element is 5, 10, 14, 16, 19, 5, 7, and 10 mm. Array spacing is $d_x = 38$ mm ($= 0.507\lambda$@4 GHz), the size of the metallic ground plane is $W \times D = 304 \times 45$ mm^2. Interested readers can refer [5] for details of design which is omitted here.

3 Measurement Results

3.1 Scattering Performance

The bistatic radar cross section (BRCS) pattern of the fabricated linear Ninja array antenna was measured in our radio anechoic chamber. Double-ridged wave-guide horn antennas (Schwarzbeck BBHA9120D) were used as transmitting/receiving antennas. Spacing between transmitting antenna and an antenna under study (AUT) was 0.7 m while that between receiving antenna and the AUT was 2.4 m. Although the spacings were the maximum, it should be noted that the AUT was not in far-field region of the transmitting/receiving antenna during measurement due to the limitation of our measurement system. All the central elements were terminated with 50 Ω resistances during measurement.

Measured BRCS pattern of the fabricated Ninja array antenna is shown in Fig. 2(a). As a reference, simulated/measured BRCS patterns of the fabricated Yagi-Uda array antenna with identical elements ($l_3 = 15$ mm) are also shown. Its dimensions except for l_3 are the same with those described in previous section. It is found that the measured and simulated BRCS of the designed Ninja array antenna show a good agreement. Mainbeam of the designed Ninja array antenna is directed to $(\theta, \phi) = (\theta_s, \phi_s)$, not specular direction. As a result, level of backscattering wave of the fabricated Ninja array antenna is 7.3 dB lower than a Yagi-Uda array antenna with identical elements. On the other hand, measured backscattering cross section (BSCS) versus frequency is shown in Fig. 2(b). Here, 3 dB bandwidth of BSCS is defined as follows.

$$3\,\mathrm{dB\,bandwidth} = \frac{f_2 - f_1}{f_2 + f_1} \times 200 \quad [\%]. \tag{1}$$

f_1 and f_2 are the minimum/maximum frequency where BSCS of the fabricated Ninja array antenna is 3 dB lower than that of the fabricated Yagi-Uda array antenna, respectively. It is found that 3 dB bandwidth of the BSCS of the fabricated Ninja array antenna is over 61 % because $f_1 = 3.7$ GHz and $f_2 > 7$ GHz. According to these measured results, low backscattering performance of the designed Ninja array antenna is demonstrated experimentally. Difference between measured and simulated BSCS/BRCS comes from fabrication/measurement error and the effect of near-field.

3.2 Radiation Performance

Radiation performance of the fabricated Ninja array antenna was obtained via measured its array element pattern in xz plane. Antenna gain pattern of the Ninja array antenna is obtained as a weighted sum of the array element patterns. In our previous work [5], a weight obtained using the array element patterns has been proposed for beam scanning of the Ninja array antenna. On the other hand, our previous work has also demonstrated that an array factor can be used approximately as weight for beam scanning of the Ninja array antenna composed of Yagi-Uda antennas [5]. For simplicity, the array factor is used as weight of the array element patterns.

Antenna gain patterns of the fabricated Ninja array antenna is shown in Fig. 2(c). For measured results, antenna gain patterns of the Ninja array antenna is obtained as a weighted sum of the measured array element patterns multiplying by the array factor. For simulated results, antenna gain patterns are directly obtained via full-wave simulation of the Ninja array antenna whose excitation is given by the array factor. It is found that measured and simulated antenna gain patterns are in good agreement. Difference between measured and simulated antenna gain patterns comes from fabrication/measurement error and the effect of near-field.

4 Conclusion

In this letter, scattering/radiation performance of Ninja array antennas have been demonstrated experimentally. The Ninja array antennas are composed of non-identical Yagi-Uda monopole antenna elements. A linear Ninja array antenna with eight Yagi-Uda monopole antenna elements was fabricated. Scattering performance of the fabricated Ninja array antenna was measured and its low backscattering performance has been demonstrated experimentally. Antenna gain patterns of the fabricated Ninja array antenna were obtained via measured array element patterns. Beam scanning capability of the fabricated Ninja array antenna has been demonstrated.

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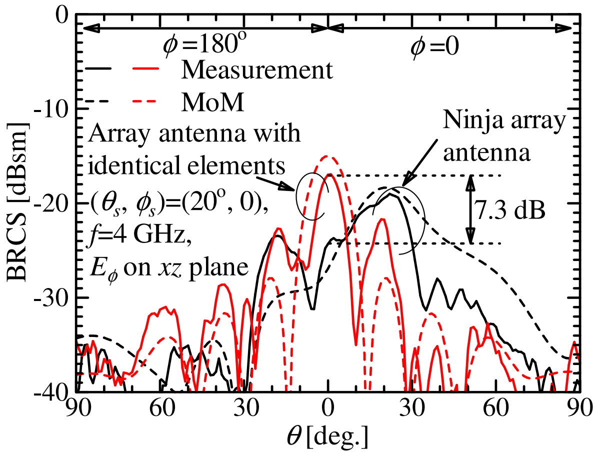
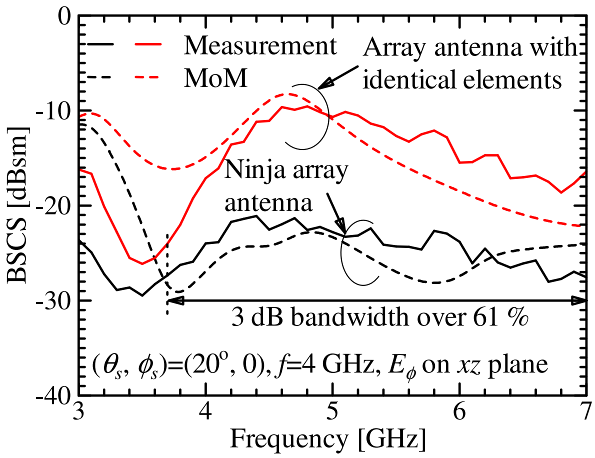
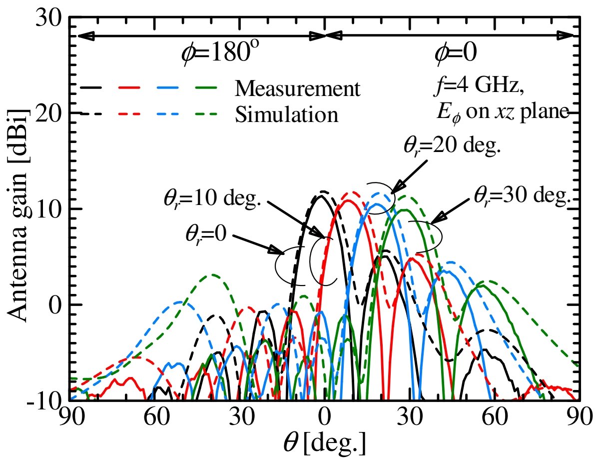


(a) BRCS patterns.



(b) BSCS versus frequency.



(c) Antenna gain patterns ($\theta = \theta_r$ is a main beam direction.).

Fig. 2. Simulated and measured performance of the designed/fabricated Ninja array antenna with Yagi-Uda monopole antenna elements.