# On the Gain of an Aperture Array Antenna with Gaps Filled by Parasites

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**Abstract**

Ultra-large antennas with a diameter of several 100 m or even 1 km are required for several applications such as microwave power transmission. The array antenna with element apertures is one of the promising concepts to construct an ultra-large aperture. In the configuration of an aperture array antenna, parasitic elements of half wavelength dipoles were proposed to be loaded between two apertures. Its objective is to fill the gaps, and to adjust the phase relation between the directly radiated wave from the element apertures and the scattered wave by the dipoles. But the subsequent research in association with experiments revealed that metallic dipoles can not increase the gain of the aperture array antenna. In this paper, the subsequent research results and the way to improve the characteristics of the aperture array antenna will be shown through theoretical analysis, simulation and experiment.

# 寄生素子による隙間埋め開口面アレーアンテナの利得について

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## 1. Introduction

Ultra-large antennas with a diameter of several 100 m or even 1 km are required for microwave power transmission aboard a solar power satellite [1][2]. The array antenna with element apertures, as illustrated in Fig.1, is one of the promising concepts to construct an ultra-large aperture [3]. This concept could be extended to the diameter of 1100 m which is equivalent in the aperture area to a parabola with 1000 m diameter. A constituent small aperture has a diameter of about 10 m. The outline of the element aperture is a hexagonal in order to bury the total aperture most densely [7].

This type of an antenna has several advantages over the equivalent single parabola. First, the radiation beam can be scanned due to phase control between the element apertures. Secondly, as the antenna is composed of independent element apertures, the transportation to an orbit and the tests in the assembly process are easier. Thirdly, the thickness of the antenna is modest value, typically 3 m, so that the effect to a satellite attitude control may be smaller than the case of a single parabola, 300 m thickness. The antenna has also a significant advantage over an array of dipole elements that the element number is $10^4$ instead of $2 \times 10^8$. Accordingly, the feeding circuits are much simplified, and the antenna can greatly contribute to the reduction of a system cost.

For the tolerance against thermal expansion or manufacturing margin, the element apertures should have mechanical gaps between the adjacent element apertures. However, the gaps cause the growth of grating lobes and the reduction of antenna gain. In order to fill the gaps, it was proposed to load parasitic elements of half wavelength dipoles between two horn apertures, and to adjust the phase relation between the directly radiated wave from the element apertures and the scattered wave by the parasitic elements through changing the height of the dipole [4]. The experiment results concluded that the gain of the array antenna with two apertures could be increased by adding parasitic elements between the apertures. Therefore, the mechanical and electrical gap between apertures is expected to be filled.

But the increase of the antenna gain is smaller than the expected value. The reason of the discrepancy is thought to be that the phase of the incident wave to the parasitic elements could not be kept constant due to spherical wavefront as the apertures were horns. It was also concluded that the scattering characteristics of parasitic elements of half wavelength dipoles loaded between two apertures should be clarified from the viewpoint of phase as well as amplitude in relation to the radiated field from the apertures. The objective of this paper is to describe the subsequent research results of the aperture array antenna using parabolic reflectors instead of horns. The characteristics of the array antenna will be clarified through theoretical analysis, simulation and experiment. The frequency is assumed to be 2.33 GHz.

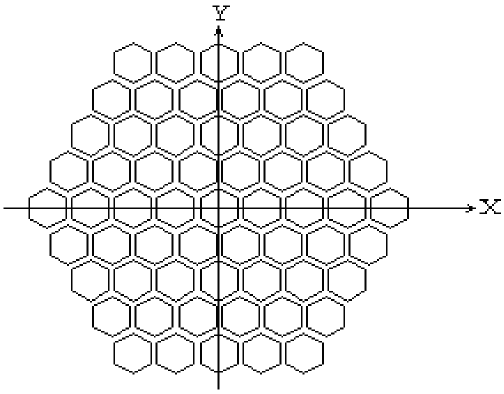



Fig. 1: Configuration of an array antenna with element apertures

The outline of this paper is arranged as follows: first, the configuration of an array antenna with parabolic reflectors and parasitic elements is introduced. Next, the radiated field from parasitic elements of half wavelength dipoles which are partly excited by the incident wave from two apertures should be solved. Pocklington's integrodifferential equation is mathematically modified to show that the incident wave is equivalent to voltage sources in infinitesimal gaps along the excited area [5]. As a result, the problem of a partly excited element can be solved with a simulator. The phase dependency on the dipole length is also clarified. Finally, we describe an experiment using metallic parasitic elements which inherently can not increase the antenna gain [6]. The objective to verify the analysis method and the simulation result was well accomplished.

## 2. Model of an Aperture Array Antenna with Parasitic Elements

### 2.1 Configuration of the Antenna

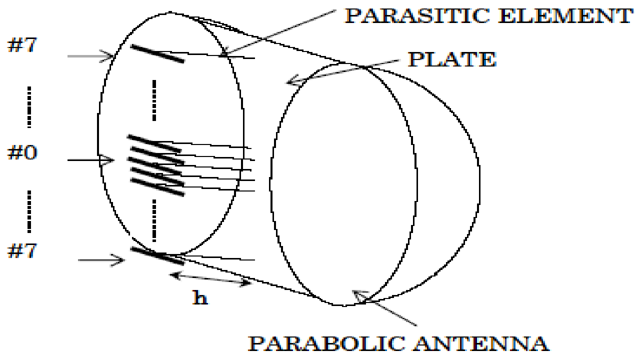



Fig. 2: Parasitic elements between two apertures

In order to study the gap filling by parasitic elements through experiment and analysis, we adopted a simplified aperture array antenna as shown in Fig.2. The antenna is composed of two familiar parabolic reflectors for the reception of satellite broadcasting and specially designed primary radiators. Parasitic elements of dipoles are installed between the apertures to be illuminated by the radiated field from the apertures. It is important to adjust the phase relation between the directly radiated wave from the apertures and the scattered wave by the parasitic elements.

## 2.2 Components of the Radiated Field

A parabolic reflector converts a spherical wave from a primary radiator to a plane wave which propagates perpendicularly to its aperture. As parasitic elements are installed in the manner to bridge two reflectors, both tips of parasitic elements are illuminated by the plane wave, and the remaining part of the element is not illuminated. As a result, the plane wave is scattered or reradiated into space.

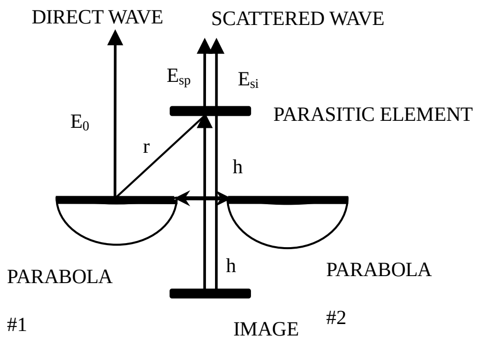



Fig. 3: Components of radiated field

The radiation in the far field is composed of the following components as shown in Fig.3.

(1) Diffracted wave originated by the plane wave from a parabola ( $E_0$ ),
(2) Re-transmitted wave from parasitic elements ( $\dot{E}_{sp}$ ),
(3) The wave coming from the images of the parasitic elements ( $\dot{E}_{si}$ ).

## 3. Scattering Characteristics of a Dipole Illuminated on Both Ends

### 3.1 Modification of Pocklington's Integrodifferential Equation and a Simulation Softwar

Let us consider one parasitic element shown in Fig.4. At the initial state, both tips of a parasitic element are illuminated by the electric field $E_0$(x) which is well approximated by rectangles. Being excited by $E_0$(x), the current I(x) is expected to flow on the element. This phenomenon is analyzed using the method of moment (MOM).

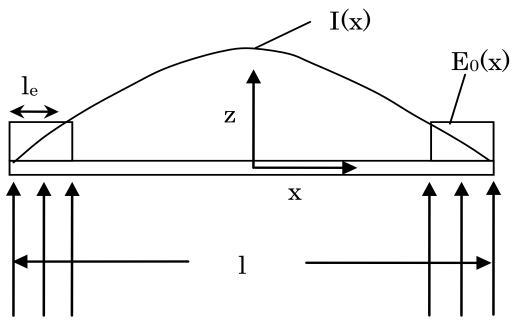



Fig.4: A parasitic element partly excited by incident wave

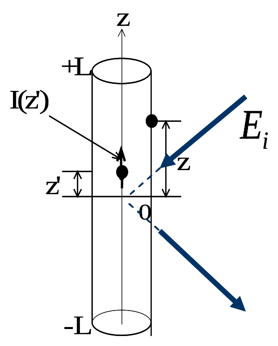



Fig.5: Pocklington's model

As shown in Fig.5, let us consider a part of the illuminated tip with a length of $\Delta z$ . We assume that a parasitic element is a very thin metal rod. The equation that explains the relation between the incident wave and the current on the surface of a parasitic element is given as follows[8] :

$$\int_{\Delta z} I_z(z') * [\frac{\partial^2}{\partial z^2} + k^2] G(z,z') dz' = -j\omega\varepsilon E_{iz} \tag{1}$$

where $I_z$ : induced current in parasitic element, $\Delta z$ : the region excited by a plane wave (excitation area) in this case from –L to +L, G( $z$ , $z'$ ): Green function, $E_{iz}$ : the electric field of an incident wave in z-component (electric field tangent to a parasitic element).

Equation (1), can be solved by the method of moment. The term $I_z(z')$ is expanded as follows :

$$I_z(z') = \sum_{n=1}^{N} a_n B_n(z') \tag{2}$$

where $a_n$ : unknown value, $B_n(z')$ : basis function.

Using weighting function $W_m(z)$ , $a_n$ ( n=1,2,...,N) are obtained in matrix form as follows :

$$[b_{nm}][a_n] = [C_m] \tag{3}$$

where $b_{nm} = \iint_{\Delta z} B_n(z') W_m(z) (\frac{\partial^2}{\partial z^2} + k^2) G(z,z') dz dz'$ ; n=1,2,…,N; m=1,2,…,N, (4)

$$C_m = -4j\pi\omega\varepsilon \int_{\Delta z} W_m(z) E_{iz} dz \text{ ; m=1,2,…,N.} \tag{5}$$

However, it is necessary to modify Pocklington's integrodifferential equation in order to apply a simulator software to the phenomena that a parasite is partly excited by an incident wave.

### 3.2 The Equivalence of an Incident Wave and a Voltage Source in an Infinitesimal Gap

In Eq.(6), $E_{iz}$ is constant. If we select the value of $\Delta z$ sufficiently small, $W_m(z)$ is also constant. Therefore we obtain, :

$$C_m = -4j\pi\omega\varepsilon W_m(z_0)E_{iz}\Delta z\,. \tag{6}$$

By the way, if a voltage source in the infinitesimal gap inside $\Delta z$ is assumed, $E_{iz}$ in the right side of Eq.(1) should be replaced with $-j\omega\varepsilon V_0\delta(z)$ so that

$$C_m = -4j\pi\omega\varepsilon\int_{\Delta z} W_m(z)V_0\delta(z)dz\,. \tag{7}$$

Due to the definitions of the delta function,

$$C_m = -4j\pi\omega\varepsilon V_0 W_m(z_0) \tag{8}$$

From equation (6) and (8), we can conclude their equivalence as follows :

$$V_0 = E_{iz}\Delta z\,. \tag{9}$$

This equation is physically represented as Fig.6. As one can substitute the incident wave by a voltage source, a simulation software with a voltage source and an infinitesimal gap can be applied to simulate a parasite partly excited by the incident wave. Accordingly, Eq.(3) can be solved to obtain the current distribution expressed by Eq.(2) on the parasite.

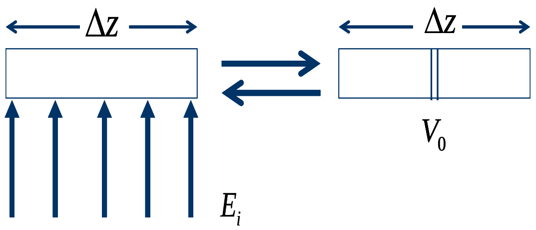



Fig.6: The equivalence of incident wave and voltage source in infinitesimal gap inside $\Delta z$

### 3.3 Radiation Pattern of Partly Excited Parasitic Elements

Based on the current distribution on parasitic elements, we can calculate radiation patters by the MMANA-GAL software. The length and height of a parasite is a half wavelength and a quarter wavelength, respectively. The value of $\Delta z$ is 6mm. The obtained pattern is shown in Fig.7, which has the same shape as the pattern of a dipole in free space.

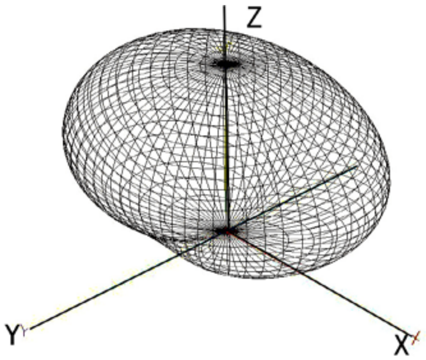



Fig.7: Radiation pattern in case quarter wavelength above PEC

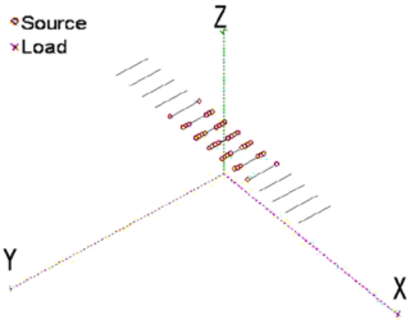



Fig.8: Simulation model of array of partly excited parasitic elements located quarter wavelength above PEC

Next, we will calculate the radiation pattern from the dipole array shown in Fig.8. In this model, there are 15 parasitic elements, but only the elements #0, #1, #2, and #3 are partly excited by the incident wave from the parabola antennas. The distance between the adjacent elements is a quarter wavelength.

The method of simulation is as follows: first the element #0 is simulated, and the radiation pattern is obtained as Fig.7. Next, the element #1 in the +x side, is simulated to obtain its radiation pattern. The same step is repeated the end of until the end of the elements number. And all radiation patterns are superimposed.

As the number of parasitic elements increases, the radiation beam becomes narrower and the gain is higher than the case of a single parasite shown in Fig.7. Fig.9, indicates that the gain is constant for the number of parasitic elements larger than 5. Fig.10 shows the result of radiation pattern for the case of 15 elements.

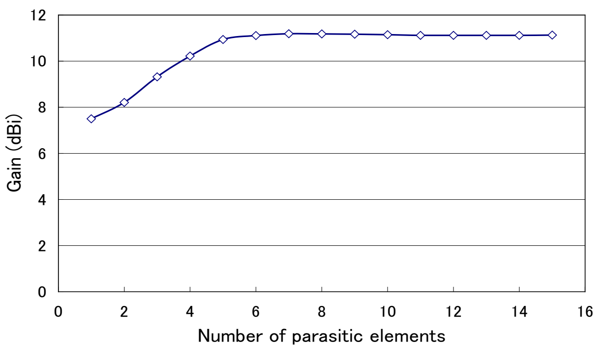



Fig.9: Maximum gain versus number of parasitic elements

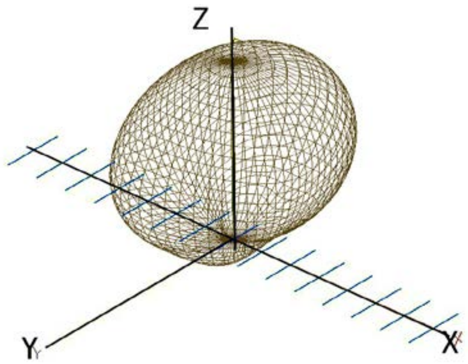



Fig.10: Radiation pattern of 15 partly excited parasitic elements located quarter wavelength above PEC

## 4. Expression of the Radiation from the Array Antenna

### 4.1 Vectorial Relation of the Field Components

Let us express the total radiated field $E_t \exp(j\phi_t)$ in a complex form taking account of three components as follows :

$$E_t \exp(j\phi_t) = E_0 + E_{sp} \exp(j\phi_{sp}) + E_{si} \exp(j\phi_{si}) \quad (11)$$

where all "E" and "$\phi$" are real, and all "E" are of plus sign.

We assume $E_{sp}$ and $E_{si}$ to be an equal amplitude for simplicity. In order to satisfy the boundary condition on the reflecting plate, we obtain.

$$\phi_{sp} = \phi_s \quad (12)$$

$$\phi_{si} = \phi_{sp} + \pi + 2kh \quad (13)$$

where $\phi_s$ is the phase change due to scattering by the parasitic element.

Therefore, the amplitude of the total field $E_t$ is presented in Fig.11(a). As the phase angle $\phi_s$ moves from 0 to 2 $\pi$, the two significant cases are given by

$$Max : E_t^2 = (E_0 + 2E_{sp})^2, \text{ when } \phi_s = 0 \text{ and } h = \lambda / 4 \quad (14)$$

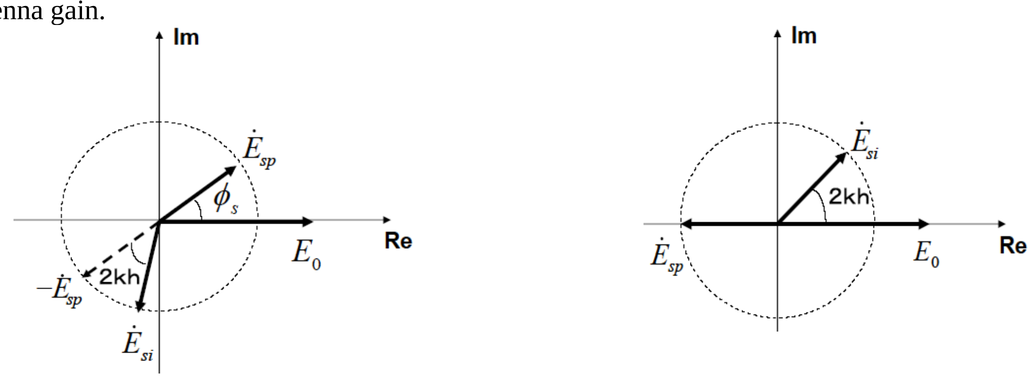
$$Min : E_t^2 = (E_0 - 2E_{sp})^2, \text{ when } \phi_s = \pi \text{ and } h = \lambda / 4 \quad (15)$$

The $\phi_s$ is determined by the phase shift from the incident electric field $E_0$ onto a parasitic element to the scattered electric field $E_{sp}$ in order to satisfy the boundary condition on the element. In the case of a metallic parasitic element, therefore, $\phi_s = \pi$. Two significant configurations are seen from Fig.11(b) as follows :

$$Max : E_t^2 = (E_0)^2, \text{ when } h = \lambda / 2 \quad (16)$$

$$Min : E_t^2 = (E_0 - 2E_{sp})^2, \text{ when } h = \lambda / 4 \quad (17)$$

Accordingly, it is apparent from that metallic parasitic element is not preferred to incredse the antenna gain.




(a) General parasitic element (b) Metallic parasitic element

Fig.11: Vectorial relation of each component contribution

### 4.2 Antenna Gain

The relation between $E_0$ and $E_{sp}$ will be formulated. First, if the electric field $e_{ap}(r_p)$ is given at a point $r_{ap}$ on a parabola, the direct wave $E_0$ from two parabolas at the distance $r$ is calculated by

$$E_0 = 2\sqrt{G_{ap}\frac{\int_0^{r_{pm}} \pi r_p e_{ap}^2 dr_p / \xi}{4\pi r^2}\cdot \xi} = \sqrt{2G_{ap}}\frac{r_{pm}}{r}E_{apa} \tag{18}$$

where $r_{pm}$ is the radius of the parabola aperture, $\xi$ is the free space impedance and $G_{ap}$ is the antenna gain of an aperture.

Then, we will deduce the expression of $E_{sp}$ in terms of the edge level $\mathrm{E}_{ape} = e_{ap}(r_{pm})$. The maximum current on a dipole excited by a voltage source of 1 V at the center and a dipole excited by a plane wave of 1 V/m on the both ends are calculated to be $7.3\times10^{-3}$ A and $2.7\times10^{-4}$ A, respectively. When the dipole is illuminated by the incident electric field of $E_{ape}$ at the both ends, the equivalent $V_e$ of a voltage source at the dipole center is expressed by

$$V_e = \frac{1}{E_{ape}} \times \frac{2.7\times10^{-4}}{1} \times \frac{1}{7.3\times10^{-3}} \tag{19}$$

Therefore, the scattered field $E_{sp}$ is calculated through the equivalent power $|V_e|^2 / R_{in}$ fed to the center driven dipole and its gain $G_{dip}$ as follows ;

$$E_{sp} = \sqrt{G_{dip}\cdot\frac{|V_e|^2}{R_{in}}\cdot\frac{1}{4\pi r^2}\cdot\xi} \tag{20}$$

where $R_{in}$ is the input impedance of the equivalent dipole.

The gain increase $\Delta G$ after the dipole insertion in the aperture gap is obtained as follows:

$$\Delta G = \left(\frac{E_0 + 2E_{sp}}{E_0}\right)^2 \fallingdotseq 1 + 4E_{sp}/E_0 \tag{21}$$

## 5. Experimental Verification

We constructed an experimental model as shown in Fig.12. Two parabolic reflectors are diverted from receiving terminals of satellite broadcast service. The diameter is 450 mm each. They are fixed with the minimum gap of 10 mm between the rims. A plate of aluminum is placed between the rims as a reflection plate to parasitic elements. The element apertures are fed from a microwave source though a power divider and a phase shifter to realize co-phase condition. The electric field in the aperture is parallel to the connecting line of two parabola centers. Frequency is 2.33 GHz so that a wavelength is 129.2 mm.

The parasitic element is a thick wire of 2mm diameter and 64.6 mm length (a half wavelength). We prepared 15 elements. Each element is kept at a desired height from the reflection plate. The elements are arrayed on the reflection plate with the separation of 32.3 mm, a quarter wavelengths with an orientation in parallel to the electric field in the apertures. For convenience, the parasitic elements are numbered 1 at the center, and ± n where + sign corresponds to +x direction.

In the first experiment, the aperture array antenna with a reflecting plate and without parasitic elements was measured. The antenna gain is 20.9 dBi which is equivalent to 44.3 % aperture efficiency. This configuration is taken as the reference to show the improvement due to the subsequent means.

In the second experiment, the parasitic elements were installed, whose heights were changed with the same value. The result is shown in Fig.18 where the ordinate presents the gain increase from the reference gain obtained in the first experiment. We can see periodic variation with about 60 mm period, a half wavelength. The maximum gain is obtained at 70 mm height, and the value is +0.24 dB, almost the same value as the reference configuration, as is indicated by equation (16). At h = 32 mm, a quarter wavelength, the gain is at the minimum, as is indicated by equation (17), and of the value is -0.6 dB. Therefore, $E_{sp}$ in equation (17) is obtained to be $0.032\,E_0$. The maximum gain is 21.1 dBi which is equivalent to 46.2 % aperture efficiency.

Fig.12: Array antenna element apertures with partly excited parasitic elements

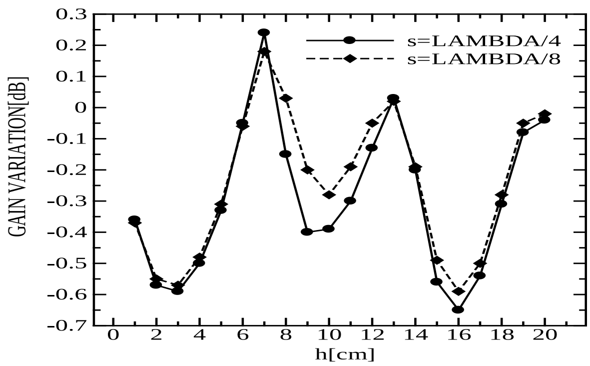



Fig.13: Gain versus parasitic elements height

In the present case, the field distribution is approximated by a Gaussian function with a edge level of -10 dB. Therefore, the following result is obtained:

$$E_{sp} / E_{ape} = 0.069 \qquad (22)$$

This value is correspondent to the value of $E_{sp}$ which is deduced from Fig.13.

## 6. Conclusions

The array antenna of element parabolas with partly excited parasitic elements has been investigated using theoretical, simulation, and experimental methods. The following results are obtained in this paper :

(1) The radiated field is composed of the direct wave from parabolas, the scattered wave from parasitic elements, and the radiated wave from the images of parasitic elements.

(2) Considering boundary conditions on a reflecting plate and a parasitic element, the total radiated field is formulated with the phase shift due to scattering and the separation h between a parasite and a reflecting plate.

(3) In the case of a metallic parasite, the total radiated field can not be larger than the original field from parabolas.

(4) In order to increase the antenna gain, the phase shift should be small and $h = \lambda / 4$.

(5) The effect of incident wave to a parasite is derived to be equivalent to the voltage sources in infinitesimal gaps along the excited area.

(6) The induced current on a parasitic element is sinusoidal in shape and increases according to the excitation length of parasitic element.

(7) Radiation pattern of a parasitic element located quarter wavelength above PEC provides the desired radiation pattern without significant sidelobes. The parasite can play a role of a coupler to both parabolas.

(8) As the number of parasitic elements increase, the radiation beam becomes narrower but the gain is constant for the parasitic elements more than 5 in the experimental case.

(9) Experiment has been carried out using two parabolas. As the parasitic elements are of metal, the effect of parasitic elements is to lower the antenna gain.

(10) The theoretical and simulation results have been verified almost completely through experiment.


**Acknowledgement**

This paper was partly supported by the Ministry of Internal Affairs and Communications. The authors would like to thank Mr. Y. Munemasa and other members in Takano Laboratory for their help and useful comments in writing this paper.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