Multi-beam Design Method for Reflectarray Antenna using Aberration Theory

Yoshimi Sunaga, Kento Takeshima, Shigeru Makino, Takeshi Shiode and Michio Takikawa  
Kanazawa Institute of Technology, 7-1 Ohgigaoka, Nonoichi, Ishikawa, Japan  
Mitsubishi Electric Corporation, 5-1-1 Otuna, Kamakurashi, Kanagawa, Japan

Abstract—Aberration theory has been proposed to estimate the frequency characteristics of a reflectarray antenna. In this paper, a multi-beam design of a reflectarray antenna by using first-order aberration is proposed. The validity of the design method is then quantitatively verified through simulations.

Index Terms—Reflectarray antenna, Aberration theory, Multi-beam antenna.

1. Introduction

According to aberration theory, beam squint occurs owing to first-order aberration and phase error in the aperture occurs owing to second-order aberration [1]. The reflect-array antenna can radiate a beam in different directions depending on the frequency and using first-order residual aberration. In this paper, a design method of the dual-beam reflectarray antenna that radiates two beams with a primary radiator is proposed. A very simple design can obtained by introducing aberration theory.

2. First-order aberration

Fig.1 shows the geometrical configuration of the reflectarray antenna. A primary radiator is located at $F$. $D$ is the aperture diameter. $O$ is the center point of the reflectarray antenna with a diameter $D$, and the distance from the point $F$ to $O$ is $R$. $c$ is the clearance to avoid the blocking of a primary radiator. $d$ is the inclination angle of the mirror surface of the reflectarray antenna. The wavefront obtained, when the spherical wavefront radiating from point $F$ is reflected by the primary radiator, is the image of point $F$ in the plane surface. Fig.2 shows the geometry of the first-order aberration. The beam squint angle $\theta_s$ caused by the first-order residual aberration is geometrically determined from the aperture diameter $D$ and inclination angle $\theta$ of the image of the primary radiator with respect to the beam direction as shown in Fig.2. The first-order aberration $L$ is obtained when the aperture diameter $D$ and $\theta$ are determined as follows.

$$L = D \tan \theta$$  \hspace{1cm} (1)

The first-order residual aberration $\Delta L$ at frequency $f$ is as follows.

$$\Delta L = \frac{\lambda_0 - \lambda}{\lambda_0} L$$  \hspace{1cm} (2)

Where $\lambda_0$ is the wavelength of the design frequency $f_0$, $\lambda$ is the wavelength of the frequency $f$. The beam shift angle $\theta_s$ is as follows.

$$\theta_s = \tan^{-1} \frac{\Delta L}{D}$$  \hspace{1cm} (3)

When these formulas are rearranged, the following equation is obtained.

$$\tan \theta_s = \frac{\lambda_0 - \lambda}{\lambda_0} \tan \theta$$  \hspace{1cm} (4)

The beam squint angle $\theta_s$ depends on the inclination angle $\theta$.

3. Multibeam design

In this paper, a design proposal of a dual beam reflectarray antenna is presented, where the reflectarray antenna radiates two beams of frequencies $f_L$ and $f_H$. The beams overlap each other at approximately $-3$dB below their peaks. The necessary beam squint angle $\theta_s$ from the beam of center frequency $f_0 = (f_L + f_H)/2$ should be half of the beam width $\theta_3$. Here, the beam width $\theta_3$ is expressed as follows.

$$\theta_3 = \frac{\alpha \lambda_0}{D}$$  \hspace{1cm} (5)

Where $\alpha$ is a constant that depends on the aperture amplitude distribution and its nominal value is approximately $70$. Therefore, the necessary beam squint angle $\theta_s$ is as follows.

$$\theta_s = \frac{\theta_3}{2} = \frac{\alpha \lambda_0}{2 D}$$  \hspace{1cm} (6)

By substituting (6) in (4), the necessary inclination angle $\theta$ can be obtained as follows.

$$\theta = \tan^{-1} \left( \frac{\lambda_0}{\lambda_0 - \lambda_{\text{worst}}} \tan \left( \frac{\alpha \lambda_0}{2 D} \right) \right)$$  \hspace{1cm} (7)

The necessary inclination angle $\theta$ is determined from the aperture diameter $D$ and the frequency arrangement.
The design parameters are calculated as follows. As an example, it is assumed that the aperture diameter \( D = 1000 \) mm, \( f_L = 12.3 \) GHz, and \( f_H = 12.7 \) GHz. Using (7), the inclination angle \( \theta \) is determined to be \( 42.5^\circ \). Further, the clearance \( c \) and the distance \( R \) from point \( F' \) to \( O \) are considered to be 50 mm and 1000 mm, respectively. The position \( F' \) of the image of the primary radiator and the position \( F \) of the real primary radiator are then determined. The points \( F \) and \( F' \) are expressed as follows.

\[
\overrightarrow{OF'} = R \sin \theta \hat{i} - R \cos \theta \hat{k} \tag{8}
\]

\[
\overrightarrow{OF} = -\left( \frac{D}{2} + c \right) \hat{i} + \sqrt{R^2 - \left( \frac{D}{2} + c \right)^2} \hat{k} \tag{9}
\]

Then, the position \( F' \) of the image of the primary radiator and the position \( F \) of the real primary radiator are determined. Further, the orientation of the plane surface of the reflectarray antenna is determined as \( \theta_d = 37.93^\circ \). Fig.3 shows the design parameters of the dual beam reflectarray antenna. The element type is a ring and the reflection phase is controlled by its radius. Fig.4 shows the radiation patterns at 12.3 GHz, 12.5 GHz, and 12.7 GHz. As shown in the figure, the 12.3 GHz and 12.7 GHz beams overlap each other at approximately \(-3\) dB below their peaks as expected. Fig.5 shows the frequency characteristics of the beam squint angle. The red solid line represents the value calculated using (4), and the blue solid line represents the analyzed value for the designed model. Both lines coincide very well, and their difference is approximately 3%.

4. Conclusion

In this paper, a dual beam design of a reflectarray antenna radiating two beams with one horn is presented. Analysis confirmed that the beams overlap each other approximately \(-3\) dB below their peak. The validity of the design was verified based on the fact that the difference between the calculated value using (4), and the analyzed value for the designed model is very small. It is quite easy to obtain the beam squint angle using aberration theory.