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**Study of Dual-band Circularly Polarized
Planar Feeds and Application to
Reflector Antenna
for Satellite Broadcasting Reception**

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Chapter 1

Introduction

1.1 Background

Broadcasting services such as 4K/8K ultra-high definition television (UHDTV) [1.1] are attracting attention all over the world. In Japan, the Ministry of Internal Affairs and Communications has issued a road map that calls for UHDTV satellite broadcasting [1.2]. UHDTV satellite broadcasting services [1.3] were launched with the use of the latest broadcasting satellite, BSAT-4a, on December 1st, 2018 [1.4]. 2K high-definition television (HDTV) has been provided with right-hand circular polarization (RHCP) in the 12-GHz band (11.7 to 12.75 GHz) since 2000, and UHDTV satellite broadcasting has been additionally broadcasted with right- and left-hand circular polarization (LHCP) in the same frequency band since 2018. The channel allocation of satellite broadcasting in the 12-GHz band is shown in Fig. 1.1 [1.5]. The BSAT satellites (BS) have been transmitted the signals of the 2K, 4K, and 8K services in the lower 500-MHz band (11.7 to 12.2 GHz), and the JSAT satellites (CS) have been provided the 2K and 4K services in the upper 550-MHz band (12.2 to 12.75 GHz). The signals have been transmitted from the geostationary orbital position of 110 degrees East.

Table 1.1 shows the frequency bands for satellite broadcasting [1.6]. The 21-GHz (21.4 to 22 GHz) band has also been allocated as the downlink for broadcasting satellite service in ITU-R Regions 1 (Europe, Africa) and 3 (Asia Pacific). To provide advanced services, such as 3DTV, onboard antennas and wide-bandwidth transponders for a 21-GHz-band broadcasting satellite have been studied [1.7]–[1.10].

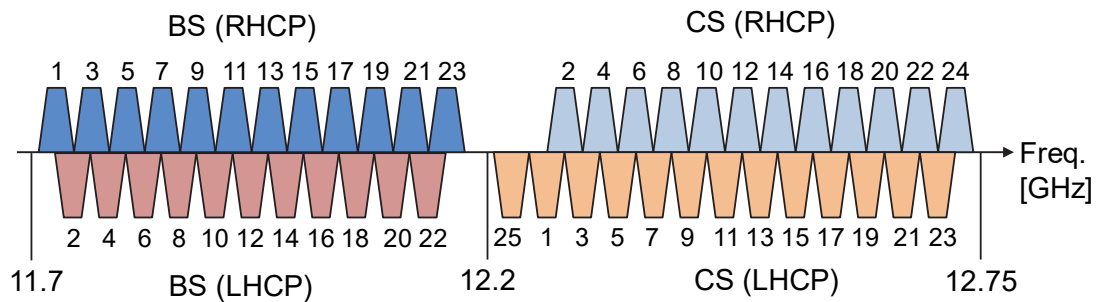


Fig. 1.1 Channel allocation of satellite broadcasting in the 12-GHz band.

Table 1.1 Frequency bands for satellite broadcasting.

Regions		Frequency [GHz]					
		L-band	S-band	Ku-band	K-band	V-band	
ITU-R Region 1	Europe, Africa	1.452– 1.492	2.52– 2.67	11.7– 12.5	21.4– 22	40.5– 42.5	74– 76
ITU-R Region 2	America	1.452– 1.492	2.52– 2.67	12.2– 12.7	17.3– 17.8	40.5– 42.5	74– 76
ITU-R Region 3	Asia Pacific	1.452– 1.492	2.52– 2.67	11.7– 12.2 12.5– 12.75	21.4– 22	40.5– 42.5	74– 76
Domestic (Japan)		–	–	11.7– 12.75	21.4– 22	40.5– 42.5	74– 76

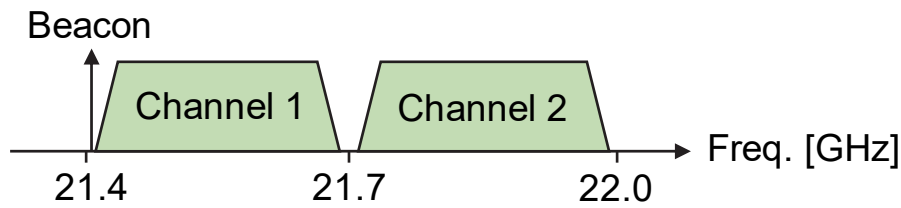


Fig. 1.2 Channel allocation of 21-GHz-band transponders of BSAT-4a.

The broadcasting satellite BSAT-4a was successfully launched into its geostationary orbital position of 110 degrees East in September 2017 [1.11]. This satellite has not only 12-GHz-band RHCP and LHCP transponders but also 21-GHz-band experimental transponders. The channel allocation of the 21-GHz-band transponders of BSAT-4a is shown in Fig. 1.2 [1.12]. A 278-MHz bandwidth wideband signal [1.13] can be transmitted by the 21-GHz-band transponders, and a beacon signal (non-modulated) is also being transmitted from BSAT-4a continuously. The 21-GHz-band transponder will be used for various experiments, for example, wideband transmission and long-term measurement of rain attenuation. Table 1.2 summarizes the transmission parameters of 12- and 21-GHz-band satellite broadcasting in Japan, and Fig. 1.3 shows the capacity enlargement of transponders for satellite broadcasting. The 21-GHz band can be used to

provided various satellite broadcasting services because a bit rate of about 530 Mbps can be obtained with an 8PSK (coding rate 3/4) modulation scheme using the single wideband transponder [1.14]. However, installation of the receiving antennas corresponding to each frequency band requires a wider space and incurs higher costs. To solve these problems, a 12- and 21-GHz dual-band dual-circularly polarized reflector antenna will be required, which can receive the broadcasting services provided over these two different frequency bands and with dual-polarization.

Table 1.2 Transmission parameters of 12- and 21-GHz-band satellite broadcasting.

Item	12-GHz band	21-GHz band
Frequency	11.7 to 12.75 GHz	21.4 to 22 GHz
Satellite orbital position	110 deg. East (geostationary orbit)	
Occupied bandwidth	34.5 MHz	278 MHz
Bit rate	About 100 Mbps with 16APSK (coding rate 7/9)	About 530 Mbps with 8PSK (coding rate 3/4)

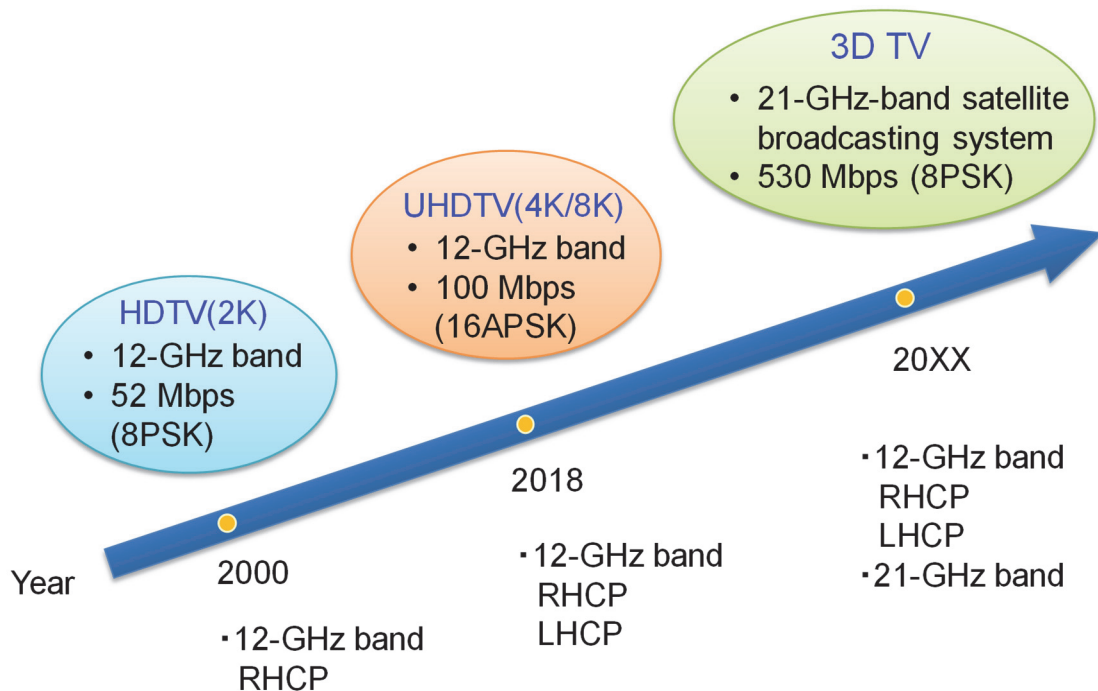


Fig. 1.3 Capacity enlargement of transponders for satellite broadcasting.

1.2 Antennas for Satellite Broadcasting Reception

For satellite broadcasting reception in Ku-band, various types of antennas have been studied, as shown in Table 1.3. For example, a radial line slot antenna (RLSA) [1.15], helical array antenna [1.16], microstrip array antenna [1.17], and leaky waveguide array antenna [1.18] have been reported. These antennas were designed to receive signals transmitted with RHCP in the 12-GHz band. A dual-circularly polarized RLSA [1.19] has also been reported. The diameter of the RLSA was 50 cm, and the gain was 35 dBi at 12.4 GHz. This RLSA was designed in accordance with the specifications for satellite broadcasting in the United States at the time (12.2 to 12.7 GHz), whose frequency bandwidth was half that of the 12-GHz band (11.7 to 12.75 GHz).

Offset parabolic reflector antennas are generally used for satellite broadcasting reception because the costs of producing the reflector antennas are lower than those of array antennas. Septum polarizers, which provide good circularity and require no adjustments, have been reported for a polarizer of dual-circularly polarized reflector antennas [1.20]–[1.22]. Then, an offset parabolic reflector antenna that uses a septum polarizer for the 12-GHz band was manufactured [1.23], [1.24]. The diameter of the fabricated reflector antenna was 45 cm, and the gain was 34 dBi at 12.0 GHz. The cross-polarization discrimination (XPD) was more than 27 dB throughout the 12-GHz band. However, it is difficult to share a septum polarizer with the 12- and 21-GHz bands because its design parameters are decided in accordance with each frequency band. A horn antenna is connected to the septum polarizer, and the aperture diameter suitable for the 12- and 21-GHz band is also different. Two horn antennas with the septum polarizer, for each frequency band, cannot be set at the focal point of a parabolic reflector. Therefore, it is impossible for a conventional receiving antenna to capture 12- and 21-GHz band signals with dual polarizations (LHCP and RHCP) simultaneously. Characteristics of fabricated single-band feed horns for each frequency band are described in Appendix.

Table 1.3 Comparison of antennas for satellite broadcasting reception.

Item	Antenna types				
	Helical array	Microstrip array	Leaky waveguide array	RLSA	Parabolic (with septum polarizer)
Structure	Planar				Three dimensional
Polarization	Right-hand circular			Dual circular	
Frequency band	Ku-band				

1.3 Dual-band Antennas

Various types of dual-band antennas have been studied, as shown in Table 1.4. For receiving Ku- and Ka-bands, a reflectarray antenna is reported [1.25]. This antenna can receive 12.25 to 12.75 GHz and 19.6 to 21.2 GHz simultaneously. The receiving polarizations of Ku- and Ka-bands are linear polarization and LHCP, respectively. The reflectarray antenna requires frequency selective surfaces and multiple feed horns. Hence, its configuration is complicated. For circularly polarized antennas in dual-frequency bands, various microstrip antennas (MSAs) have been studied [1.26]–[1.28]. The ratios of the higher to lower frequency-band in the reports are 1.3 to 4.8. Enough gain for satellite communications can be obtained by configuring an array antenna with MSAs. However, assuming a receiving antenna for 12- and 21-GHz-band satellite broadcasting, grating lobes will appear in the 21-GHz band when the spacing of elements is more than one wavelength (λ) in the 21-GHz band, which is equivalent to 0.56λ in the 12-GHz band. This is a restriction on the design of array antennas using dual-band MSAs.

A dual-band reflector antenna that has a feed composed of a horn antenna and an MSA array was also reported [1.29]. The horn antenna and MSA array were set at the focal point of the offset parabolic reflector, and the ratio of the higher to lower frequency-band had to be more than 5 to adopt the technique in the report. Since parabolic reflectors can be used in wide frequency range, a dual-band and dual-circularly polarized feed has been demanded, which makes it possible to optimize its beamwidth in each frequency band.

Table 1.4 Comparison of dual-band antennas.

Item		Antenna types		
		MSA	Reflectarray	Parabolic (with horn and MSA)
Structure of feed		Planar	Three dimensional	
Polarizations	Lower freq.	Dual circular	Linear	Linear or circular
	Higher freq.		Left-hand circular	
Ratio of higher to lower freq.		1.3 to 4.8	1.6	≥ 5

1.4 Planar Feeds for Reflector Antennas

Reflector antennas have been used for satellite communications because of their simplicity, low cost, and high gain. Various planar feeds for reflector antennas have been studied, as shown in Fig. 1.4. A planar feed with a 2×2 microstrip array antenna was proposed in 2005 [1.30]. The feed was evaluated with a 60-cm offset parabolic reflector. However, this feed was designed as a linear polarization antenna and measured at only 12.1 GHz. A dual-polarized feed for satellite broadcasting system was reported in 2010 [1.31]. This planar feed is composed of a 2×2 array antenna with MSAs that have an aperture coupled feed and a microstrip feed, as shown in Fig. 1.5. The radiation pattern of the feed was similar to those of a conventional feed horn. The spacing of elements was 0.65λ , and the design frequency was 12.2 GHz. However, the measured gain of the 46-cm offset parabolic reflector fed by the planar feed was 30 dBi, and the aperture efficiency was 29%.

Year	2005	...	2010	...	2012	2013	2014	...	2017
CP feeds						20/30 GHz*, CP [1.34]	12/17 GHz, 12GHz: LP 17GHz: CP [1.36]		30 GHz, Active, CP [1.37]
LP feeds	12 GHz, LP [1.30]		14/36 GHz, Dual-LP [1.32]		12/14 GHz, Dual-LP [1.33]				

CP: Circular polarization

LP: Linear polarization

* A scale model (4- and 6-GHz bands) was evaluated.

Single-band feeds

Dual-band feeds

Fig. 1.4 Planar feeds for reflector antennas.

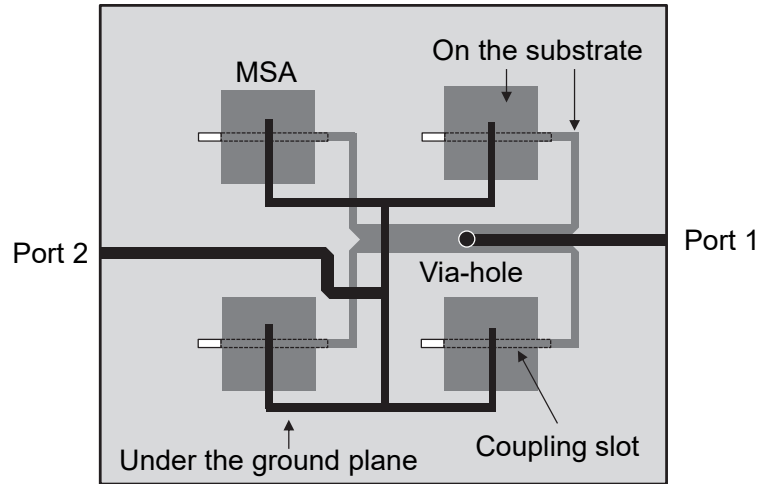


Fig. 1.5 Dual-polarized planar feed composed of 2×2 array antenna with MSAs.

A dual-band planar feed with microstrip array antenna was proposed in 2010 [1.32]. The antenna was designed as a feed of a parabolic cylindrical reflector antenna. Dual-polarized crossed slots fed by microstrip lines are used as 14-GHz-band antennas, and single-polarized square microstrip antennas are used as 36-GHz-band antennas. By sharing the same antenna aperture, the problem of placing two feeds at a focus has been solved. However, this feed was operated as a linear polarization antenna in both bands. In 2012, a dual-band planar feed for 12- and 14-GHz bands was also reported (Fig. 1.6) [1.33]. This feed was designed for Ku-band satellite communications. However, the spacing of elements cannot be optimized in each frequency band individually because the feed was composed of dual-band MSAs.

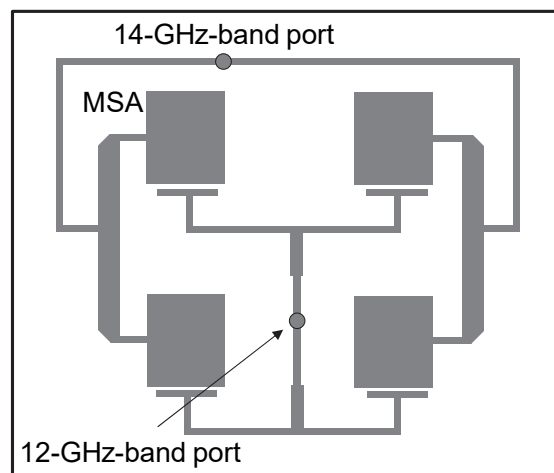


Fig. 1.6 Dual-band planar feed for 12- and 14-GHz bands.

A dual-band circularly polarized planar feed was reported in 2013 [1.34]. The feed was assumed to be used for satellite communications in 20- and 30-GHz bands. A prototype feed was fabricated and measured in 4- and 6-GHz bands as a scale model, which is composed of a 2×2 microstrip array antenna with dual-band linear-polarization MSAs. The feed was operated as a circularly polarized antenna by using a sequentially rotated array technique [1.35], as shown in Fig. 1.7. However, this antenna cannot radiate RHCP and LHCP simultaneously.

A dual-band and dual-polarized planar feed was designed and simulated in 2014 [1.36]. Its target frequency bands are from 11.7 to 12.7 GHz and from 17.3 to 17.8 GHz. The design utilizes a multilayer printed circuit board to separate its complex feed circuit. The feed is composed of two 2×2 microstrip array antennas whose elements are square MSAs fed by two via-holes. The simulation results showed that the 10-dB impedance bandwidth was 640 MHz (12.15 to 12.79 GHz) in Ku-band and that the 15-dB bandwidth was 350 MHz (17.47 to 17.82 GHz) in Ka-band. However, this feed cannot cover the 12-GHz band and the 21-GHz band, whose bandwidths are 1050 and 600 MHz, respectively. In addition, the polarizations of the feed are linear polarization in Ku-band and circular polarization in Ka-band.

In 2017, an active focal-plane feed for a spherical reflector was reported. The feed is composed of a 49-element array antenna and monolithic microwave integrated circuits [1.37]. The array elements are circular MSAs with a single feed point, and the designed frequency is 30 GHz. The system's performance was demonstrated through simulations and measurements. A scanning range of ± 6 degrees was achieved with the fabricated 49-element array. However, this antenna cannot radiate RHCP and LHCP simultaneously.

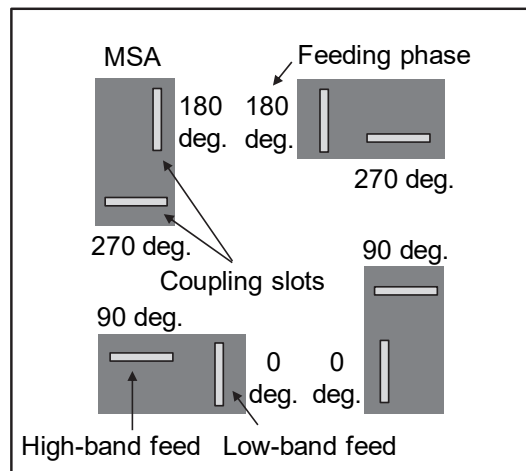


Fig. 1.7 Dual-band circularly polarized feed with sequentially rotated array.

1.5 Example of Link Calculation for Satellite Broadcasting

This section shows link calculations for 12- and 21-GHz-band satellite broadcasting systems. The calculations are based on the calculation method described in ARIB STD B-44 [1.38]. Table 1.5 summarizes the parameters and calculation methods in this study. The target service availability is 99.9% in both bands. The atmospheric absorption and the rain attenuation are calculated by using Rec. ITU-R P.618 [1.39], [1.40], P.676 [1.41], P.837 [1.42], and P.840 [1.43]. The total atmospheric attenuation L is given by

$$L = L_g + \sqrt{(L_r + L_c)^2 + L_s^2} \quad (1.1)$$

where L_g is gaseous attenuation, L_r is rain attenuation, L_c is clouds attenuation, and L_s is scintillation fading [1.39], [1.44].

The calculated results are shown in Tables 1.6 and 1.7. The assumed 21-GHz-band broadcasting satellite can make a 7-dB boosted beam with an array fed reflector antenna [1.7]–[1.10], [1.14]. The results indicate that the required gains for receiving antennas in the 12- and 21-GHz bands are 33 and 38 dBi, respectively. These gains correspond to the aperture efficiency of 60% for a 45-cm diameter parabolic reflector antenna.

Table 1.5 Parameters and calculation methods in this study.

Item	Value
Orbital position of satellite	110 deg. East
Receiving location	Tokyo (35.7 deg. N, 139.7 deg. E)
Calculated frequencies	12-GHz band: 12.225 GHz 21-GHz band: 21.7 GHz
Atmospheric absorption, Rain attenuation	Rec. ITU-R P.618, P.676, P.840 ITU-R, Dynamic Link Library (DLL) for calculation of propagation losses for Earth to space (or space to Earth) transmission links [1.40]
Point rainfall rate in an average year	Rec. ITU-R P.837
Required carrier-to-noise ratio (C/N) [1.38]	8PSK (coding rate 3/4): 8.9 dB 16APSK (coding rate 7/9): 12.2 dB
Target of service availability	99.9% (annual year)

Table 1.6 Example of link calculation for 12-GHz-band satellite broadcasting.

		Clear sky	Rain
Satellite Parameters			
Bandwidth	[MHz]	33.7561	33.7561
EIRP	[dBW]	60.0	60.0
XPD (including uplink XPD)	[dB]	27.0	27.0
Propagation Losses (at 12.225 GHz, Tokyo)			
Free space loss L_f	[dB]	205.8	205.8
Total atmospheric attenuation L	[dB]	0.1	3.6
Gaseous attenuation L_g	[dB]	0.1	0.1
Rain attenuation L_r	[dB]	0.0	2.9
Clouds attenuation L_c	[dB]	0.0	0.5
Scintillation fading L_s	[dB]	0.0	0.3
Total loss $L_f + L$	[dB]	205.9	209.4
Receiving Station Parameters			
Receiving antenna gain	[dBi]	33.0	33.0
Pointing loss	[dB]	0.1	0.1
Noise figure	[dB]	1.0	1.0
Equivalent noise temperature	[K]	75.1	75.1
Antenna noise temperature	[K]	50.0	192.7
Equivalent system noise temperature	[K]	125.1	267.8
XPD	[dB]	25.0	25.0
Downlink (satellite to station)			
Received power	[dBW/MHz]	-128.2	-131.7
Noise power	[dBW/MHz]	-147.6	-144.3
Downlink C/N	[dB]	19.4	12.6
Total XPD	[dB]	22.9	22.9
Cross-pol. EIRP	[dBW]	60.0	60.0
C/I	[dB]	22.9	22.9
C/(N+I)	[dB]	17.8	12.2
Required C/N	[dB]	12.2	12.2
Link margin	[dB]	5.6	0.0
Service availability (annual year)	[%]	—	99.90

Table 1.7 Example of link calculation for 21-GHz-band satellite broadcasting.

		Clear sky	Rain
Satellite Parameters			
Bandwidth	[MHz]	250.0	250.0
Satellite RF output power	[kW]	0.8	0.8
Satellite antenna gain	[dBi]	40.0	47.0
EIRP (locally variable EIRP system)	[dBW]	69.0	76.0
XPD (including uplink XPD)	[dB]	27.0	27.0
Propagation Losses (at 21.7 GHz, Tokyo)			
Free space loss L_f	[dB]	210.8	210.8
Total atmospheric attenuation L	[dB]	0.8	12.7
Gaseous attenuation L_g	[dB]	0.8	0.8
Rain attenuation L_r	[dB]	0.0	10.2
Clouds attenuation L_c	[dB]	0.0	1.7
Scintillation fading L_s	[dB]	0.0	0.5
Total loss $L_f + L$	[dB]	211.6	223.4
Receiving Station Parameters			
Receiving antenna gain	[dBi]	38.0	38.0
Pointing loss	[dB]	0.5	0.5
Noise figure	[dB]	1.5	1.5
Equivalent noise temperature	[K]	119.6	119.6
Antenna noise temperature	[K]	45.7	246.0
Equivalent system noise temperature	[K]	165.3	365.6
XPD	[dB]	25.0	25.0
Downlink (satellite to station)			
Received power	[dBW/MHz]	-129.0	-133.9
Noise power	[dBW/MHz]	-146.4	-143.0
Downlink C/N	[dB]	17.4	9.1
Total XPD	[dB]	22.9	22.9
Cross-pol. EIRP	[dBW]	69.0	76.0
C/I	[dB]	22.9	22.9
C/(N+I)	[dB]	16.3	8.9
Required C/N	[dB]	8.9	8.9
Link margin	[dB]	7.4	0.0
Service availability (annual year)	[%]	—	99.90

1.6 Objectives

In this thesis, dual-band and dual-circularly polarized planar feeds for an offset parabolic reflector antenna are proposed. The proposed feeds are composed of two 2×2 MSA arrays to obtain suitable beamwidth by changing the spacing of elements in each frequency band. Because the MSA arrays are designed with a multilayer structure, the MSA array of each band can be set at the focal point of a parabolic reflector. It is also possible to downsize a feed of reflector antennas since the proposed feeds have a planar structure. Feed circuits are designed on the substrates to divide the right- and left-hand-circularly polarized signals in both bands. The proposed feeds applied to a receiving reflector antenna, satellite broadcasting signals provided by the right- and left-hand circular polarizations in the 12- and 21-GHz bands can be received with a single reflector antenna.

The objective of this thesis is to reveal the operation of the dual-band and dual-circularly polarized planar feeds as a feasibility study. Also, the characteristics of offset parabolic reflector antennas fed by the planar feeds are elucidate. In addition, it is demonstrated that the proposed antenna can receive small signals transmitted from satellites using the dual-circular polarizations in two frequency bands simultaneously. In this thesis, the 12-GHz band (11.7 to 12.75 GHz) and the 21-GHz band (21.4 to 22 GHz) are set as target frequency bands, and the receiving polarizations are the right- and left-hand circular polarizations in both bands. As described in Section 1.5, target gains of the 12- and 21-GHz bands are 33 and 38 dBi, respectively.

1.7 Outlines of Remaining Chapters

The flow chart of this thesis is shown in Fig. 1.8.

Chapter 2 presents the basic design of the proposed feeds that are composed of two 2×2 MSA arrays. In the design process, the size of square and circular MSAs are discussed, and the frequency ratio of the higher to lower frequency-band for the proposed feed is obtained. The frequency ratio is derived from the geometry and the array factor. Moreover, far field conditions of the proposed feed are also derived. Due to the asymmetry of the offset parabolic reflector, the angle deviates between both circularly polarized pattern peaks [1.45]–[1.47], resulting in pointing losses when applying the reflector to a dual-circularly polarized antenna. Therefore, parameters of a reflector used with the proposed feed are studied to achieve enough gain for the right- and left-hand circular polarizations.

Chapter 3 presents the design process and characterization of a dual-circularly polarized planar feed, which has a 12-GHz-band MSA array, for an offset parabolic reflector antenna. In this chapter, the feasibility of the dual-circularly polarized feed composed of the MSA array is evaluated. For obtaining enough gain and XPD throughout the 12-GHz band for satellite broadcasting reception, the feed is composed of a 2×2 MSA array that is sequentially rotated to enhance polarization purity [1.35]. The performance of a prototype reflector antenna with the proposed feed is discussed, whose diameter is 50 cm.

Chapter 4 presents the design process and characterization of a dual-band dual-circularly polarized planar feed, which has 12- and 21-GHz-band MSA arrays, for offset parabolic reflector antenna. The feed is composed of two 2×2 MSA arrays that are sequentially rotated to enhance polarization purity, which are located at the same focal point with a multilayer structure. A feed circuit is also designed on the substrate, which makes it possible to divide the right- and left-hand-circularly polarized signals in both bands. The performance of a prototype 50-cm reflector antenna with the proposed feed is discussed.

Chapter 5 presents the design process and characterization of a dual-band and dual-circularly polarized planar feed whose feeding loss in the 21-GHz band is mitigated. From the evaluation results in Chapter 4, it is appeared that the feeding loss of the 21-GHz band increases because the feed circuit is enlarged to secure space for the feeding slots. Therefore, the 21-GHz-band MSA is fed with via-holes to downsize a 21-GHz-band feed circuit for mitigating the feeding loss. The performance of a 50-cm offset parabolic reflector antenna with the designed feed is described.

Chapter 6 presents the experimental results of receiving 12- and 21-GHz-band

signals transmitted from broadcasting satellites by using the prototype antenna. The 12-GHz-band signals are transmitted from the BSAT and JCSAT satellites whose orbital positions are 110 degrees East. In the 21-GHz band, an LHCP signal, which is the beacon signal, is transmitted by the BSAT-4a satellite.

In Chapter 7, this thesis is summarized, and future studies are proposed.

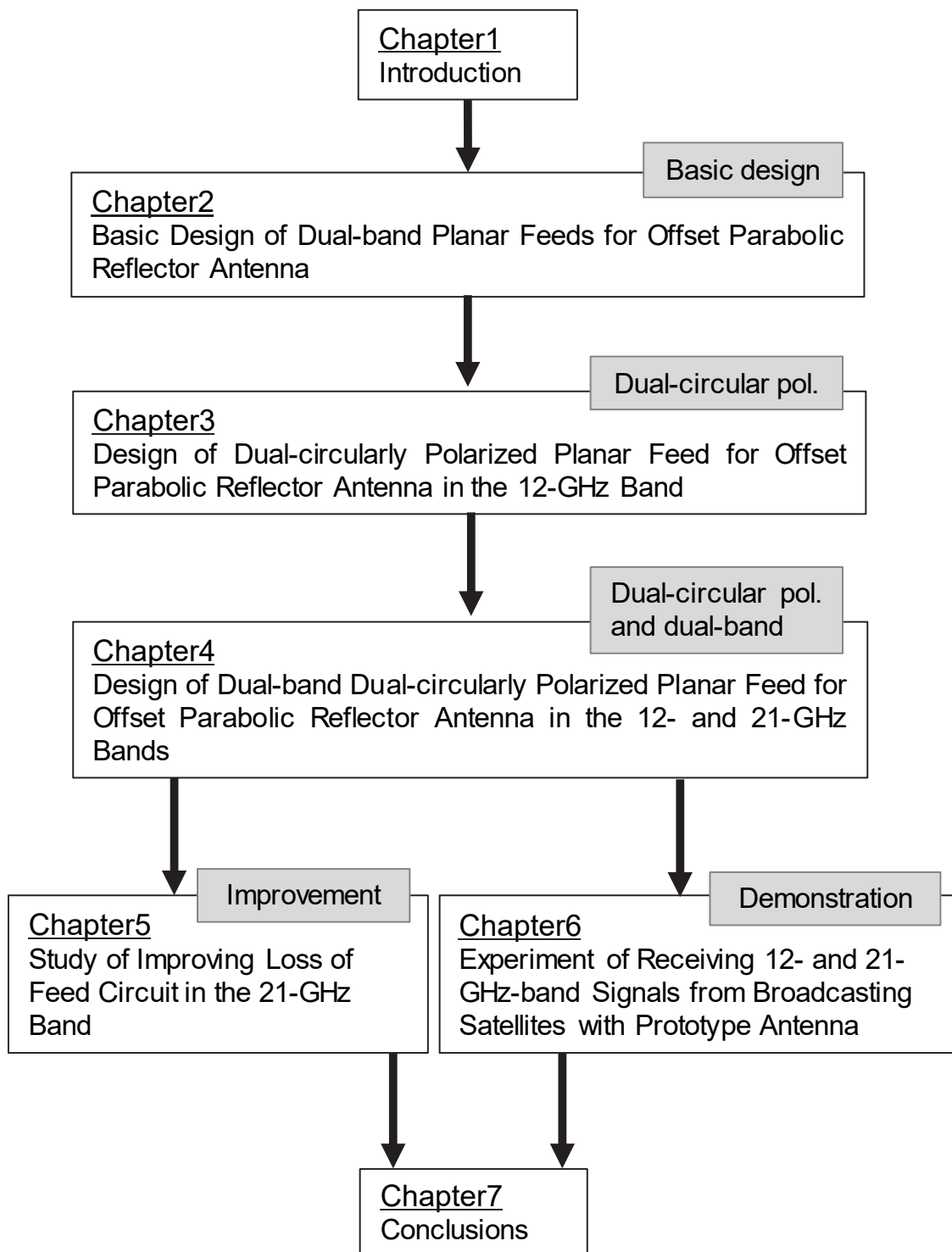


Fig. 1.8 Flow chart of thesis.

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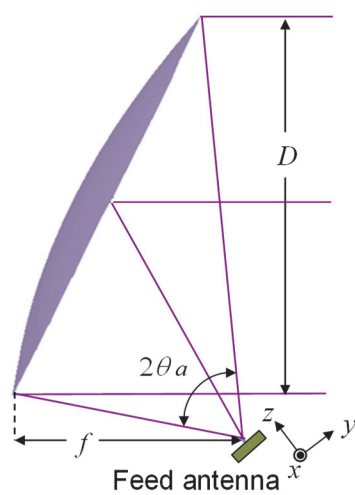
Chapter 2

Basic Design of Dual-band Planar Feeds for Offset Parabolic Reflector Antenna

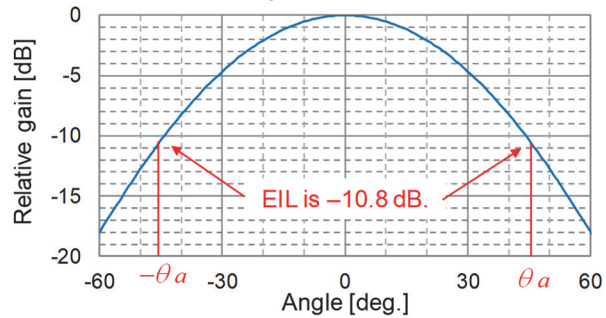
2.1 Introductory Remarks

This chapter presents a basic design of the proposed dual-band feeds for an offset parabolic reflector antenna. A horn antenna is generally used for a feed of a parabolic reflector antenna. Usually, an edge illumination level (EIL) of the reflector antenna is optimized with the aperture of the horn antenna. The target EIL is -11 dB [2.1] to obtain a high aperture efficiency, as shown in Fig. 2.1 [2.2]. However, the suitable aperture of the higher-frequency-band horn antenna is narrower than that of the lower-frequency-band one. It is difficult to achieve a suitable beamwidth with a common feed horn for both bands. Therefore, a feed composed of two 2×2 microstrip array antennas is proposed, whose configuration is shown in Fig. 2.2, to control the beamwidth for each band individually.

Offset parabolic reflector antenna



Radiation pattern of feed antenna



Antenna parameters	Diameter D	450 mm
	Aperture angle $2\theta_a$	92 deg.
	Focal length f	212 mm
Calculated values	Frequency	12.225 GHz
	Antenna gain	33.6 dBi
	Aperture efficiency	68%

Fig. 2.1 Example of designing offset parabolic reflector antenna.

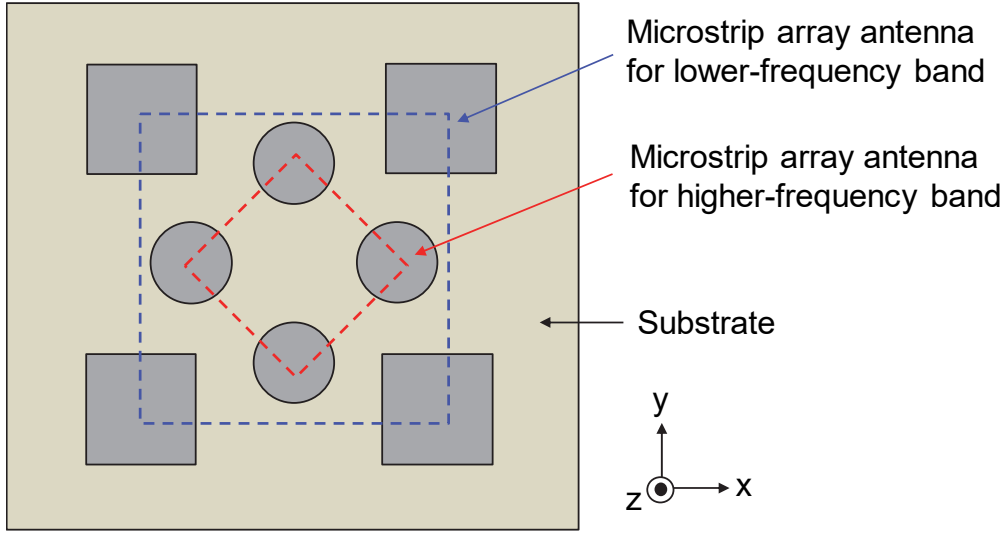


Fig. 2.2 Basic configuration of proposed feed.

This chapter is organized as follows. Section 2.2 describes the shape of microstrip antenna (MSA) elements of the array antenna. In Section 2.3, the frequency ratio of the higher to lower frequency-band is presented, which is derived from the geometry and the array factor. In Section 2.4, parameters of the offset parabolic reflector, which is used with the proposed dual-band and dual-circularly polarized planar feed, is studied. Section 2.5 concludes this chapter.

2.2 Study of Element Shapes

The proposed feed has eight MSAs for the elements of two 2×2 microstrip array antennas. In this study, the combination of a two-port MSA and 90-deg. hybrid coupler (3dB-HYB) was chosen because the MSAs need to be a dual-circularly polarized antennas. The dual-circularly polarized MSAs are shown in Fig. 2.3 [2.3]. Because the radiation patterns of the square and circular MSAs are same [2.4], the size of the MSAs is compared.

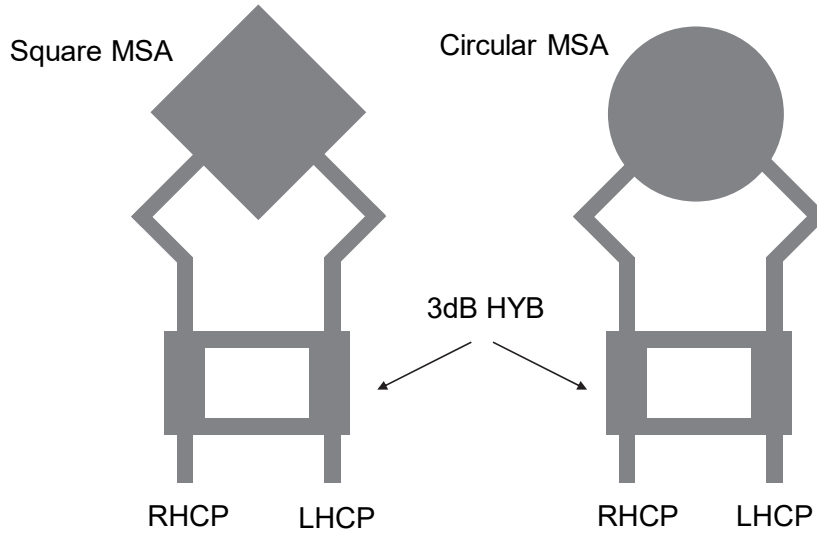


Fig. 2.3 Dual-circularly polarized MSAs.

The resonance frequency of square MSA is given by

$$f = \frac{c}{2l\sqrt{\epsilon_r}} \quad (2.1)$$

where l is the length of one side of the square MSA, ϵ_r is the dielectric constant, and c is the speed of light in free space [2.5]. The resonance frequency of the circular MSA is also given by

$$f = \frac{1.841c}{2\pi a\sqrt{\epsilon_r}} \quad (2.2)$$

where a is the radius of the circular MSA [2.5].

The wavelength λ is given by

$$\lambda = \frac{c}{f}. \quad (2.3)$$

Therefore, l and a are given by

$$l = \frac{\lambda}{2\sqrt{\epsilon_r}} \quad (2.4)$$

$$a = \frac{1.841\lambda}{2\pi\sqrt{\epsilon_r}}. \quad (2.5)$$

In this study, the MSAs are made by using polytetrafluoroethylene (PTFE) substrates whose ϵ_r is 2.55. Then, the size of MSAs (l and a) are given by

$$l \cong 0.313\lambda \quad (2.6)$$

$$a \cong 0.183\lambda. \quad (2.7)$$

Fig. 2.4 shows the size of the square and circular MSAs. For studying the lower-frequency-band array, it is important to compare the length of one side of the square MSA and the diameter of the circular MSA. Fig. 2.4(a) shows that the size of the square MSA is smaller than that of the circular MSA. For studying the higher-frequency-band array, the diagonal of the square MSA and the diameter of the circular MSA are compared because the higher-frequency-band array is rotated 45 deg., as shown in Fig. 2.2. Fig. 2.4(b) shows that the size of the circular MSA is smaller than that of the square MSA.

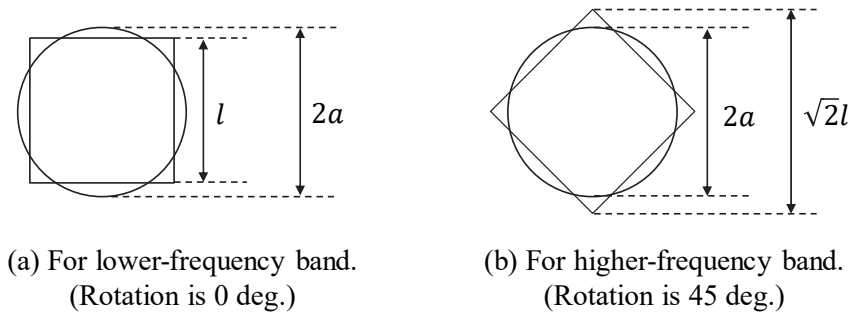


Fig. 2.4 Size of MSAs.

2.3 Study of Frequency Ratio on Proposed Dual-band Feed

The frequency ratio on the proposed dual-band feed is studied in this section. The frequency ratio can be derived from the geometry (the size and spacing of elements). The square and circular MSAs can be a candidate for the lower-frequency-band array element. Then, the two array configurations shown in Table 2.1 are compared in this study. For the higher-frequency-band array, the circular MSA is chosen for the element because its size is smaller than that of the square MSA, as shown in Fig. 2.4 (b).

Table 2.1 Array configurations in this study.

Arrays	Array configurations	
	Type 1	Type 2
Lower-freq.-band array	Square MSA	Circular MSA
Higher-freq.-band array*	Circular MSA	Circular MSA

*For the higher-frequency-band array, the circular MSA is chosen for the element because its size is smaller than that of the square MSA, as shown in Fig. 2.4 (b).

Fig. 2.5 shows the configuration and parameters of Type 1, where d_L is the spacing of elements in the lower frequency band, l is the length of one side of the square MSA, and a is the radius of the circular MSA.

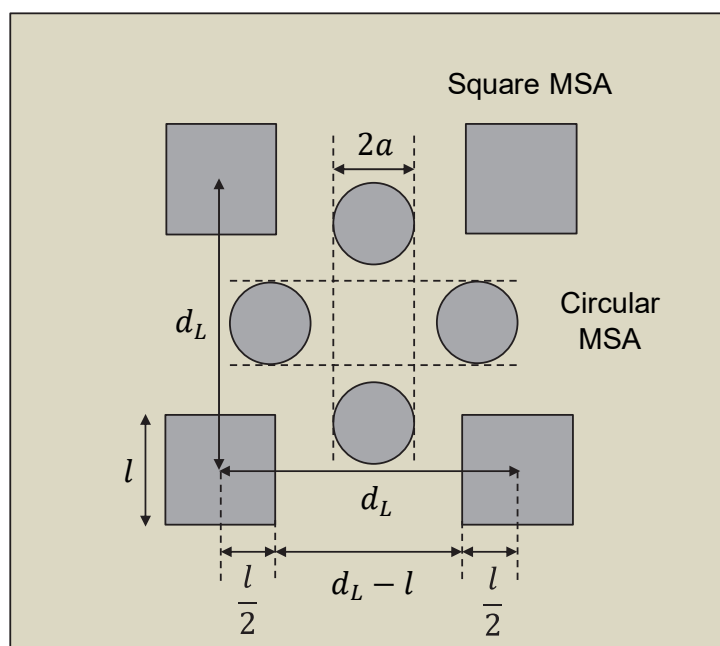


Fig. 2.5 Configuration and parameters of Type 1.

The diameter of the circular MSA in the higher frequency band is given by

$$2a < d_L - l. \quad (2.8)$$

From the equations (2.3), (2.4), and (2.5), l and a are given by

$$l = \frac{c}{2f_L\sqrt{\epsilon_r}} \quad (2.9)$$

$$a = \frac{1.841c}{2\pi f_H\sqrt{\epsilon_r}} \quad (2.10)$$

where f_L is the lower frequency, f_H is the higher frequency, and c is the speed of light in free space. The spacing of elements d_L is expressed with the ratio of the wavelength λ_L in the lower frequency band. Therefore, d_L is given by,

$$d_L = s\lambda_L = \frac{c}{f_L}s \quad (2.11)$$

where s is the ratio of the spacing to the wavelength λ_L . From the equations (2.9), (2.10), and (2.11), the inequality (2.8) is

$$2 \times \frac{1.841c}{2\pi f_H\sqrt{\epsilon_r}} < \frac{c}{f_L}s - \frac{c}{2f_L\sqrt{\epsilon_r}} \quad (2.12)$$

$$\frac{1.841}{\pi} f_L < \left(s\sqrt{\epsilon_r} - \frac{1}{2} \right) f_H. \quad (2.13)$$

In this study, the MSAs are made of PTFE substrates whose ϵ_r is 2.55. Then, the frequency ratio is given by

$$\frac{f_H}{f_L} > \frac{1.841}{\pi \left(s\sqrt{\epsilon_r} - \frac{1}{2} \right)} \cong \frac{0.586}{1.596s - 0.5}. \quad (2.14)$$

Fig. 2.6 shows the configuration and parameters of Type 2, where a_L and a_H are the radius of the lower and higher frequency-band circular MSAs, respectively.

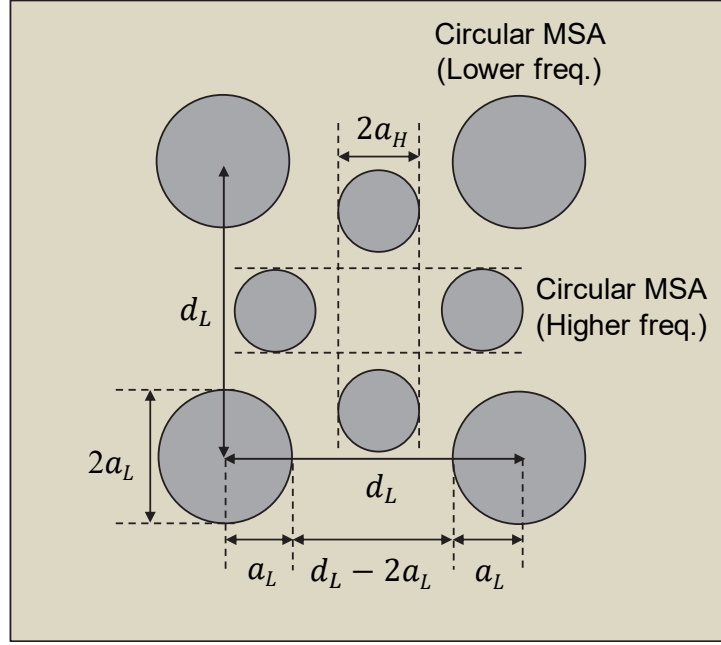


Fig. 2.6 Configuration and parameters of Type 2.

The diameter of the circular MSA in the higher frequency band is given by

$$2a_H < d_L - 2a_L. \quad (2.15)$$

From the equations (2.3) and (2.5), a_L and a_H are given by

$$a_L = \frac{1.841c}{2\pi f_L \sqrt{\epsilon_r}} \quad (2.16)$$

$$a_H = \frac{1.841c}{2\pi f_H \sqrt{\epsilon_r}} \quad (2.17)$$

where f_L is the lower frequency, f_H is the higher frequency, and c is the speed of light in free space. The spacing of elements d_L is expressed with the ratio of the wavelength λ_L in the lower frequency band. Therefore, d_L is given by,

$$d_L = s\lambda_L = \frac{c}{f_L} s \quad (2.18)$$

where s is the ratio of the spacing to the wavelength λ_L . From the equations (2.16), (2.17), and (2.18), the inequality (2.15) is

$$2 \times \frac{1.841c}{2\pi f_H \sqrt{\epsilon_r}} < \frac{c}{f_L} s - 2 \times \frac{1.841c}{2\pi f_L \sqrt{\epsilon_r}} \quad (2.19)$$

$$\frac{1.841}{\pi} f_L < \left(s\sqrt{\epsilon_r} - \frac{1.841}{\pi} \right) f_H. \quad (2.20)$$

In this study, ϵ_r is 2.55. Then, the frequency ratio is given by

$$\frac{f_H}{f_L} > \frac{1.841}{\pi s \sqrt{\epsilon_r} - 1.841} \cong \frac{1.841}{5.017s - 1.841}. \quad (2.21)$$

Therefore, the frequency ratios of Types 1 and 2 are given by following inequalities.

$$Type1: \quad \frac{f_H}{f_L} > \frac{0.586}{1.596s - 0.5} \quad (2.22)$$

$$Type2: \quad \frac{f_H}{f_L} > \frac{1.841}{5.017s - 1.841} \quad (2.23)$$

These inequalities show that the frequency ratio is obtained by the spacing of elements s , which is expressed by the ratio to the wavelength, in the lower frequency band.

Suitable beamwidth can be obtained by changing the spacing of elements s . For a feed of reflector antennas, the beamwidth is decided so that the EIL become -11 dB to obtain a high aperture efficiency [2.1]. Therefore, the spacing of elements s is derived from the radiation pattern of the array antenna and an aperture angle of the reflector. In this study, a planar array antenna that is a square- and uniform-array is assumed. The configuration is shown in Fig. 2.7.

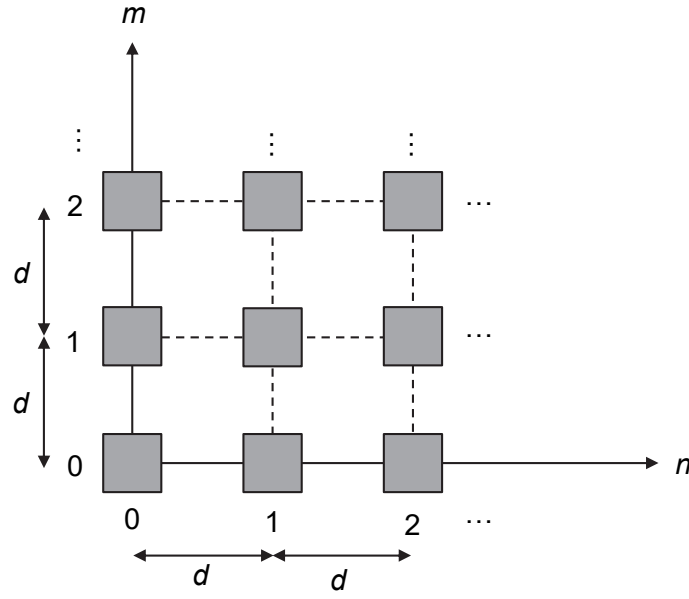


Fig. 2.7 Configuration of assumed planar array antenna.

The radiation pattern of the $N \times N$ array is expressed by the array factor that is given by

$$AF(\theta, \varphi) = \sum_{n=0}^{N-1} \exp(jnu) \sum_{m=0}^{N-1} \exp(jmv) \quad (2.24)$$

$$u = k_0 d \sin \theta \cos \varphi \quad (2.25)$$

$$v = k_0 d \sin \theta \sin \varphi \quad (2.26)$$

$$k_0 = \frac{2\pi}{\lambda}. \quad (2.27)$$

The spacing of elements d expressed by s is given by

$$d = s\lambda. \quad (2.28)$$

Therefore, u and v are given by

$$u = 2\pi s \times \sin \theta \cos \varphi \quad (2.29)$$

$$v = 2\pi s \times \sin \theta \sin \varphi. \quad (2.30)$$

The equations (2.24), (2.29), and (2.30) show that the radiation pattern of the array antenna is expressed by the spacing of elements s and the angle values.

Fig. 2.8 shows the radiation patterns of 2×2 array antennas ($N = 2$) obtained from the equations (2.24), (2.29), and (2.30). This figure shows that the value of s can be decided according to the aperture angle $2\theta_a$ of an assumed parabolic reflector. Table 2.2 shows the example of the relationship between θ_a , s , and the frequency ratio f_H / f_L . When the proposed feed is used for a parabolic reflector antenna whose aperture angle ($2\theta_a$) is 100 degrees, the frequency ratio (f_H / f_L) values of Types 1 and 2 are 1.62 and 2.12, respectively. In this study, Type 1 was chosen for the basic configuration of the proposed feed because the applicable frequency range of Type1 is wider than that of Type2.

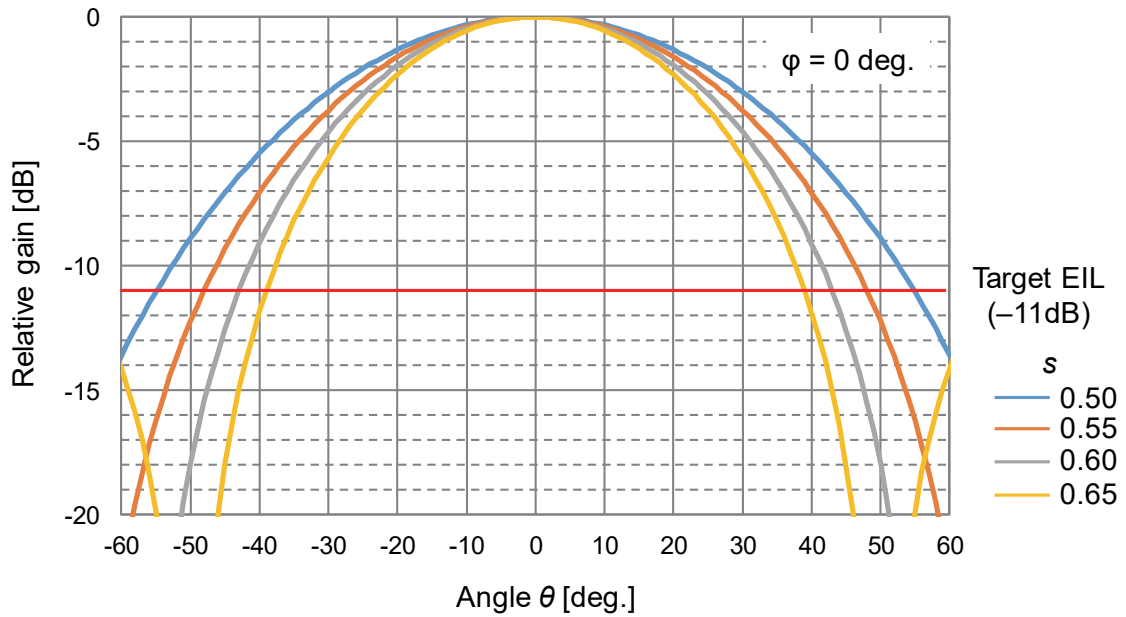


Fig. 2.8 Radiation patterns of 2×2 array antennas.

Table 2.2 Example of relationship between θ_a , s , and f_H / f_L .

$2\theta_a$	θ_a	s	f_H / f_L	
			Type 1	Type 2
80 deg.	40 deg.	0.64	> 1.12	> 1.34
90 deg.	45 deg.	0.58	> 1.38	> 1.72
100 deg.	50 deg.	0.54	> 1.62	> 2.12
110 deg.	55 deg.	0.50	> 1.97	> 2.76

The frequency ratio f_H / f_L is derived from the size of the MSAs obtained by the equations (2.1) and (2.2). The measured resonant frequencies of MSAs are lower than the frequencies calculated by the equations (2.1) and (2.2), as shown in Table 2.3 [2.5]. This result shows that the size of the square and circular MSAs will decrease by 3% and 5%, respectively. Therefore, the derived frequency ratio f_H / f_L has a margin.

Table 2.3 Example of resonant frequencies of MSAs [2.5].

Shape	Dimension	Measured resonant frequency (f_1)	Calculated resonant frequency (f_2)	f_1 / f_2
Square	$l = 1.0$ inch (25.4 mm)	3.57 GHz	3.67 GHz	97%
Circular	$a = 0.5$ inch (12.7 mm)	4.07 GHz	4.29 GHz	95%

2.4 Far Field Conditions of Proposed Dual-band Feed

In the previous section, the array configuration of Type 1 was chosen for the basic design of the proposed dual-band feed. In this section, far field conditions are derived from the aperture size of the proposed feed. Fig. 2.9 shows the configuration and parameters for this study, where d_L and d_H are the spacing of elements in the lower and higher frequency bands, l is the length of one side of the square MSA, and a is the radius of the circular MSA.

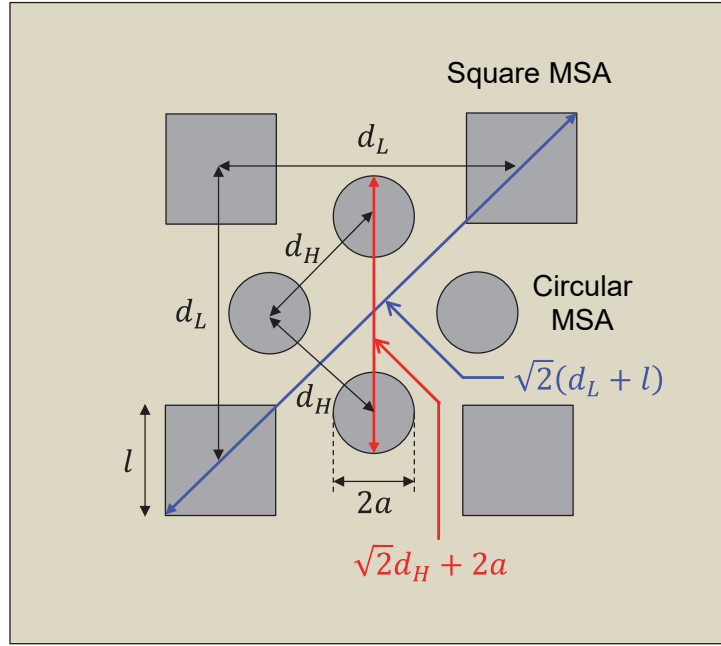


Fig. 2.9 Configuration and parameters for studying far field conditions.

For the lower-frequency-band array, the aperture size D_L is given by

$$D_L = \sqrt{2}(d_L + l). \quad (2.31)$$

From the equations (2.4) and (2.11), d_L and l are given by

$$d_L = s_L \lambda_L \quad (2.32)$$

$$l = \frac{\lambda_L}{2\sqrt{\epsilon_r}} \quad (2.33)$$

where s_L is the ratio of the spacing d_L to the wavelength λ_L in the lower frequency band.

Therefore, D_L is given by

$$D_L = \sqrt{2} \left(s_L \lambda_L + \frac{\lambda_L}{2\sqrt{\epsilon_r}} \right) = \left(\sqrt{2}s_L + \frac{1}{\sqrt{2\epsilon_r}} \right) \lambda_L. \quad (2.34)$$

For the higher-frequency-band array, the aperture size D_H is given by

$$D_H = \sqrt{2}d_H + 2a. \quad (2.35)$$

From the equations (2.5) and (2.11), d_H and a are given by

$$d_H = s_H \lambda_H \quad (2.36)$$

$$a = \frac{1.841\lambda_H}{2\pi\sqrt{\epsilon_r}} \quad (2.37)$$

where s_H is the ratio of the spacing d_H to the wavelength λ_H in the higher frequency band. Therefore, D_H is given by

$$D_H = \sqrt{2}s_H \lambda_H + 2 \times \frac{1.841\lambda_H}{2\pi\sqrt{\epsilon_r}} = \left(\sqrt{2}s_H + \frac{1.841}{\pi\sqrt{\epsilon_r}} \right) \lambda_H. \quad (2.38)$$

In this study, the feed is made by using PTFE substrates whose ϵ_r is 2.55. Then, the aperture size of the lower and higher frequency-band arrays (D_L and D_H) are given by

$$D_L \cong (\sqrt{2}s_L + 0.443)\lambda_L \quad (2.39)$$

$$D_H \cong (\sqrt{2}s_H + 0.367)\lambda_H. \quad (2.40)$$

The far field condition [2.6] is given by

$$R_p = \frac{2D^2}{\lambda}. \quad (2.41)$$

When the measurement distance is larger than R_p , far field radiation patterns are obtained.

Therefore, the far field conditions of the proposed feed were expressed by the wavelength and the spacing of elements.

$$\text{Lower frequency band: } R_p \cong 2(\sqrt{2}s_L + 0.443)^2 \lambda_L \quad (2.42)$$

$$\text{Higher frequency band: } R_p \cong 2(\sqrt{2}s_H + 0.367)^2 \lambda_H \quad (2.43)$$

When s_L and s_H have the same value, the far field condition is decided by R_p of the lower frequency band because λ_L is larger than λ_H . In this study, the spacing of elements is less than one wavelength so that grating lobes will not appear. Hence, the sufficient condition is given by

$$\text{Sufficient condition: } R_p \cong 6.90\lambda_L \quad (s_L = s_H = 1, \varepsilon_r = 2.55). \quad (2.44)$$

This sufficient condition is inversely proportional to the frequency of the lower-frequency-band array, as shown in Fig. 2.10.

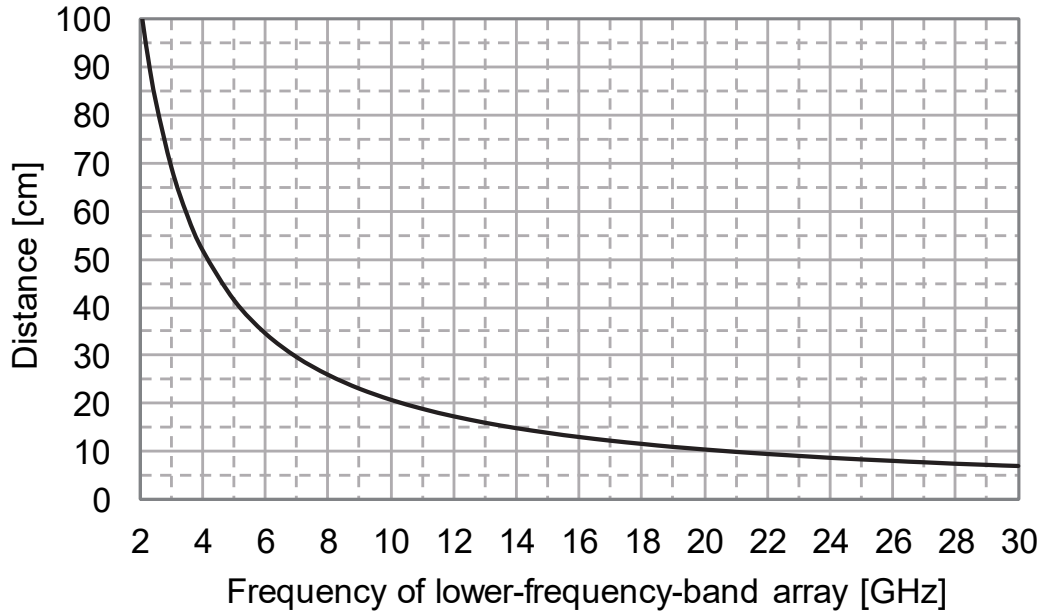


Fig. 2.10 Far field condition of proposed feed (sufficient condition).

2.5 Parameter Study of Offset Parabolic Reflector

In this section, parameters of the offset parabolic reflector, which is used with the proposed dual-band and dual-circularly polarized planar feed, is studied. Due to the asymmetry of its offset geometry, the angle deviates between both circularly polarized pattern peaks [2.7]–[2.9], resulting in pointing losses when applying the reflector to a dual-circularly polarized antenna. To achieve sufficient gain for both polarizations, the FD ratio (F/D) of the reflector was optimized for the designed feed. The relationship between antenna characteristics and F/D was calculated with the antenna geometry shown in Fig. 2.11.

In this study, the F/D was varied from 0.3 to 0.8. The edge illumination level (EIL), which was -11 ± 0.5 dB to obtain high aperture efficiency [2.1], was optimized by the spacing of the MSAs in accordance with the F/D. There was a possibility of gain degradation, which is caused by the feeding loss and angle deviations between both circularly polarized pattern peaks. Therefore, the diameter (D) of 50 cm was selected to obtain enough gain for satellite broadcasting reception. The size of the feed is assumed to be 5×5 cm, which is equivalent to that of a low-noise block converter with a horn antenna for consumer use in Japan. Therefore, to avoid blocking receiving signals, the clearance (X_c) of the reflector is 3 cm.

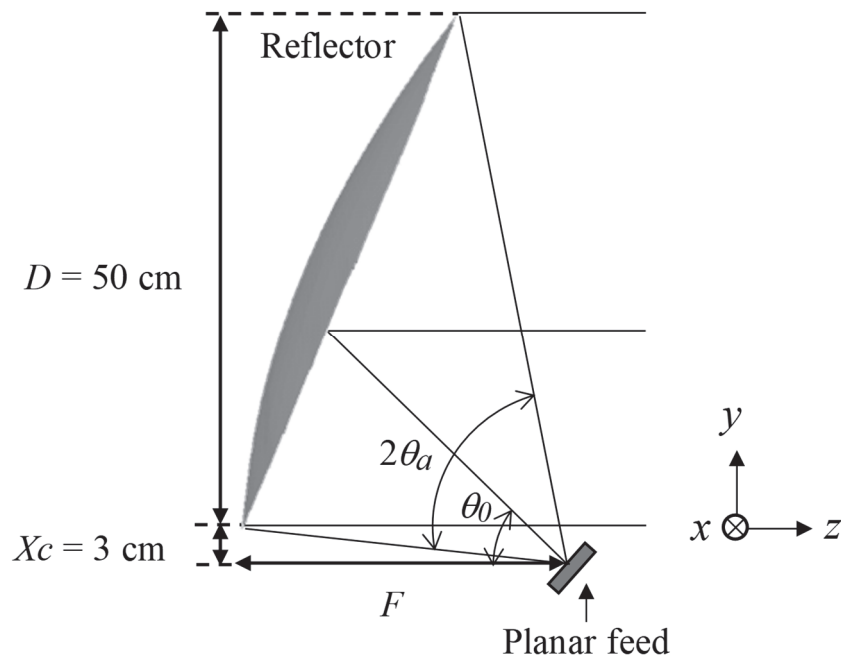


Fig. 2.11 Configuration of proposed antenna with planar feed.

The angle and gain differences were defined in this study, as shown in Fig. 2.12. The angle difference is the direction of the LHCP pattern peak when the RHCP pattern peak is at a boresight. The gain difference, which occurs with the angle difference, is a gain degradation of LHCP from the RHCP peak gain. When a dual-circularly polarized antenna is pointed to the broadcasting satellite by using the RHCP receiving power, the receiving carrier-to-noise ratio of the LHCP signal decreases because of the gain difference. The worst case, which is the antenna adjustment by receiving satellite broadcasting with RHCP, was assumed because satellite broadcasting of HDTV (2K) has been provided with RHCP in the 12-GHz band in Japan since 2000. Therefore, the reflector antenna was designed to maximize the LHCP's gain when the RHCP's gain is peak. In this study, the horizontal plane was evaluated, which corresponds to the geostationary orbit.

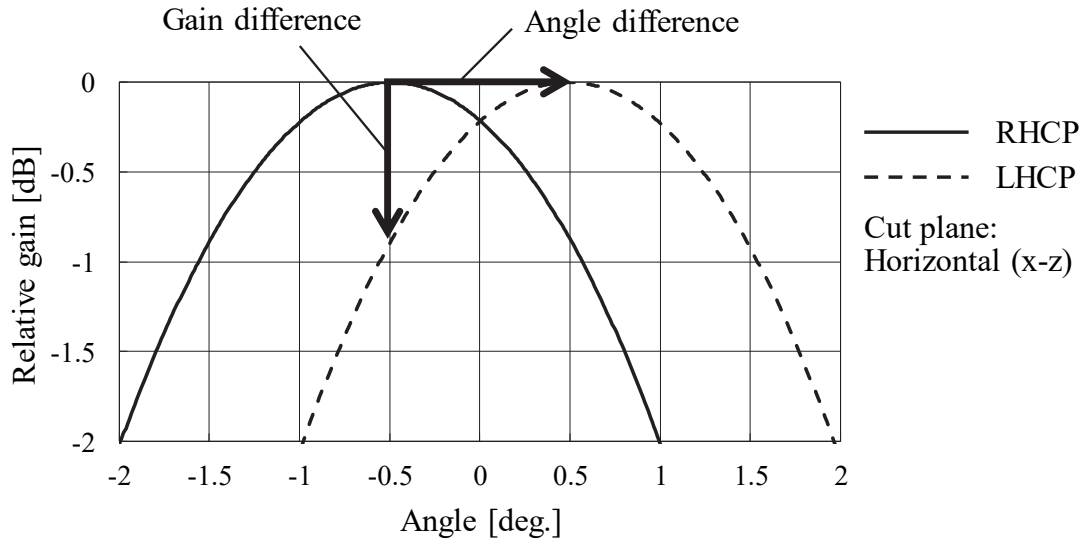


Fig. 2.12 Definition of angle and gain differences (cut plane is horizontal, i.e., x-z plane shown in Fig. 2.11).

The gain and angle differences are caused by a beam-shift angle ψ_s , which is given by

$$\psi_s = \mp \sin^{-1} \left(\frac{\lambda \sin \theta_0}{4\pi F} \right) \quad (2.45)$$

where θ_0 is the tilt angle shown in Fig. 2.11, F is the focal length of the paraboloid, and

λ is the wavelength [2.7]. The angle ψ_s decreases as F increases, and D is constant. Therefore, the gain and angle differences become smaller when the F/D increases. The equation (2.45) also shows that the angle ψ_s in the lower-frequency band is larger than that in the higher-frequency band. Hence, it is important that the gain and angle differences in the 12-GHz band are studied to design a dual-band and dual-circularly polarized planar feed in the 12- and 21-GHz bands.

In this study, the calculated radiation pattern of the 2×2 MSA array shown in Fig. 2.13 was used by varying the spacing of the MSAs, whose detailed design is described in Section 3. Fig. 2.14 shows an example calculated radiation pattern of the MSA array. The calculation frequency was 12.225 GHz that is the center frequency of the 12-GHz band. To obtain the target EIL (-11 ± 0.5 dB), F/D s of 0.3, 0.5 and 0.8 should require the spacing of 0.42, 0.52 and 0.74 wavelengths, respectively. The sidelobe level of the feed was varied in accordance with the spacing of elements. When the F/D increases, the gain decreases because of the spillover caused by the relatively high sidelobes of the feed. The 3D electromagnetic field analysis simulator, CST Studio Suite [2.10], was used to calculate the radiation pattern of the MSA array.

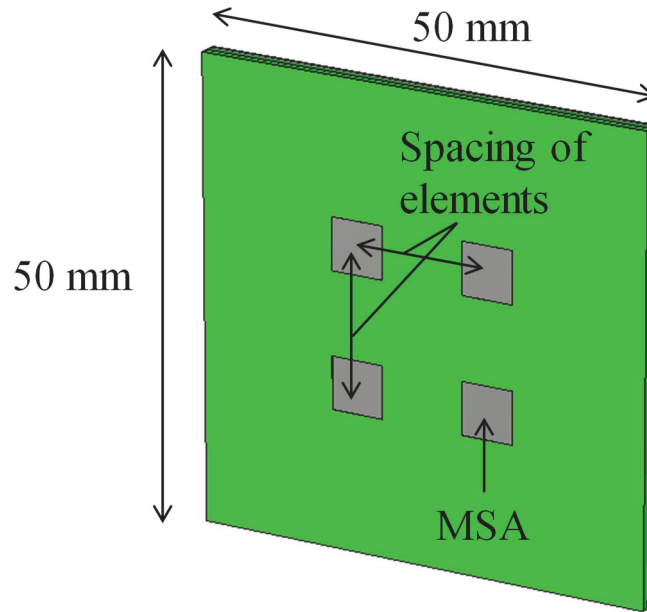
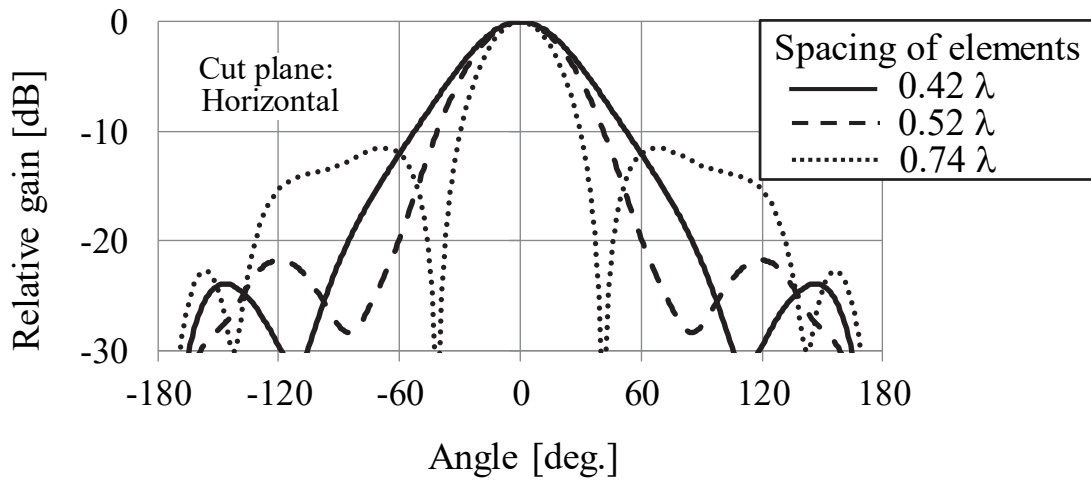


Fig. 2.13 2×2 MSA array assumed in this study.



0.42 wavelength was used for $F/D = 0.3$.

0.52 wavelength was used for $F/D = 0.5$.

0.74 wavelength was used for $F/D = 0.8$.

Fig. 2.14 Example of feed pattern.

Figs. 2.15 to 2.17 show the results of the evaluation. The reflector antenna analysis software, GRASP [2.11], was used to calculate the radiation patterns of the reflector antenna. The radiation patterns of the offset reflector antenna with the MSA array for RHCP and LHCP were calculated, and the gain and angle differences were evaluated. In Figs. 2.15 and 2.16, both the gain and angle differences decreased when the F/D increased. Specifically, there was a large change in the gain difference when the F/D was less than 0.5.

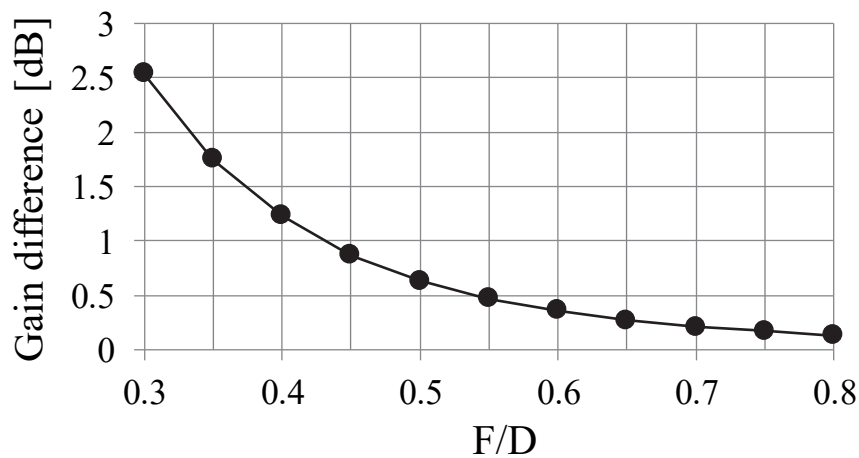


Fig. 2.15 Deviation of pattern peaks (gain difference).

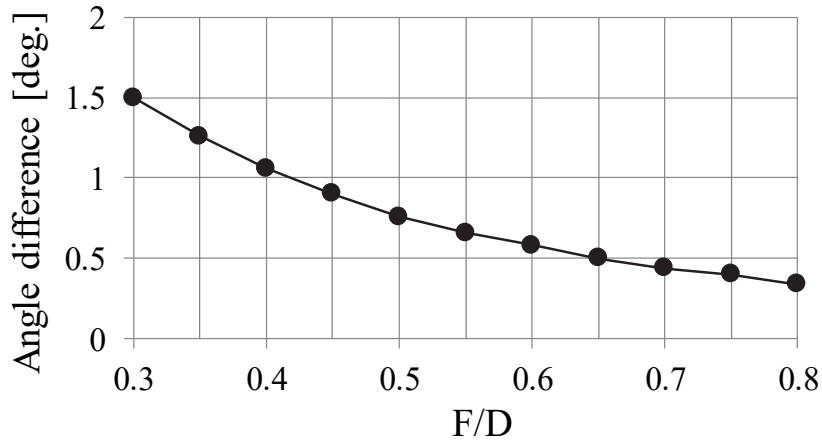


Fig. 2.16 Deviation of pattern peaks (angle difference).

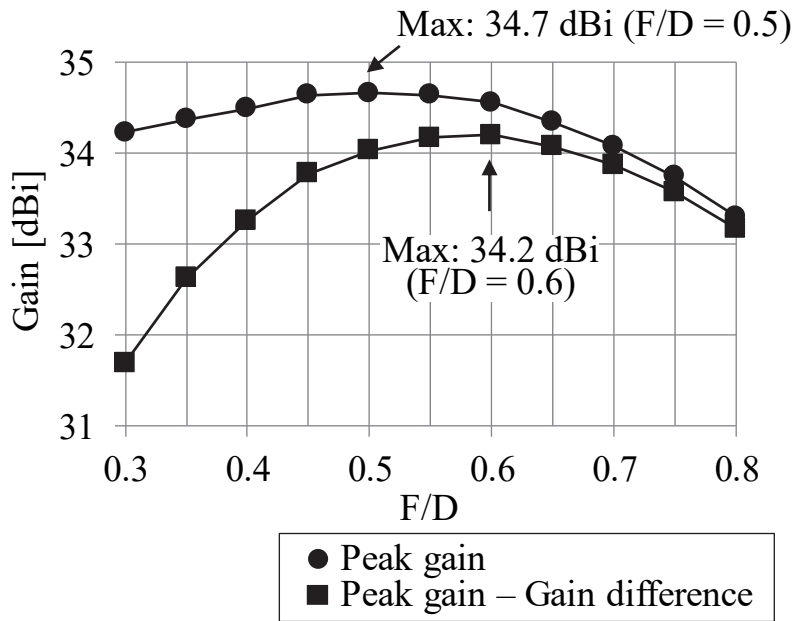


Fig. 2.17 Calculated gain (12.225 GHz).

Fig. 2.17 shows the subtraction of the gain difference from the peak gain. The gains do not include the feeding loss. The subtraction was maximized at an F/D of 0.6 because the gain difference increased at an F/D of under 0.5 and the peak gain decreased at an F/D of over 0.7 due to the increase in the feed's sidelobe level. Therefore, to sufficiently improve the gain of both polarizations, F/D of 0.6 was selected. The reflector parameters are summarized in Table 2.4. The aperture angle ($2\theta_a$) of 77.2 deg. was

obtained, and the frequency ratio (f_H / f_L) of the proposed planar feed was 1.07, as shown in Table 2.5, which is derived from the results described in Section 2.3. Therefore, the proposed feed can be applied to the dual-circularly polarized offset parabolic reflector antenna for the 12- and 21-GHz-band satellite broadcasting reception, whose frequency ratio is 1.78 at the center frequency of each frequency band.

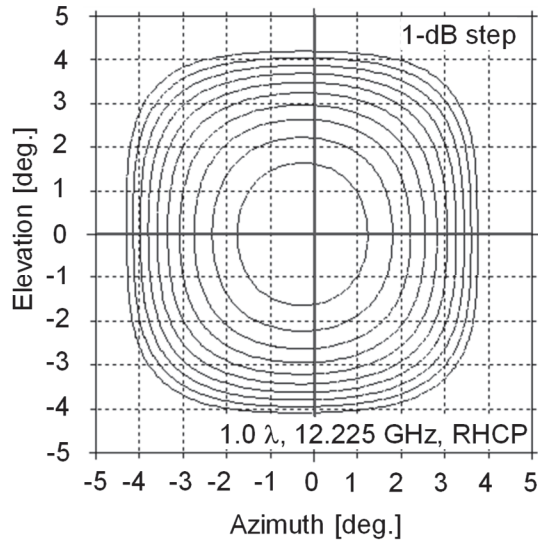
Table 2.4 Summary of reflector parameters.

Item	Value
Diameter (D)	50 cm
Focal length (F)	30 cm
F/D	0.6
Clearance (X_c)	3 cm
Aperture angle ($2\theta_a$)	77.2 deg.

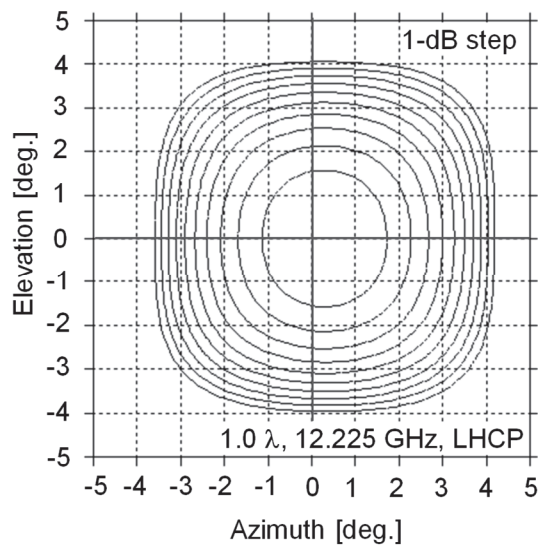
Table 2.5 Relationship between θ_a , s , and f_H / f_L .

$2\theta_a$	θ_a	s	f_H / f_L
77.2 deg.	38.6 deg.	0.66	> 1.07

Since the reflector parameters were obtained, the radiation patterns of the reflector antenna can be studied, which is fed by the proposed planar feed shown in Fig. 2.9. Figs. 2.18 to 2.29 show the main lobes of the reflector antenna at 12.225 and 21.7 GHz that are the center frequencies of each band. The contour indicates the relative gain with 1-dB step (−1 to −10 dB). These radiation patterns were calculated by changing the spacing of elements, i.e., s_L and s_H described in Section 2.4. The reflector antenna analysis software, GRASP [2.11], was used to calculate the radiation patterns. The radiation pattern of the array element is an ideal Gaussian feed pattern whose 3 dB beamwidth is 80 degrees (± 40 degrees). The calculated results confirmed that the contour of the main lobe is not a perfect circle when the spacing of elements is more than 0.8 wavelength.

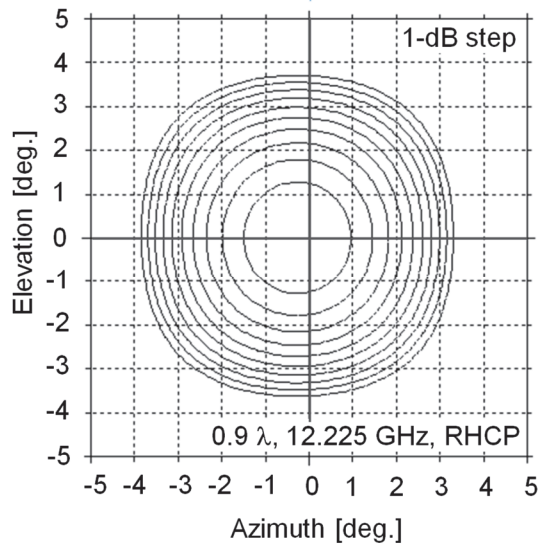


(a) RHCP antenna.

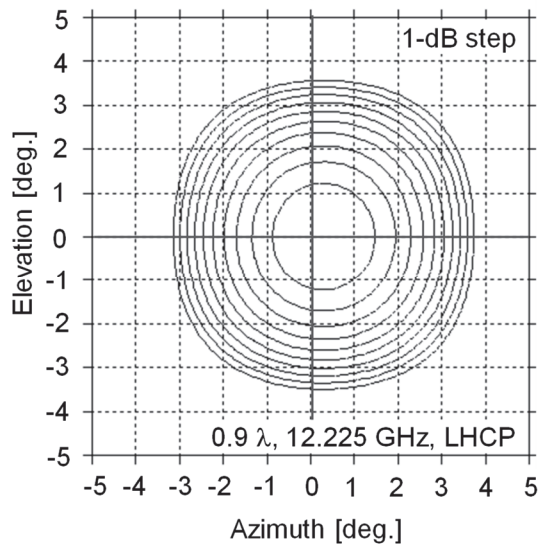


(b) LHCP antenna.

Fig. 2.18 Calculated main lobes of offset parabolic reflector antenna fed by 12-GHz-band 2×2 array antenna (spacing of elements is 1.0 wavelength).

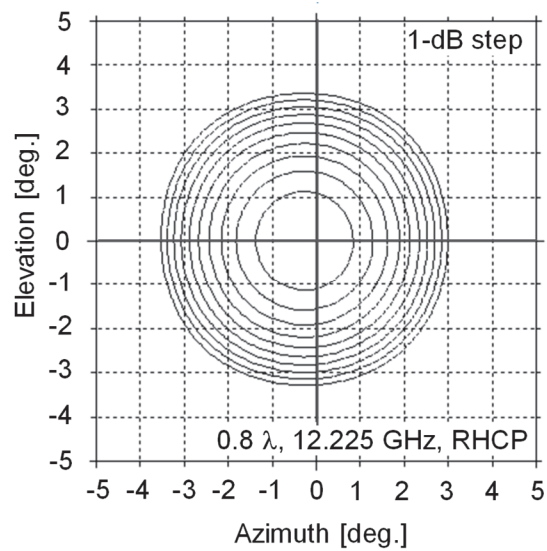


(a) RHCP antenna.

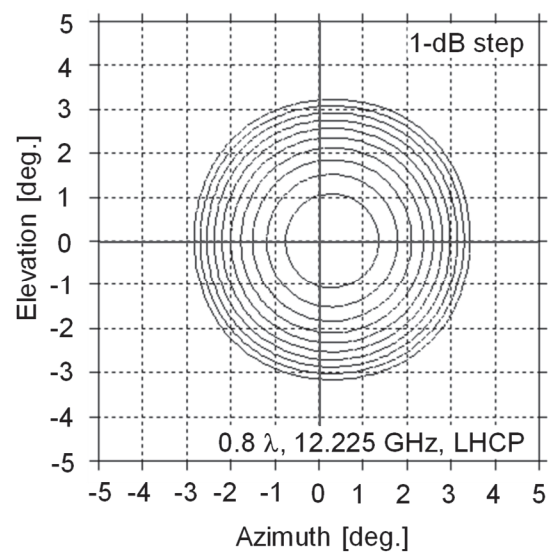


(b) LHCP antenna.

Fig. 2.19 Calculated main lobes of offset parabolic reflector antenna fed by 12-GHz-band 2×2 array antenna (spacing of elements is 0.9 wavelength).

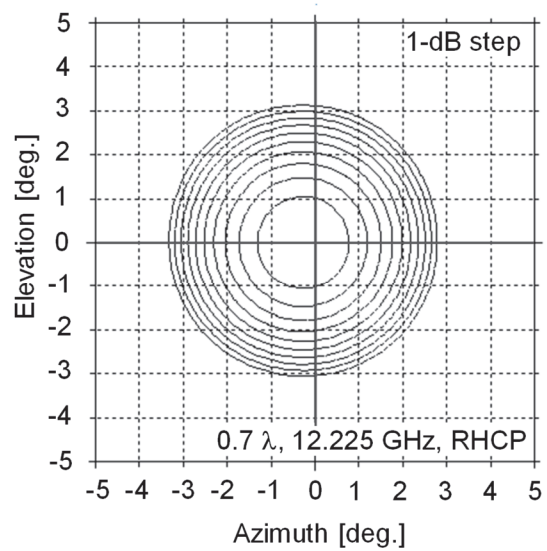


(a) RHCP antenna.

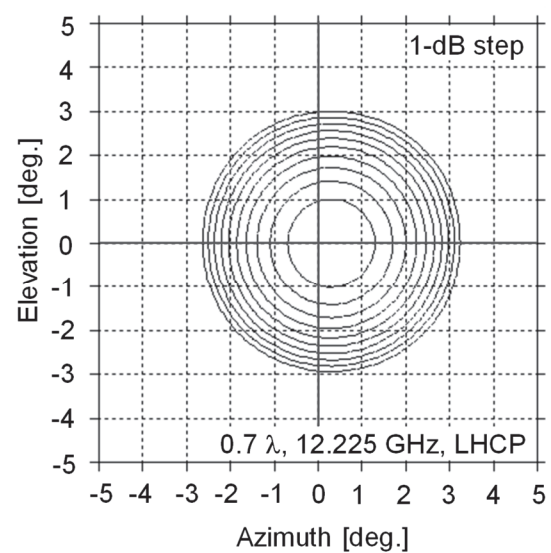


(b) LHCP antenna.

Fig. 2.20 Calculated main lobes of offset parabolic reflector antenna fed by 12-GHz-band 2×2 array antenna (spacing of elements is 0.8 wavelength).

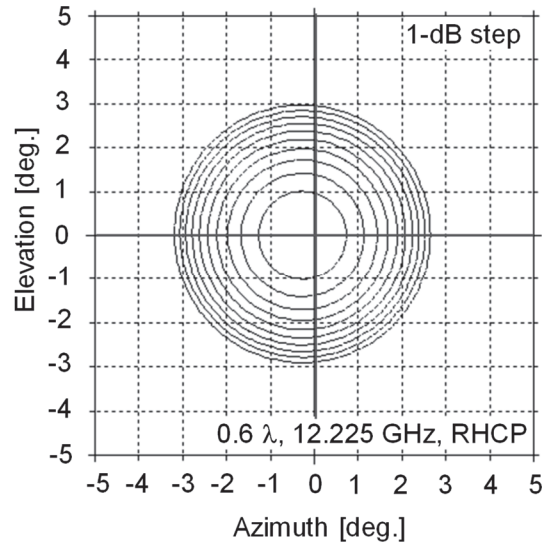


(a) RHCP antenna.

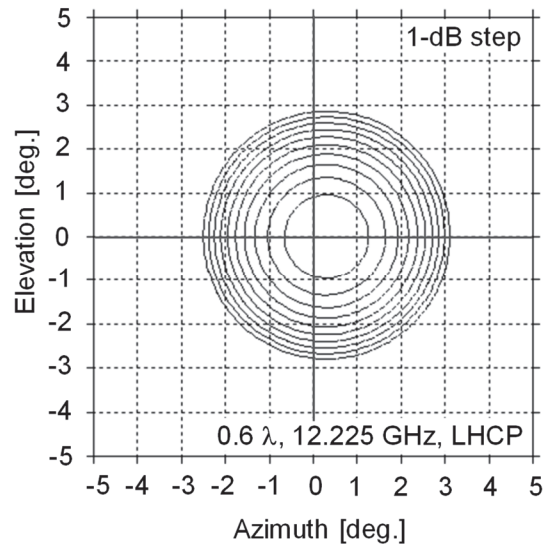


(b) LHCP antenna.

Fig. 2.21 Calculated main lobes of offset parabolic reflector antenna fed by 12-GHz-band 2×2 array antenna (spacing of elements is 0.7 wavelength).

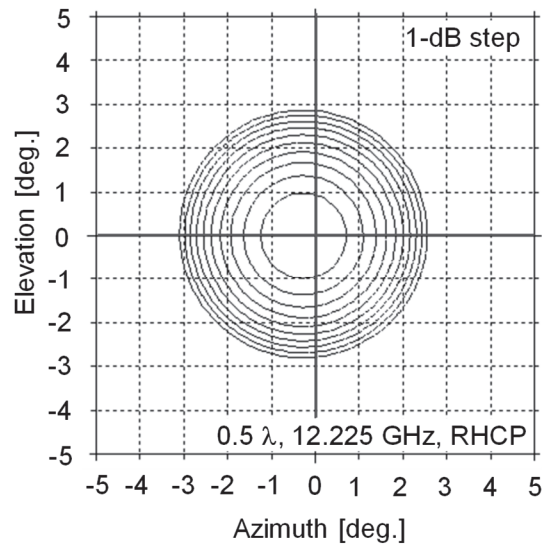


(a) RHCP antenna.

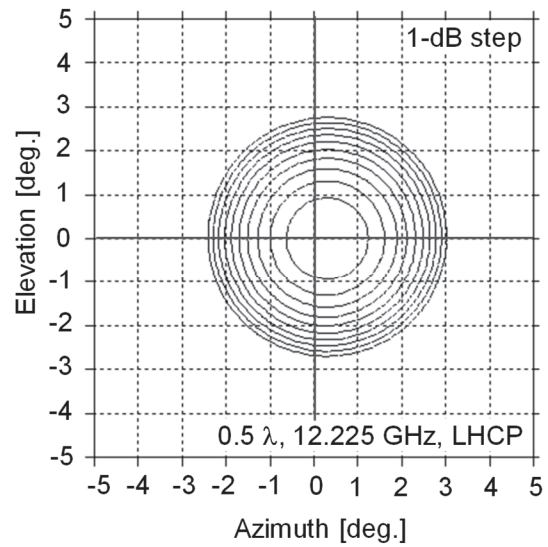


(b) LHCP antenna.

Fig. 2.22 Calculated main lobes of offset parabolic reflector antenna fed by 12-GHz-band 2×2 array antenna (spacing of elements is 0.6 wavelength).

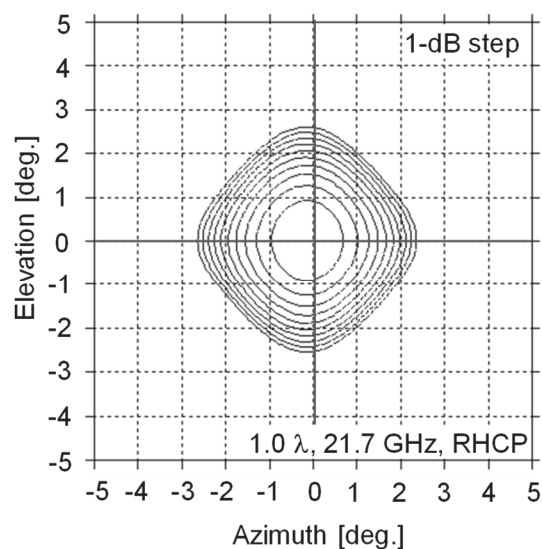


(a) RHCP antenna.

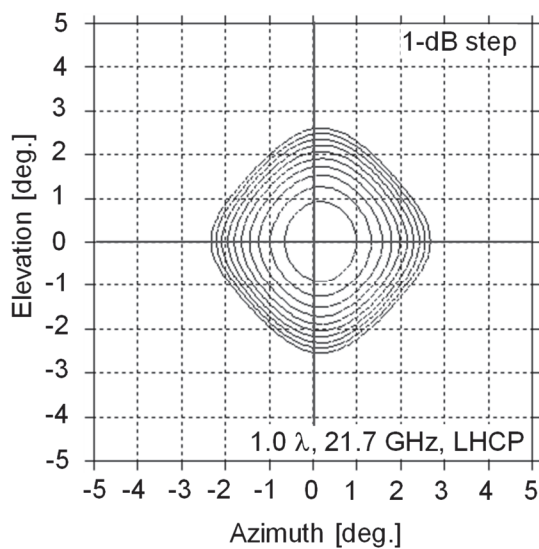


(b) LHCP antenna.

Fig. 2.23 Calculated main lobes of offset parabolic reflector antenna fed by 12-GHz-band 2×2 array antenna (spacing of elements is 0.5 wavelength).

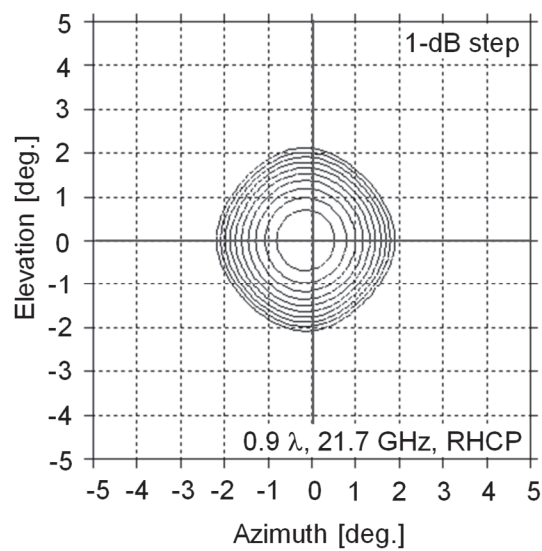


(a) RHCP antenna.

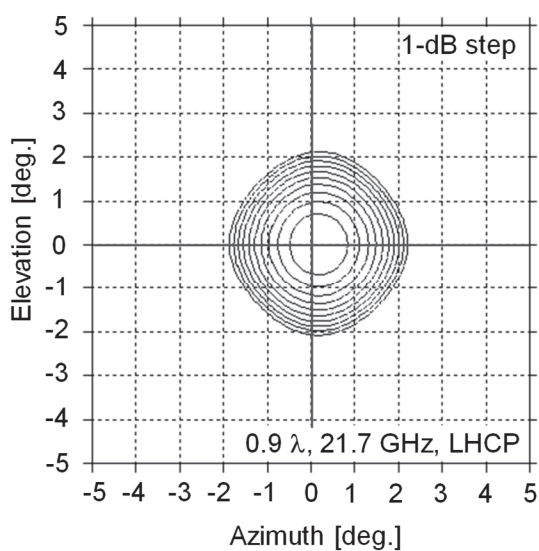


(b) LHCP antenna.

Fig. 2.24 Calculated main lobes of offset parabolic reflector antenna fed by 21-GHz-band 2×2 array antenna (spacing of elements is 1.0 wavelength).

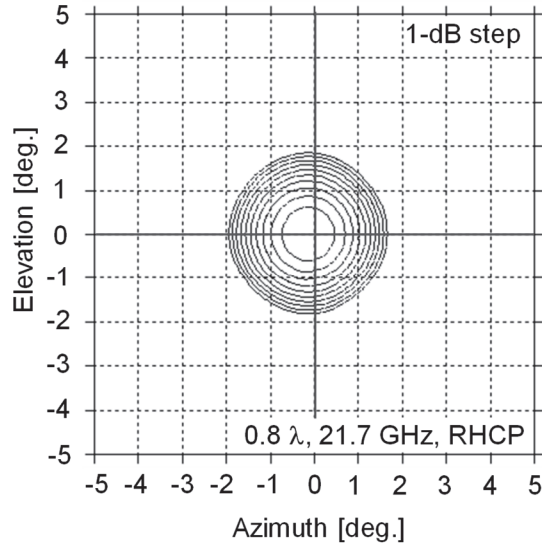


(a) RHCP antenna.

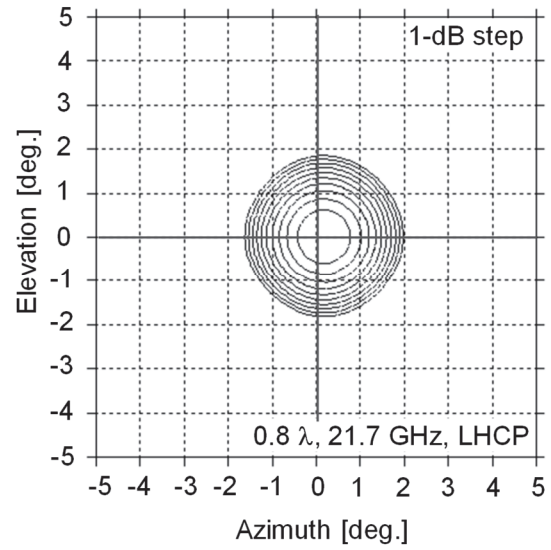


(b) LHCP antenna.

Fig. 2.25 Calculated main lobes of offset parabolic reflector antenna fed by 21-GHz-band 2×2 array antenna (spacing of elements is 0.9 wavelength).

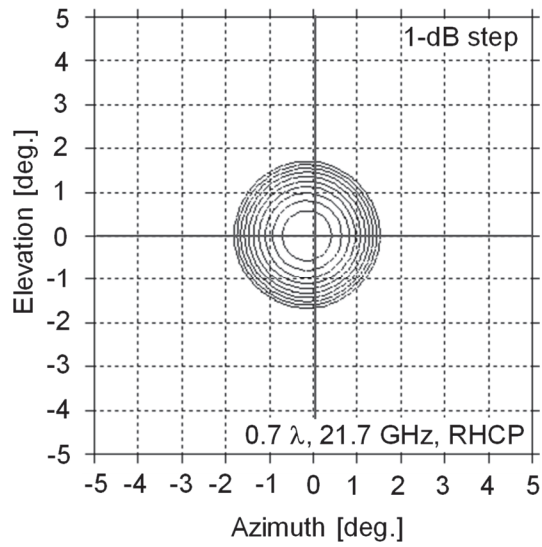


(a) RHCP antenna.

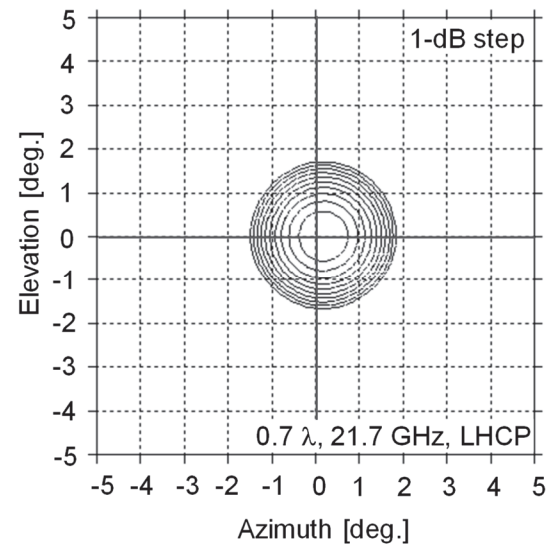


(b) LHCP antenna.

Fig. 2.26 Calculated main lobes of offset parabolic reflector antenna fed by 21-GHz-band 2×2 array antenna (spacing of elements is 0.8 wavelength).

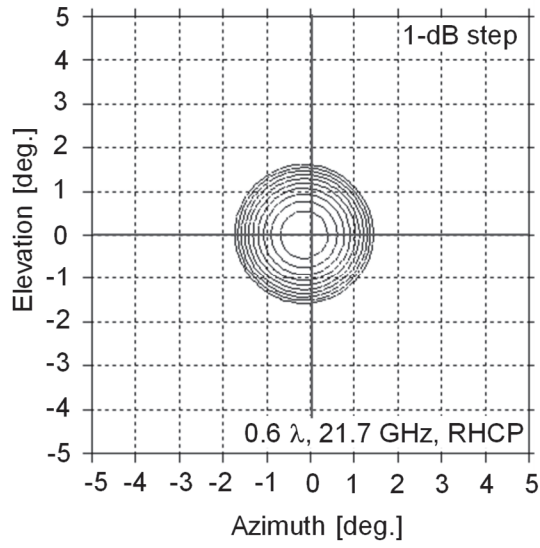


(a) RHCP antenna.

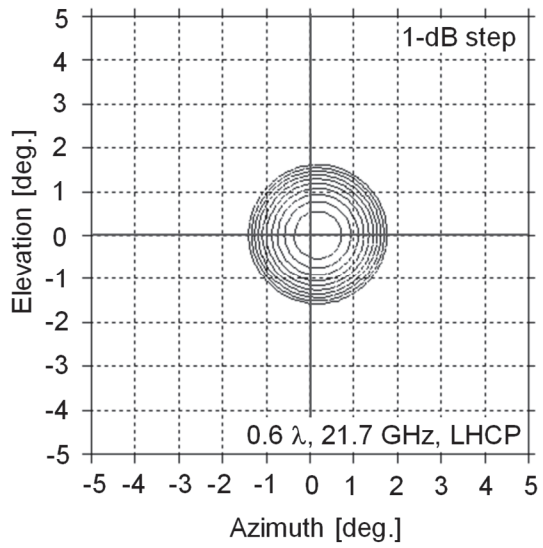


(b) LHCP antenna.

Fig. 2.27 Calculated main lobes of offset parabolic reflector antenna fed by 21-GHz-band 2×2 array antenna (spacing of elements is 0.7 wavelength).

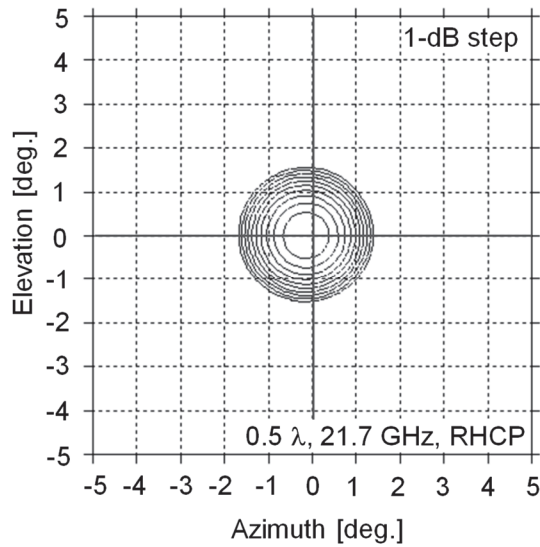


(a) RHCP antenna.

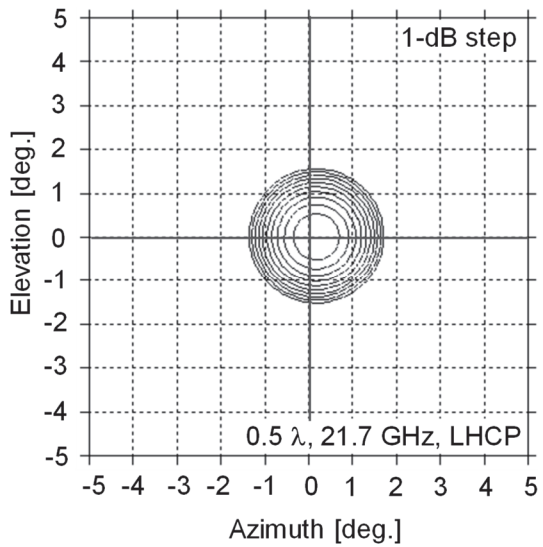


(b) LHCP antenna.

Fig. 2.28 Calculated main lobes of offset parabolic reflector antenna fed by 21-GHz-band 2×2 array antenna (spacing of elements is 0.6 wavelength).



(a) RHCP antenna.



(b) LHCP antenna.

Fig. 2.29 Calculated main lobes of offset parabolic reflector antenna fed by 21-GHz-band 2×2 array antenna (spacing of elements is 0.5 wavelength).

2.6 Concluding Remarks

In this chapter, the basic design of the proposed feed that is composed of two 2×2 microstrip array antennas was shown. The size of the square and circular MSAs were compared, and the ratio of the higher to lower frequency-band for the proposed feed was obtained. Then, the square and circular MSAs were chosen for the elements of the lower and higher frequency-band arrays, respectively. The far field conditions of the feed were also derived. Moreover, parameters of a reflector used with the proposed feed were studied to achieve enough gain for the right- and left-hand circular polarizations. The FD ratio of 0.6 was selected, and the aperture angle of 77.2 deg. was obtained.

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Chapter 3

Design of Dual-circularly Polarized Planar Feed for Offset Parabolic Reflector Antenna in the 12-GHz Band

3.1 Introductory Remarks

This chapter presents the design process and characterization of a dual-circularly polarized planar feed, which has a 12-GHz-band microstrip antenna (MSA) array, for an offset parabolic reflector antenna. In this chapter, the feasibility of the dual-circularly polarized feed composed of the MSA array is evaluated. For obtaining enough gain and cross polarization discrimination (XPD) throughout the 12-GHz band for satellite broadcasting reception, the feed is composed of a 2×2 MSA array that is sequentially rotated to enhance polarization purity [3.1].

This chapter is organized as follows. Section 3.2 describes the design procedure of a dual-circularly polarized planar feed that is composed of wide-band microstrip antennas. In Section 3.3, measured results of the fabricated antenna are shown. Section 3.4 concludes this chapter.

3.2 Design of Dual-circularly Polarized Planar Feed for 12-GHz Band Satellite Broadcasting Receiving Antenna

3.2.1 Performance Targets and Basic Configuration

The performance targets for a dual-circularly polarized receiving reflector antenna are listed in Table 3.1. The gain is 33 dBi, which was determined from the peak gain of a 45-cm parabolic reflector antenna (aperture efficiency: 60%), as described in Section 1.5. The XPD was derived from the reference pattern in Recommendation ITU-R BO.1213 [3.2]. To receive small signals from satellites, the upper limit of the voltage standing wave ratio (VSWR) is 1.5 throughout the 12-GHz band. The edge illumination level (EIL) is -11 ± 1 dB to obtain high aperture efficiency [3.3].

The configuration of the reflector antenna with the proposed planar feed is shown in Fig.3.1. This antenna has a feed that uses a 2×2 MSA array to obtain higher XPD. The size of the feed is assumed to be 5×5 cm, which is equivalent to that of a low-noise block converter with a horn antenna for consumer use in Japan. Therefore, to avoid blocking receiving signals, the clearance (X_c) of the reflector is 3 cm. The diameter (D) is 50 cm to obtain enough gain throughout the 12-GHz band for both polarizations. In this study, a dual-polarization reflector antenna with the dual-polarization feed is manufactured and tested.

Table 3.1 Performance targets for receiving reflector antenna.

Item	Value
Receiving frequencies	11.7 to 12.75 GHz
Polarizations	RHCP and LHCP
Gain	33 dBi
XPD	≥ 25 dB (at boresight)
EIL	-11 ± 1 dB
VSWR	< 1.5
Impedance	50Ω

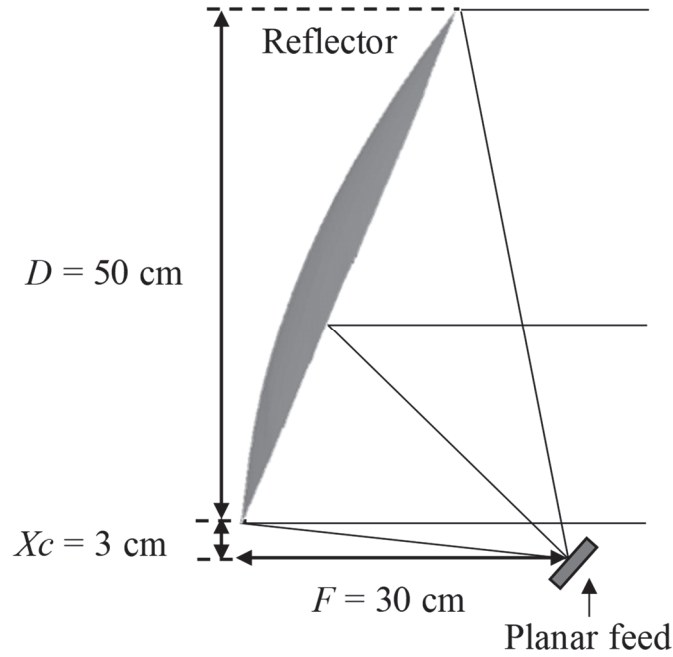


Fig. 3.1 Configuration of proposed antenna with planar feed.

3.2.2 Design of Dual-circularly Polarized Wide-band Microstrip Antenna

Fig. 3.2 shows the configuration of the designed MSA. Its multilayer structure uses polytetrafluoroethylene (PTFE, ϵ_r is 2.59, $\tan\delta$ is 0.0018, typically) substrates to obtain a wide frequency bandwidth, which is 1050 MHz (i.e., the fractional bandwidth is 8.6%). The impedance bandwidth can increase with a thick substrate, but there is a physical limit of the substrate thickness. Hence, the maximum substrate thickness was set to $\lambda_\epsilon / 16$ [3.4], where λ_ϵ is the wavelength in the dielectric. This MSA had two feeding ports to obtain circular polarization. Feeding is realized by electromagnetic coupling with the bottom patch via feeding slots. In the following sections, the 3D electromagnetic field analysis simulator, CST Studio Suite [3.5], was used to analyze the antenna characteristics of the MSA and MSA array. Fig. 3.3 shows the calculated VSWR of the designed MSA and the effectiveness of the multilayer structure. In Fig. 3.3, the red line shows an MSA with the top layer and the blue line shows the MSA without the top layer. The calculated VSWR was within the 1.5 limit for the 12-GHz band with the multilayer structure. Its maximum value was 1.25.

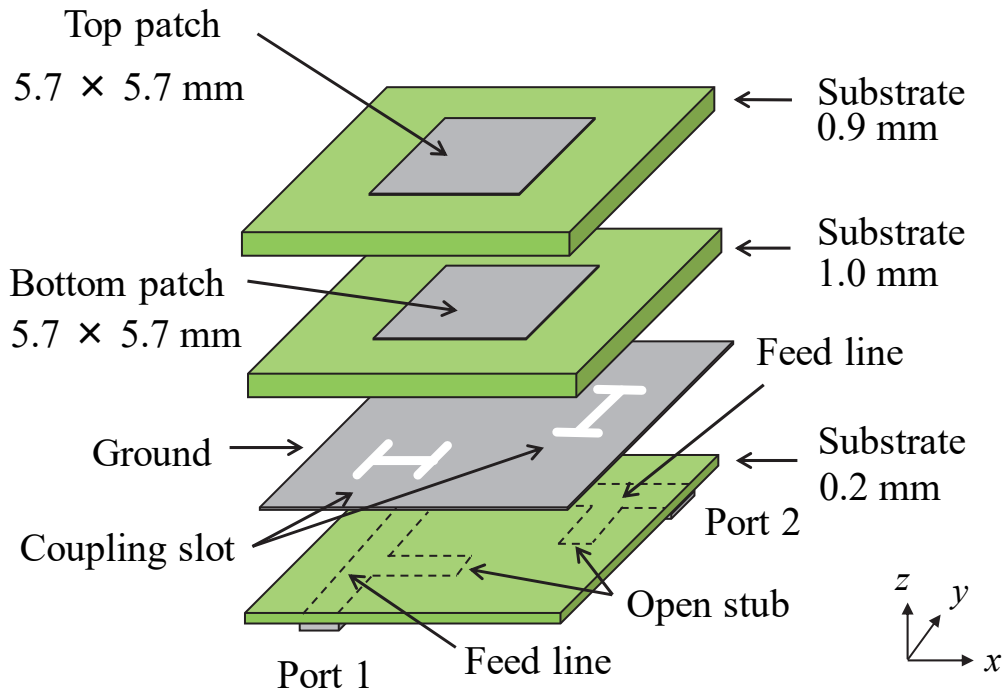


Fig. 3.2 Wide-band MSA with multilayer structure.

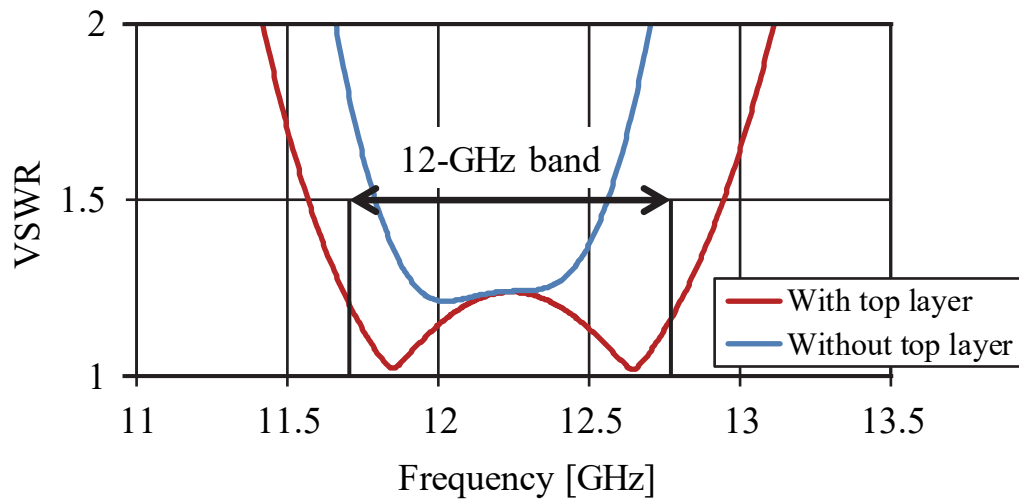


Fig. 3.3 Calculated VSWR of MSA.

Circular polarization was provided by feeding 90-degree-shifted signals to the two feed lines. When the feeding phase of port 2 was delayed for 90 degrees, the MSA radiated RHCP, and when the feeding phase of port 1 was delayed for 90 degrees, the MSA radiated LHCP. Fig. 3.4 shows the calculated radiation pattern of the MSA. This radiation pattern indicates that the designed MSA operates as a circular polarized antenna. However, the beamwidth of the co-polarization pattern was too broad to use as the feed of the offset parabolic reflector antenna. The XPD was 20 dB (at 0 deg.) and was less than the target value listed in Table 3.1. The cross-polarization pattern was also asymmetric because the coupling slots were not in the center of the patch.

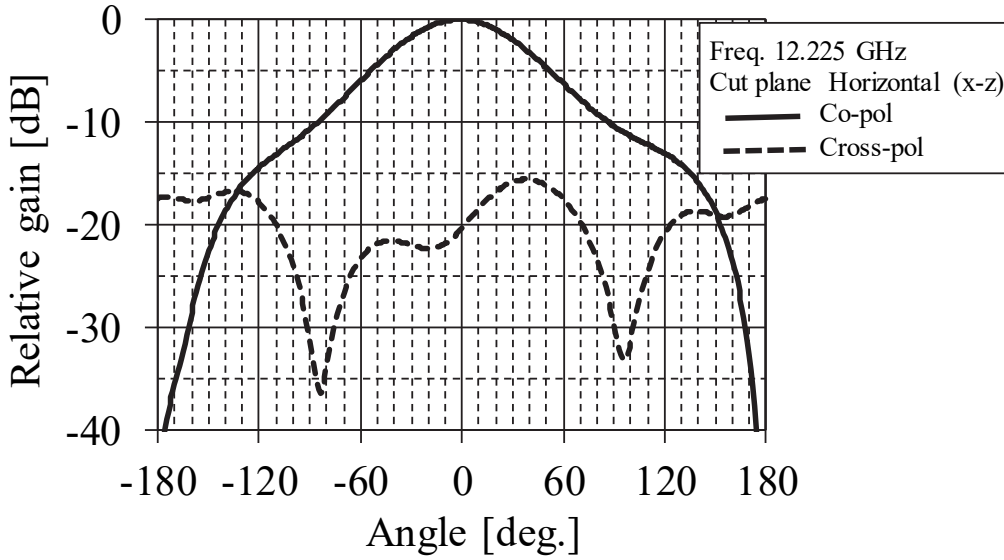


Fig. 3.4 Calculated radiation pattern of MSA.

3.2.3 Design of Dual-circularly Polarized Feed with Four-element Microstrip Antenna Array

Fig. 3.5 shows the configuration of the designed feed that is composed of a 2×2 MSA array in which the elements are sequentially rotated to enhance the polarization purity [3.1]. An element spacing of 0.6 wavelengths (14.7 mm) was determined to obtain a suitable beamwidth for the offset parabolic reflector antenna. The basic design of the parabolic reflector is described in Section 3.2.1. The size of the feed is 50×50 mm, which was derived from a low-noise block converter with a horn antenna for consumer use in Japan.

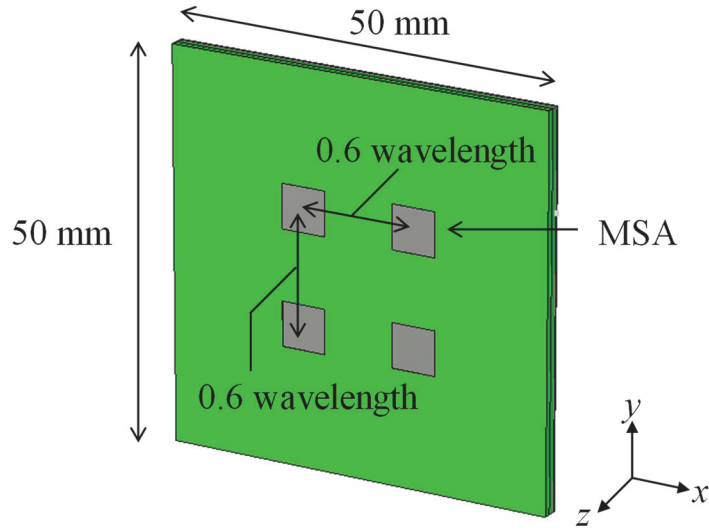


Fig. 3.5 Top view of designed MSA array.

Fig. 3.6 shows the designed feed circuit, which is in the back of the MSA array. The feeding phase of the m -th patch is shifted to $90 \times (m-1)$ degrees by using 3-dB, 90-degree hybrid couplers (3dB-HYBs) and differences in the line length. Because the MSAs are fed two 90-degree-shifted signals, the feeding phases of the adjacent MSA are the same by applying the sequentially rotation technique. Therefore, there are no cross sections of the feeding lines in the designed circuit.

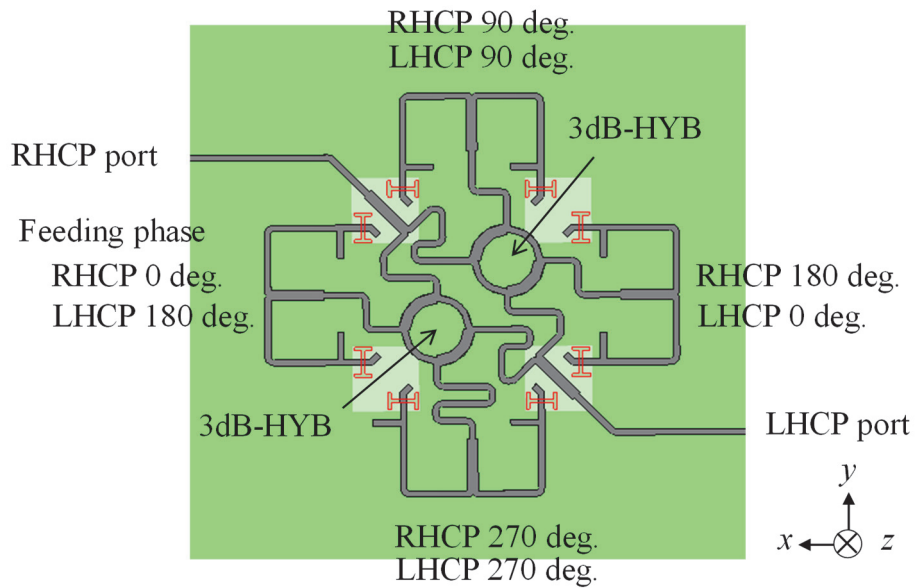


Fig. 3.6 Feed circuit (back view).

Fig. 3.7 shows a calculated radiation pattern of the designed MSA array. The solid- and dashed-line show co-polarization (RHCP) and cross-polarization (LHCP), respectively. The calculated frequency was 12.225 GHz (the center frequency of the 12-GHz band). The calculated gain was 12.1 dBi. As shown in Fig. 3.7, a suitable beamwidth was obtained since the aperture angle of the designed reflector was 77.2 deg. (± 38.6 deg.), which is described in Section 2.5. Moreover, the XPD was more than 30 dB, which complied with the target value (25 dB).

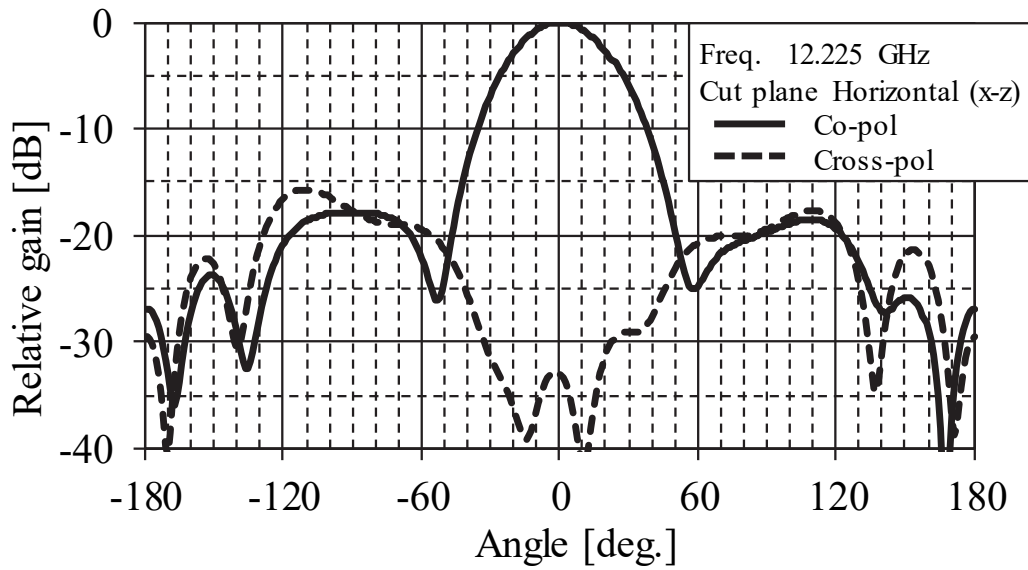


Fig. 3.7 Calculated radiation pattern of MSA array.

3.3 Prototype of Dual-circularly Polarized Offset Parabolic Reflector Antenna

3.3.1 Prototype Antenna

The designed dual-circularly polarized offset parabolic reflector antenna was fabricated and tested. Fig. 3.8 shows the prototype antenna. To prevent degradation of the radiation patterns stemming from reflector errors, the reflector was fabricated by machining an aluminum panel. A reflector made with press is generally used for consumer use. The estimated gain degradation due to reflector errors [3.6] is less than 0.1 dB because the error of a reflector made with press was 0.26 mm RMS based on the measured results [3.7]. Fig. 3.9 shows the 2×2 MSA array, which has two SMP connectors to connect the coaxial cables for the measurements. The substrates, of which the multilayer structure is configured, are fixed with plastic screws, and prepreps are not used for attaching the substrates.

In Section 3.3.2, the electric characteristics of the feed are explained. In Section 3.3.3, the performance of the reflector antenna is described. The feed and reflector antenna were measured by using a compact antenna test range (CATR) at five frequency points (11.7, 12, 12.225, 12.5, and 12.75 GHz), and the measured radiation patterns in the lower- end, center, and upper-end frequencies of the 12-GHz band are presented, which are 11.7, 12.225, and 12.75 GHz, respectively. The horizontal plane that corresponds to the geostationary orbit was evaluated.

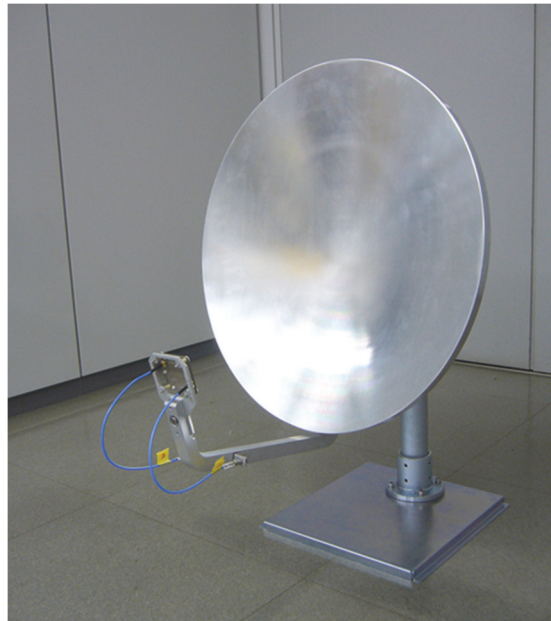
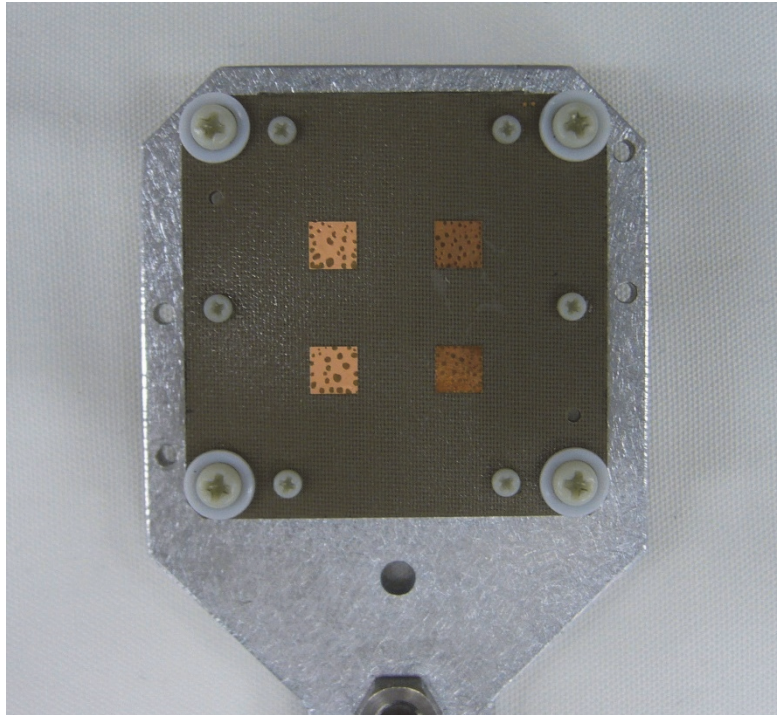
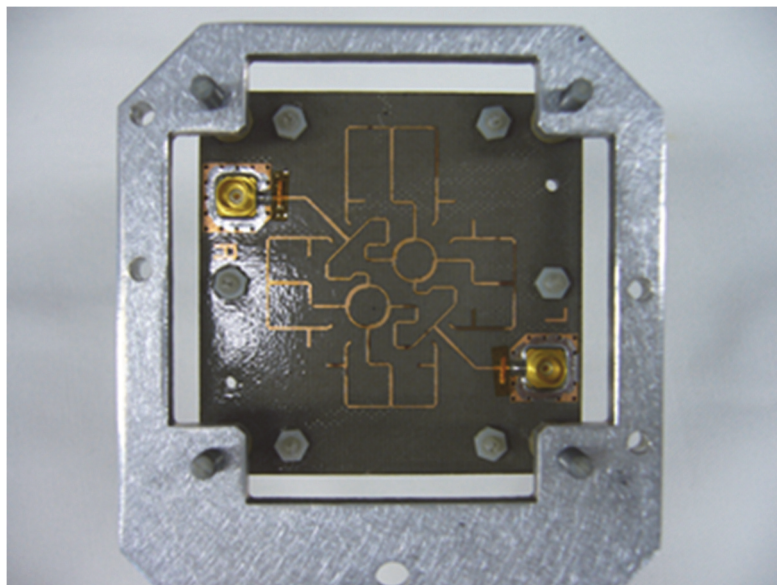


Fig. 3.8 Fabricated receiving antenna.



(a) Front view.



(b) Back view.

Fig. 3.9 Feed composed of 2×2 MSA array.

3.3.2 Measured Characteristics of Feed

In this section, the measured results of the fabricated feed are explained. The polarizations, which are discussed in this section, are defined as the radiated polarizations from the feed. Fig. 3.10 shows the measured VSWR of the feed that is installed to the reflector as shown in Fig. 3.8. The VSWR was less than 1.4 in the target range of the frequency band, which satisfied the target value (VSWR 1.5). The impedance bandwidth of the feed was wider than that of the MSA (shown in Fig. 3.3) because the reflected power of the MSA was canceled in the feed circuit.

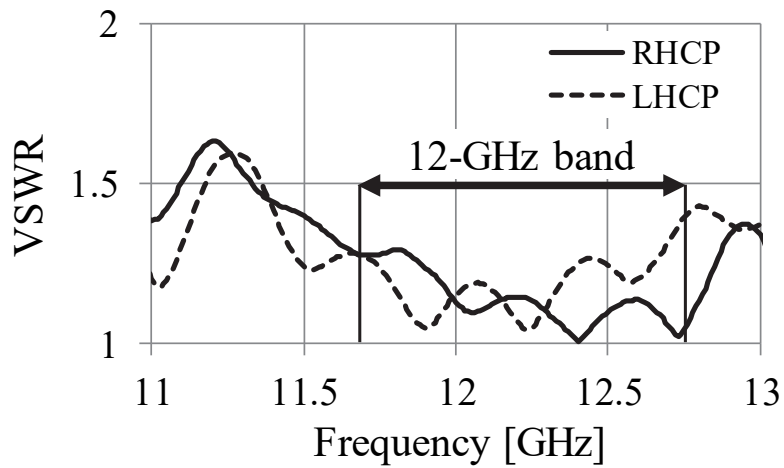
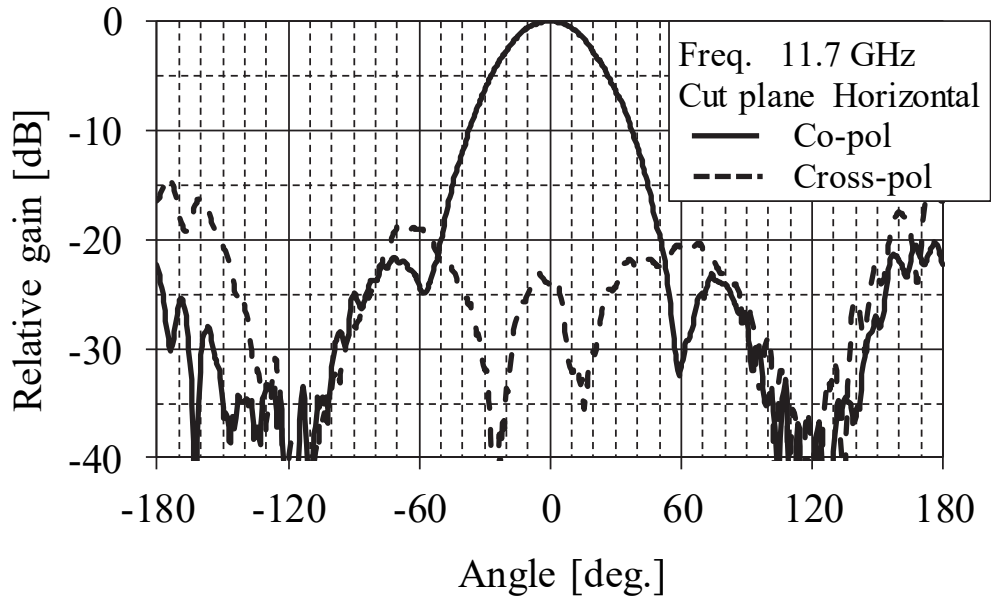


Fig. 3.10 Measured VSWR of feed.

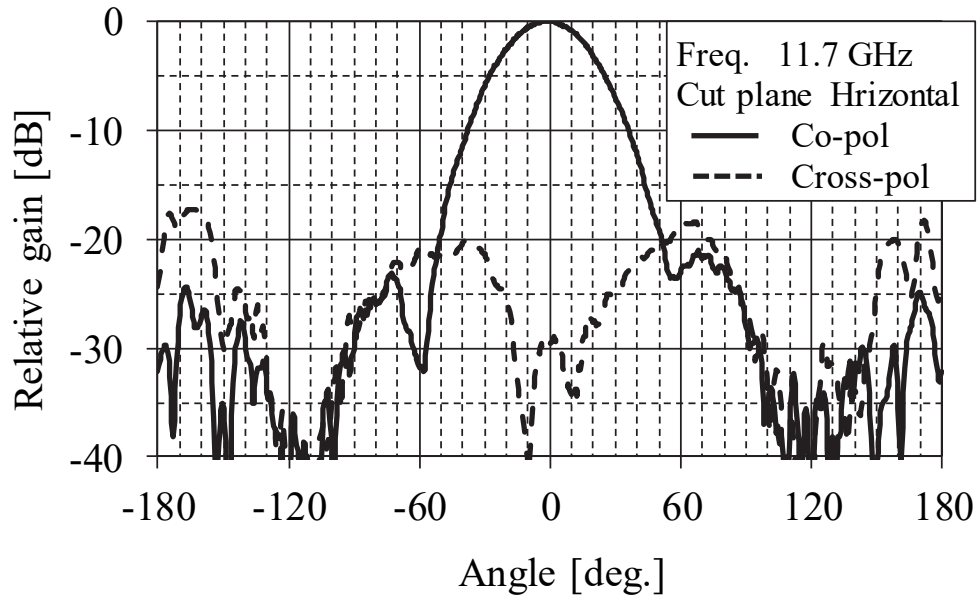
The measured gain and XPD are listed in Table 3.2. The measured gain includes the feeding loss. The fabricated feed operated as a dual-circularly polarized antenna in the 12-GHz band because the frequency response of the gain was flat in both polarizations. The gain and XPD were about 12 dBi and 30 dB, respectively. The difference in measured and calculated gain was less than 0.2 dB at the center frequency (12.225 GHz). Since the PTFE substrates have varied electrical performance in manufacturing, the measured gain value is reasonable. The worst value of XPD was 23.9 dB (at 11.7 GHz). The XPD with a combination of the feed and offset parabolic reflector is evaluated since the target values are for a receiving antenna. Figs. 3.11 to 3.13 show the measured radiation patterns of the feed. At the center frequency (12.225 GHz), the EILs of RHCP and LHCP were -12 to -10 dB, which complied with the target EIL value. The radiation of the feed circuit was less than -15 dB.

Table 3.2 Measured gain and XPD of fabricated feed.

Frequency [GHz]	Gain [dBi]	XPD (at boresight) [dB]
11.7	RHCP: 11.9 LHCP: 11.9	RHCP: 23.9 LHCP: 29.2
12	RHCP: 12.0 LHCP: 11.9	RHCP: 31.1 LHCP: 32.6
12.225	RHCP: 12.3 LHCP: 12.2	RHCP: 35.5 LHCP: 36.8
12.5	RHCP: 11.7 LHCP: 11.6	RHCP: 32.7 LHCP: 41.4
12.75	RHCP: 12.1 LHCP: 12.0	RHCP: 32.0 LHCP: 31.4

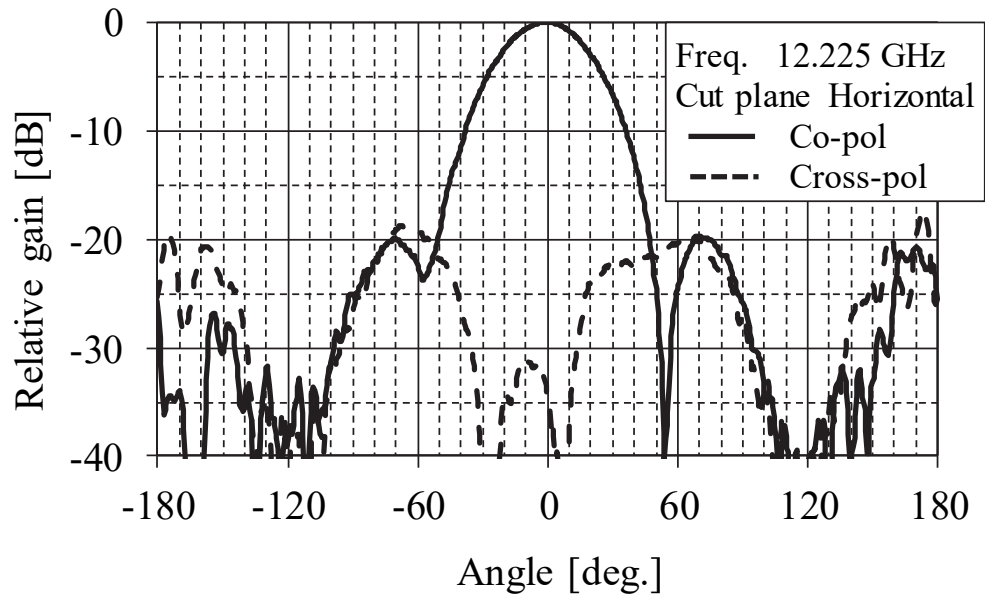


(a) RHCP antenna.

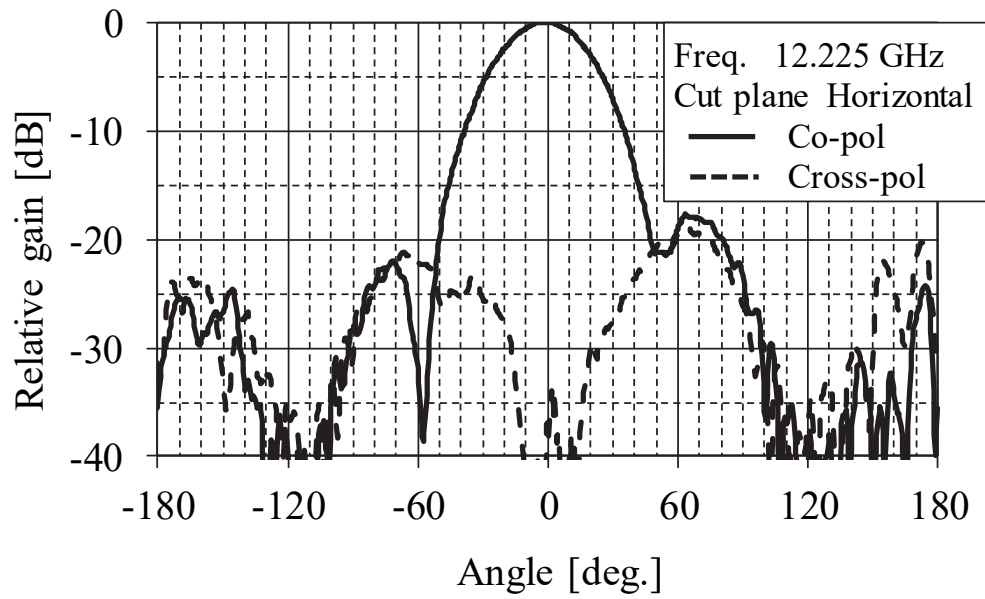


(b) LHCP antenna.

Fig. 3.11 Measured radiation patterns of feed (11.7 GHz).

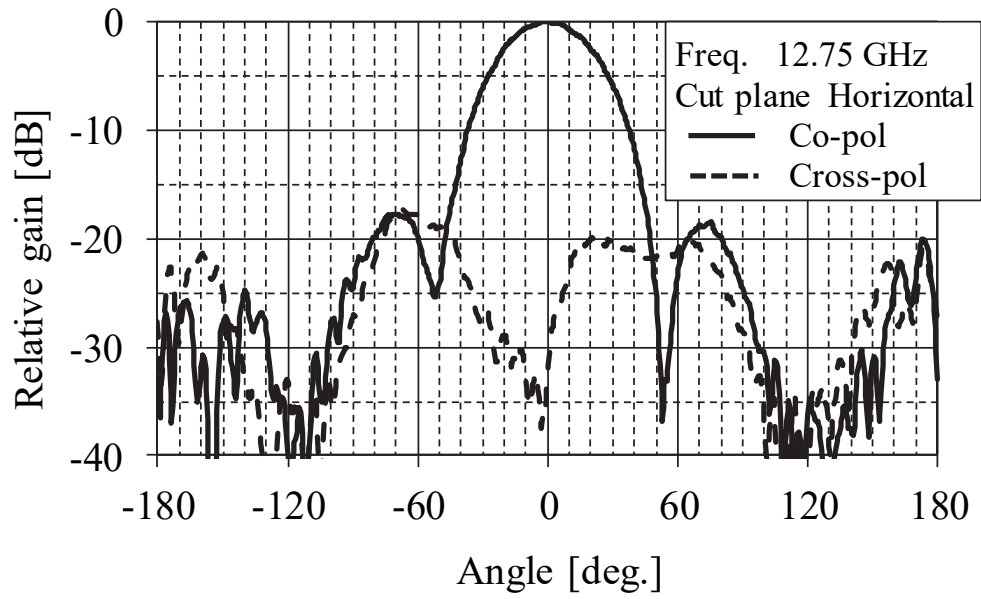


(a) RHCP antenna.

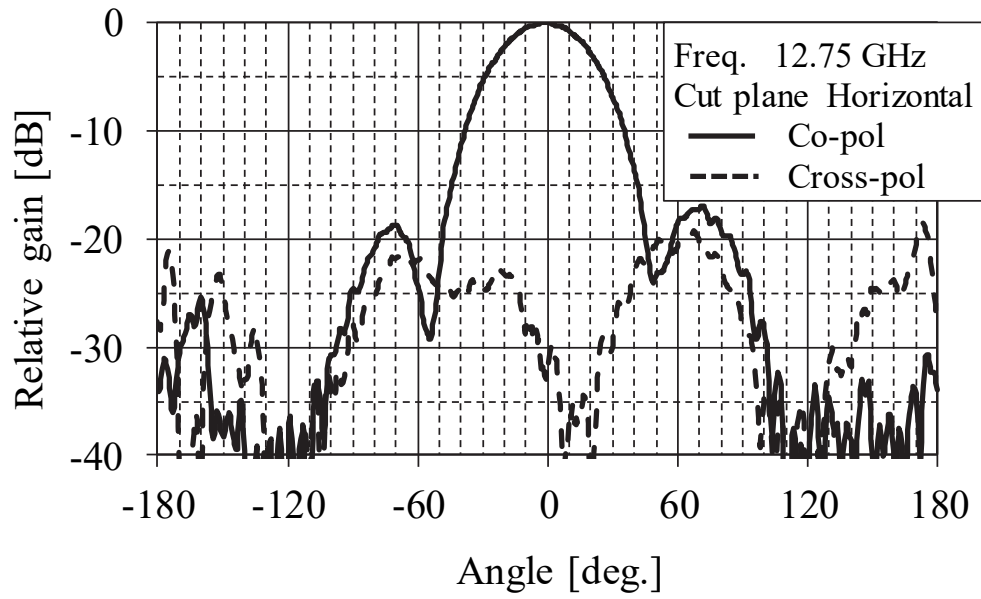


(b) LHCP antenna.

Fig. 3.12 Measured radiation patterns of feed (12.225 GHz).



(a) RHCP antenna.



(b) LHCP antenna.

Fig. 3.13 Measured radiation patterns of feed (12.75 GHz).

3.3.3 Measured Characteristics of Receiving Reflector Antenna

The measured results of the gain and XPD of the fabricated receiving reflector antenna are listed in Table 3.3. The polarization discussed in this section is defined as the radiated polarization from the reflector antenna. At the center frequency in the 12-GHz band (12.225 GHz), the gain and XPD were 34.5 dBi (i.e., the aperture efficiency was 69%) and 28.7 dB (at boresight), respectively. The gain of LHCP was lower than that of RHCP by 0.1 dB at the center frequency. The reason is that the EILs of RHCP and LHCP differed. The gains and XPDs satisfied the target values throughout the 12-GHz band.

Table 3.3 Measured gain and XPD of fabricated reflector antenna.

Frequency [GHz]	Gain [dBi]	XPD (at boresight) [dB]
11.7	RHCP: 33.6 LHCP: 33.4	RHCP: 26.0 LHCP: 41.1
12	RHCP: 33.1 LHCP: 33.2	RHCP: 28.4 LHCP: 31.0
12.225	RHCP: 34.6 LHCP: 34.5	RHCP: 28.7 LHCP: 32.7
12.5	RHCP: 33.8 LHCP: 34.6	RHCP: 30.2 LHCP: 25.6
12.75	RHCP: 33.6 LHCP: 34.7	RHCP: 26.4 LHCP: 25.7

Figs. 3.14 to 3.17 show the measured radiation patterns of the prototype antenna. Fig. 3.14 shows a gain of the co-polarization pattern peaks relative to RHCP. In this figure, the gain and angle difference, which are discussed in Section 2.5, were 0.4 dB and 0.5 degrees, respectively. Figs. 3.15 to 3.17 indicate the measured radiation patterns and reference patterns that are shown in Recommendation ITU-R BO.1213 (BO.1213) [3.2]. The measured radiation patterns were compared to the reference pattern of BO.1213 because BO.1213 is used for the interference calculation in the coordination of satellite networks. The measured patterns slightly exceeded the reference.

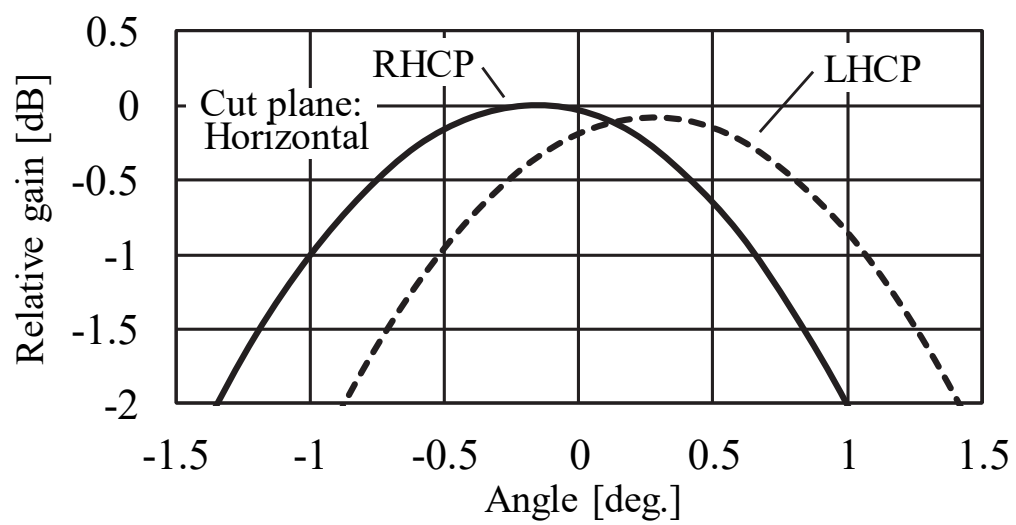
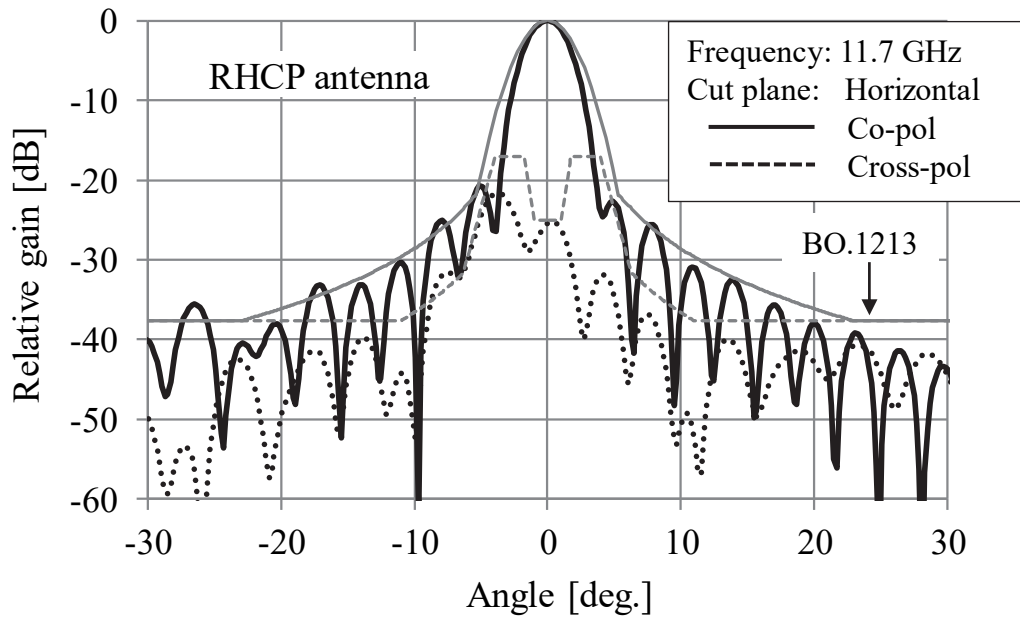
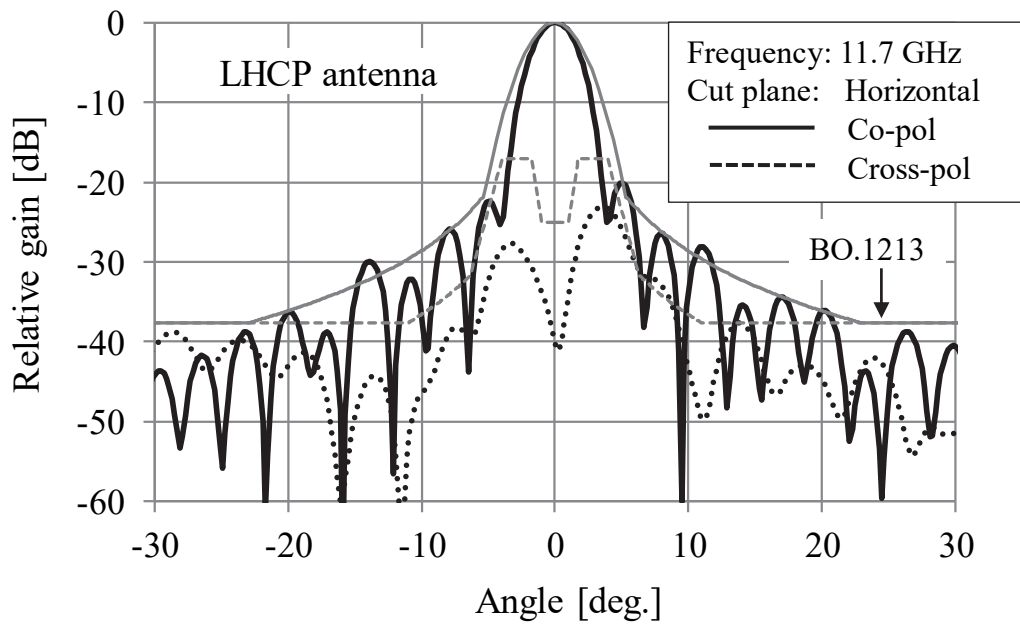


Fig. 3.14 Measured pattern peaks of fabricated reflector antenna (12.225 GHz).

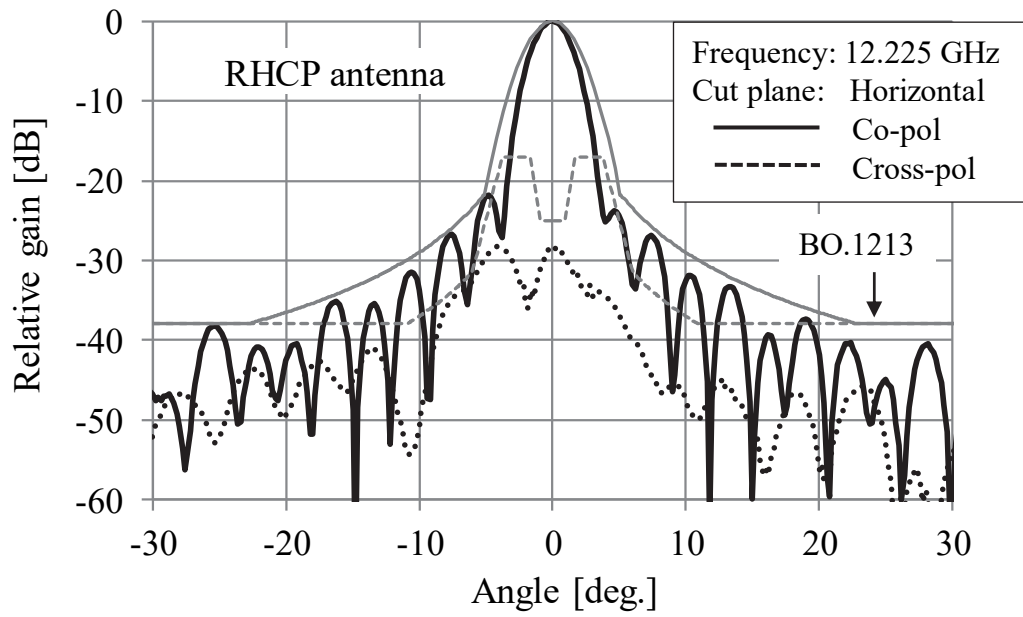


(a) RHCP antenna.

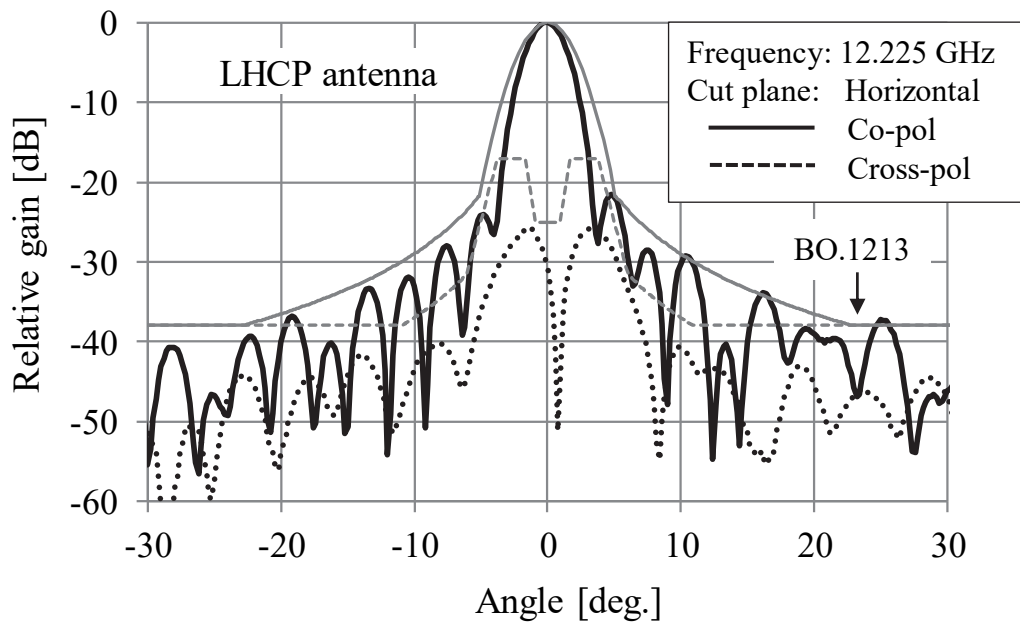


(b) LHCP antenna.

Fig. 3.15 Measured radiation patterns of fabricated reflector antenna (11.7 GHz).

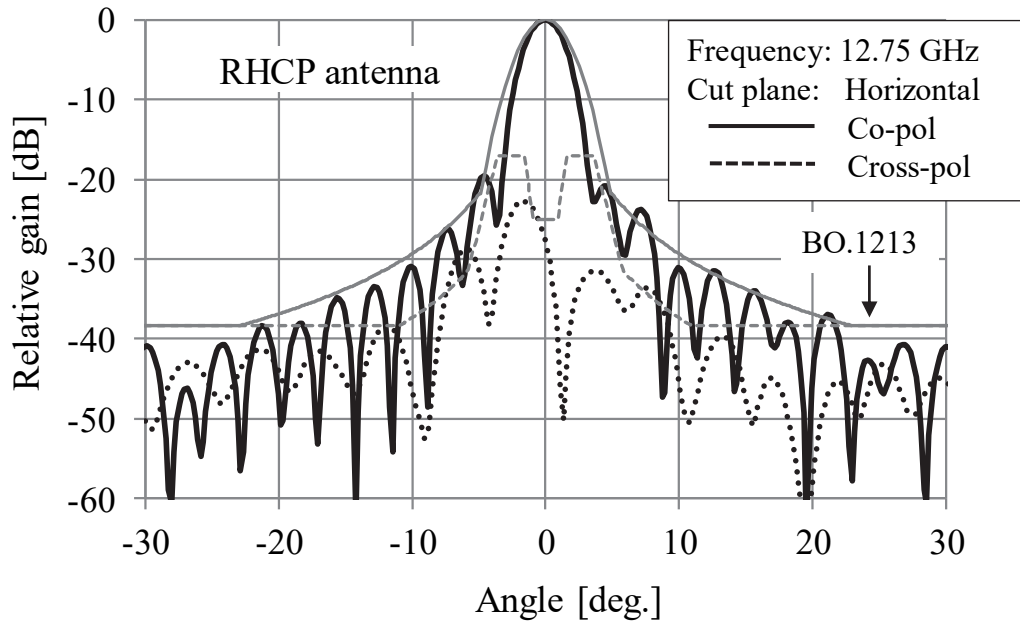


(a) RHCP antenna.

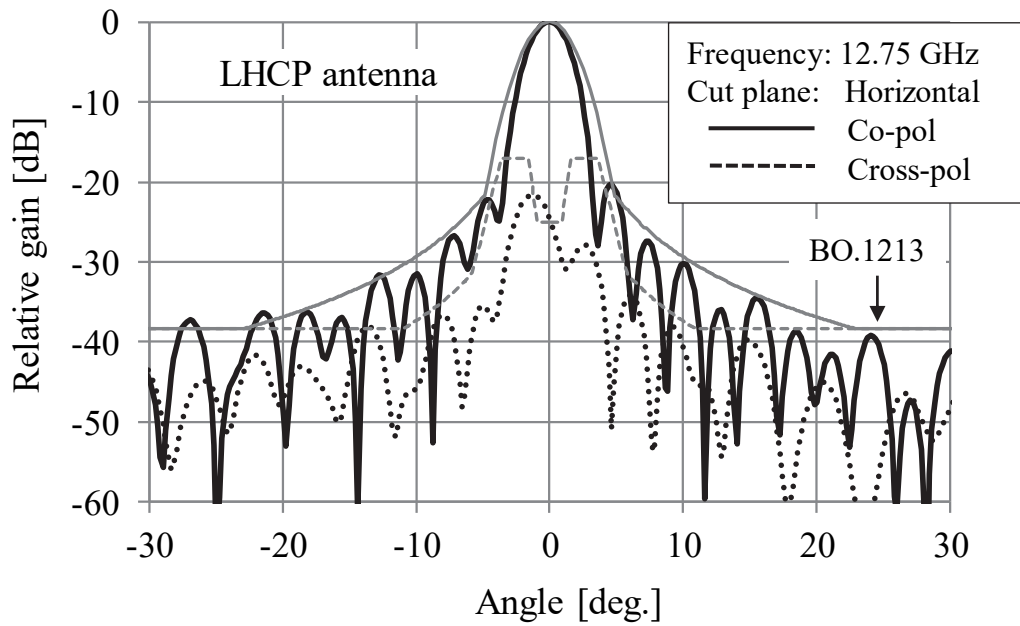


(b) LHCP antenna.

Fig. 3.16 Measured radiation patterns of fabricated reflector antenna (12.225 GHz).



(a) RHCP antenna.



(b) LHCP antenna.

Fig. 3.17 Measured radiation patterns of fabricated reflector antenna (12.75 GHz).

3.4 Concluding Remarks

A dual-circularly polarized receiving reflector antenna for satellite broadcasting in the 12-GHz band was manufactured and evaluated. The antenna has a 50-cm offset parabolic reflector and a feed composed of a 2×2 MSA array. The measured results indicate that the gain in the 12-GHz band was more than 33.1 dBi. The VSWR was less than 1.4, and the XPD was more than 25.6 dB throughout the band. The fabricated antenna complied with the performance targets.

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Chapter 4

Design of Dual-band Dual-circularly Polarized Planar Feed for Offset Parabolic Reflector Antenna in the 12- and 21-GHz Bands

4.1 Introductory Remarks

This chapter presents the design process and characterization of a dual-band dual-circularly polarized planar feed, which has a 12- and 21-GHz-band microstrip antenna (MSA) arrays, for an offset parabolic reflector antenna. To obtain enough gain and cross polarization discrimination (XPD) throughout both bands for satellite broadcasting reception, the feed is composed of two 2×2 MSA arrays that are sequentially rotated to enhance polarization purity [4.1], which are located at the same focal point with a multilayer structure. A feed circuit is also designed on the substrate, which makes it possible to divide the right- and left-hand-circularly polarized signals in both bands. The performance with a prototype reflector antenna, whose diameter is 50 cm, is discussed.

This chapter is organized as follows. Section 4.2 describes the design procedure of a dual-band dual-circularly polarized planar feed that is composed of dual-circularly polarized microstrip antennas. Section 4.3 shows the measured results of the fabricated offset parabolic reflector antenna with the feed. Section 4.4 concludes this chapter.

4.2 Design of 12- and 21-GHz Dual-band Dual-circularly Polarized Planar Feed for Satellite Broadcasting Receiving Reflector Antenna

4.2.1 Performance Targets and Basic Configuration

The performance targets for the 12- and 21-GHz dual-band dual-circularly polarized receiving reflector antenna are listed in Table 4.1. The gain values in the 12- and 21-GHz bands are 33 and 38 dBi, respectively, which were determined from the peak gain of a 45-cm parabolic reflector antenna (aperture efficiency: 60%), as described in Section 1.5. The XPD was derived from the reference pattern in Recommendation ITU-R BO.1213 [4.2] at boresight. The upper limit of the voltage standing wave ratio (VSWR) is 1.5 throughout the 12- and 21-GHz bands to receive small signals from the satellite.

The configuration of the reflector antenna with the proposed planar feed is shown in Fig. 4.1. In this study, an offset parabolic reflector, which is generally used for satellite receiving antennas, was selected. The reflector is fed by 12- and 21-GHz-band MSA arrays located at the same focal point with a multilayer structure. This feed uses two 2×2 MSA arrays to obtain a suitable beamwidth for each band. The size of the feed was assumed to be 50×50 mm, which is equivalent to that of a low-noise block converter with a horn antenna for consumer use in Japan. Therefore, to avoid blocking receiving signals, the clearance (X_c in Fig. 4.1) of the reflector is 3 cm. A 50-cm-diameter reflector was selected to obtain enough gain in both bands assuming feeding loss in the MSA arrays. To mitigate a beam squint angle [4.3], the focal length is 30 cm, i.e., the ratio of the focal length to the diameter (F/D) is 0.6, as discussed in Section 2.5. In this study, a 12- and 21-GHz-band dual-circularly polarized parabolic reflector antenna fed by the MSA arrays was manufactured and tested.

Table 4.1 Performance targets for receiving reflector antenna

Item	Frequency bands	
	12-GHz band	21-GHz band
Receiving frequencies	11.7 to 12.75 GHz	21.4 to 22 GHz
Polarizations	RHCP and LHCP	RHCP and LHCP
Gain	33 dBi	38 dBi
XPD	≥ 25 dB (at boresight)	≥ 25 dB (at boresight)
VSWR	≤ 1.5	≤ 1.5
Impedance	50Ω	50Ω

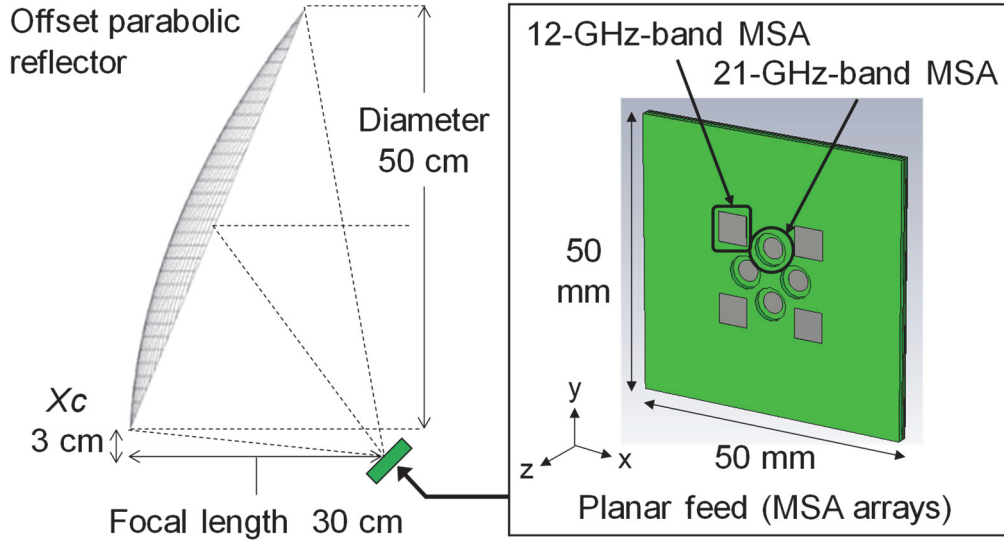


Fig. 4.1 Configuration of proposed antenna with planar feed.

4.2.2 Design of Dual-circularly Polarized Wide-band Microstrip Antenna

Figs. 4.2 and 4.3 show the configuration of the designed 12- and 21-GHz-band MSAs. Each MSA has an open stub for impedance matching, which makes it possible to adjust the impedance of the MSAs widely. To obtain a wide frequency bandwidth in the 12-GHz band (11.7 to 12.75 GHz), which is 1050 MHz, i.e., the fractional bandwidth is 8.6%, the MSAs have a multilayer structure that uses polytetrafluoroethylene (PTFE) substrates (ϵ_r is 2.55, and $\tan\delta$ is 0.0015, typically). A stacked structure was used for the MSAs to obtain enough frequency bandwidth, especially in the 12-GHz band. This structure for the 21-GHz band was also used to avoid mismatching due to frequency-shifting by fabrication error. The impedance bandwidth can increase with a thick substrate, but there is a physical limit to the substrate thickness. Hence, the maximum substrate thickness was set to $\lambda_\epsilon/16$ [4.4], where λ_ϵ is the wavelength in the dielectric. Three substrates were arranged between the ground plane and the 12-GHz-band bottom patch, as shown in Fig. 4.4, since the maximum thickness in the 21-GHz band is smaller than that in the 12-GHz band.

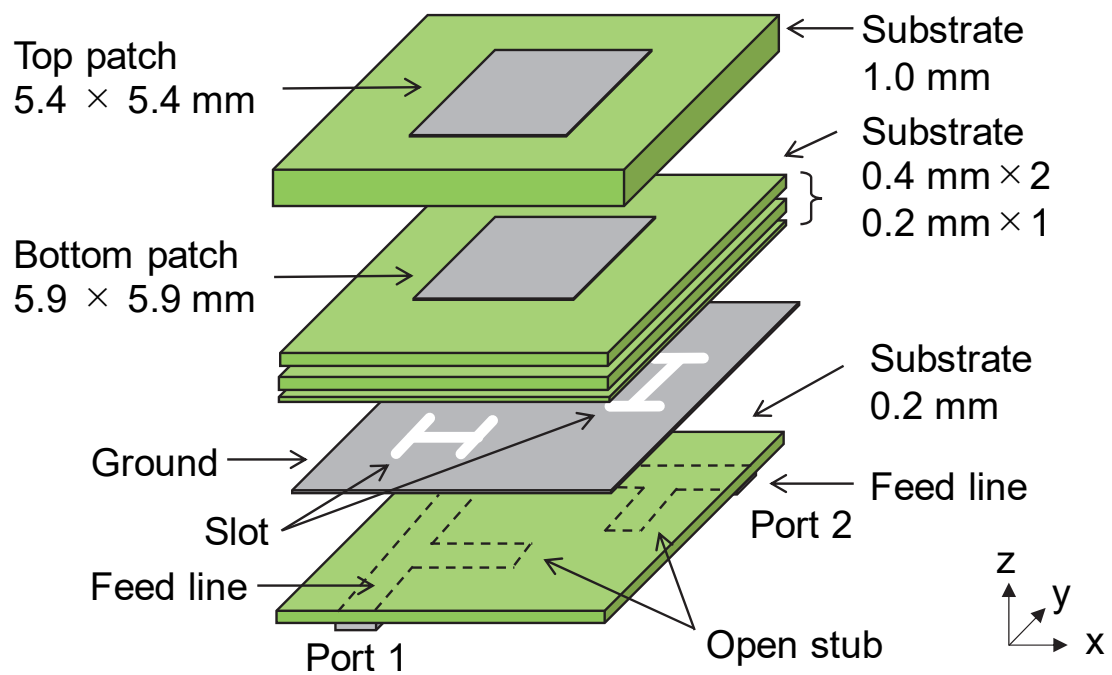


Fig. 4.2 Designed 12-GHz-band MSA.

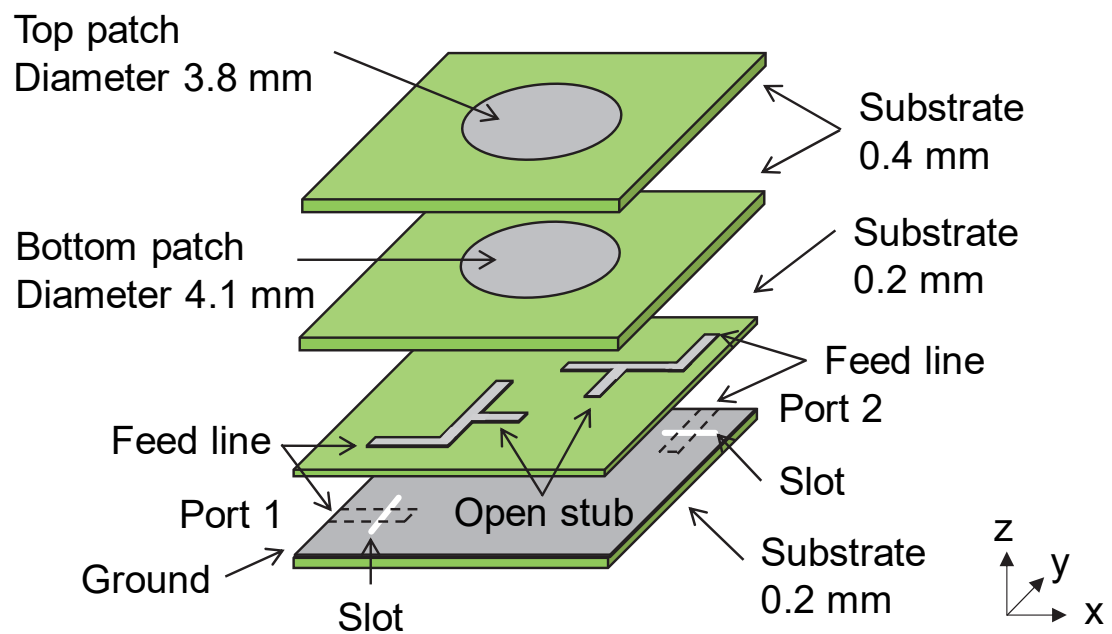


Fig. 4.3 Designed 21-GHz-band MSA.

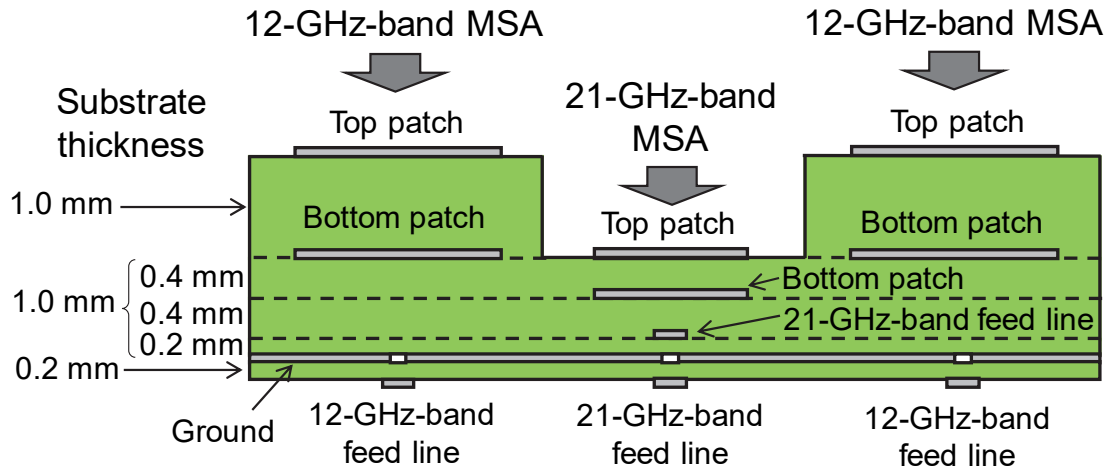
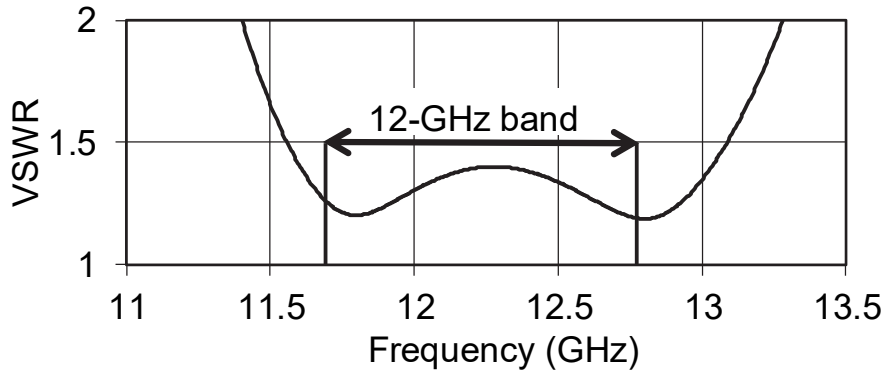
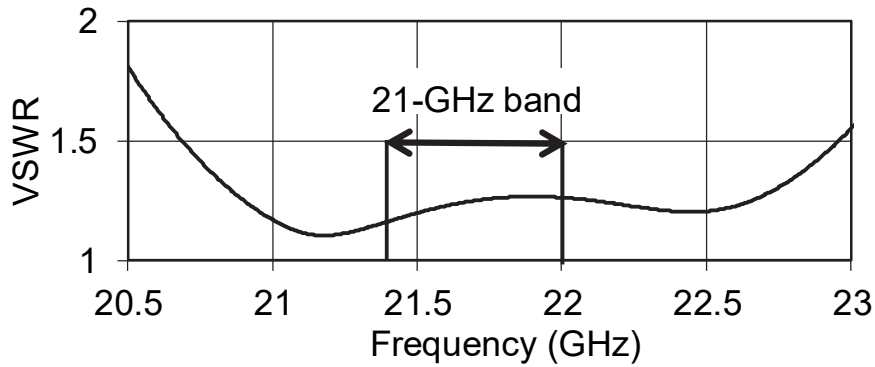


Fig. 4.4 Layer configuration of MSAs (schematic).

The MSAs have two feeding ports to obtain circular polarization. For the 12-GHz-band MSA, feeding is realized by electromagnetic coupling with the bottom patch via feeding slots. For the 21-GHz band, the 21-GHz-band feed lines were arranged above the ground plane and coupled onto the feed circuit with slots because a dual-band feed circuit became complicated. Then, feeding is realized by proximity coupling with the bottom patch for the 21-GHz band. The coupling slot on the ground plane for the 21-GHz band has a width of 0.1 mm and a length of 4.6 mm, and the calculated VSWR and insertion loss of the slot were not more than 1.14 and 0.5 dB throughout the 21-GHz band, respectively. In the following sections, a 3D electromagnetic field analysis simulator, CST Studio Suite [4.5], was used to analyze the antenna characteristics of the MSAs and MSA arrays. Fig. 4.5 shows the calculated VSWRs of the MSAs. The VSWR was within the target throughout both bands. The maximum values of the 12- and 21-GHz bands were 1.4 and 1.3, respectively.



(a) VSWR in the 12-GHz band.



(b) VSWR in the 21-GHz band.

Fig. 4.5 Calculated VSWR of designed MSAs.

The circular polarization was provided by feeding 90-deg.-shifted signals to the two feed lines. When the feeding phase of port 2 was delayed for 90 deg., the MSAs radiated RHCP, and when the feeding phase of port 1 was delayed for 90 deg., the MSAs radiated LHCP. Figs. 4.6 and 4.7 show the calculated radiation patterns of the MSAs. The solid and dashed lines show co-polarization (co-pol) and cross-polarization (cross-pol) patterns, respectively. The calculated frequencies were 12.225 and 21.7 GHz (the center frequency of each band). These radiation patterns indicate that the designed MSAs operate as circular polarized antennas.

However, the beamwidth of the co-pol patterns was too broad to use for the feed of the offset parabolic reflector antenna. The XPDs (at 0 deg.) were also less than 25 dB, which is the target. The radiation pattern of the 12-GHz band MSA was asymmetric because the coupling slots were not in the center of the patch. It is difficult to obtain a narrower beamwidth with a single MSA, and the coupling slots cannot be set in the center

of the 12-GHz-band MSA because its size is small. Therefore, a 2×2 MSA array for each band was designed to obtain a narrower beamwidth.

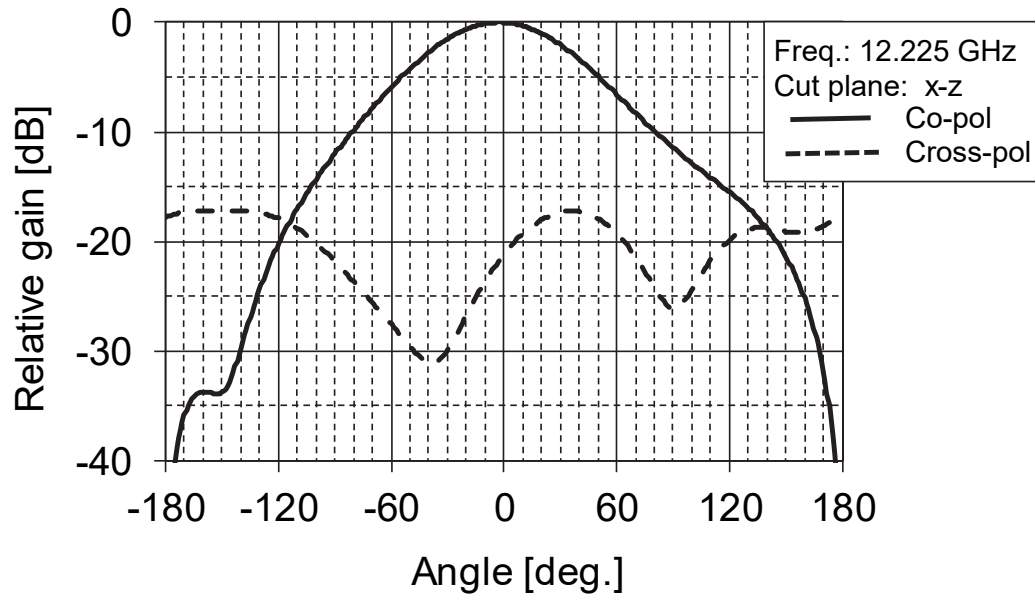


Fig. 4.6 Calculated radiation pattern of 12-GHz-band MSA.

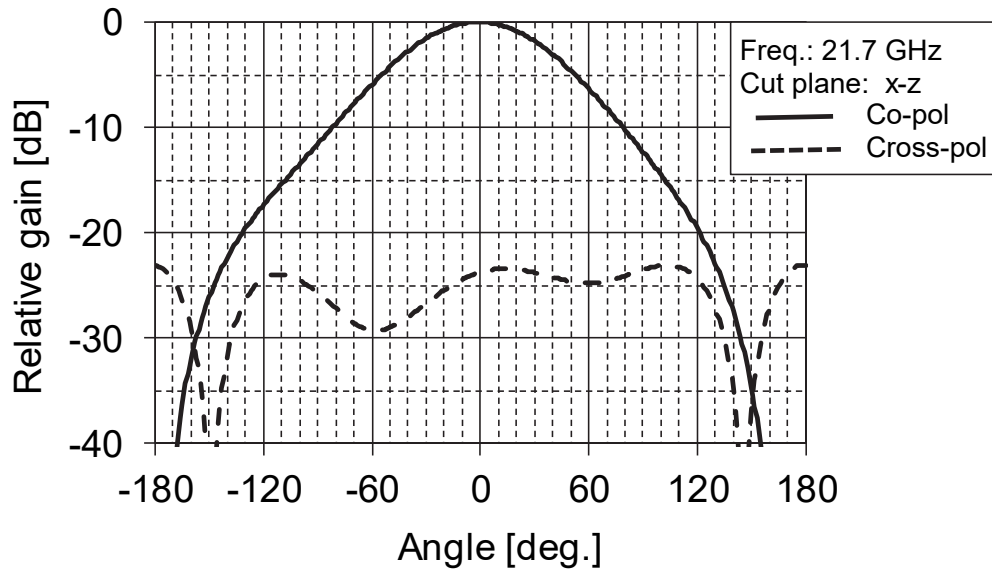


Fig. 4.7 Calculated radiation pattern of 21-GHz-band MSA.

4.2.3 Design of Dual-band and Dual-circularly Polarized Feed with Microstrip Antenna Arrays

Figs. 4.8 to 4.10 show the configuration and feed circuit of the designed feed using the MSAs described in the previous subsection. This antenna was composed of two 2×2 MSA arrays in which the elements were sequentially rotated to enhance the polarization purity [4.1]. The 21-GHz-band feed lines were arranged above the ground plane and coupled them onto the feed circuit with slots, which are at the eight points shown in Fig. 4.9, to configure a 12- and 21-GHz-band feed circuit on the substrate. The slot coupling was selected to avoid cost increases because of via holes under the assumption of mass production. The designed feed circuit can output 12- and 21-GHz-band dual-polarized signals into the four ports shown in Fig. 4.10. The polarizations, which are discussed in this section, are defined as the polarizations radiated from the feed.

The feeding phases in the 12- and 21-GHz bands are shown in Figs. 4.11 and 4.12, respectively. The feeding phase of the m -th patch is shifted to $90 \times (m-1)$ deg. by using 3-dB, 90-deg. hybrid couplers (3dB-HYBs) and differences in the line length. Because the MSAs are fed two 90-deg.-shifted signals, the feeding phases of the adjacent MSA are made the same by applying the sequential rotation technique. Therefore, there are no cross sections of the feeding lines in the designed circuit except for the 21-GHz-band feed lines above the ground plane.

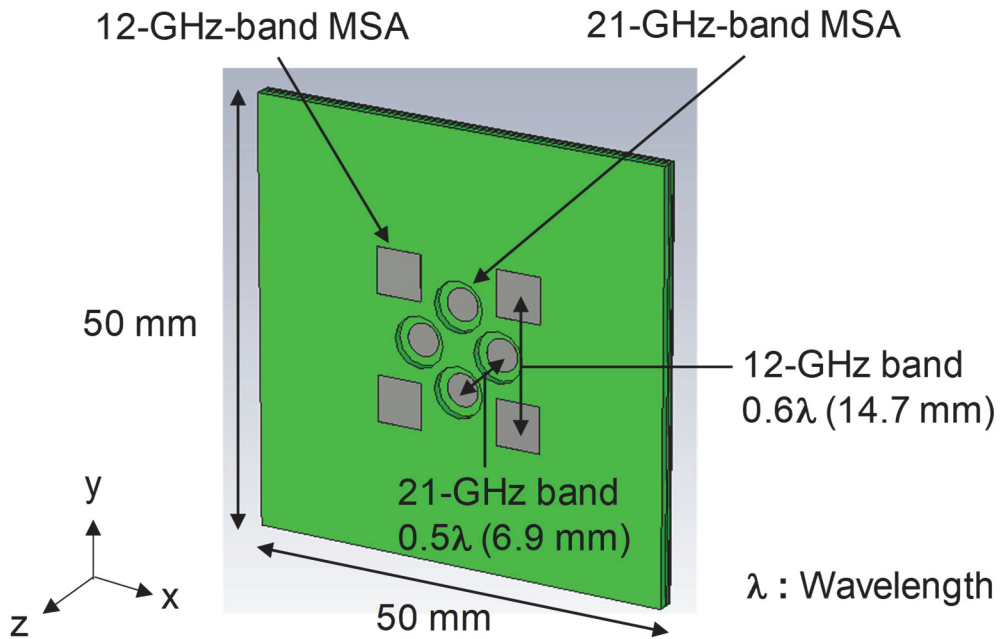


Fig. 4.8 Top view of designed feed (MSA arrays).

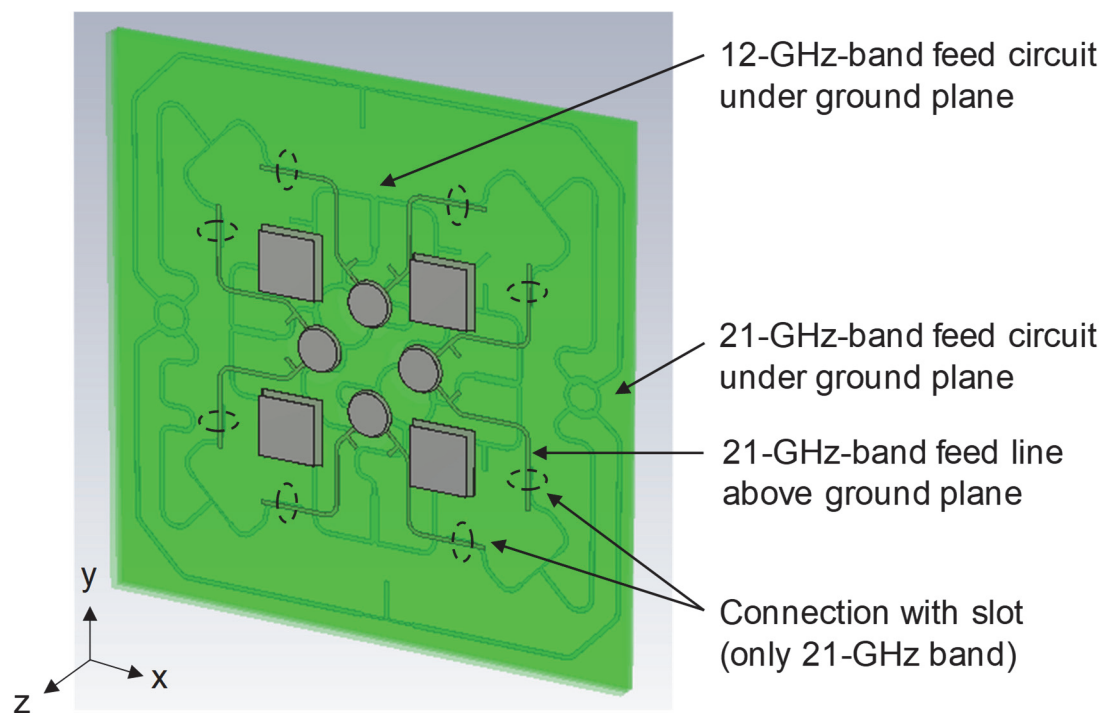


Fig. 4.9 Perspective view of designed feed.

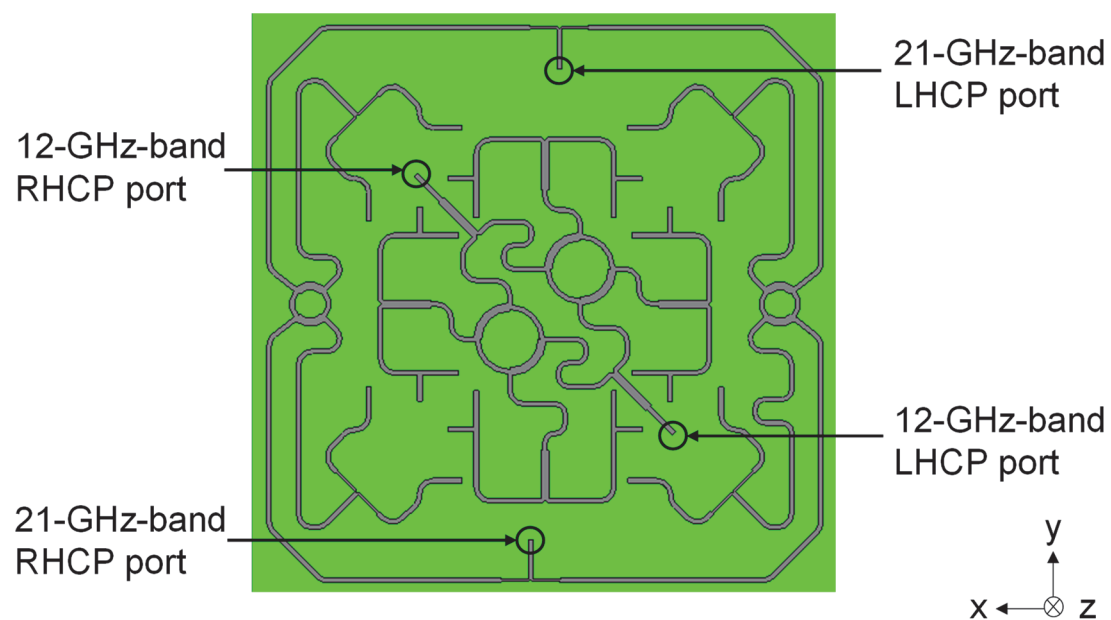


Fig. 4.10 Feed circuit (back view).

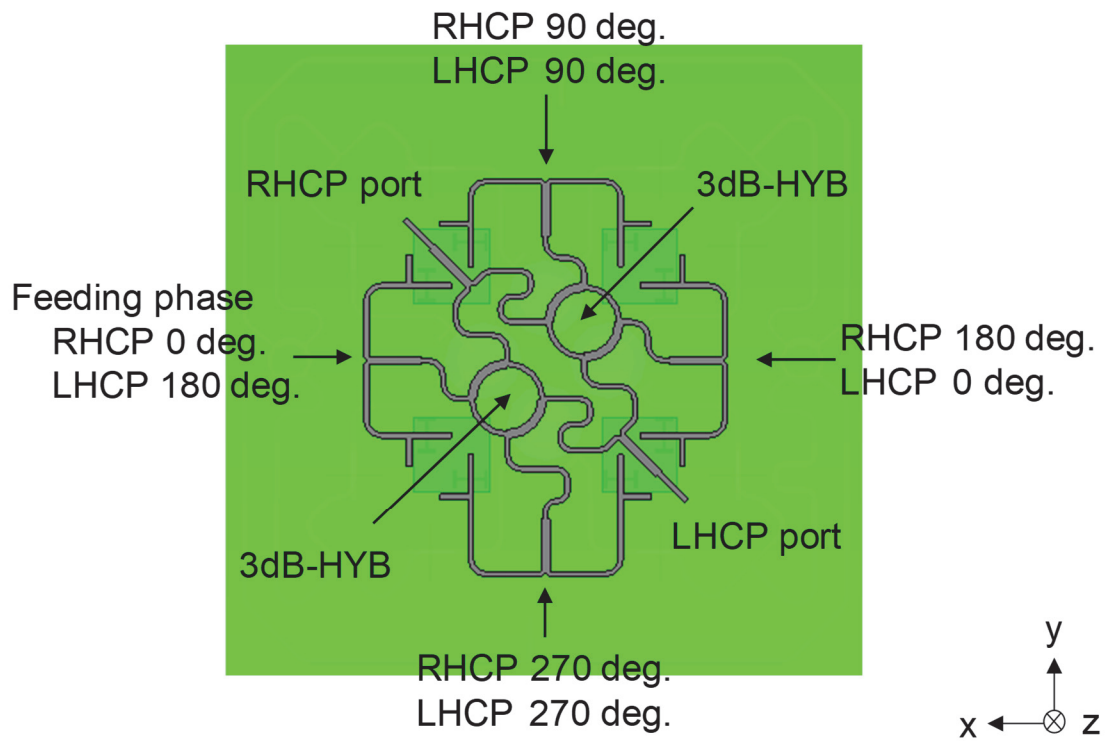


Fig. 4.11 Feeding phase in the 12-GHz band (perspective view).

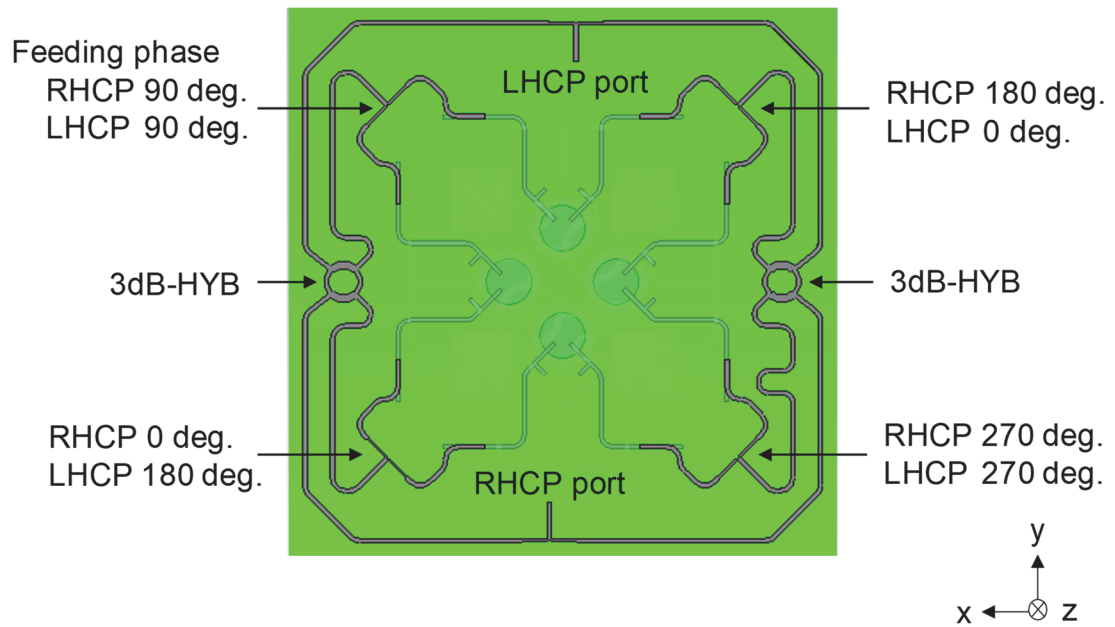
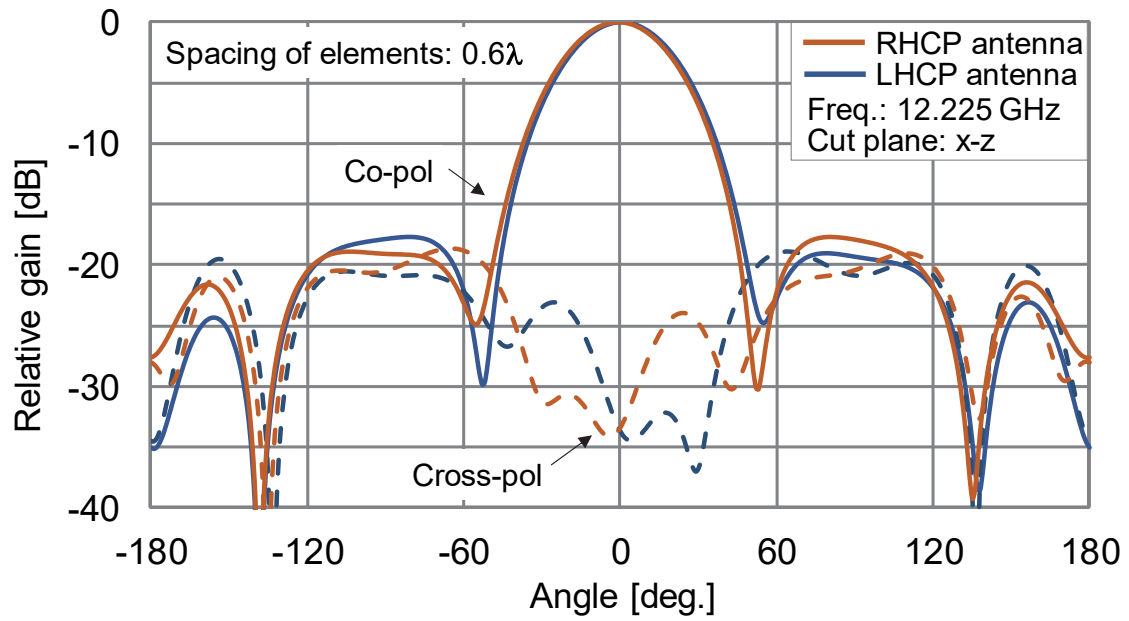


Fig. 4.12 Feeding phase in the 21-GHz band (perspective view).

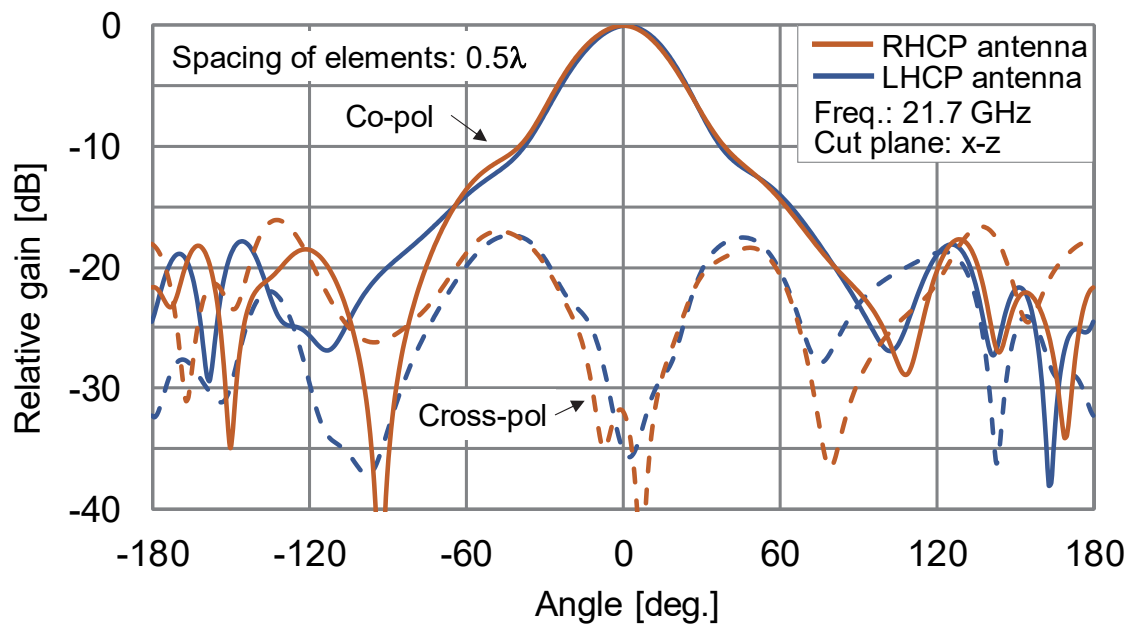
The spacing of elements was optimized to obtain a higher gain for each band, respectively. As described in Section 2.5, the F/D of the designed reflector was 0.6, and the target edge illumination level (EIL) was -11 dB [4.6] for both 12- and 21-GHz bands. The calculated radiation patterns of the feed are shown in Fig. 4.13. The solid and dashed lines show the co- and cross-polarization patterns, respectively. In the 12-GHz band, 0.6 wavelength (λ) was selected for the spacing of elements, and the calculated EILs of the RHCP and LHCP were -11.7 and -11.8 dB, respectively. Moreover, the XPD was more than 30 dB, which achieved the target value (25 dB), and the axial ratio of the RHCP and LHCP were 0.37 and 0.36 dB, respectively.

For the 21-GHz band, the radiation patterns were distorted because of unwanted emissions and mutual coupling, as shown in Fig. 4.13(b). The emissions were radiated from the 21-GHz-band feed lines above the ground plane. Since the 21-GHz-band array is surrounded by the 12-GHz-band array, the mutual coupling of the arrays makes the beamwidth in the 21-GHz band narrow, as shown in Fig 4.14, and the gain in the 21-GHz band becomes higher. The calculated gains of Models A and B that are shown in Fig. 4.14(a) were 10.8 and 11.3 dBi at 21.7 GHz, respectively. Therefore, EILs in the 21-GHz-band were studied so that the reflector antenna's gain became peak. In this study, the radiation patterns of the feed were calculated by changing the spacing of elements in the 21-GHz band. Then, the gains of the reflector antenna were obtained from the feed's radiation patterns. The reflector antenna analysis software, GRASP [4.7], was used to calculate the gain.

Table 4.2 shows the calculated gain, which does not include the feeding loss. From this result, the spacing was decided to be 0.5λ in the 21-GHz band because the highest gain was obtained. The EILs of the RHCP and LHCP were -9.9 and -10.4 dB, respectively. Moreover, the XPD was more than 30 dB, and the axial ratios of the RHCP and LHCP were 0.44 and 0.31 dB, respectively.

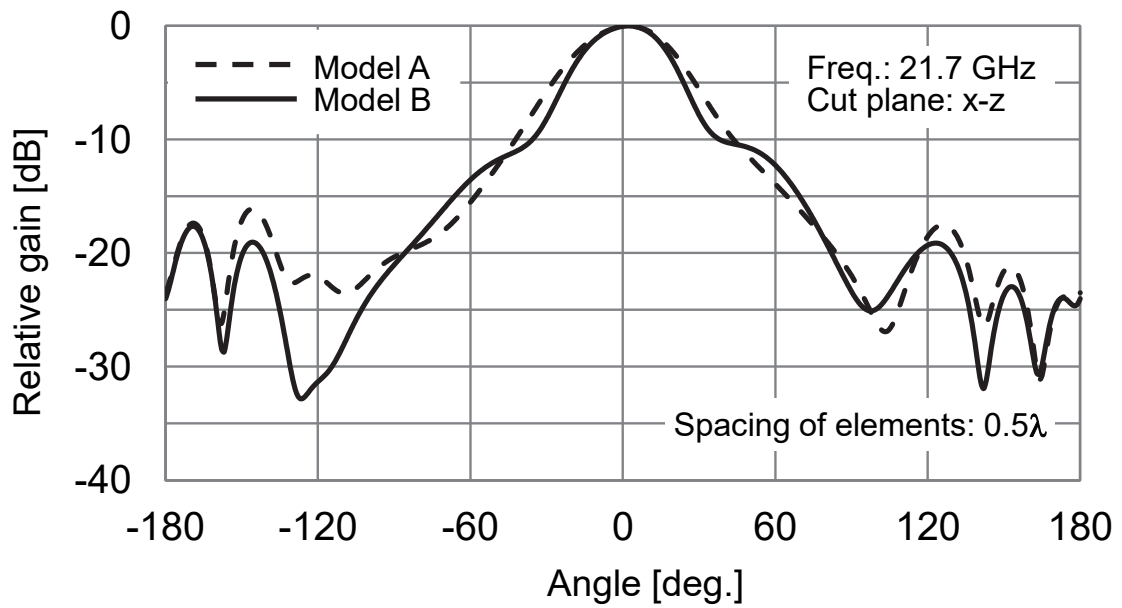
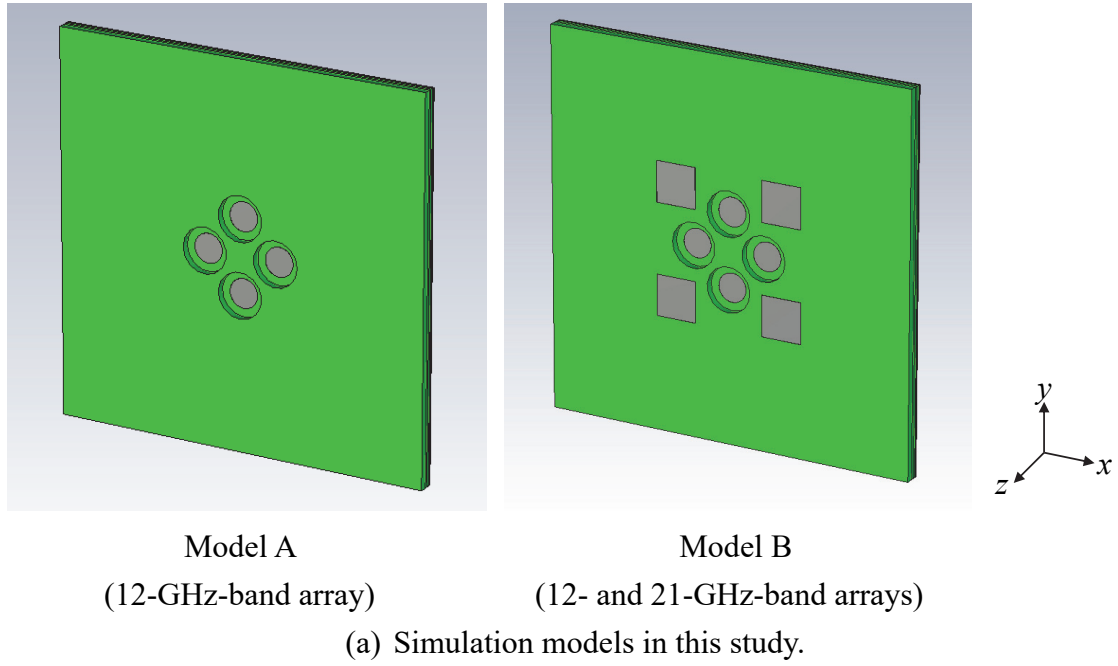


(a) 12-GHz-band array.



(b) 21-GHz-band array.

Fig. 4.13 Calculated radiation patterns of feed (MSA arrays).



(b) Calculated radiation patterns of Models A and B (co-polarization).

Fig. 4.14 Effect of mutual coupling between 12- and 21-GHz-band arrays on 21-GHz-band radiation pattern.

Table 4.2 Calculated gain of reflector configuration (without feeding loss).

Frequency [GHz]	Spacing of elements [λ]	EIL [dB]		Gain [dBi]		Selection
		RHCP	LHCP	RHCP	LHCP	
12.225	0.600	-11.7	-11.8	34.5	34.6	✓
21.7	0.475	-9.8	-10.2	38.2	38.2	
	0.500	-9.9	-10.4	38.2	38.3	✓
	0.525	-10.4	-10.8	38.2	38.2	
	0.550	-10.4	-10.9	38.2	38.2	
	0.600	-11.1	-11.6	37.8	37.9	
	0.650	-12.3	-12.8	37.3	37.3	

4.3 Prototype of 12- and 21-GHz Dual-band Dual-circularly Polarized Parabolic Reflector Antenna

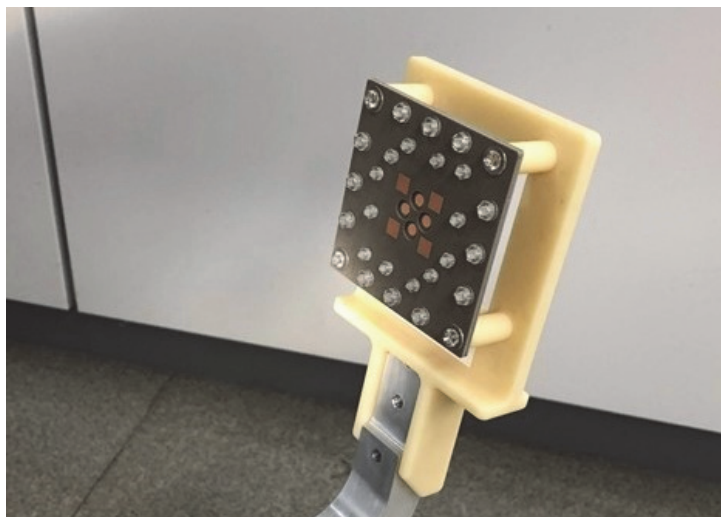
4.3.1 Prototype Antenna

The designed 12- and 21-GHz dual-band dual-circularly polarized offset parabolic reflector antenna were fabricated and tested. Fig. 4.15 shows the prototype antenna. The reflector was fabricated by machining an aluminum panel to evaluate the radiation patterns of the reflector accurately. Reflectors made with pressed aluminum are generally used for consumer use. The estimated gain degradation in the 12- and 21-GHz bands due to reflector error [4.8] was 0.1 and 0.2 dB, respectively. The error of a reflector made with pressed aluminum was 0.26 mm RMS based on the measurement results [4.9].

Fig. 4.16 shows the fabricated feed composed of two 2×2 MSA arrays. The antenna has four SMP connectors to connect the coaxial cables for the measurements. The substrates, of which the multilayer structure is configured, are fixed with plastic screws, and prepregs are not used for attaching the substrates. A photograph of each substrate is shown in Fig. 4.17. The size of the substrate is 65×65 mm to make space for the screw holes. The ground plane is smaller than the substrate, as shown in the 5th layer substrate of Fig. 4.17. The size is 50×50 mm and equals to the initial design shown in Fig. 4.8. The copper thickness of the 5th layer is $35 \mu\text{m}$, and that of the other layers is $18 \mu\text{m}$.

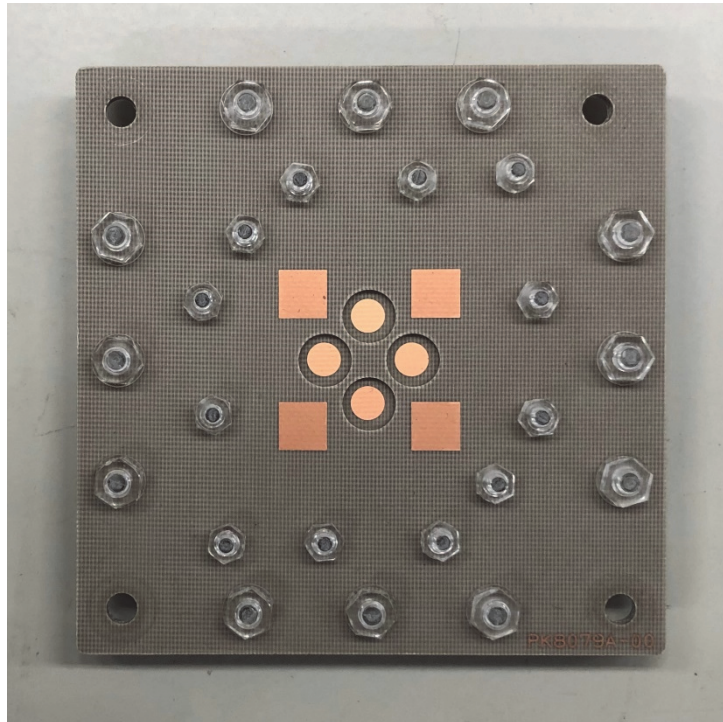


(a) Reflector.

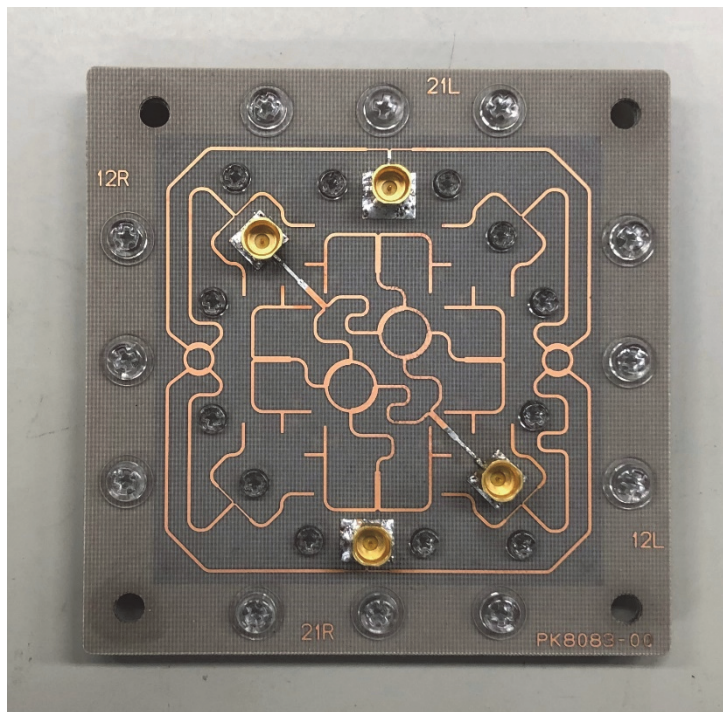


(b) Feed.

Fig. 4.15 Fabricated receiving reflector antenna.



(a) Front view.



(b) Back view.

Fig. 4.16 Fabricated feed composed of MSA arrays.

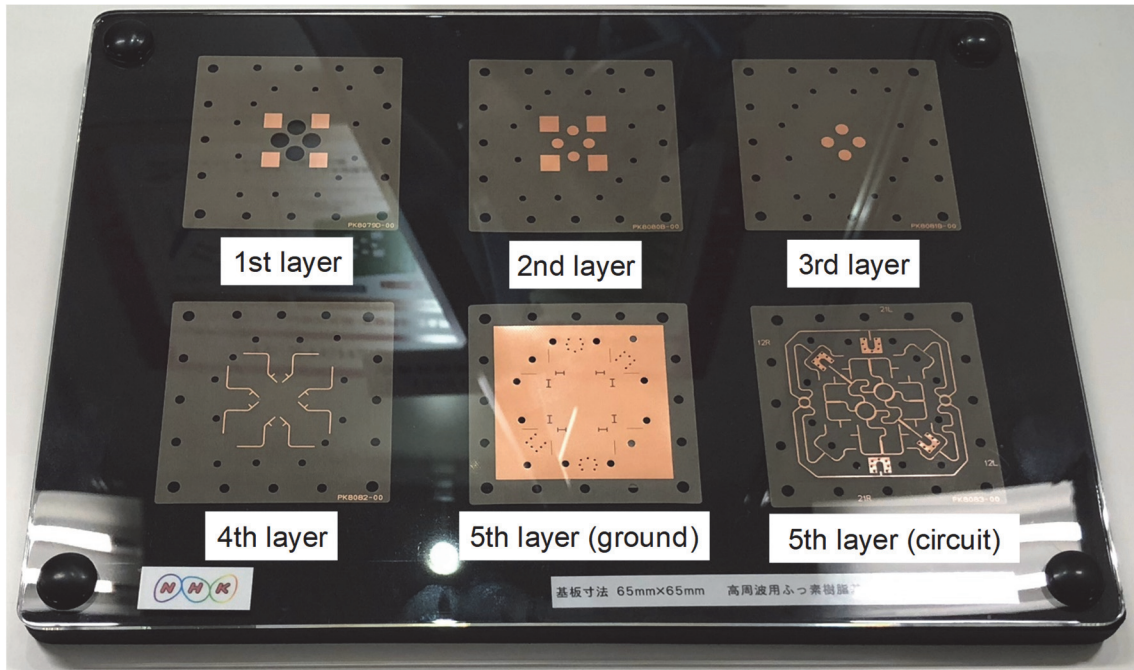


Fig. 4.17 Substrates composing feed.

4.3.2 VSWR

Figs. 4.18 and 4.19 show the measured VSWRs of the fabricated antenna. The VSWRs of the feed were measured, which was installed on the reflector as shown in Fig. 4.15. The polarizations, which are discussed in this section, are defined as the polarizations radiated from the parabolic reflector antenna. This antenna covered the 12- and 21-GHz bands with VSWRs of 1.9 and 1.3, respectively. The measured values in the 21-GHz band met the performance target (VSWR of 1.5), but that in the 12-GHz band slightly exceeded the target. It is assumed that the degradation in VSWR was caused by variations in the substrate thickness.

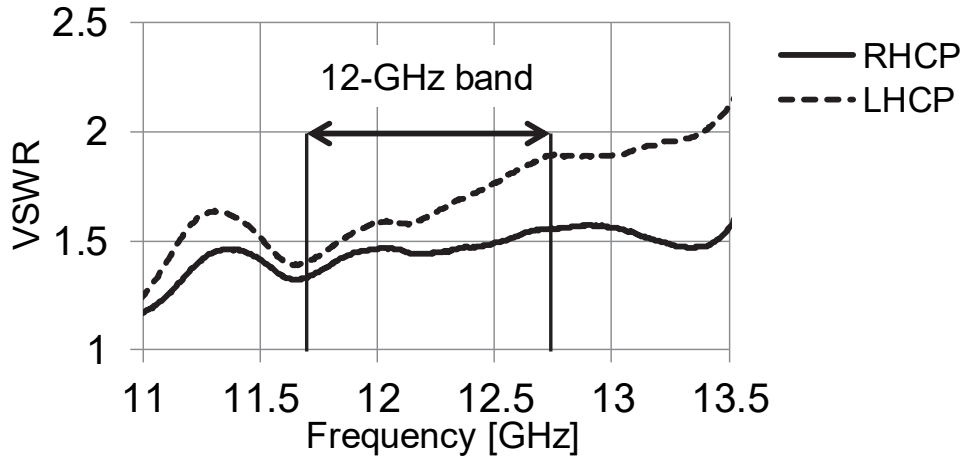


Fig. 4.18 Measured VSWR in the 12-GHz band.

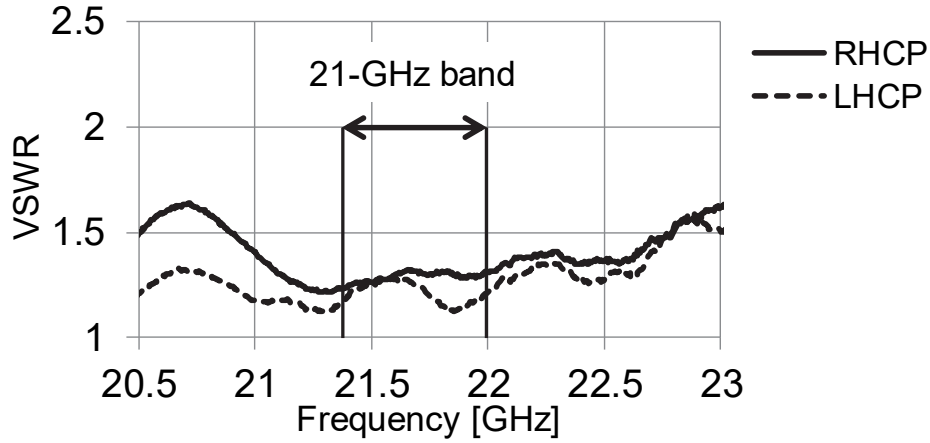


Fig. 4.19 Measured VSWR in the 21-GHz band.

4.3.3 Gain, Aperture Efficiency, and XPD

The measured gain, aperture efficiency, and XPD in the 12- and 21-GHz bands are listed in Tables 4.3 and 4.4, respectively. The gain was obtained by comparing a standard gain horn antenna and the fabricated antenna. They were evaluated in the lower-end, center, and upper-end frequencies of both bands. The measured values include the feeding loss. The deviation of the frequency response in the gain was less than 1 dB, and the XPD was more the 20 dB in the 12- and 21-GHz bands for both polarizations. These results indicate that the fabricated antenna performed as a dual-circularly polarized antenna in both bands.

The measured gain met the target (33 dBi) in the 12-GHz band but was lower than that of the target (38 dBi) in the 21-GHz band. The gains at each center frequency in the 12- and 21-GHz bands were about 34 and 36 dBi, respectively. Comparing these gains and the calculated values (Table 4.2), it is necessary to reduce the feeding loss, especially in the 21-GHz band. The measured XPDs were also lower than that of the target (25 dB) because the feeding phase was shifted with the dimension error in the lines and 3-dB hybrid couplers.

Table 4.3 Gain, aperture efficiency, and XPD of fabricated receiving reflector antenna in the 12-GHz band (include feeding loss).

Frequency [GHz]	Gain [dBi]	Aperture efficiency [%]	XPD [dB] (at boresight)
11.7	RHCP: 33.5 LHCP: 33.7	RHCP: 59.3 LHCP: 62.0	RHCP: 24.3 LHCP: 23.7
12.225	RHCP: 34.1 LHCP: 33.6	RHCP: 62.7 LHCP: 55.7	RHCP: 28.0 LHCP: 30.7
12.75	RHCP: 33.8 LHCP: 33.2	RHCP: 53.5 LHCP: 46.6	RHCP: 21.3 LHCP: 21.5

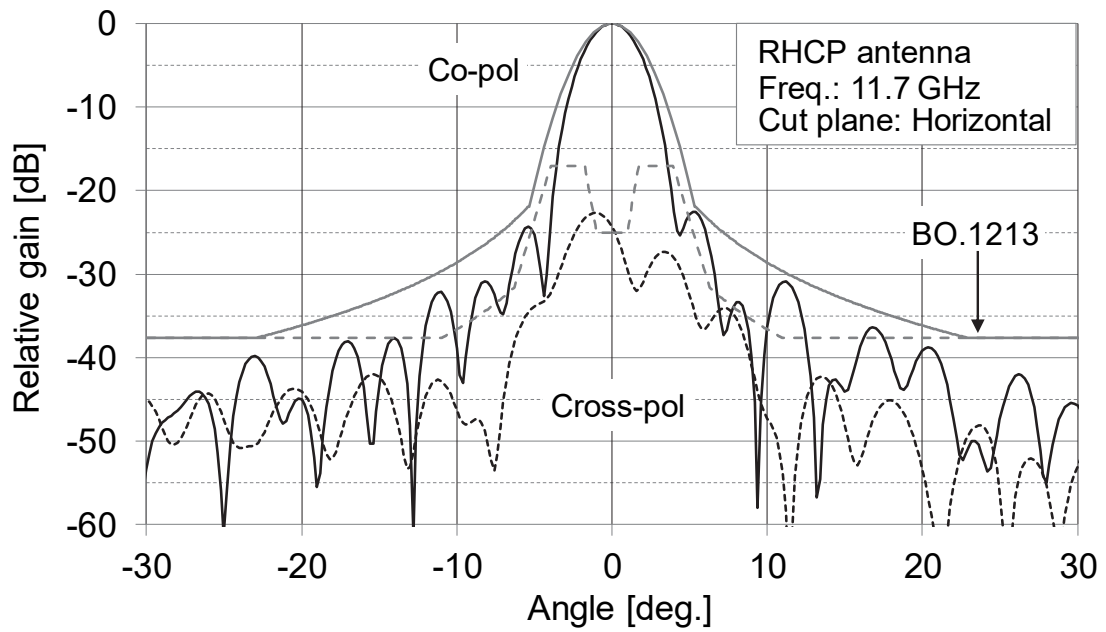
Table 4.4 Gain, aperture efficiency, and XPD of fabricated receiving reflector antenna in the 21-GHz band (include feeding loss).

Frequency [GHz]	Gain [dBi]	Aperture efficiency [%]	XPD [dB] (at boresight)
21.4	RHCP: 36.3 LHCP: 36.7	RHCP: 33.9 LHCP: 37.1	RHCP: 25.8 LHCP: 23.1
21.7	RHCP: 35.9 LHCP: 36.8	RHCP: 30.1 LHCP: 36.7	RHCP: 23.4 LHCP: 20.2
22	RHCP: 36.0 LHCP: 36.7	RHCP: 30.0 LHCP: 35.3	RHCP: 25.6 LHCP: 29.6

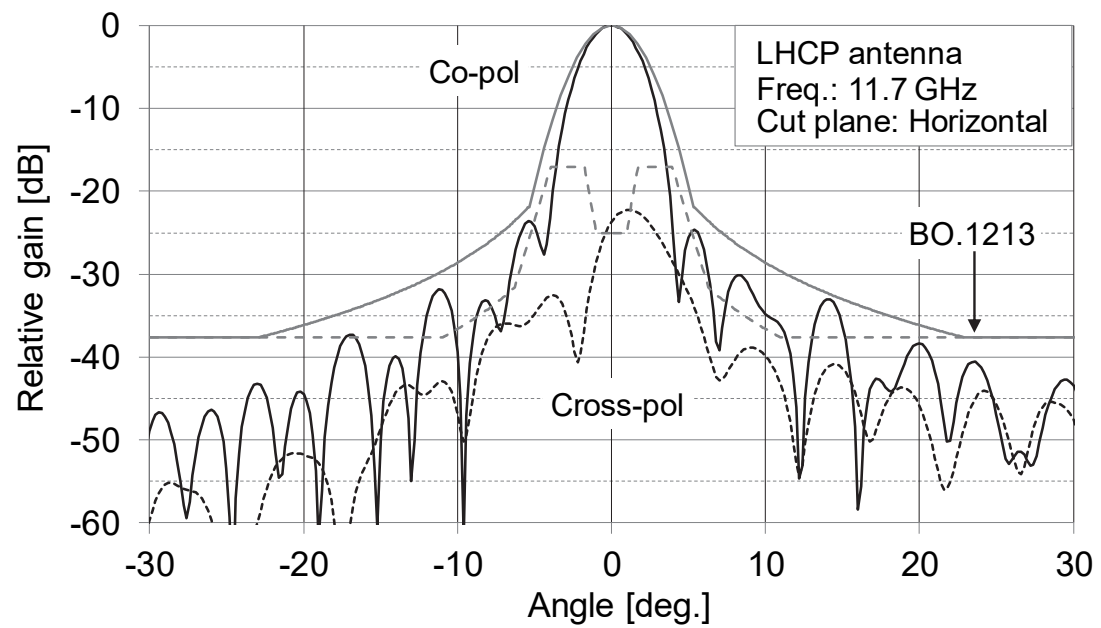
4.3.4 Radiation Patterns

The radiation patterns of the fabricated reflector antenna were measured by using a spherical near-field antenna measurement system in an anechoic chamber [4.10]. The measured frequencies were the lower-end, center, and upper-end frequencies of the 12- and 21-GHz bands, which were 11.7, 12.225, 12.75, 21.4, 21.7, and 22 GHz. The horizontal plane was evaluated, which corresponds to geostationary orbit.

Figs. 4.20 to 4.25 show the measured radiation patterns of the fabricated reflector antenna. The solid and dashed lines indicate co- and cross-polarization patterns, respectively. These figures also show the reference radiation patterns recommended by ITU-R for receiving earth station antennas. Rec. ITU-R BO.1213 (BO.1213) [4.2] is a reference pattern for the 12-GHz band, and Rec. ITU-R BO.1900 (BO.1900) [4.11] is that for the 21-GHz band. The measured radiation patterns were compared with the reference patterns because BO.1213 and BO.1900 are used for calculating interference in the coordination of satellite networks. The measured results confirmed that the radiation patterns mostly satisfied the reference patterns.

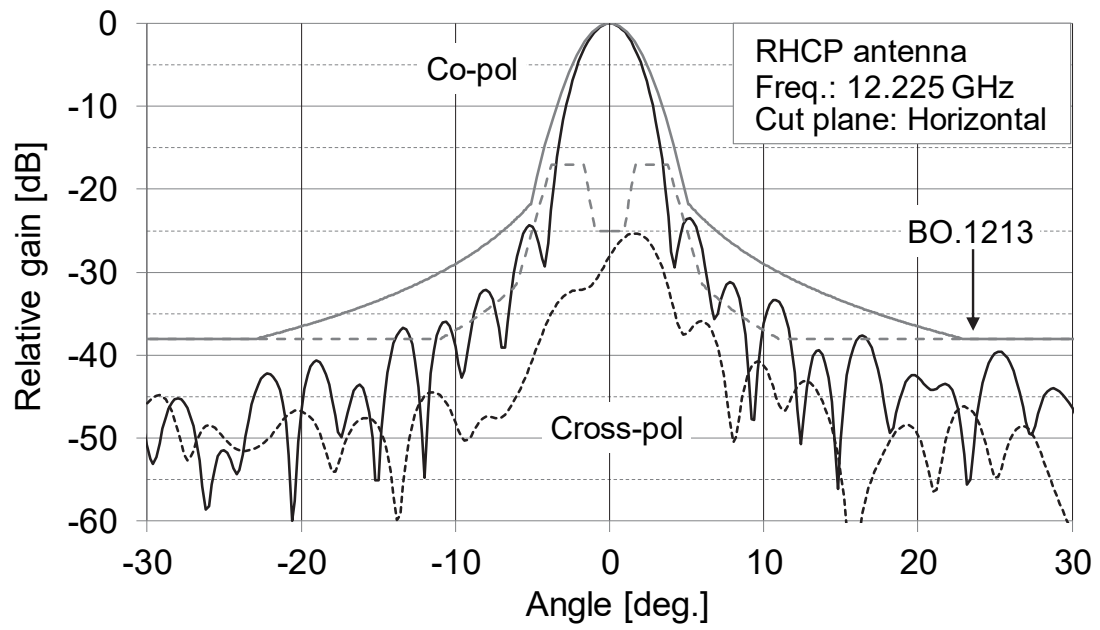


(a) RHCP antenna.

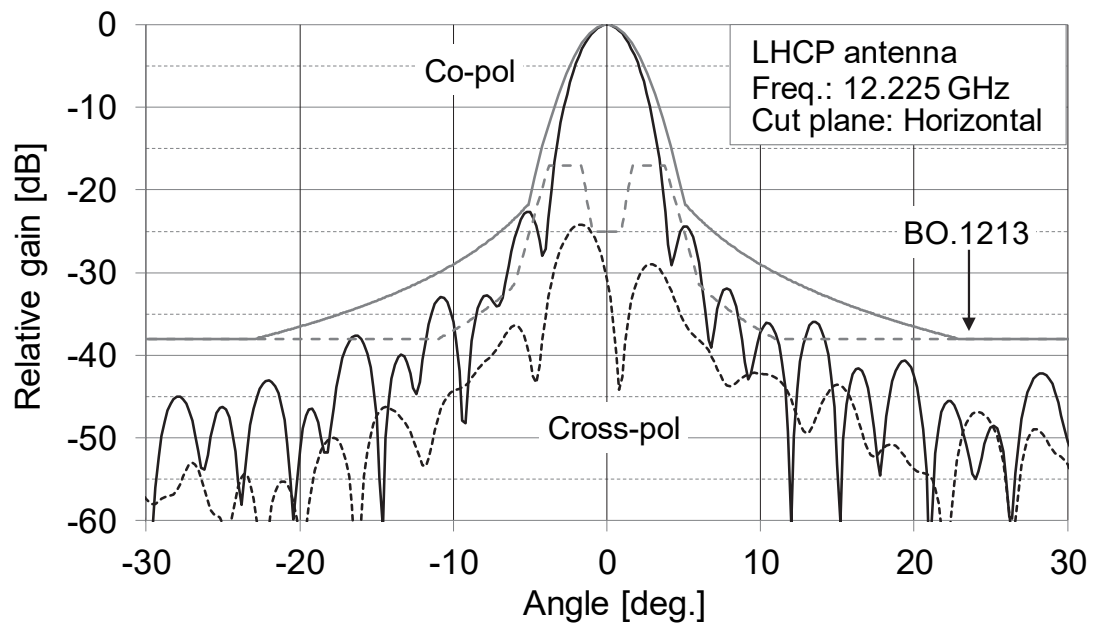


(b) LHCP antenna.

Fig. 4.20 Measured radiation patterns of fabricated reflector antenna (11.7 GHz).

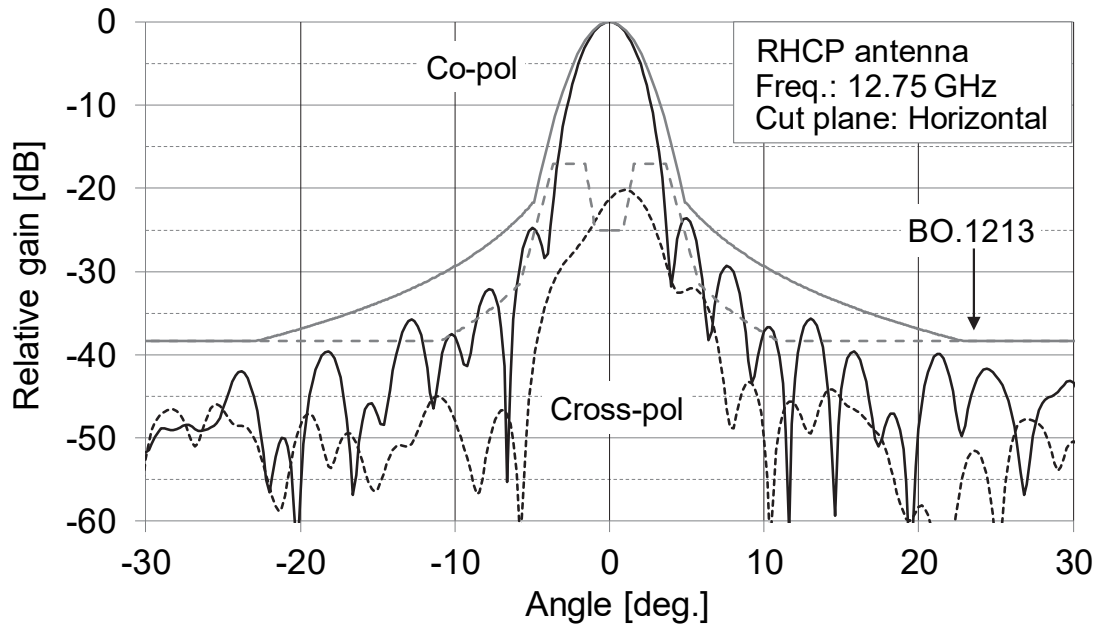


(a) RHCP antenna.

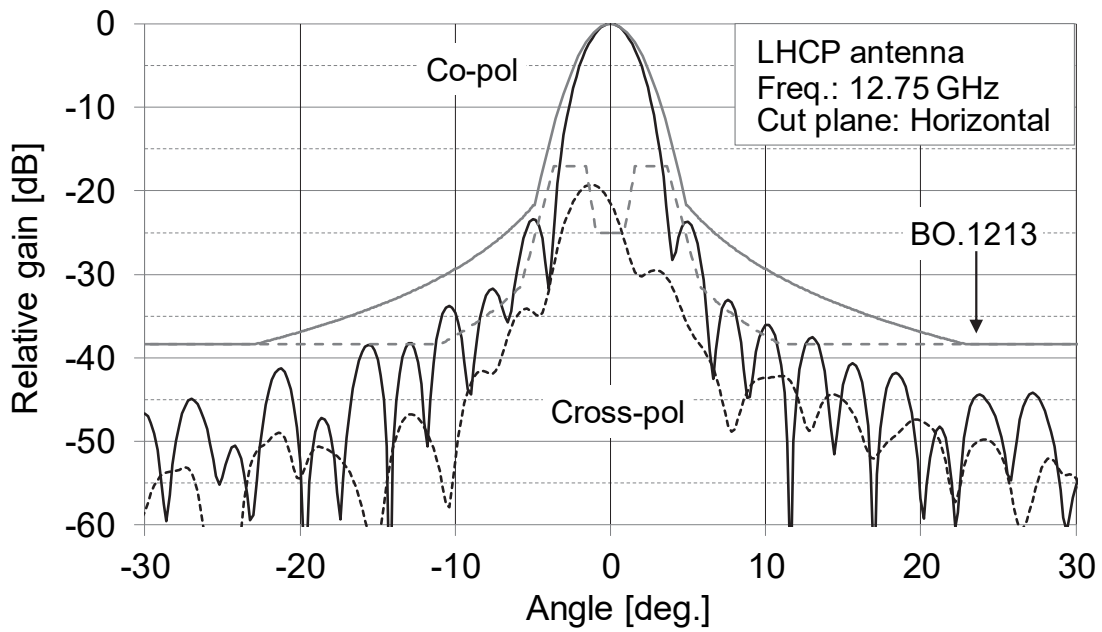


(b) LHCP antenna.

Fig. 4.21 Measured radiation patterns of fabricated reflector antenna (12.225 GHz).

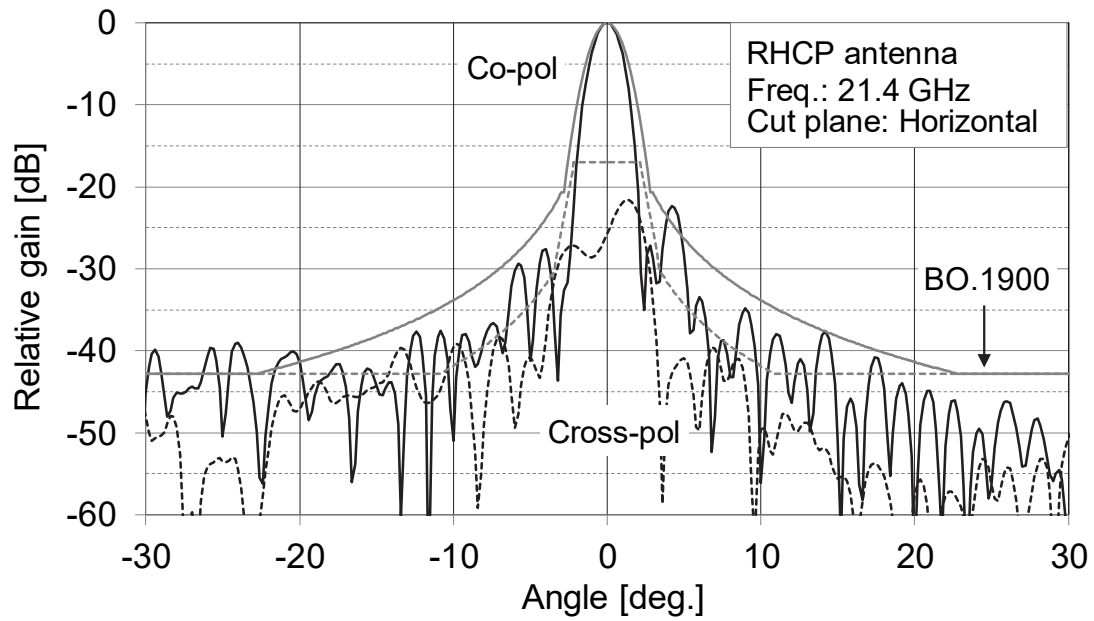


(a) RHCP antenna.

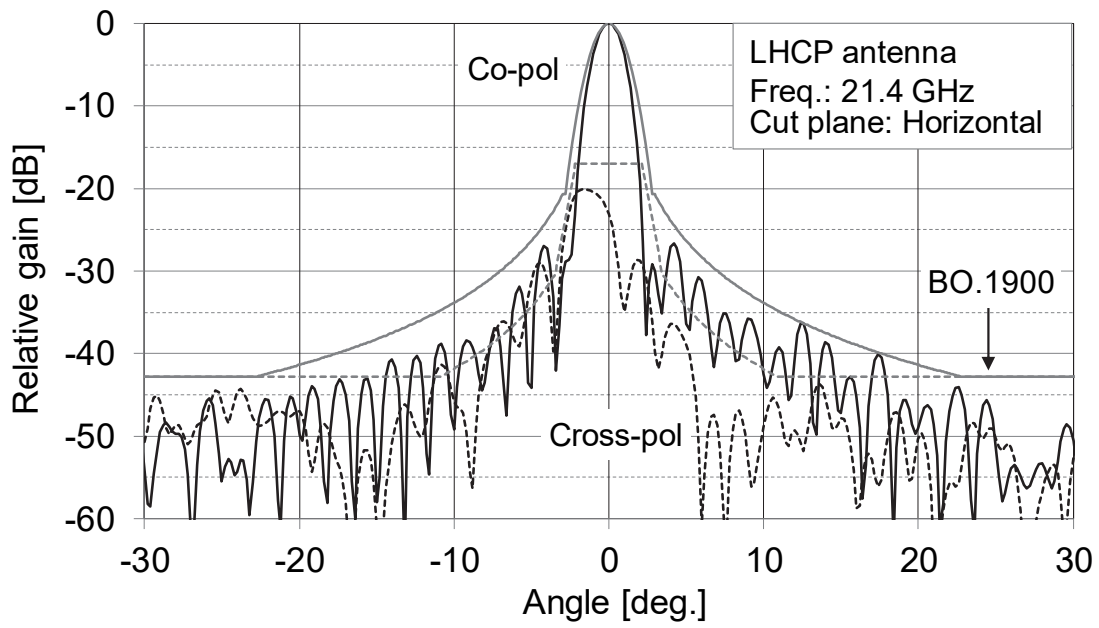


(b) LHCP antenna.

Fig. 4.22 Measured radiation patterns of fabricated reflector antenna (12.75 GHz).

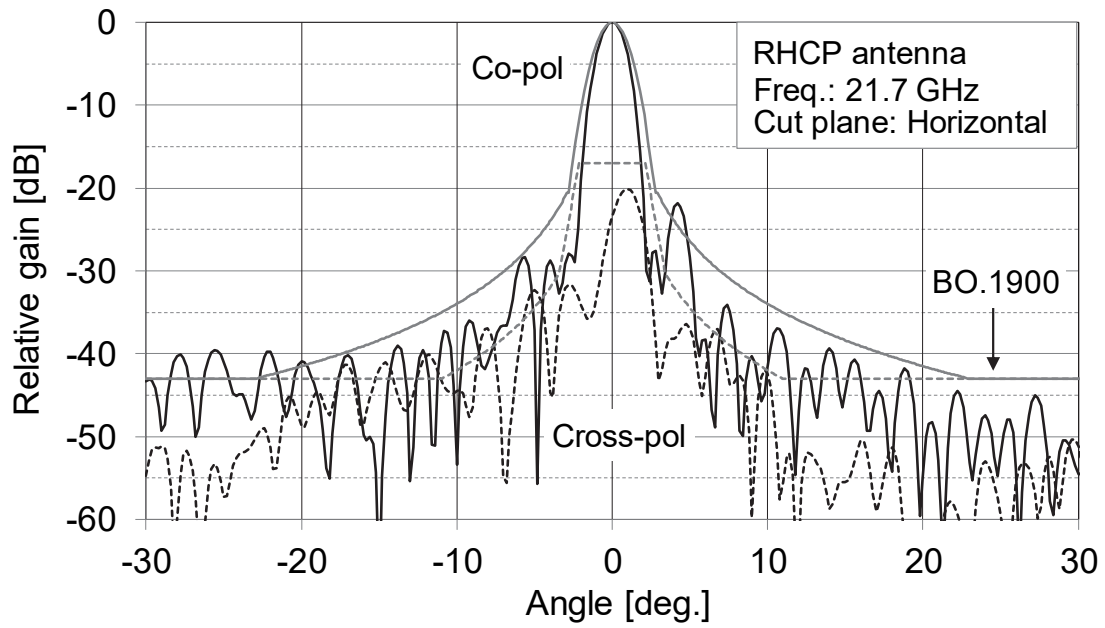


(a) RHCP antenna.

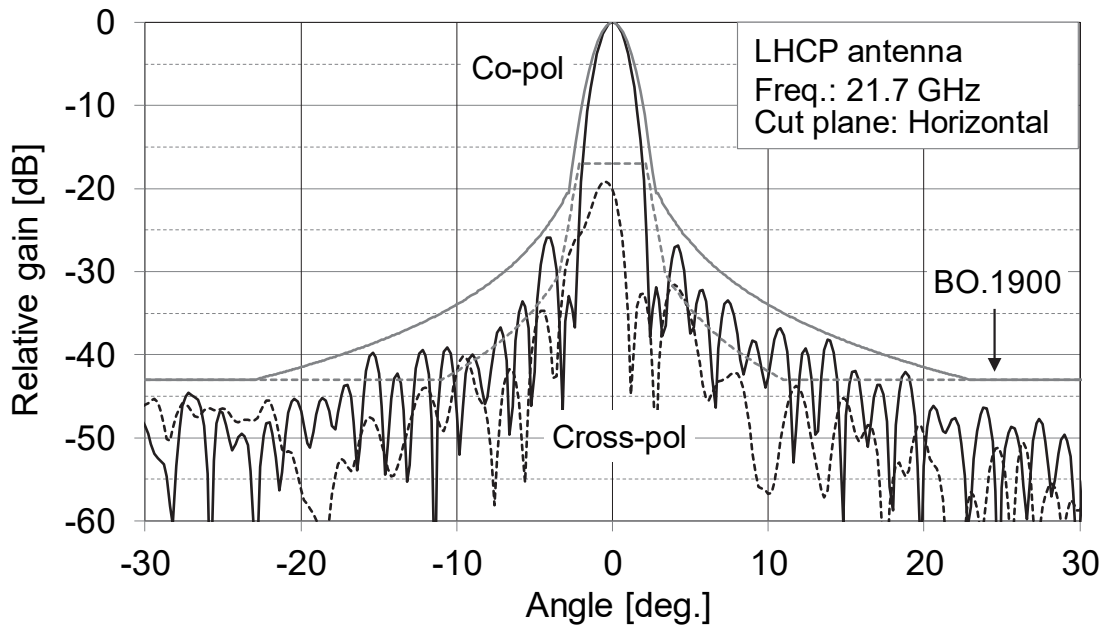


(b) LHCP antenna.

Fig. 4.23 Measured radiation patterns of fabricated reflector antenna (21.4 GHz).

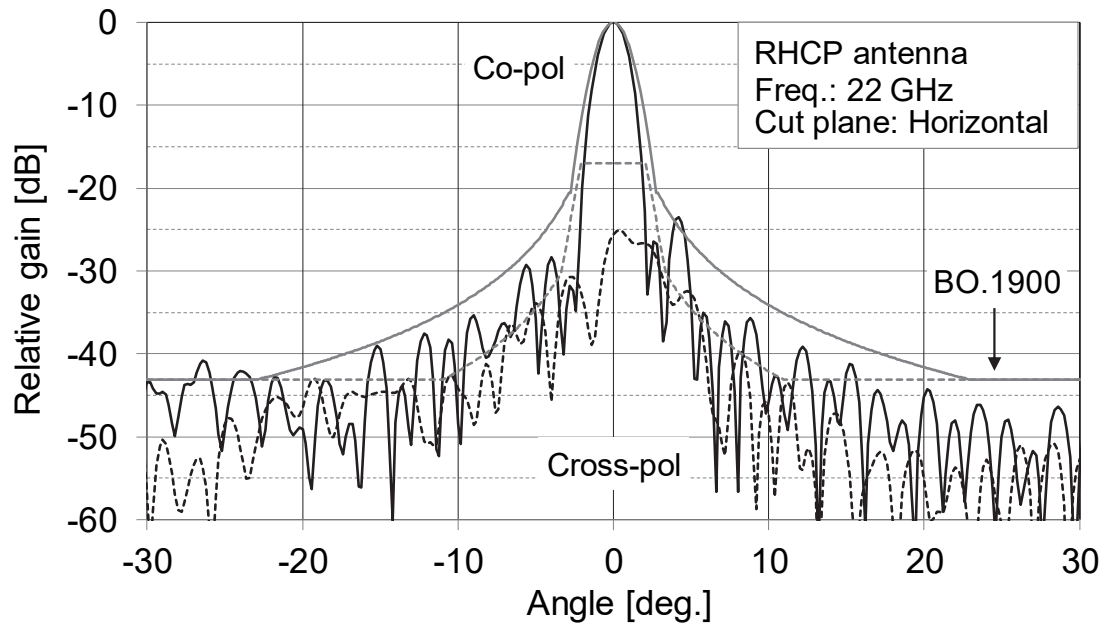


(a) RHCP antenna.

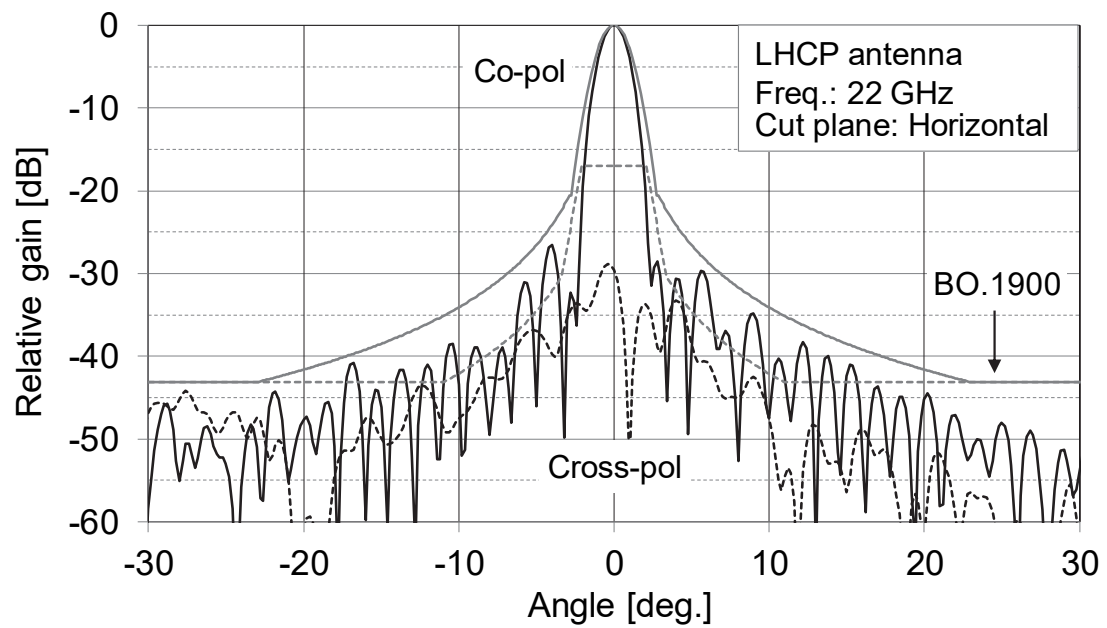


(b) LHCP antenna.

Fig. 4.24 Measured radiation patterns of fabricated reflector antenna (21.7 GHz).



(a) RHCP antenna.



(b) LHCP antenna.

Fig. 4.25 Measured radiation patterns of fabricated reflector antenna (22 GHz).

4.4 Link Calculation for Satellite Broadcasting with Prototype Antenna

This section shows link calculations for the satellite broadcasting systems using the prototype receiving antenna. The calculations are based on the calculation method described in ARIB STD B-44 [4.12]. Table 4.5 summarizes the parameters and calculation methods in this study. The atmospheric absorption and the rain attenuation are calculated by using Rec. ITU-R P.618 [4.13], [4.14], P.676 [4.15], P.837 [4.16], and P.840 [4.17]. The receiving antenna gains and XPDs are the measured values shown in Tables 4.3 and 4.4. Table 4.6 shows the bit rates of 12- and 21-GHz-band satellite broadcasting systems.

Tables 4.7 to 4.9 show the calculated results. The results confirmed that the service availability of the 12-GHz-band system was 99.92%, and that the availability of the 21-GHz-band system reached 99.90% by using 8PSK (3/5). Therefore, in the 21-GHz band, the bit rate of 435 Mbps can be obtained with the prototype antenna.

Table 4.5 Parameters and calculation methods in this study.

Item		Value
Orbital position of satellite		110 deg. East
Receiving location		Tokyo (35.7 deg. N, 139.7 deg. E)
Calculated frequencies		12.225 and 21.7 GHz
Atmospheric absorption, Rain attenuation		Rec. ITU-R P.618, P.676, P.840 ITU-R, Dynamic Link Library (DLL) for calculation of propagation losses for Earth to space (or space to Earth) transmission links
Point rainfall rate in an average year		Rec. ITU-R P.837
Required carrier-to-noise ratio (C/N) [4.12]		8PSK (coding rate 3/5): 6.9 dB 8PSK (coding rate 3/4): 8.9 dB 16APSK (coding rate 7/9): 12.2 dB
Receiving antenna	Gain	12.225 GHz: 33.6 dBi, 21.7 GHz: 35.9 dBi
	XPD	12.225 GHz: 28.0 dB, 21.7 GHz: 20.2 dB
Target of service availability		99.9% (annual year)

Table 4.6 Bit rates of 12- and 21-GHz-band satellite broadcasting systems.

Freq. band	Modulation scheme	Symbol rate	Bit rate
12-GHz band	16APSK (coding rate 7/9)	33.7561 Mbaud	100 Mbps
21-GHz band	8PSK (coding rate 3/5)	250 Mbaud [4.18]	435 Mbps
	8PSK (coding rate 3/4)		531 Mbps

Table 4.7 Link calculation for 12-GHz-band satellite broadcasting.

		Clear sky	Rain
Satellite Parameters			
Bandwidth	[MHz]	33.7561	33.7561
EIRP	[dBW]	60.0	60.0
XPD (including uplink XPD)	[dB]	27.0	27.0
Propagation Losses (at 12.225 GHz, Tokyo)			
Free space loss	[dB]	205.8	205.8
Total atmospheric attenuation	[dB]	0.1	4.1
Gaseous attenuation	[dB]	0.1	0.1
Rain attenuation	[dB]	0.0	3.4
Clouds attenuation	[dB]	0.0	0.6
Scintillation fading	[dB]	0.0	0.3
Total loss	[dB]	205.9	209.9
Receiving Station Parameters			
Receiving antenna gain	[dBi]	33.6	33.6
Pointing loss	[dB]	0.1	0.1
Noise figure	[dB]	1.0	1.0
Equivalent noise temperature	[K]	75.1	75.1
Antenna noise temperature	[K]	50.0	207.6
Equivalent system noise temperature	[K]	125.1	282.7
XPD	[dB]	28.0	28.0
Downlink (satellite to station)			
Received power	[dBW/MHz]	−127.6	−131.6
Noise power	[dBW/MHz]	−147.6	−144.1
Downlink C/N	[dB]	20.0	12.5
Total XPD	[dB]	24.5	24.5
Cross-pol. EIRP	[dBW]	60.0	60.0
C/I	[dB]	24.5	24.5
C/(N+I)	[dB]	18.7	12.2
Required C/N	[dB]	12.2	12.2
Link margin	[dB]	6.5	0.0
Service availability (annual year)	[%]	—	99.92

Table 4.8 Link calculation for 21-GHz-band satellite broadcasting with 8PSK (3/5).

		Clear sky	Rain
Satellite Parameters			
Bandwidth	[MHz]	250.0	250.0
Satellite RF output power	[kW]	0.8	0.8
Satellite antenna gain	[dBi]	40.0	47.0
EIRP (locally variable EIRP system)	[dBW]	69.0	76.0
XPD (including uplink XPD)	[dB]	27.0	27.0
Propagation Losses (at 21.7 GHz, Tokyo)			
Free space loss	[dB]	210.8	210.8
Total atmospheric attenuation	[dB]	0.8	12.5
Gaseous attenuation	[dB]	0.8	0.8
Rain attenuation	[dB]	0.0	10.0
Clouds attenuation	[dB]	0.0	1.7
Scintillation fading	[dB]	0.0	0.5
Total loss	[dB]	211.6	223.3
Receiving Station Parameters			
Receiving antenna gain	[dBi]	35.9	35.9
Pointing loss	[dB]	0.5	0.5
Noise figure	[dB]	1.5	1.5
Equivalent noise temperature	[K]	119.6	119.6
Antenna noise temperature	[K]	45.7	245.5
Equivalent system noise temperature	[K]	165.3	365.1
XPD	[dB]	20.2	20.2
Downlink (satellite to station)			
Received power	[dBW/MHz]	−131.1	−135.8
Noise power	[dBW/MHz]	−146.4	−143.0
Downlink C/N	[dB]	15.3	7.2
Total XPD	[dB]	19.4	19.4
Cross-pol. EIRP	[dBW]	69.0	76.0
C/I	[dB]	19.4	19.4
C/(N+I)	[dB]	13.8	6.9
Required C/N	[dB]	6.9	6.9
Link margin	[dB]	6.9	0.0
Service availability (annual year)	[%]	—	99.90

Table 4.9 Link calculation for 21-GHz-band satellite broadcasting with 8PSK (3/4).

		Clear sky	Rain
Satellite Parameters			
Bandwidth	[MHz]	250.0	250.0
Satellite RF output power	[kW]	0.8	0.8
Satellite antenna gain	[dBi]	40.0	47.0
EIRP (locally variable EIRP system)	[dBW]	69.0	76.0
XPD (including uplink XPD)	[dB]	27.0	27.0
Propagation Losses (at 21.7 GHz, Tokyo)			
Free space loss	[dB]	210.8	210.8
Total atmospheric attenuation	[dB]	0.8	10.5
Gaseous attenuation	[dB]	0.8	0.8
Rain attenuation	[dB]	0.0	8.1
Clouds attenuation	[dB]	0.0	1.6
Scintillation fading	[dB]	0.0	0.4
Total loss	[dB]	211.6	221.2
Receiving Station Parameters			
Receiving antenna gain	[dBi]	35.9	35.9
Pointing loss	[dB]	0.5	0.5
Noise figure	[dB]	1.5	1.5
Equivalent noise temperature	[K]	119.6	119.6
Antenna noise temperature	[K]	45.7	236.7
Equivalent system noise temperature	[K]	165.3	356.3
XPD	[dB]	20.2	20.2
Downlink (satellite to station)			
Received power	[dBW/MHz]	−131.1	−133.8
Noise power	[dBW/MHz]	−146.4	−143.1
Downlink C/N	[dB]	15.3	9.3
Total XPD	[dB]	19.4	19.4
Cross-pol. EIRP	[dBW]	69.0	76.0
C/I	[dB]	19.4	19.4
C/(N+I)	[dB]	13.8	8.9
Required C/N	[dB]	8.9	8.9
Link margin	[dB]	4.9	0.0
Service availability (annual year)	[%]	—	99.85

4.5 Concluding Remarks

A dual-band and dual-circularly polarized receiving reflector antenna for satellite broadcasting in the 12-GHz and 21-GHz bands was manufactured and evaluated. The antenna has a 50-cm offset parabolic reflector and a feed composed of 12- and 21-GHz-band MSA arrays with a multilayer structure. The measured results indicate that the gains in the 12- and 21-GHz bands were more than 33.2 and 35.9 dBi, respectively. The VSWR was less than 1.9, and the XPD was more than 20 dB throughout both bands. The proposed antenna performed as a dual-circularly polarized antenna in those two frequency bands.

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Chapter 5

Study of Improving Loss of Feed Circuit in the 21-GHz Band

5.1 Introductory Remarks

This chapter presents the design process and characterization of a dual-band and dual-circularly polarized feed whose feeding loss in the 21-GHz band is mitigated. From the evaluation results in Chapter 4, it is appeared that the feeding loss of the 21-GHz band increased because the feed circuit is enlarged to secure space for the feeding slots. Therefore, the 21-GHz-band microstrip antenna (MSA) is fed with via-holes to downsize the 21-GHz-band feed circuit and mitigate the feeding loss. The performance of a 50-cm offset parabolic reflector antenna with the designed feed is described.

This chapter is organized as follows. Section 5.2 describes the performance targets of the study and the basic configuration of receiving reflector antenna with a planar feed. Section 5.3 explains the design proses of the proposed feed. This section shows the design of MSAs, array antennas, and a feed circuit. Section 5.4 describes the characteristics of a receiving reflector antenna with the designed feed. Section 5.5 concludes this chapter.

5.2. Performance Targets and Basic Configuration of Receiving Reflector Antenna with Planar Feed

Table 5.1 shows the performance targets for the study. The gains were determined from the peak gain of a 45-cm parabolic reflector antenna (aperture efficiency: 60%), as described in Section 1.5. Assuming an aperture diameter of 50 cm, the gains correspond to an aperture efficiency of 50% in each frequency band. The XPD was derived from the reference pattern in Recommendation ITU-R BO.1213 (BO.1213) at boresight [5.1]. The upper limit of the VSWR is 1.5 to receive small signals from the satellite. Fig. 5.1 shows the configuration of the designed receiving reflector antenna with a planar feed. The reflector is fed by 12- and 21-GHz-band MSA arrays that are located at the same focal point with a multilayer structure. A suitable beamwidth for both bands can be obtained by changing the spacing of elements individually.

Table 5.1 Performance targets.

Item	Frequency bands	
	12-GHz band	21-GHz band
Receiving frequency	11.7 to 12.75 GHz	21.4 to 22 GHz
Receiving polarizations	RHCP and LHCP	RHCP and LHCP
Gain	33 dBi	38 dBi
XPD (at boresight)	≥ 25 dB	≥ 25 dB
VSWR	≤ 1.5	≤ 1.5

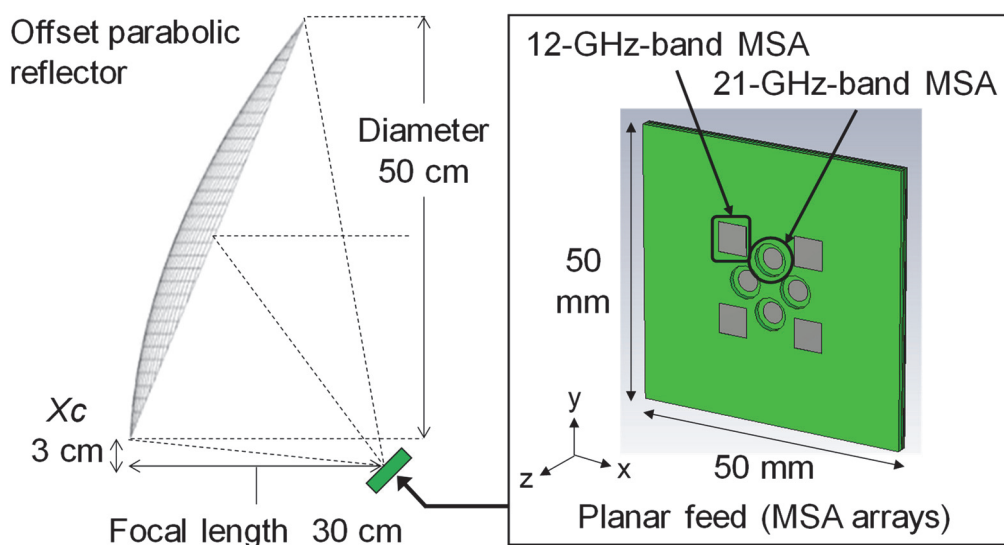
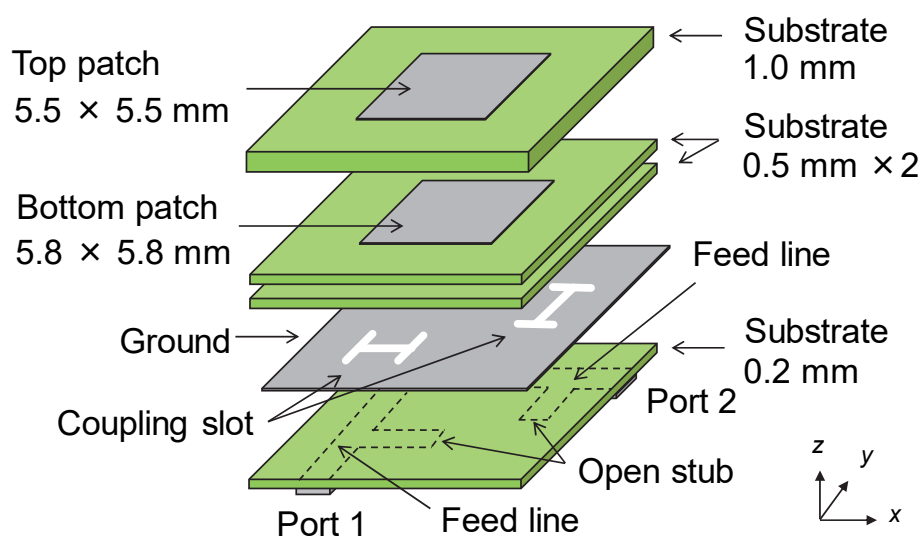


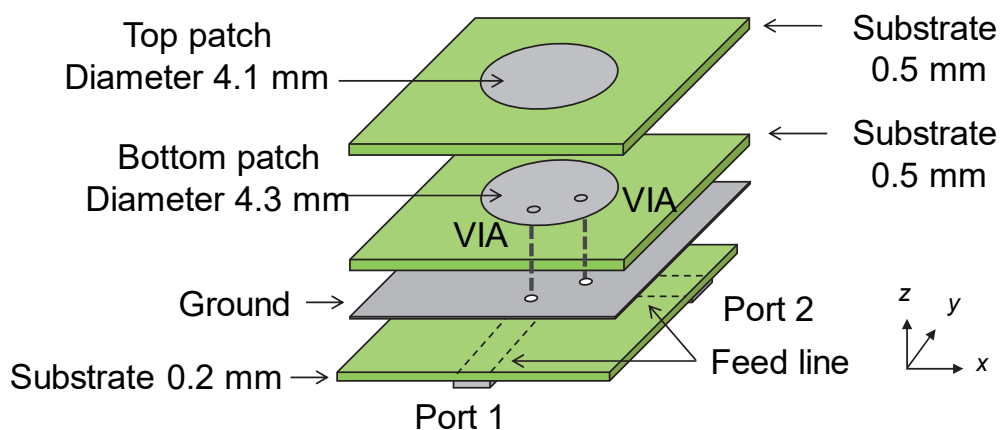
Fig. 5.1 Configuration of designed reflector antenna with planar feed.

5.3. Design of Feed

Fig. 5.2 shows the multilayer structure of the MSAs composed of polytetrafluoroethylene (PTFE) substrates. The impedance bandwidth can increase with a thick substrate, but there is a physical limit to the substrate thickness. Hence, the maximum substrate thickness was set to $\lambda_c/16$ [5.2], where λ_c is the wavelength in the dielectric.



(a) 12-GHz-band MSA.



(b) 21-GHz-band MSA.

Fig. 5.2 Layer configuration of MSAs.

In Chapter 4, a slot coupling for the 12- and 21-GHz-band MSAs was chosen. However, the feeding loss of the 21-GHz band increased, as shown in Table 5.2, because the feed circuit was enlarged to secure space for the slots. The feeding loss was evaluated from the difference between the gain for a perfect electric conductor (PEC) and that of copper (conductivity of 59.0×10^6 S/m). Therefore, in this study, the 21-GHz-band MSA was excited with via-holes (VIAs) in order to downsize the 21-GHz-band feed circuit and mitigate the feeding loss. The MSAs are operated as circularly polarized MSAs by feeding 90-degree shifted signals to the two feed lines.

Table 5.2 Calculated feeding loss of prototype feed shown in Chapter 4.

Item	12.225 GHz		21.7 GHz	
	RHCP	LHCP	RHCP	LHCP
Gain (PEC) (1)	12.3 dBi	12.3 dBi	11.5 dBi	11.6 dBi
Gain (copper) (2)	12.0 dBi	12.0 dBi	10.6 dBi	10.7 dBi
Feeding loss (1) – (2)	0.3 dB	0.3 dB	0.9 dB	0.9 dB

Figs. 5.3 to 5.7 show the configuration, feed circuit, and feeding phase of the designed feed. The antenna is composed of two 2×2 MSA arrays, in which the elements are sequentially rotated to enhance the polarization purity [5.3]. The feeding phase of the m -th patch is shifted to $90 \times (m-1)$ deg. by using 3-dB, 90-deg. hybrid couplers (3dB-HYBs) and differences in the line length. From the study described in Chapter 3, 0.6 wavelength was chosen for the spacing of elements.

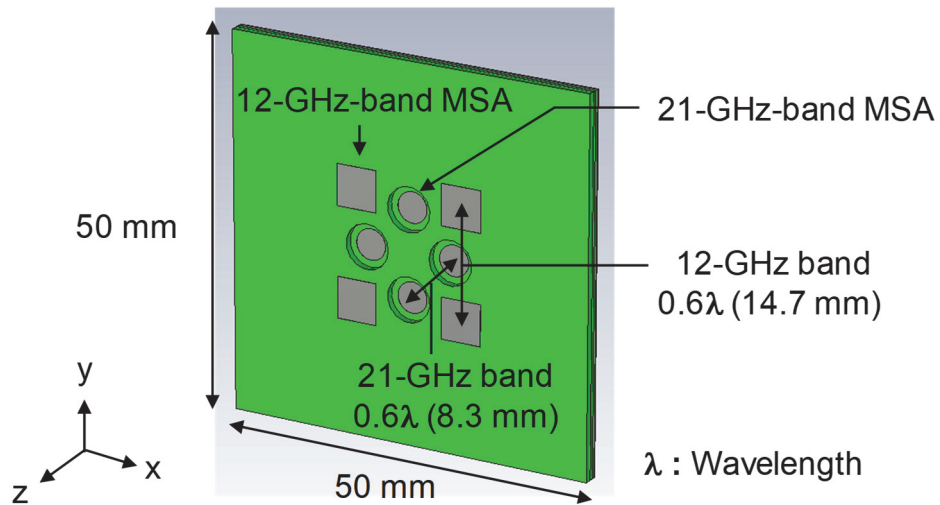


Fig. 5.3 Top view of designed feed (MSA arrays).

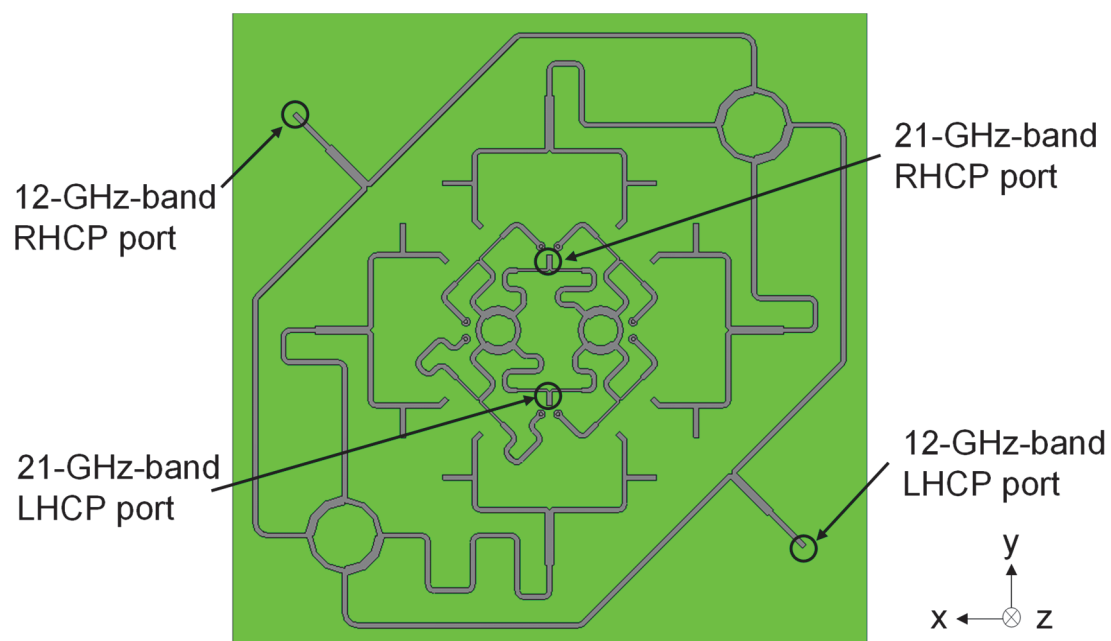


Fig. 5.4 Feed circuit (back view).

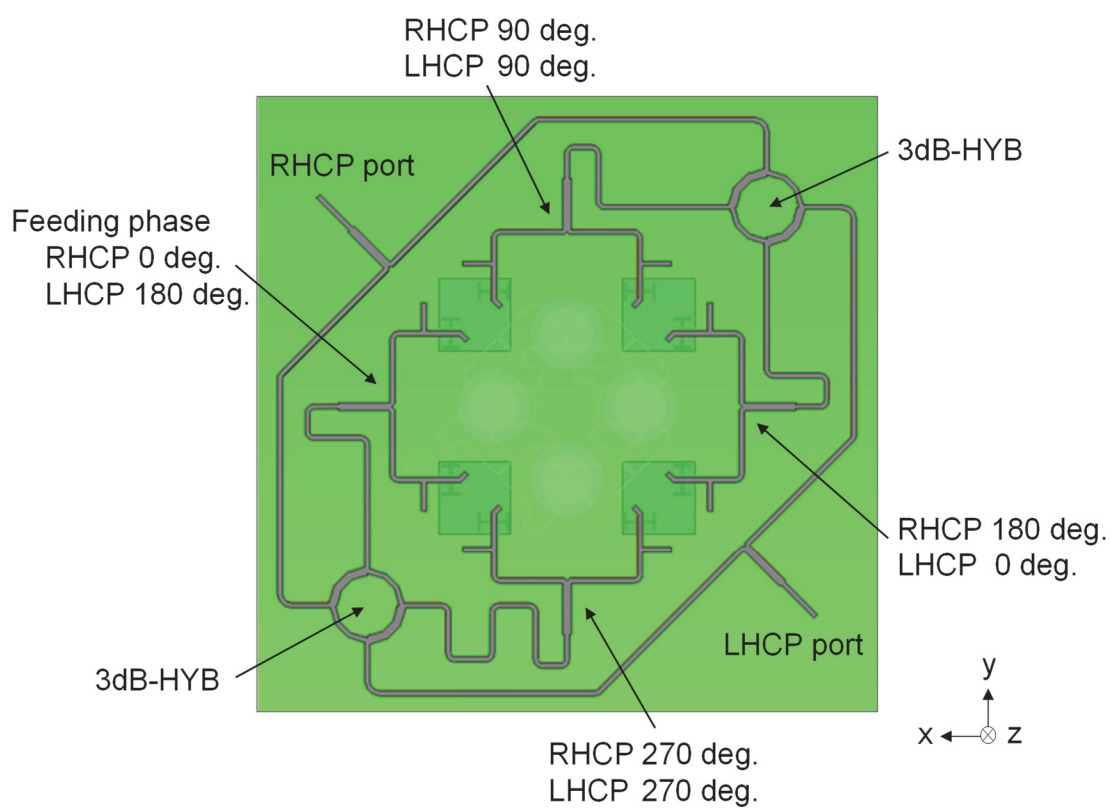


Fig. 5.5 Feeding phase in the 12-GHz band (perspective view).

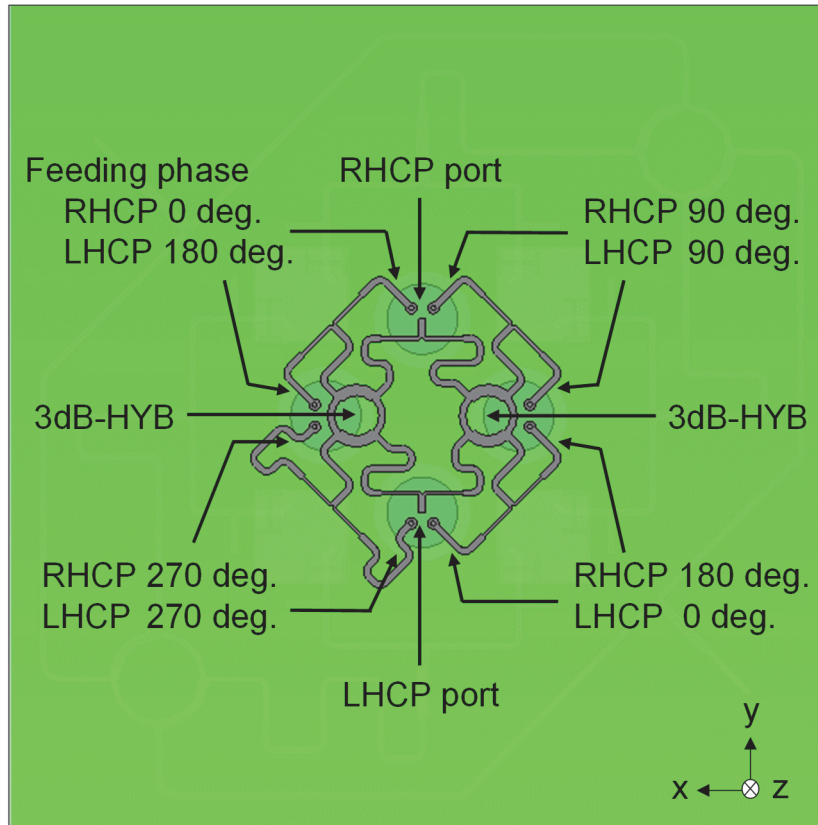


Fig. 5.6 Feeding phase in the 21-GHz band (perspective view).

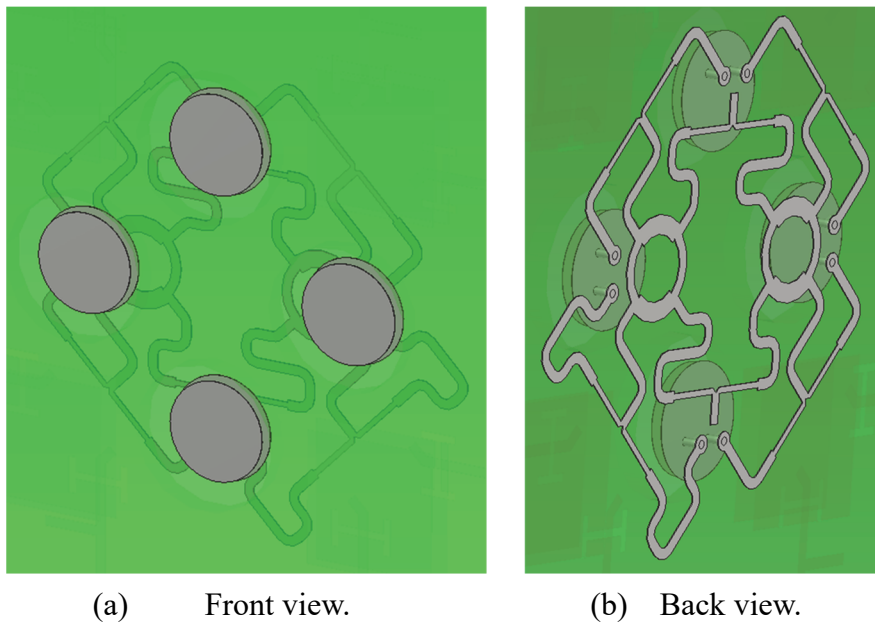
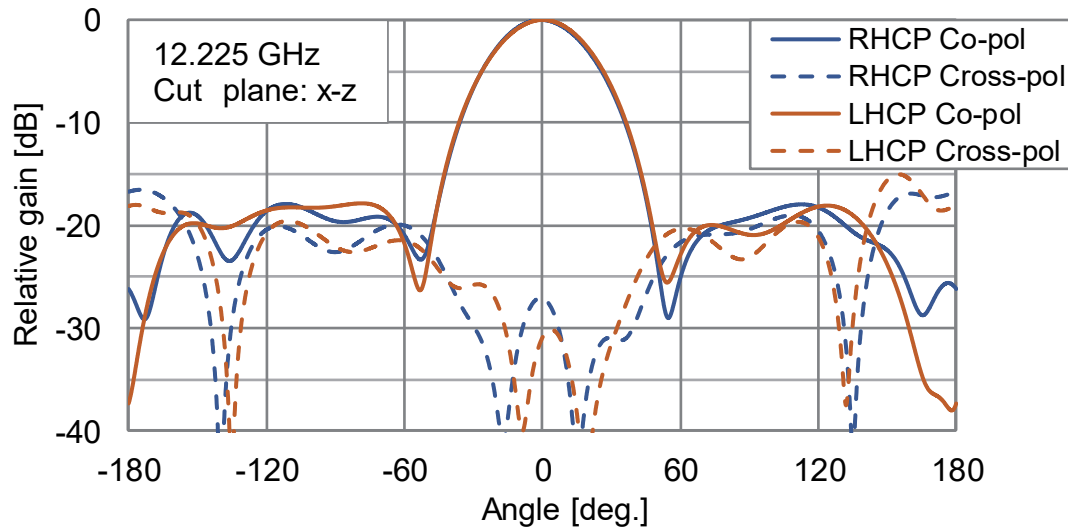
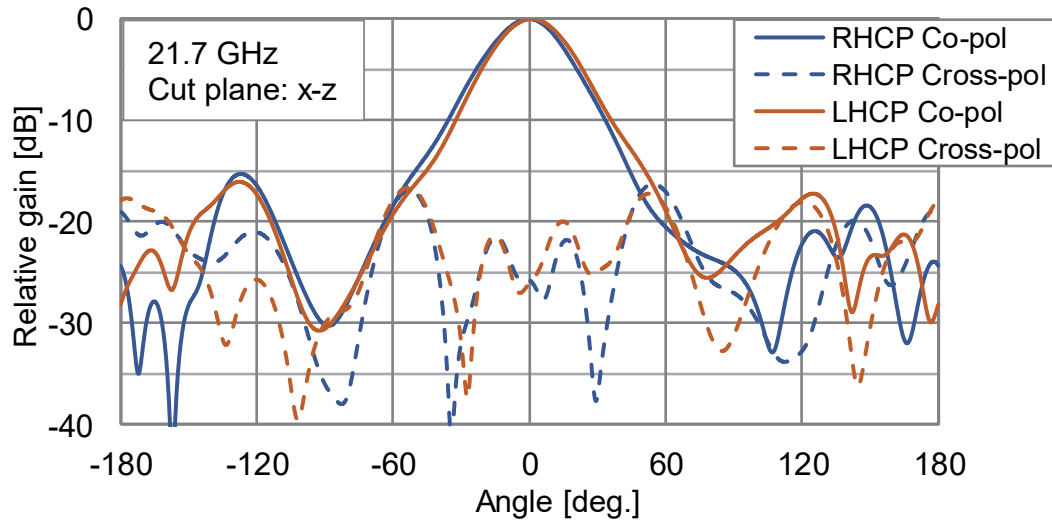


Fig. 5.7 Connection of 21-GHz-band MSAs and feed circuit.

Fig. 5.8 shows the calculated radiation patterns of the designed feed. This figure shows that the designed feed can radiate RHCP and LHCP in the 12- and 21-GHz bands simultaneously. The polarizations, which are discussed in this section, are defined as the polarizations radiated from the feed.



(a) 12-GHz-band MSA array.



(b) 21-GHz-band MSA array.

Fig. 5.8 Calculated radiation patterns of feed (MSA arrays).

Table 5.3 shows the calculated characteristics of the feed. The feeding loss was evaluated from the difference between the gain for a PEC and that of copper. It turned out that the feeding loss in the 21-GHz band was 0.6 dB lower than that of the previous design shown in Table 5.2. On the other hand, the loss in the 12-GHz band increased by 0.3 dB because the microstrip lines in the 12-GHz-band feed circuit were longer than those of the previous design. In this study, the EILs are defined as an average value of the relative gains at ± 38.6 degrees because the aperture angle is 77.2 degrees. The EILs in each band were about -12 dB for both polarizations.

Table 5.3 Calculated characteristics of designed feed.

Item	12.225 GHz		21.7 GHz	
	RHCP	LHCP	RHCP	LHCP
Gain (PEC) (1)	12.1 dBi	12.0 dBi	12.7 dBi	12.6 dBi
Gain (copper) (2)	11.6 dBi	11.4 dBi	12.4 dBi	12.4 dBi
Feeding loss (1) – (2)	0.5 dB	0.6 dB	0.3 dB	0.2 dB
EIL	-11.8 dB	-11.5 dB	-11.7 dB	-11.7 dB
XPD (at boresight)	27.1 dB	30.9 dB	25.8 dB	26.0 dB

5.4. Simulation Results of Designed Reflector Antenna

Tables 5.4 and 5.5 summarize the simulation results of gain, XPD, and VSWR of the designed receiving reflector antenna in the 12- and 21-GHz band, respectively. They were calculated at the lower-end, center, and upper-end frequencies in each band. The gains include the feeding loss. The simulation results show that the designed 50-cm reflector antenna satisfied the performance targets of the gain and VSWR shown in Table 5.1 throughout both bands, and that the XPD was similar to the target value (25 dB).

Table 5.4 Calculated gain, XPD, and VSWR of designed receiving reflector antenna with proposed feed in the 12-GHz band (gains include feeding loss).

Frequency [GHz]	Gain [dBi]	XPD [dB] (at boresight)	VSWR
11.7	RHCP: 33.4 LHCP: 33.4	RHCP: 22.1 LHCP: 22.9	RHCP: 1.26 LHCP: 1.21
12.225	RHCP: 33.7 LHCP: 33.8	RHCP: 28.8 LHCP: 31.9	RHCP: 1.06 LHCP: 1.03
12.75	RHCP: 34.1 LHCP: 34.1	RHCP: 26.2 LHCP: 26.5	RHCP: 1.29 LHCP: 1.27

Table 5.5 Calculated gain, XPD, and VSWR of designed receiving reflector antenna with proposed feed in the 21-GHz band (gains include feeding loss).

Frequency [GHz]	Gain [dBi]	XPD [dB] (at boresight)	VSWR
21.4	RHCP: 38.5 LHCP: 38.4	RHCP: 26.6 LHCP: 26.9	RHCP: 1.13 LHCP: 1.13
21.7	RHCP: 38.3 LHCP: 38.3	RHCP: 24.7 LHCP: 25.4	RHCP: 1.16 LHCP: 1.16
22	RHCP: 38.0 LHCP: 38.2	RHCP: 24.0 LHCP: 24.1	RHCP: 1.16 LHCP: 1.20

Table 5.6 shows the calculated gain at the lower-end, center, and upper-end frequencies of each band in comparison with that of the designed antenna in Chapter 4 (calculated values). This table shows that the proposed design can improve the gain in the 21-GHz band. The amount of increase was more than 0.6 dB. Since the line length of the 12-GHz-band feed circuit become longer, the gain in the 12-GHz band decreased. However, there is a margin for the target gain value in the 12-GHz band.

Table 5.6 Calculated gain in comparison with that of designed antenna described in Chapter 4 (gains include feeding loss).

(a) Lower end frequency.

Item	11.7 GHz		21.4 GHz	
	RHCP	LHCP	RHCP	LHCP
(1) Parabolic reflector antenna designed in this chapter	33.4 dBi	33.4 dBi	38.5 dBi	38.4 dBi
(2) Parabolic reflector antenna designed in Chapter 4	33.6 dBi	33.7 dBi	37.1 dBi	37.1 dBi
Difference of gain (1) – (2)	–0.2 dB	–0.3 dB	+1.4 dB	+1.3 dB

(b) Center frequency.

Item	12.225 GHz		21.7 GHz	
	RHCP	LHCP	RHCP	LHCP
(1) Parabolic reflector antenna designed in this chapter	33.7 dBi	33.8 dBi	38.3 dBi	38.3 dBi
(2) Parabolic reflector antenna designed in Chapter 4	34.2 dBi	34.3 dBi	37.3 dBi	37.4 dBi
Difference of gain (1) – (2)	–0.5 dB	–0.5 dB	+1.0 dB	+0.9 dB

(c) Upper end frequency.

Item	12.75 GHz		22 GHz	
	RHCP	LHCP	RHCP	LHCP
(1) Parabolic reflector antenna designed in this chapter	34.1 dBi	34.1 dBi	38.0 dBi	38.2 dBi
(2) Parabolic reflector antenna designed in Chapter 4	34.3 dBi	34.4 dBi	37.4 dBi	37.5 dBi
Difference of gain (1) – (2)	–0.2 dB	–0.3 dB	+0.6 dB	+0.7 dB

Table 5.7 shows the calculated XPD at the lower-end, center, and upper-end frequencies of each band in comparison with that of the designed antenna in Chapter 4 (calculated values). The proposed design can improve the gain in the 21-GHz band; however, its calculated XPD becomes lower than that of the designed antenna described in Chapter 4 except for 12.75 GHz. It is assumed that the feeding phase in the circuit was shifted from the ideal value.

Table 5.7 Calculated XPD in comparison with that of designed antenna described in Chapter 4.

(a) Lower end frequency.

Item	11.7 GHz		21.4 GHz	
	RHCP	LHCP	RHCP	LHCP
(1) Parabolic reflector antenna designed in this chapter	22.1 dB	22.9 dB	26.6 dB	26.9 dB
(2) Parabolic reflector antenna designed in Chapter 4	26.1 dB	25.4 dB	32.0 dB	38.3 dB
Difference of XPD (1) – (2)	–4.0 dB	–2.5 dB	–5.4 dB	–11.4 dB

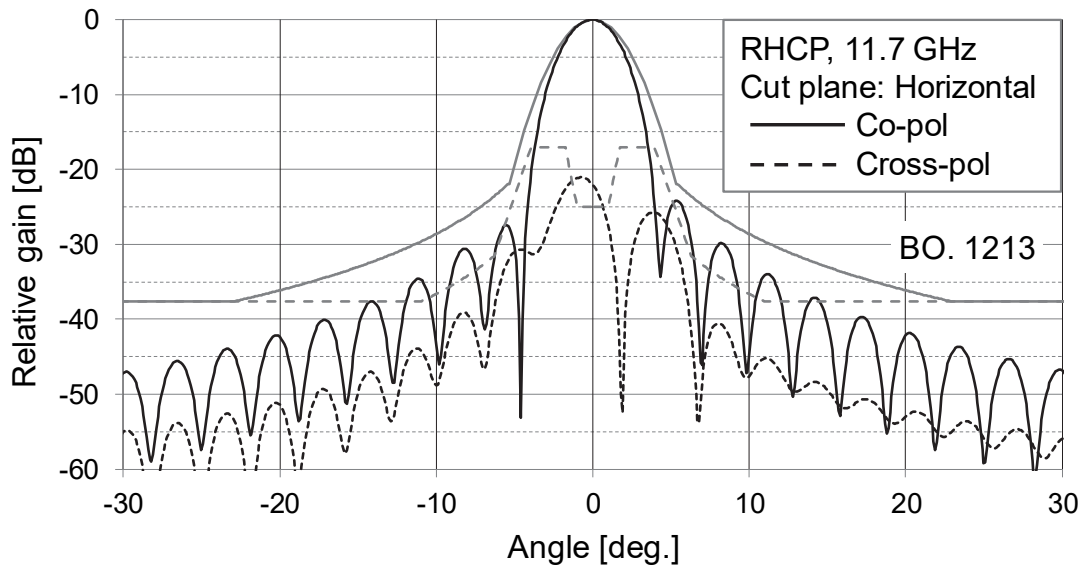
(b) Center frequency.

Item	12.225 GHz		21.7 GHz	
	RHCP	LHCP	RHCP	LHCP
(1) Parabolic reflector antenna designed in this chapter	28.8 dB	31.9 dB	24.7 dB	25.4 dB
(2) Parabolic reflector antenna designed in Chapter 4	31.9 dB	34.2 dB	34.3 dB	34.7 dB
Difference of XPD (1) – (2)	–3.1 dB	–2.3 dB	–9.6 dB	–9.3 dB

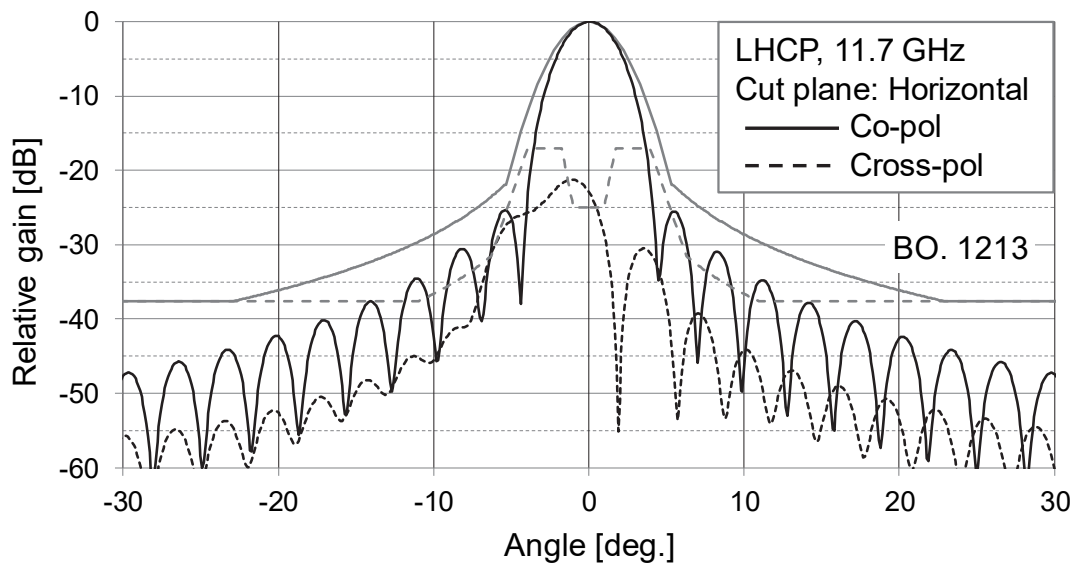
(c) Upper end frequency.

Item	12.75 GHz		22 GHz	
	RHCP	LHCP	RHCP	LHCP
(1) Parabolic reflector antenna designed in this chapter	26.2 dB	26.5 dB	24.0 dB	24.1 dB
(2) Parabolic reflector antenna designed in Chapter 4	25.4 dB	25.2 dB	50.6 dB	36.0 dB
Difference of XPD (1) – (2)	+0.8 dB	+1.3 dB	–26.6 dB	–11.9 dB

Figs. 5.9 to 5.14 show the calculated radiation patterns of the designed reflector antenna. GRASP [5.4] was used to calculate the patterns. The figures also show the reference patterns recommended by ITU-R for the 12-GHz band (BO.1213) [5.1] and the 21-GHz band (BO.1900) [5.5]. The co-polarization patterns satisfied the reference patterns throughout both bands, and the cross-polarization patterns slightly exceeded the reference patterns at the lower- and upper-end frequencies in the 12-GHz band.

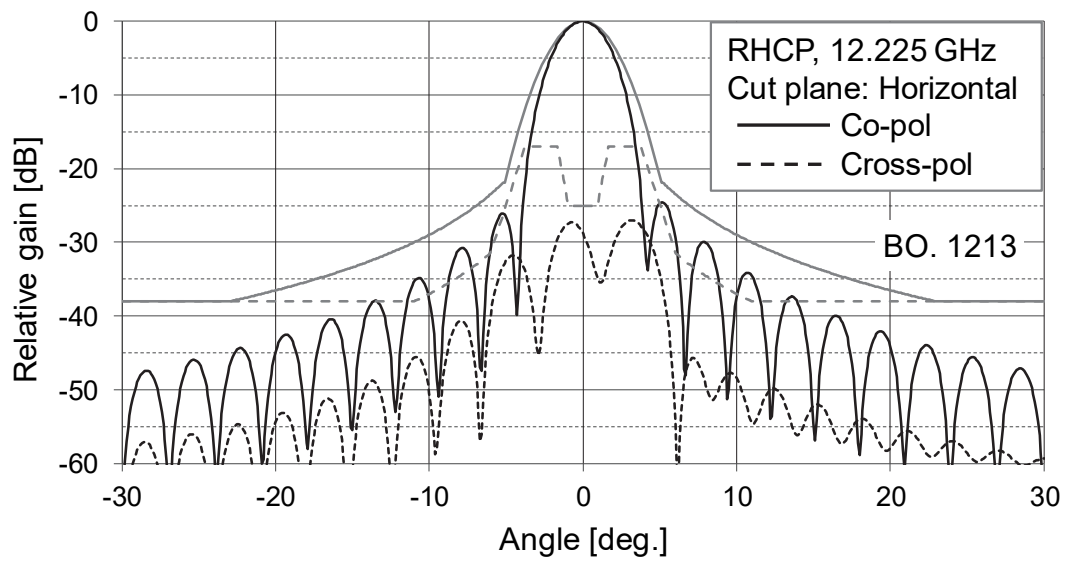


(a) RHCP antenna.

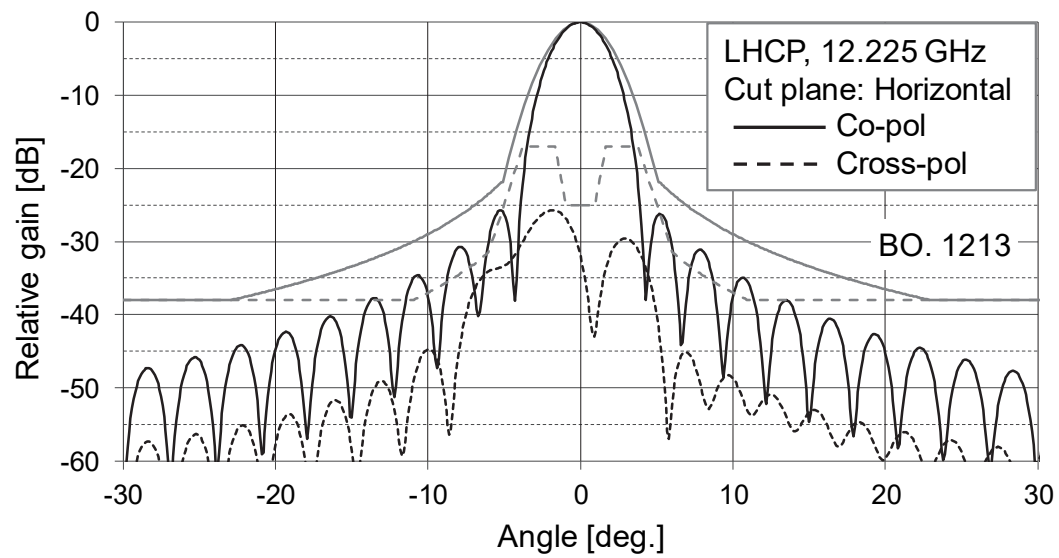


(b) LHCP antenna.

Fig. 5.9 Calculated radiation patterns of designed reflector antenna (11.7 GHz).

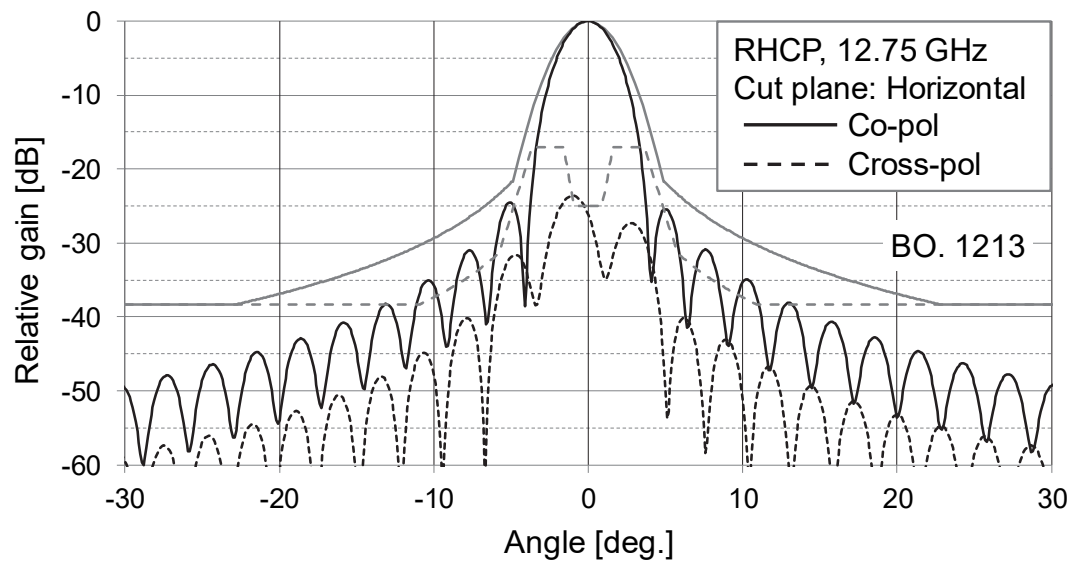


(a) RHCP antenna.

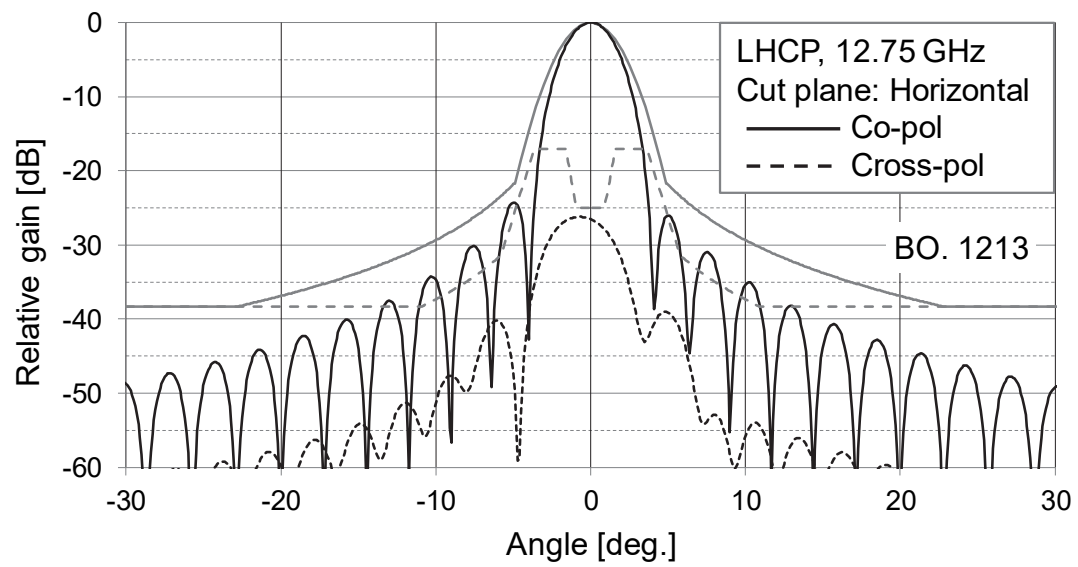


(b) LHCP antenna.

Fig. 5.10 Calculated radiation patterns of designed reflector antenna (12.225 GHz).

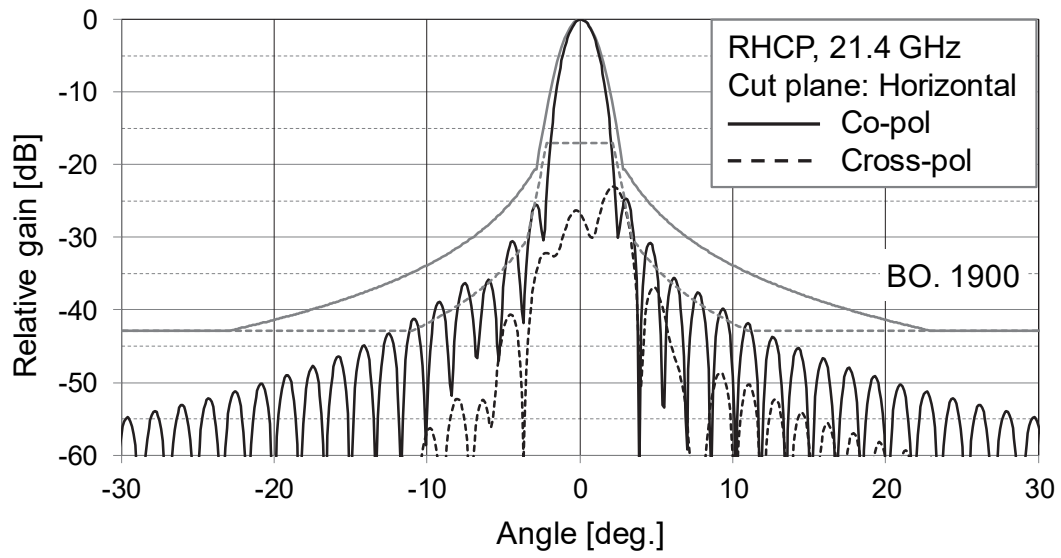


(a) RHCP antenna.

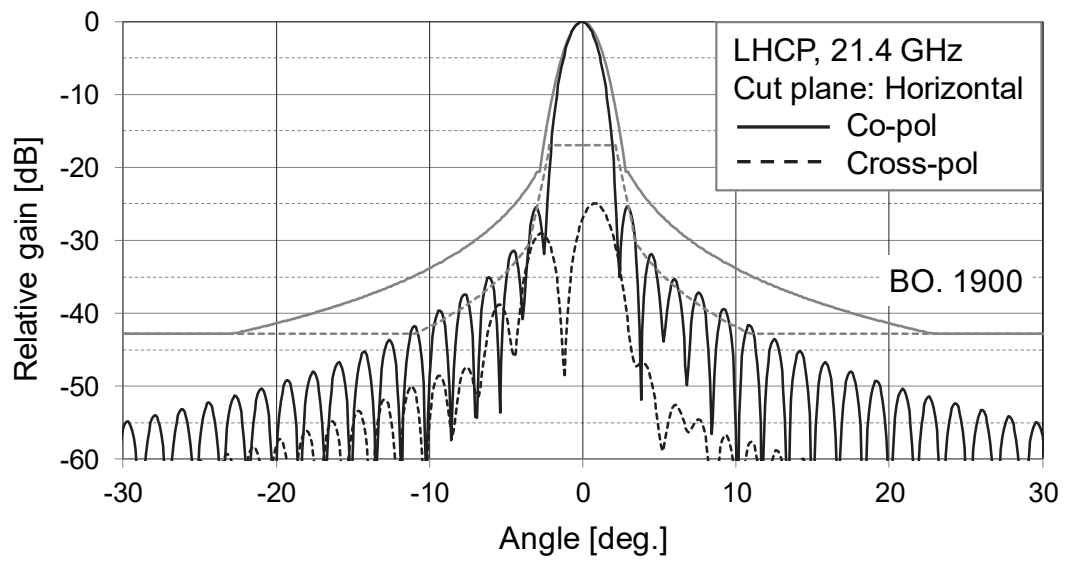


(b) LHCP antenna.

Fig. 5.11 Calculated radiation patterns of designed reflector antenna (12.75 GHz).

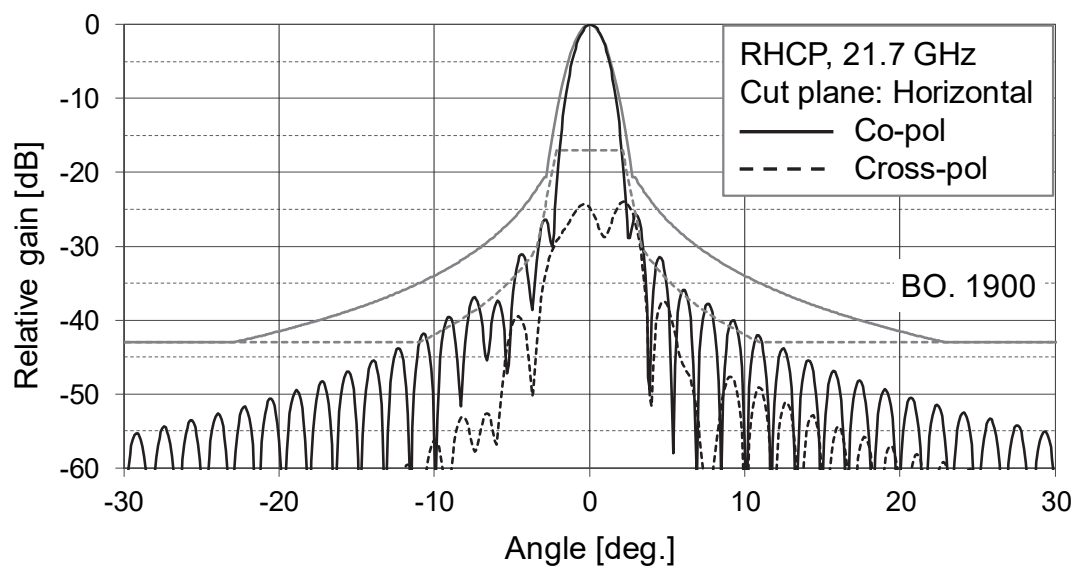


(a) RHCP antenna.

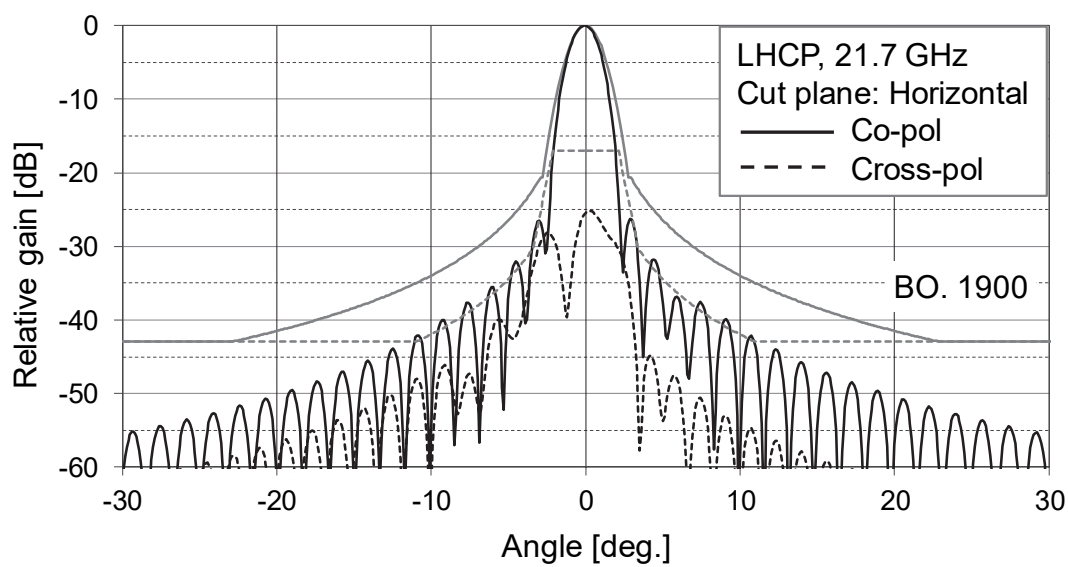


(b) LHCP antenna.

Fig. 5.12 Calculated radiation patterns of designed reflector antenna (21.4 GHz).

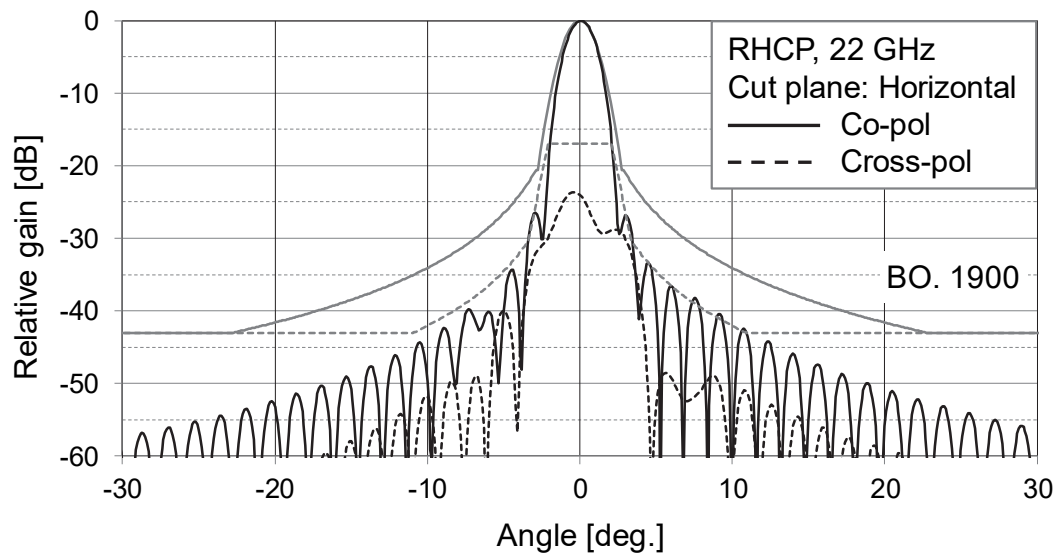


(a) RHCP antenna.

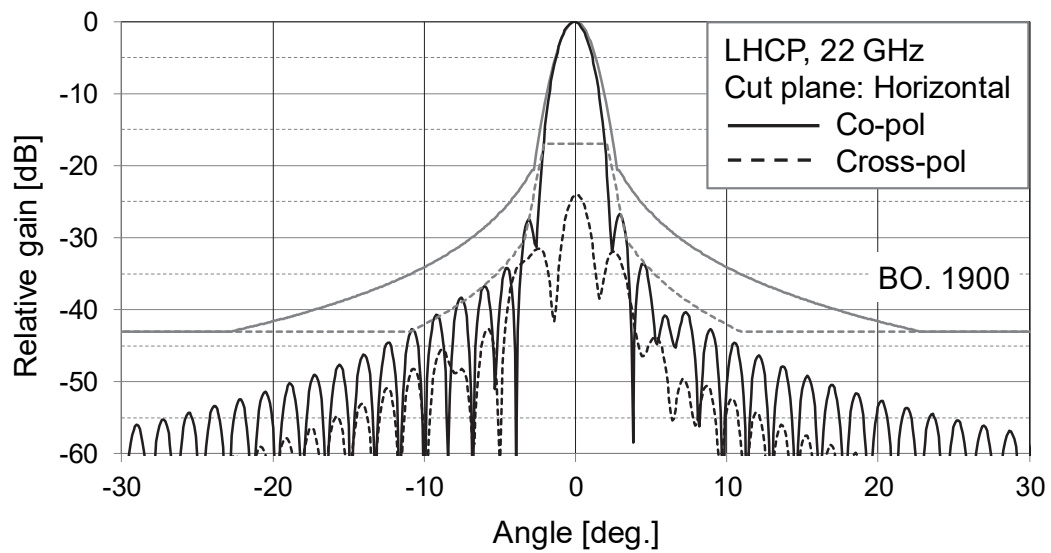


(b) LHCP antenna.

Fig. 5.13 Calculated radiation patterns of designed reflector antenna (21.7 GHz).



(a) RHCP antenna.



(b) LHCP antenna.

Fig. 5.14 Calculated radiation patterns of designed reflector antenna (22 GHz).

5.5 Concluding Remarks

The design process and characterization of a dual-band and dual-circularly polarized feed, whose feeding loss in the 21-GHz band was mitigated, were described. From the evaluation results in Chapter 4, it was appeared that the feeding loss of the 21-GHz band increased because the feed circuit is enlarged to secure space for the feeding slots. Therefore, the 21-GHz-band MSA was fed with via-holes to downsize the 21-GHz-band feed circuit and mitigate the feeding loss.

The simulation results confirmed that the proposed feed can improve the gain of the reflector antenna in the 21-GHz band. The amount of increase was more than 0.6 dB. Moreover, the calculated radiation patterns almost satisfied the reference patterns recommended by ITU-R.

References

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- [5.4] TICRA GRASP: <https://www.ticra.com/software/grasp/>
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Chapter 6

Experiment of Receiving 12- and 21-GHz-band Signals from Broadcasting Satellites with Prototype Antenna

6.1 Introductory Remarks

This chapter presents the experimental results of receiving 12- and 21-GHz-band signals transmitted from broadcasting satellites by using the prototype antenna. The 12-GHz-band signals are transmitted from the BSAT [6.1] and JCSAT [6.2] satellites whose orbital positions are 110 degrees East. In the 21-GHz band, an LHCP signal, which is the beacon signal, is transmitted by the satellite BSAT-4a [6.3].

This chapter is organized as follows. Section 6.2 describes the experiment that was performed at NHK Science & Technology Research Laboratories (Setagaya, Tokyo) on June 1st, 2018. In this section, the configuration of the experiment and the characteristics of the fabricated low noise block converters are explained. Section 6.3 describes the experiment performed on April 22nd, 2019, after the start of UHDTV satellite broadcasting. In this section, the experimental results using by a consumer UHDTV (4K) receiver are shown. Section 6.4 concludes this chapter.

6.2 Experiment Performed on June 1st, 2018

6.2.1 Configuration of Experiment

The 12- and 21-GHz-band signals transmitted from broadcasting satellites were received with the prototype antenna. The configuration of the experiment is shown in Fig. 6.1. The 12-GHz-band signals are transmitted from the BSAT [6.1] and JCSAT [6.2] satellites whose orbital positions are 110 deg. E. In the 21-GHz band, an LHCP signal that is the beacon (continuous wave) transmitted by BSAT-4a [6.3] can be received. An RHCP signal in the 21-GHz band can be received only when an experimental signal is being transmitted from the transponder because there is no commercial broadcast service in the 21-GHz band yet [6.4].

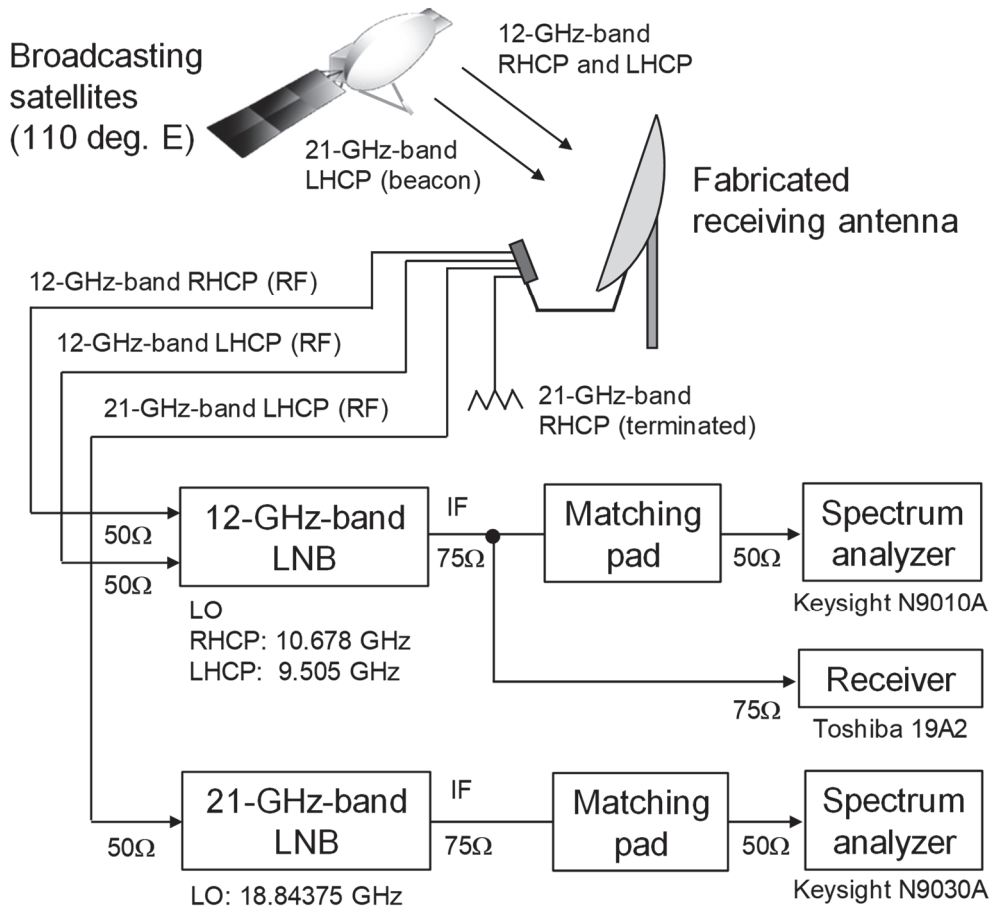


Fig. 6.1 Configuration of experiment performed on June 1st, 2018.

Since the receiving power from the satellites is low, low-noise block converters (LNBs) were connected to the output of the receiving antenna. Therefore, the presence of the receiving signals in the intermediate frequency (IF) bands was confirmed. The specifications of the LNBs are listed in Table 6.1, and the LNBs were customized for this experiment. The block diagram of the 12-GHz-band LNB, which has two LNB circuits, is also shown in Fig. 6.2. The local oscillator frequency (LO) for the 12-GHz band complies with ARIB STD-B63 [6.5], which is a standard for 4K/8K UHD TV satellite broadcasting receivers in Japan, and that for the 21-GHz band was chosen to correspond with the input frequency of a wide-band demodulator [6.6]. When this experiment was performed, 4K/8K UHD TV receivers were not available yet, and the 21-GHz-band wide-band modulated signal was not transmitted; therefore, spectrum analyzers and a consumer HDTV (2K) receiver for satellite broadcasting were used to verify the received signals.

Table 6.1 Specifications of LNBs used for experiment.

Item	Frequency bands	
	12-GHz band	21-GHz band
Input freq. [GHz]	11.7 to 12.75	21.4 to 22
Local oscillator freq. [GHz]	RHCP: 10.678 LHCP: 9.505	18.84375
Gain [dB]	RHCP: 52 to 55 LHCP: 51 to 54	57 to 59
Noise figure [dB]	1.3 (typ.)	1.5 (typ.)
Output freq. [GHz]	RHCP: 1.03 to 2.07 LHCP: 2.22 to 3.22	2.55 to 3.16

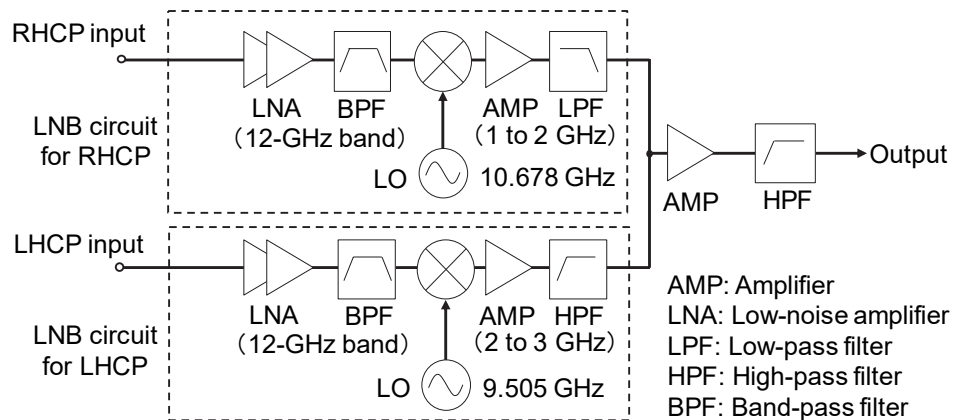


Fig. 6.2 Block diagram of 12-GHz-band LNB.

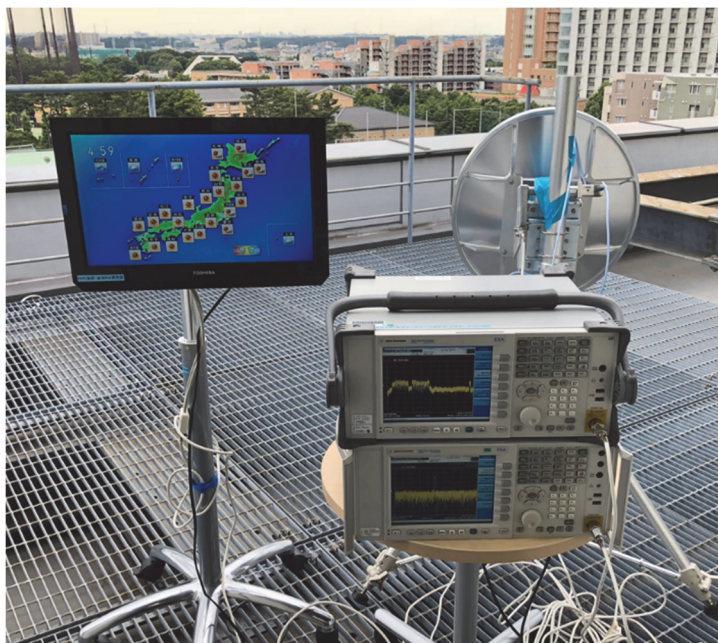
6.2.2 Experimental Results

The experiment was performed at NHK Science & Technology Research Laboratories (Setagaya, Tokyo) on June 1st, 2018. Pictures of the experiment are shown in Fig. 6.3. The BSAT and JCSAT satellites were transmitting signals from 24 transponders for RHCP and from one transponder for LHCP in the 12-GHz band on that day. BSAT-4a was also transmitting the beacon with LHCP in the 21-GHz band; however, the experimental signal with RHCP was not transmitting in the band.

The frequency spectra of the received signals are shown in Figs. 6.4 and 6.5. The RHCP and LHCP signals in the 12-GHz band were received simultaneously. For the 21-GHz band, the beacon signal was received adequately, as shown in Fig. 6.5. The 12-GHz-band receiving signal was demodulated with the consumer satellite broadcasting receiver. The demodulated video and audio were completely normal. The experimental results confirmed that the developed antenna could receive the dual-circular polarizations in the 12-GHz band and the LHCP in the 21-GHz band simultaneously.



(a) Prototype antenna receiving signals from satellites.



(b) Receiver and spectrum analyzers.

Fig. 6.3 Experiment performed on June 1st, 2018.

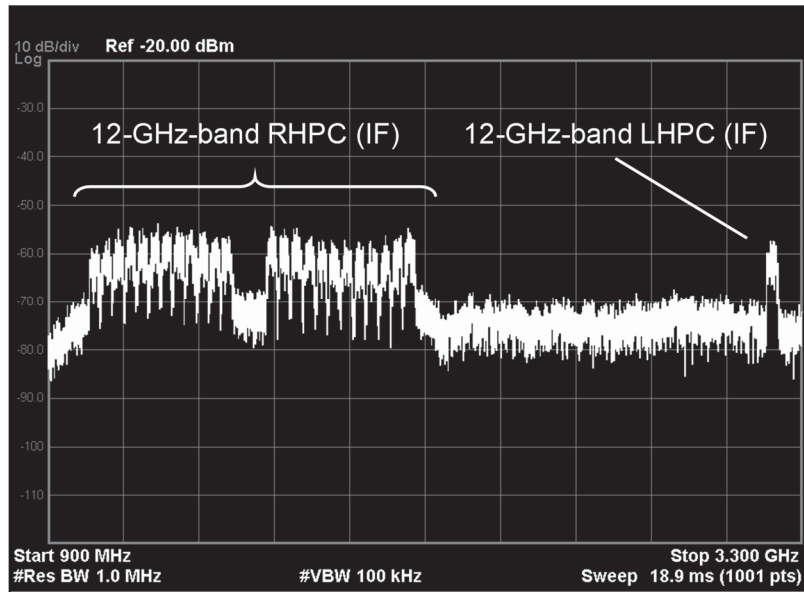


Fig. 6.4 Received spectrum of 12-GHz-band satellite broadcasting.

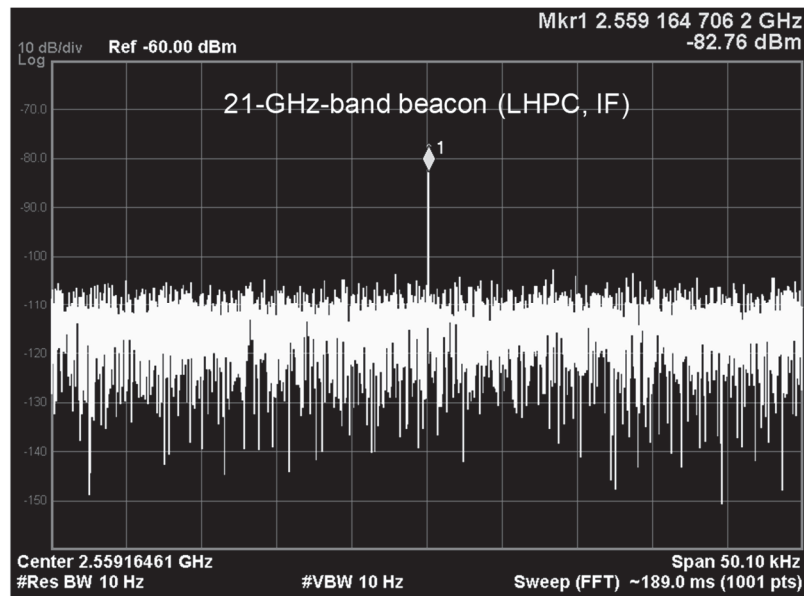


Fig. 6.5 Received spectrum of 21-GHz-band beacon.

6.3 Experiment Performed on April 22nd, 2019

6.3.1 Configuration of Experiment

The experiment described in Section 6.2 was performed before the start of UHDTV satellite broadcasting. Therefore, another experiment was carried out to receive 12-GHz-band signals, which include UHDTV signals at that time, and the 21-GHz-band beacon signal with the prototype antenna. Fig. 6.6 shows the configuration of the experiment. Since the received power from the satellites is low, LNBs were connected to the output of the receiving antenna. Therefore, the presence of the received signals in the IF bands was confirmed. The local oscillator frequency (LO) for the 12-GHz band complies with ARIB STD-B63 [6.5], and that for the 21-GHz-band was chosen to correspond with the input frequency of a wide-band demodulator [6.6]. A consumer UHDTV (4K) receiver and spectrum analyzers are used to examine the received signals.

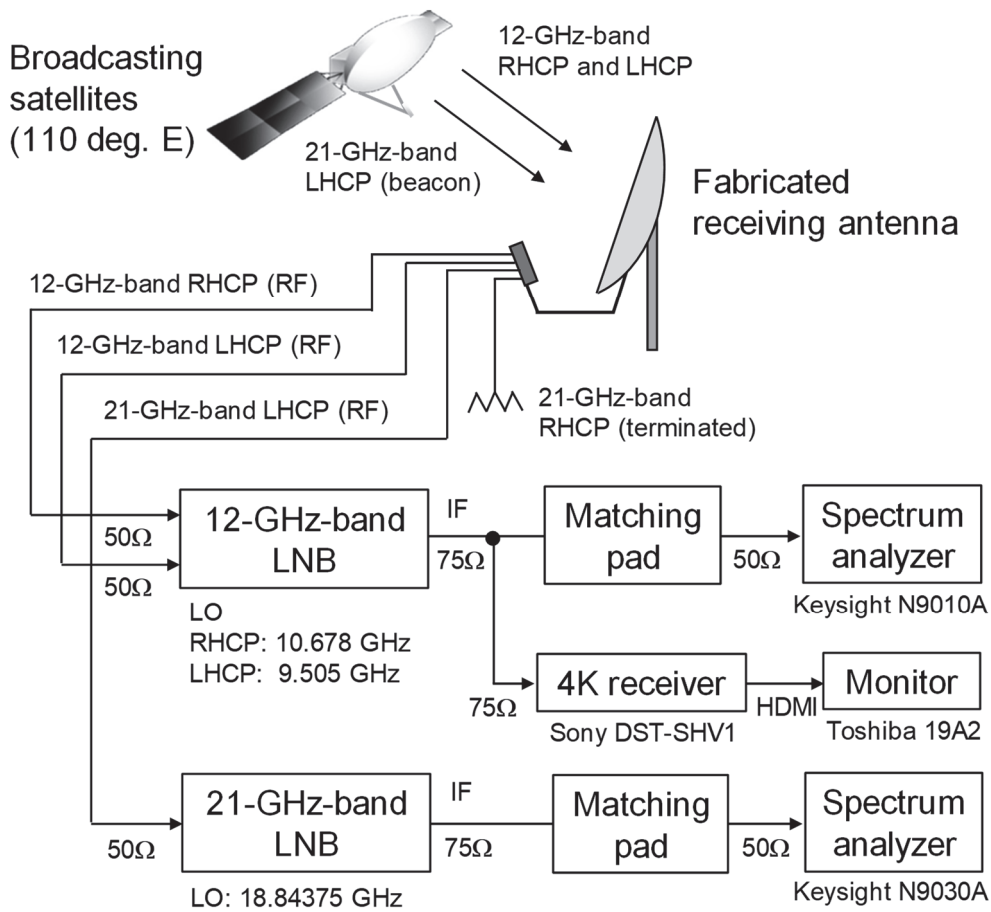
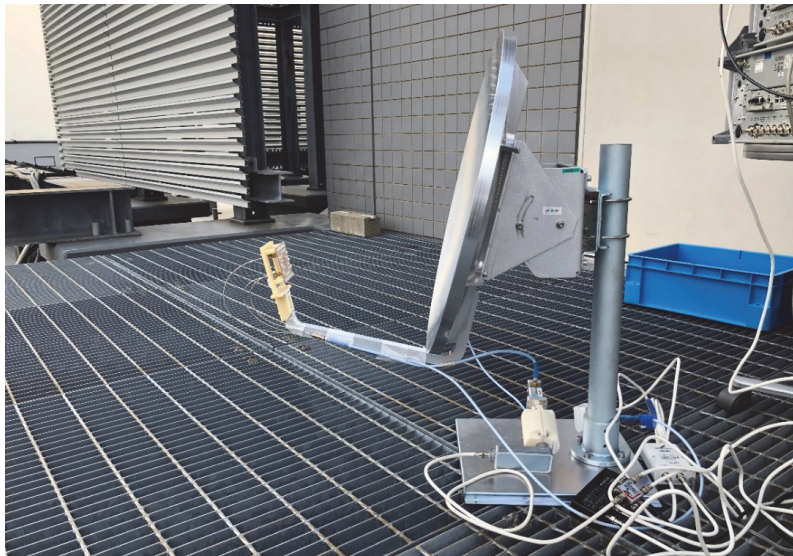
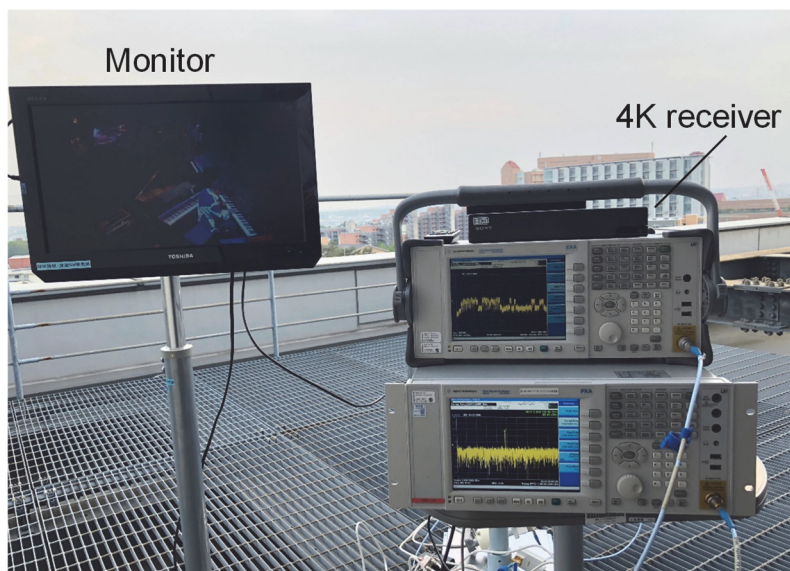


Fig. 6.6 Configuration of experiment performed on April 22nd, 2019.

The experiment was performed at NHK Science & Technology Research Laboratories on April 22nd, 2019 (Fig. 6.7). The BSAT and JCSAT satellites were transmitting RHCP signals from 24 transponders and LHCP signals from seven transponders in the 12-GHz band on that day. BSAT-4a was also transmitting the beacon with LHCP in the 21-GHz band. However, the experimental RHCP signal was not transmitting in the band on that day.



(a) Prototype antenna receiving signals from satellites.



(b) Receiver, monitor, and spectrum analyzers.

Fig. 6.7 Experiment performed on April 22nd, 2019.

6.3.2 Experimental Results

The frequency spectra of the received signals are shown in Figs. 6.8 and 6.9. The RHCP and LHCP signals in the 12-GHz band were received simultaneously. In addition, the beacon signal in the 21-GHz band was received adequately, as shown in Fig. 6.9. The received signal in the 12-GHz band was also demodulated with a consumer 4K receiver. The demodulated video and audio were completely normal.

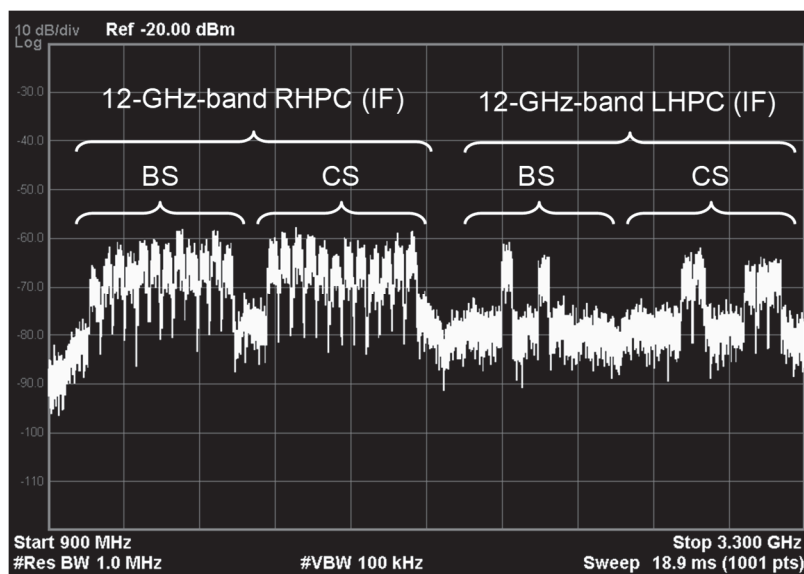


Fig. 6.8 Received spectrum of 12-GHz-band satellite broadcasting.

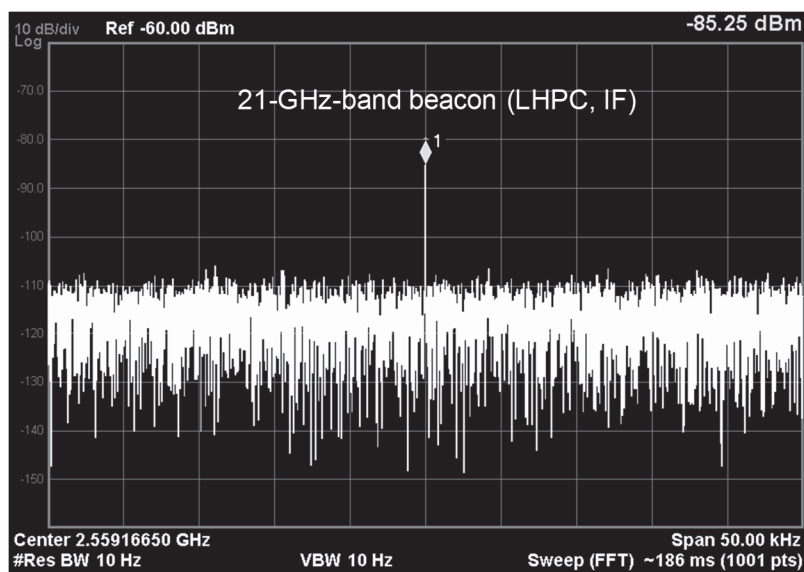


Fig. 6.9 Received spectrum of 21-GHz-band beacon signal.

6.4 Concluding Remarks

In this chapter, the experimental results of receiving the 12- and 21-GHz-band signals were presented, which were transmitted from broadcasting satellites, by using the prototype antenna. The 12-GHz-band signals were transmitted from the BSAT and JCSAT satellites whose orbital positions are 110 degrees East. In the 21-GHz band, an LHCP signal, which is the beacon signal, was transmitted by the BSAT-4a satellite. In the experiments, the RHCP and LHCP signals in the 12-GHz band were received simultaneously. The 12-GHz-band receiving signal was demodulated with the consumer UHDTV (4K) receiver. The demodulated video and audio were completely normal. For the 21-GHz band, the beacon signal was received adequately. The results confirmed that the proposed antenna performed as a dual-circularly polarized antenna in those two frequency bands.

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Chapter 7

Conclusions

7.1 Summary of Preceding Chapters

In this thesis, dual-band and dual-circularly polarized planar feeds for an offset parabolic reflector antenna were proposed. The proposed feeds were composed of two 2×2 microstrip antenna (MSA) arrays to obtain suitable beamwidth by changing the spacing of elements in each frequency band. Because the MSA arrays were designed with a multilayer structure, the MSA array of each band was set at the focal point of a parabolic reflector. It is also possible to downsize a feed of reflector antennas since the proposed feeds have a planar structure. The feed circuits were designed on the substrate to divide the right- and left-hand-circularly polarized signals in both bands. The proposed feeds applied to a receiving reflector antenna, satellite broadcasting signals provided by the right- and left-hand circular polarizations in the 12- and 21-GHz bands were received with a single reflector antenna.

In Chapter 1, the background of this study was presented by descriptions of advanced satellite broadcasting systems, antennas for satellite broadcasting reception, dual-band antennas, planar feeds for reflector antennas, and link calculations.

Chapter 2 presented the basic design of the proposed feeds that were composed of two 2×2 MSA arrays. In the design process, the size of the square and circular MSAs were discussed, and the ratio of the higher to lower frequency-band for the proposed feed was obtained. Then, the square and circular MSAs were chosen for the elements of the lower and higher frequency-band arrays, respectively. The far field conditions of the feed were also derived. Moreover, parameters of a reflector used with the proposed feed were studied to achieve enough gain for the right- and left-hand circular polarizations. The FD ratio of 0.6 was selected, and the aperture angle of 77.2 deg. was obtained.

Chapter 3 presented the design process and characterization of a dual-circularly polarized planar feed, which has a 12-GHz-band MSA array, for an offset parabolic reflector antenna. In this chapter, the feasibility of the dual-circularly polarized feed composed of the MSA array was evaluated. For obtaining enough gain and cross polarization discrimination (XPD) throughout the 12-GHz band for satellite broadcasting reception, a feed was composed of a 2×2 MSA array that was sequentially rotated to

enhance polarization purity. The performance of a prototype reflector antenna with the proposed feed, whose diameter is 50 cm, was discussed. The measured results indicate that the gain in the 12-GHz band was more than 33.1 dBi. The voltage standing wave ratio (VSWR) was less than 1.4, and the XPD was more than 25.6 dB throughout the band. The fabricated antenna complied with the performance targets.

Chapter 4 presented the design process and characterization of a dual-band dual-circularly polarized planar feed, which has 12- and 21-GHz-band MSA arrays, for offset parabolic reflector antenna. The feed was composed of two 2×2 MSA arrays that were sequentially rotated to enhance polarization purity, which were located at the same focal point with a multilayer structure. A feed circuit was also designed on the substrate, which makes it possible to divide the right- and left-hand-circularly polarized signals in both bands. The performance of a prototype 50-cm reflector antenna, whose diameter is 50 cm, was discussed. The measured results indicate that the gains in the 12- and 21-GHz bands were more than 33.2 and 35.9 dBi, respectively. The VSWR was less than 1.9, and the XPD was more than 20 dB throughout both bands. The proposed antenna performed as a dual-circularly polarized antenna in those two frequency bands.

Chapter 5 presented the design process and characterization of a dual-band and dual-circularly polarized feed whose feeding loss in the 21-GHz band was mitigated. From the evaluation results in Chapter 4, it was appeared that the feeding loss of the 21-GHz band increased because the feed circuit was enlarged to secure space for the feeding slots. Therefore, the 21-GHz-band MSA was fed with via-holes to downsize the 21-GHz-band feed circuit and mitigate the feeding loss. The performance of a 50-cm offset parabolic reflector antenna with the designed planar feed was described. The simulation results confirmed that the proposed feed can improve the gain of the reflector antenna in the 21-GHz band. The amount of increase was more than 0.6 dB. Moreover, the calculated radiation patterns almost satisfied the reference patterns recommended by ITU-R.

Chapter 6 presented the experimental results of receiving 12- and 21-GHz-band signals transmitted from broadcasting satellites by using the prototype antenna. The 12-GHz-band signals are transmitted from the BSAT and JCSAT satellites whose orbital positions are 110 degrees East. In the 21-GHz band, an LHCP signal, which is the beacon signal, is transmitted by the BSAT-4a satellite. In the experiments, the RHCP and LHCP signals in the 12-GHz band were received simultaneously. The 12-GHz-band receiving signal was demodulated with the consumer UHDTV (4K) receiver. The demodulated video and audio were completely normal. For the 21-GHz band, the beacon signal was received adequately. These results confirmed that the proposed antenna performed as a dual-circularly polarized antenna in those two frequency bands.

7.2 Remarks for Future Studies

In this thesis, the planar feeds using multilayer polytetrafluoroethylene (PTFE) substrates were designed. The feeds have been measured without a waterproof case to confirm their characteristics in ideal conditions. However, in practical use, the planar feeds will be in the waterproof case made of resin since a receiving antenna for satellite broadcasting is installed outdoors. The characteristics of the feed will be change by the case, and it is important to select the material (dielectric constant) of the case and the distance between the substrate-surface and the case.

To minimize feeding loss, feeds for satellite broadcasting reception have a built-in low noise block converter (LNB). In Chapter 6, the experiments were carried out by connecting the customized LNBs to the fabricated antenna with coaxial cables, and the signals transmitted from the satellites were received adequately. LNB circuits will be configured on the substrate of the planar feeds. Then, the feeding loss will be mitigated, and a carrier to noise ratio of received signals will be improved.

In Chapters 3 and 4, the offset parabolic reflector antennas with the proposed planar feeds were measured. The reflector was fabricated by machining an aluminum panel to prevent degradation of the radiation patterns stemming from reflector errors. Reflectors made with pressed aluminum are generally used for consumer use. In this study, the estimated gain degradation in the 12- and 21-GHz bands due to reflector error [7.1] was 0.1 and 0.2 dB, respectively. The error of a reflector made with pressed aluminum was 0.26 mm RMS based on the measurement results [7.2]. The sidelobe characteristics will be evaluated by measuring an offset parabolic reflector antenna composed of a reflector made with pressed aluminum and the proposed planar feed.

In Chapter 5, the design process and characterization of the planar feed, whose feeding loss in the 21-GHz band was mitigated, were described. The designed feed will be fabricated and measured, and the characteristics (gain, XPD, and radiation pattern) will be evaluated by using an offset parabolic reflector antenna with the proposed feed. The resonant frequency will also be sifted due to the dielectric constant of prepregs for adhering substrates. The designed feed has coupling slots and via-holes (VIAs) for feeding the 12- and 21-GHz-band MSAs, respectively. Because the design is complicated, planar feeds that have only coupling slots or VIAs will also be designed and evaluated.

To design satellite broadcasting systems using the 12- and 21-GHz bands, long term measurement of rain-attenuation will be needed because rain attenuation is one of the important parameters. Rain attenuation in the 21-GHz band is higher than that of the 12-GHz band and differ from place to place [7.3], [7.4]. Therefore, it is necessary to measure rain attenuation in the 12- and 21-GHz bands in multiple locations, and the

measured data will be compared. The proposed feeds will make it possible to set up 12- and 21-GHz dual-band receiving earth stations for the measurement of rain attenuation characteristics. Moreover, rain depolarization characteristics, which have been reported by measuring beacon signals (19.45 GHz) from the CS-2 and CS-3 satellites [7.5], will be evaluated by using the 21-GHz-band beacon signal from the BSAT-4a satellite.

The 42-GHz band (40.5 to 42.5 GHz) has also been allocated for satellite broadcasting, as described in Section 1.1. Therefore, the proposed dual-band planar feed will be improved to receive the 12-, 21-, and 42-GHz bands by installing a 42-GHz-band antenna on the substrate. To mitigate the feeding loss in the 42-GHz band, various waveguide technologies, e.g., post-wall waveguides and ridge waveguides, will be applied to the planar feed. It is also assumed that requirements for receiving antennas will change to meet needs of users. For example, a small-sized Ku-band receiving antenna is being studied, which is assumed to be used for satellite broadcasting with a low required carrier-to-noise ratio [7.6]. By adopting active array technologies to a planar antenna for satellite broadcasting reception, the antenna adjustment for pointing a satellite will become unnecessary. The pointing loss due to the beam-squint phenomenon [7.7], which was discussed in Section 2.5, will also be solved by a planar feed with the active array technologies.

Finally, these efforts will contribute to the development of satellite broadcasting systems in the future.

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List of Publications

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1. M. Nagasaka, S. Nakazawa, and S. Tanaka, "Dual-Circularly Polarized Offset Parabolic Reflector Antenna with Microstrip Antenna Array for 12-GHz Band Satellite Broadcasting Reception," *IEICE Trans. Commun.*, vol.E101-B, no.2, pp.340–348, Feb. 2018.
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Appendix

Characteristics of Offset Parabolic Reflector Antennas Fed by Dual-circularly Polarized Feed Horns

A.1 Introductory Remarks

This appendix presents measured characteristics of offset parabolic reflector antennas fed by dual-circularly polarized feed horns with septum polarizers to compare the characteristics of the proposed planar feeds and the feed horns. An offset parabolic reflector antenna for satellite broadcast reception in the 12-GHz band (11.7 to 12.75 GHz) is shown, which is composed of a 45-cm reflector and a 12-GHz-band dual-circularly polarized feed horn. For the 21-GHz band (21.4 to 22 GHz), a 1.5-m offset parabolic reflector antenna fed by a 21-GHz-band dual-circularly polarized feed horn is shown. The fabricated 21-GHz-band antenna has been used for an experimental receiving earth station antenna [A.1].

This appendix is organized as follows. Section A.2 describes the characteristics of the 45-cm offset parabolic reflector antenna fed by the 12-GHz-band dual-circularly polarized feed horn. Section A.3 shows the characteristics of the 1.5-m offset parabolic reflector antenna fed by the 21-GHz-band dual-circularly polarized feed horn. Section A.4 concludes this appendix.

A.2 Offset Parabolic Reflector Antenna fed by 12-GHz-band Dual-circularly Polarized Feed Horn

Fig. A.1 shows the 12-GHz-band dual-circularly polarized receiving antenna fabricated with a 45-cm reflector made of pressed aluminum. The feed is composed of a horn antenna and a septum polarizer, as shown in Fig. A.2 [A.2]. Fig A.3 shows the operation of the septum polarizer, which is calculated with a 3D electromagnetic field analysis simulator, CST Studio Suite [A.3]. The feed also has a low noise block convertor (LNB) that can receive RHCP and LHCP simultaneously. The block diagram of the LNB is shown in Fig. A.4. Table A.1 lists the parameters of the fabricated antenna. The local oscillator frequencies were determined to convert the LHCP signals to a higher intermediate frequency band than that of the RHCP signals. The output frequencies comply with the domestic standard (ARIB STD-B63) [A.4].



(a) Prototype antenna.



(b) Feed horn and LNB.

Fig. A.1 Offset parabolic reflector antenna fed by 12-GHz-band dual-circularly polarized feed horn.

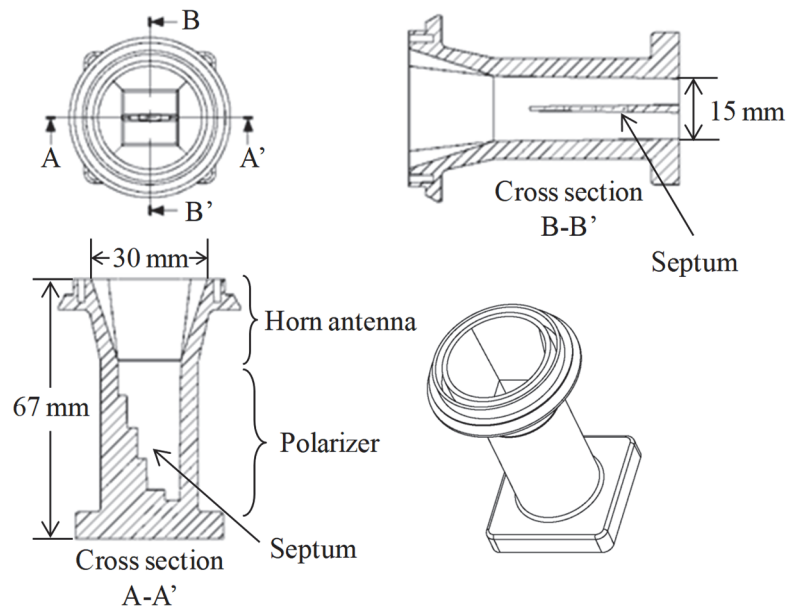
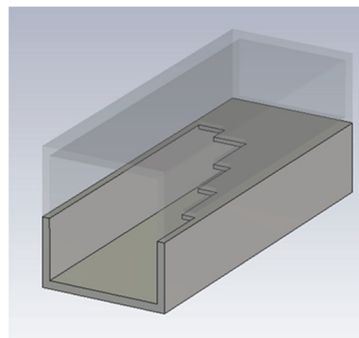
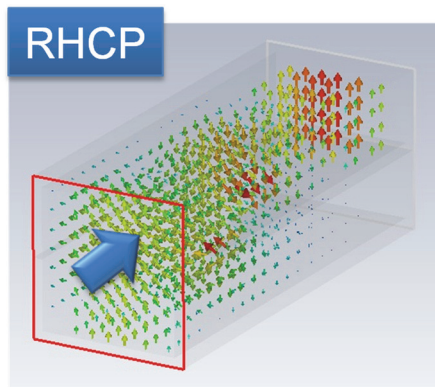


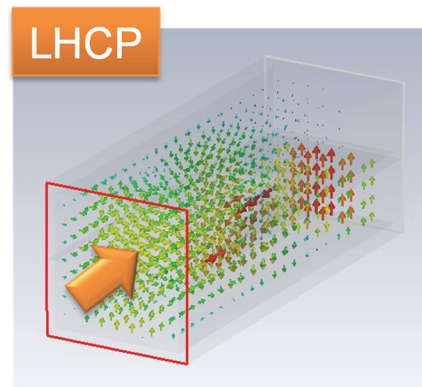
Fig. A.2 12-GHz-band feed horn with septum polarizer.



(a) Cross section.



(b) RHCP input.



(c) LHCP input.

Fig. A.3 Operation of septum polarizer (electric field).

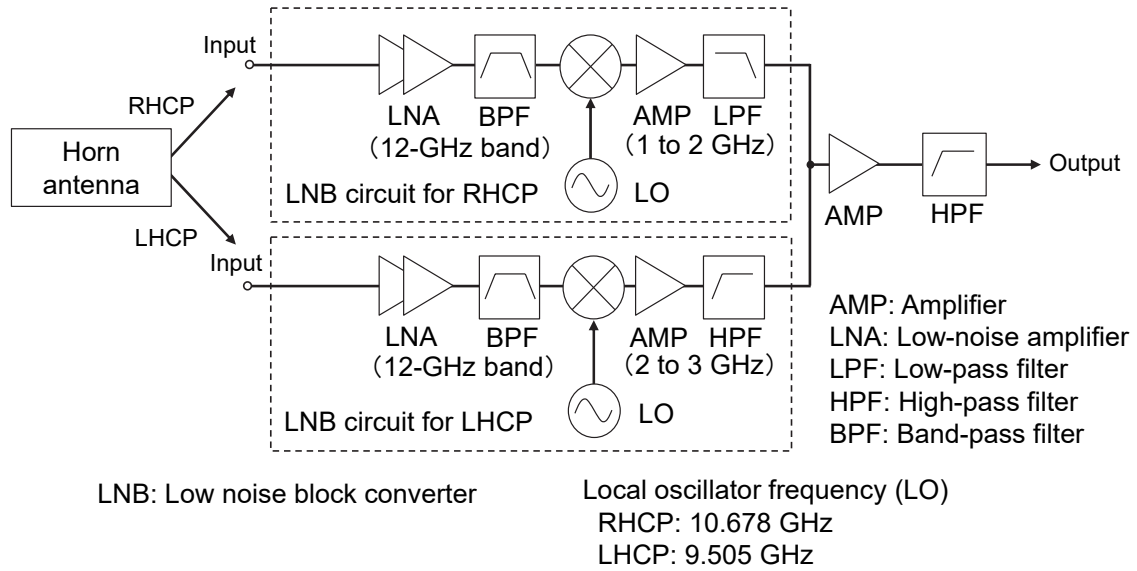


Fig. A.4 Block diagram of 12-GHz-band dual-circular LNB.

Table A.1 Parameters of 12-GHz-band dual-circularly polarized receiving antenna.

Item	Value
Diameter (D)	45 cm
Focal length (F)	21.15 cm ($F/D = 0.47$)
Receiving frequency	11.7 to 12.75 GHz
Polarizations	RHCP and LHCP
Local oscillator frequencies	RHCP: 10.678 GHz, LHCP: 9.505 GHz
Output frequencies	RHCP: 1032.23 to 2070.25 MHz LHCP: 2224.41 to 3223.25 MHz

Table A.2 summarizes the evaluation results of the fabricated antenna. The gain, aperture efficiency, and cross polarization discrimination (XPD) were more than 33.6 dBi, 75%, and 26.2 dB throughout the 12-GHz band, respectively. The edge illumination level (EIL) was about -11 dB, which was a relative gain of the horn antenna at ± 45.8 degrees, as shown in Fig. A.5. For the LNB, a gain of more than 52 dB and noise figure of less than 1 dB for both polarizations were obtained. Fig. A.6 shows the measured radiation patterns of the fabricated antenna. The fabricated antenna satisfied the reference pattern of Rec. ITU-R BO.1213 [A.5].

Table A.2 Summary of evaluation results of 12-GHz-band receiving antenna.

Item	Polarization	
	RHCP	LHCP
Gain	33.7 dBi min.	33.6 dBi min.
Aperture efficiency	76% min.	75% min.
XPD (at boresight)	26.2 dB min.	29.6 dB min.
EIL	-10.5 dB	-10.6 dB
Conversion gain of LNB	52.1 to 56.2 dB	52.1 to 56.3 dB
Noise figure of LNB	0.98 dB max.	0.97 dB max.
Reflector surface error	0.35mm RMS	

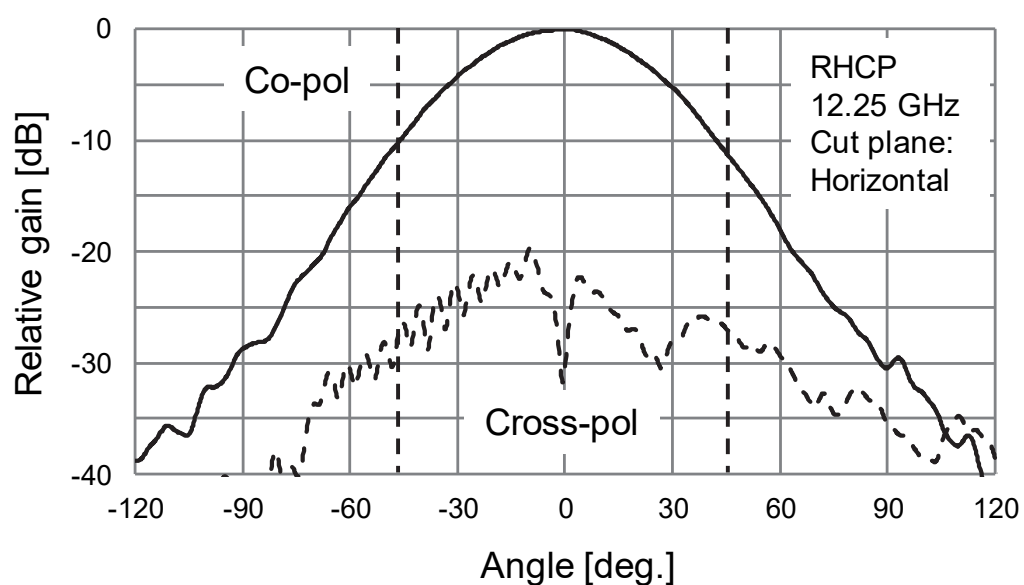
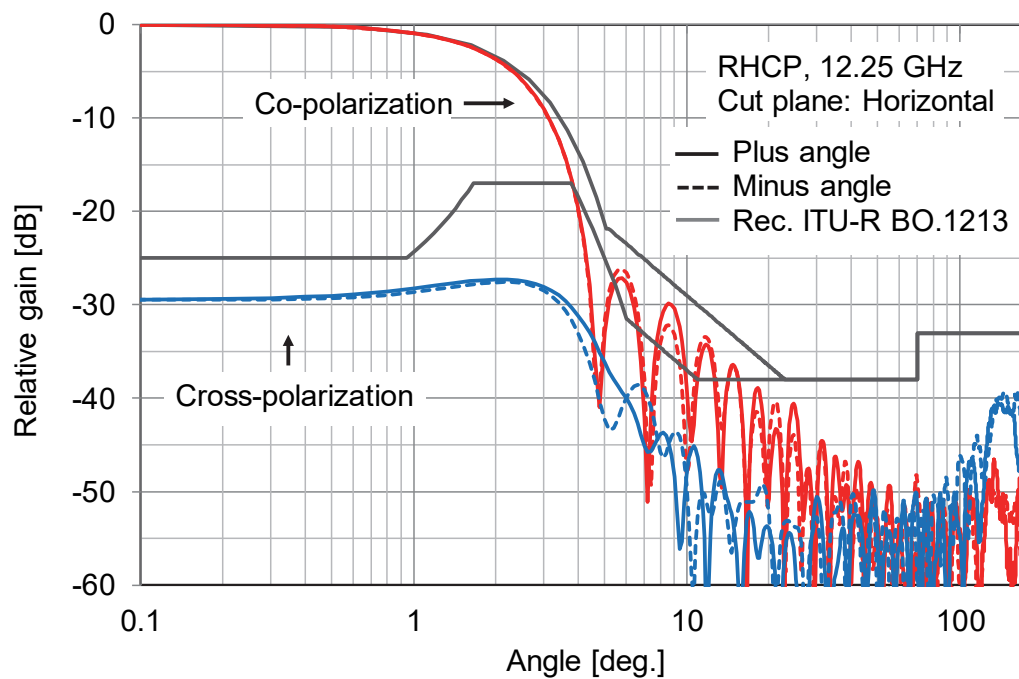
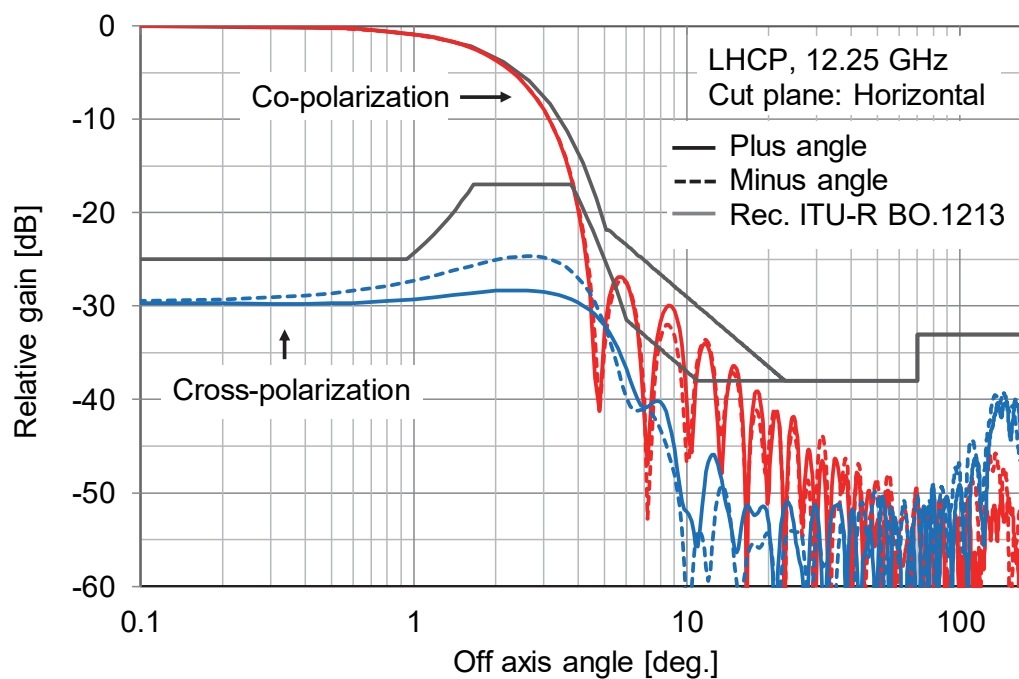


Fig. A.5 Measured radiation pattern of feed horn.



(a) RHPC antenna.



(b) LHPC antenna.

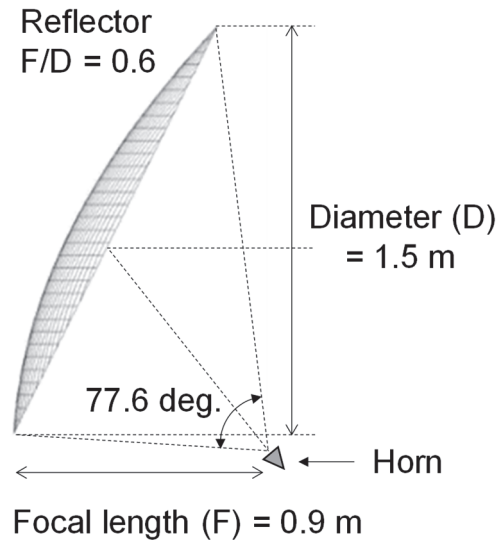
Fig. A.6 Measured radiation patterns of 12-GHz-band receiving antenna.

A.3 Offset Parabolic Reflector Antenna fed by 21-GHz Band Dual-circularly Polarized Feed Horn

Fig. A.7 shows the dual-circularly polarized offset parabolic reflector antenna for the 21-GHz band. The diameter is 1.5 m and the focal length is 0.9 m. The ratio of the focal length and diameter (F/D) is 0.6, and the aperture angle is 77.6 degrees. Figs. A.8 and A.9 show the fabricated feed and its radiation pattern, respectively. The EIL was -13 to -14 dB, which is the relative gain at ± 38.8 degrees, as shown in Fig. A.9. The horn antenna is connected to a septum polarizer, as shown in Fig. A.8(b). The RHCP and LHCP signals are separated and sent to each output port. Table A.3 shows the measured voltage standing wave ratios (VSWRs) of the fabricated feed horn. The VSWR was less than 1.1, and the feed including the polarizer is matched for the 21-GHz band.

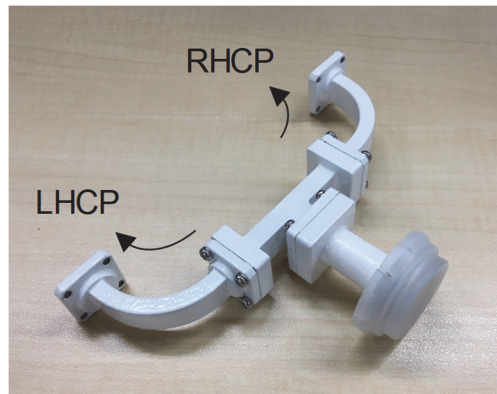


(a) Appearance.

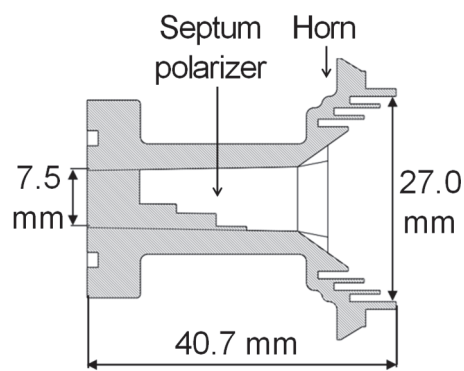


(b) Configuration.

Fig. A.7 21-GHz-band receiving antenna.



(a) Appearance.



(b) Dimension.

Fig. A.8 21-GHz-band dual-circularly polarized feed horn.

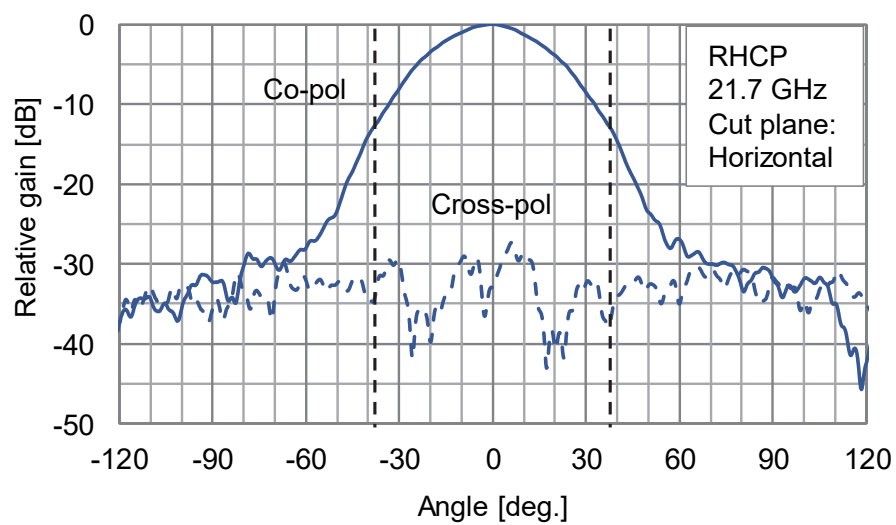


Fig. A.9 Measured radiation pattern of feed horn.

Table A.3 Measured VSWRs of feed horn.

Frequency	Polarization	
	RHCP	LHCP
21.4 GHz	1.04	1.04
21.7 GHz	1.07	1.04
22 GHz	1.06	1.04

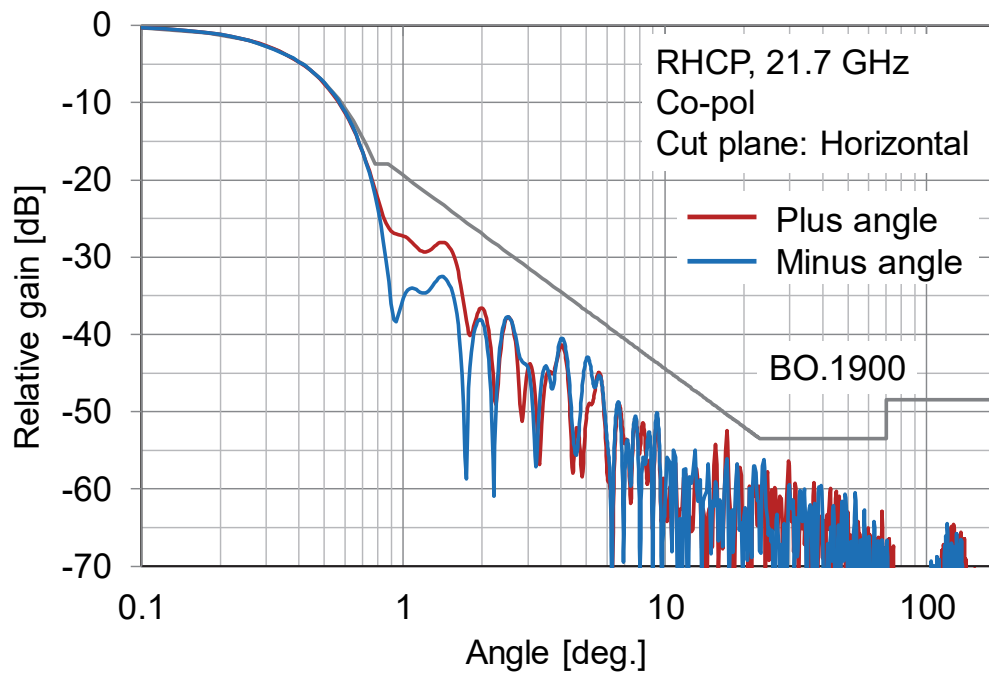
The fabricated reflector antenna was measured with a spherical near-field antenna measurement system in an anechoic chamber [A.6]. Tables A.4 and A.5 show the measured gain and XPD, respectively. A gain of more than 48.2 dBi (aperture efficiency: 55 %) and an XPD of more than 32.8 dB were obtained. Figs. A.10 and A.11 show the measured radiation patterns and the reference patterns. Recommendation ITU-R BO.1900 (BO.1900) provides the reference pattern for the 21-GHz band [A.7]. When comparing the measured radiation patterns with the reference patterns, the fabricated antenna satisfied the reference pattern.

Table A.4 Measured gains of reflector antenna.

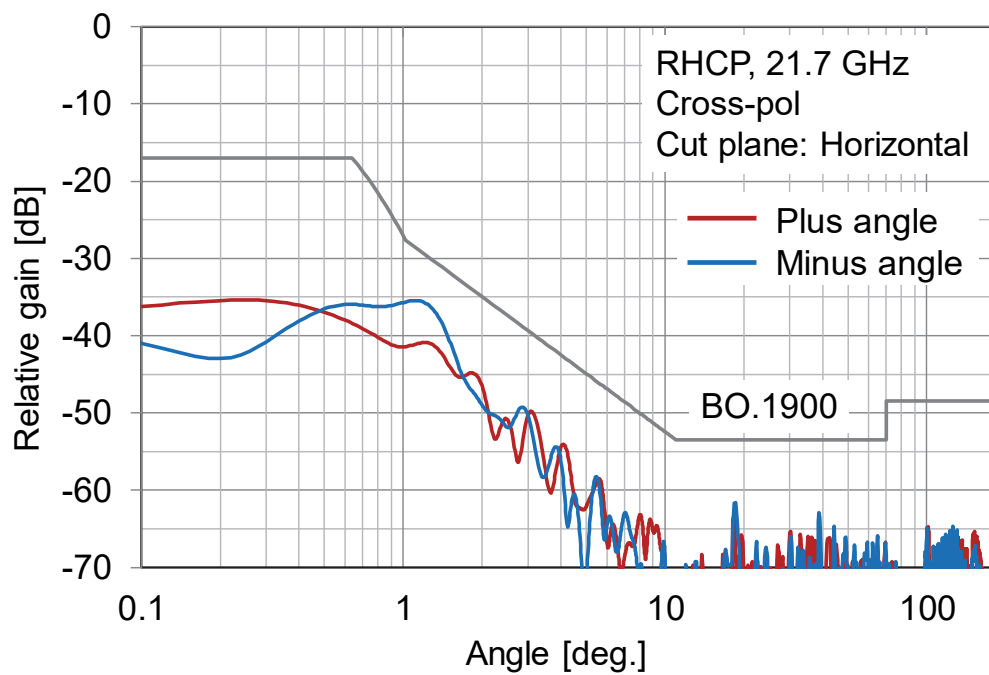
Frequency	Polarization	
	RHCP	LHCP
21.4 GHz	48.2 dBi (58.5%)	48.3 dBi (59.2%)
21.7 GHz	48.3 dBi (57.8%)	48.3 dBi (58.5%)
22 GHz	48.2 dBi (55.4%)	48.3 dBi (56.0%)

Table A.5 Measured XPDs of reflector antenna.

Frequency	Polarization	
	RHCP	LHCP
21.4 GHz	40.0 dB	33.8 dB
21.7 GHz	38.1 dB	33.4 dB
22 GHz	37.2 dB	32.8 dB

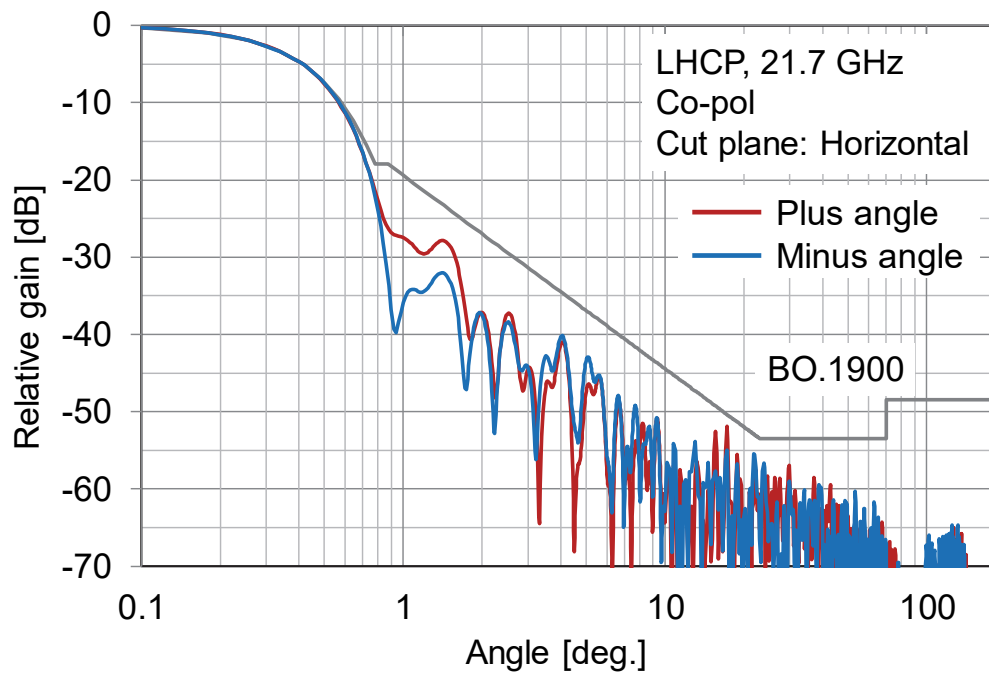


(a) Co-polarization.

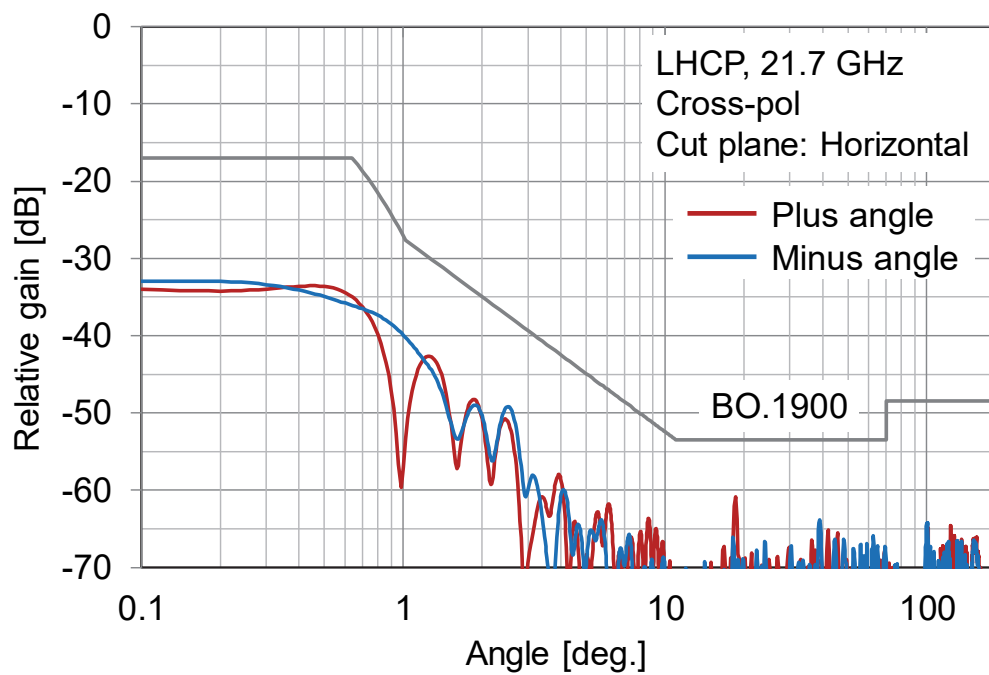


(b) Cross-polarization.

Fig. A.10 Measured radiation patterns of 21-GHz-band receiving antenna (RHCP).



(a) Co-polarization.



(b) Cross-polarization.

Fig. A.11 Measured radiation patterns of 21-GHz-band receiving antenna (LHCP).

A.4 Concluding Remarks

This appendix presented the measured characteristics of offset parabolic reflector antennas fed by the dual-circularly polarized feed horns with the septum polarizers. An offset parabolic reflector antenna for satellite broadcast reception in the 12-GHz band was fabricated. The antenna is composed of a 45-cm offset parabolic reflector and a 12-GHz-band dual-circularly polarized feed horn. Measured results indicate that the gain was more than 33.6 dBi (aperture efficiency was more than 75%) and that the XPD was more than 26.2 dB throughout the band.

An offset parabolic reflector antenna for satellite broadcast reception in the 21-GHz band was also fabricated. The antenna is composed of a 1.5-m offset parabolic reflector and a 21-GHz-band dual-circularly polarized feed horn. Measured results indicate that the gain was more than 48.2 dBi (aperture efficiency was more than 55%) and that the XPD was more than 32.8 dB throughout the band.

References

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