Design Of A Triple-Band (L/S/C) Monopulse Feed for Tracking Reflector Antenna Applications
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추적반사경 안테나용 삼중대역(L/S/C) 모노펄스 피드 설계

Design Of A Triple-Band(L/S/C) Monopulse Feed for Tracking Reflector Antenna Applications

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Abstract

This thesis presents a feed antenna for tracking reflector. The designed feed antenna covered the triple-band (L/S/C) which allowed by the tracking antenna and it has the dual circular polarization.

The designed triple-band feed used different elements for each band. The different elements common used crossed dipole. Dual-circular polarization characteristics achieved through crossed dipoles. The L-band(1.435GHz-1.535GHz) elements arranged inside the outer cavity for generation the sum and difference channel signal. 4 S-band(2.2GHz-2.4GHz) elements cross arranged inside the L-band elements arrays. The two horizontally arranged elements are used to generate azimuth difference channel signal and the two vertically arranged elements are used

* A dissertation for the degree of Doctor in August 2018.
to generate elevation difference channel pattern. In addition, they are used to generate sum channel signal together. For getting the C-band (5.09GHz-5.15GHz) signal 5 elements are used. One of them set on the center of the designed feed antenna for getting the sum channel signal and 4 elements surround around the sum element to generate the difference channel signals. The small cavities are used to improve axial ratio and adjust the phase center of C-band. A dielectric cap is used further improve the axial ratio of sum channel and matching the impedance. The arrangement of the antenna elements fully considered the size of elements, the influence of antenna elements on each other, the relationship between main lobe and side lobe of antenna array etc. At last a radome is designed for protecting the feed antenna from the weather and other conditions.

The monopulse synthesis circuit is designed for each band antenna feed. 90° hybrid coupler is used for getting dual-circular polarization. RF switch, 180° phase delay cable, power combiner consistent made up the modulator or separately used for sum and difference channel pattern combination. The monopulse synthesis circuit guaranteed monopulse signals of each band can be individually controlled.

The designed triple-band monopulse feed antenna has simulated for a 4.6m reflector antenna. The simulation results confirmed the triple-band monopulse feed antenna has a good performance.
# Contents

Abstract i

Contents iii

List of Figures iv

List of Tables vii

I Introduction 1

II Design of a triple-band dual polarization monopulse feed antenna 4

2.1 Principle of monopulse antenna ................................................................. 4
2.2 Antenna structure and design goals ............................................................ 9
2.3 L-band elements ....................................................................................... 12
2.4 S-band elements ....................................................................................... 19
2.5 C-band elements ....................................................................................... 26
2.6 L/S/C triple-band dual polarization feed antenna ...................................... 39
2.7 Monopules synthetic circuit ...................................................................... 65
2.8 Simulation results for a 4.6m reflector antenna ......................................... 94

III Conclusion 107

REFERENCES 109

APPENDIX 112
LIST OF FIGURES

Fig.1  tracking and remote data receiving mobile antenna(in Jeonnam Korea, Naro Space Center)........................................................................................................2
Fig.2 Azimuth difference pattern beams.................................................................................................................................6
Fig.3 Signal amplitude response of each beam.................................................................6
Fig.4 Sum and difference signal response (a) difference and (b) sum..........................7
Fig.5 Proposed feed antenna structure (a) Structure with radome, (b) Internal structure.10
Fig.6 Fig.6 Structure of L-band element (a) 3D structure, (b) dielectric substrate(i), (c) dielectric substrate(ii).............................................................................................................14
Fig.7 Fig.7 Design result of L-band radiation element (a) Reflection Coefficient, (b) Gain pattern, (c) Axial Ratio........................................................................................................16
Fig.8 Design parameters of L-band element (a) Substrate(i), (b) Substrate(ii) ............ 18
Fig.9 Structure of S-band element (a)3D structure, (b) dielectric substrate(i), (c) dielectric substrate(ii)..................................................................................................................21
Fig.10 Design result of S-band element (a) Reflection Coefficient, (b) Gain pattern, (c) Axial Ratio.........................................................................................................................23
Fig.11 Design parameters of S-band element (a) Substrate(i), (b) Substrate(ii) ............ 25
Fig.12 Structure of C-band element (a) 3D structure, (b) Crossed dipole substrate, (c) Feed substrate(i), (d) Feed substrate(ii).................................................................................................29
Fig.13 Design results of C-band difference channel element (a) Reflection Coefficient, (b) Gain pattern, (c) Axial Ratio........................................................................................................31
Fig.14 The effect of the cavity on design results of C-band element (a) Gain pattern, (b) Axial ratio..............................................................................................................................................32
Fig.15 Design results of C-band sum channel element (a) Reflection Coefficient, (b) Gain pattern, (c) Axial Ratio........................................................................................................34
Fig.16 Design parameters of C-band element (a) Difference channel crossed dipole substrate, (b) Sum channel crossed dipole substrate, (c) Feed substrate(i), (d) Feed substrate(ii).........................................................................................38
Fig.17 Antenna radiation waveform..................................................................................39
Fig. 18 Sum channel antenna radiation pattern in polar (a) D=1/2λ, (b) D=λ
Fig. 19 Difference channel antenna radiation in polar
Fig. 20 Final designed antenna parameters. (a) C-band, (b) Entirety, (c) Dielectric cap...
Fig. 21 Reflection coefficient of L-band
Fig. 22 Reflection coefficient of S-band
Fig. 23 Reflection coefficient of C-band
Fig. 24 Port position of L-band
Fig. 25 Port position of S-band
Fig. 26 Port position of C-band
Fig. 27 Design results of L-band sum channel (a) Gain pattern, (b) Axial ratio
Fig. 28 Design results of L-band difference channel (a) Gain pattern, (b) Axial ratio
Fig. 29 Design results of S-band sum channel (a) Gain pattern, (b) Axial ratio
Fig. 30 Design results of S-band difference channel (a) Gain pattern, (b) Axial ratio
Fig. 31 Design results of C-band sum channel (a) Gain pattern, (b) Axial ratio
Fig. 32 Design results of C-band difference channel (a) Gain pattern, (b) Axial ratio
Fig. 33 90° hybrid coupler
Fig. 34 90° hybrid coupler circuit of L-band
Fig. 35 Total phase delay of L-band sum channel
Fig. 36 Power combiner of L-band sum channel
Fig. 37 Total phase delay of L-band + EL difference channel
Fig. 38 Modulator for L-band difference channel
Fig. 39 Pattern of L-band difference channel controlled by RF switch (a) + EL, (b) - EL,
(c) + AZ, (d) - AZ
Fig. 40 Monopulse synthetic circuit diagram of S-band
Fig. 41 90° hybrid coupler diagram of S-band sum/difference channel
Fig. 42 Power combiner of S-band sum channel
Fig. 43 Total phase delay of S-band sum channel
Fig. 44 Total phase delay of S-band difference channel (a) + AZ, (b) + EL
Fig. 45 RF switch for S-band
Fig. 46 Modulator for S-band
Fig. 47 Structure of the monopulse antenna

Fig. 48 Pattern of S-band difference channel controlled by RF switch(modulator) (a)+EL, (b)-EL, (c)-AZ, (d)+AZ

Fig. 49 Monopulse synthetic circuit diagram of C-band

Fig. 50 90° hybrid coupler circuit diagram of C-band sum/difference channel

Fig. 51 Total phase delay of C-band sum channel

Fig. 52 Total phase delay of C-band +EL difference channel

Fig. 53 RF switch(modulator) for C-band difference channel

Fig. 54 Pattern of C-band difference channel controlled by RF switch(modulator) (a)+EL, (b)-EL, (c)+AZ, (d)-AZ

Fig. 55 Structure of a 4.6m reflector antenna

Fig. 56 L-band sum channel radiation pattern of a 4.6m reflector antenna (a) Gain pattern, (b) Axial ratio

Fig. 57 L-band difference channel radiation pattern of a 4.6m reflector antenna (a) Gain pattern, (b) Axial ratio

Fig. 58 S-band sum channel radiation pattern of a 4.6m reflector antenna (a) Gain pattern, (b) Axial ratio

Fig. 59 S-band difference channel radiation pattern of a 4.6m reflector antenna (a) Gain pattern, (b) Axial ratio

Fig. 60 C-band sum channel radiation pattern of a 4.6m reflector antenna (a) Gain pattern, (b) Axial ratio

Fig. 61 C-band difference channel radiation pattern of a 4.6m reflector antenna (a) Gain pattern, (b) Axial ratio
LIST OF TABLES

Table 1 Aeronautical telemetry frequency bands after WRC’07 ........................................3
Table 2 Design target of the triple-band monopulse feed antenna .......................................11
Table 3 Simulation phase delay setting of L-band ..................................................................50
Table 4 Simulation phase delay setting of S-band ..................................................................51
Table 5 Simulation phase delay setting of C-band .................................................................51
Table 6 90° hybrid coupler/port phase delay of L-band sum channel .................................67
Table 7 90° hybrid coupler/port phase delay of L-band difference channel (+EL) .............70
Table 8 RF switch control signal and phase delay of L-band difference channel ...............73
Table 9 90° hybrid coupler/port phase delay of S-band sum channel ...............................78
Table 10 90° hybrid coupler/port phase delay of S-band difference channel (-AZ, +EL). 80
Table 11 RF switch control signal and phase delay of S-band difference channel .............84
Table 12 Tabel 12: Table 90° hybrid coupler/port phase delay of C-band sum channel...88
Table 13 90° hybrid coupler/port phase delay of C-band difference channel (+EL) ........89
Table 14 RF switch control signal and phase delay of C-band difference channel ..........90
Chapter I.

Introduction

Telemetry antenna is mainly used at remote data receiving, controlling and tracking for rockets, aircraft and missiles. Because of target tracking need the high gain antenna, the reflector antenna always used at tracking antenna system.[1]-[6] Therefore, the excellent performance of a reflector feed is very important for tracking antenna system.[7-12]

According to the difference in the way of work tracking antenna can be divided into switched beam antenna, conical scan antenna and mono-pules antenna. Because of the switched beam technology and conical scan technology are sensitive to the amplitude of reflected waves, the tracking error is large. The monopulse antenna simultaneously receiving diagonal-error-sensitive reflected beam on single pulse signal. It compares each beam at the same time. So the effect of that the reflected wave amplitude varies with time is eliminated.[13]-[14]

At first telemetry frequency band was L-band and S-band. Figure 1 shows a S-band tracking and remote data receiving reflector antenna system which used a 4.6m reflector. The reflector antenna system is carried on motor vehicle. Because of increase in using the L-band and S-band frequency the problem of signal interference is more serious.[15]-[18]
ITU WRC’07 (World Radio communication Conferences) proposed that add C-band on the L-band and S-band basis for aircraft telemetry. Asian Pacific countries can use the frequency range from 5091MHz to 5150MHz (59MHz bandwidth) based on the distribution of ITU Region 3. Meanwhile, to deal the problem of telemetry signal interference at L-band and S-band the main companies (ViaSat, Orbit, General Dynamics, Quasonix from America; Zodiac from France; Highgain Antenna from South Korea) have developed L/C dual-band or S/C dual-band feed and put them into the market.
Table 1: Aeronautical telemetry frequency bands after WRC’07

<table>
<thead>
<tr>
<th>Name</th>
<th>Frequencies (MHz)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower L-Band</td>
<td>1435 – 1525</td>
<td>Telemetry is the primary service (part of mobile service) in the USA</td>
</tr>
<tr>
<td>Lower L-Band</td>
<td>1525 – 1535</td>
<td>Mobile satellite service (MSS) is the primary service, telemetry is secondary in the USA</td>
</tr>
<tr>
<td>Upper L-Band</td>
<td>1755 – 1850</td>
<td></td>
</tr>
<tr>
<td>Lower S-Band</td>
<td>2200 – 2290</td>
<td>Telemetry (for unmanned vehicles only) is a co-primary service in the USA</td>
</tr>
<tr>
<td>Upper S-Band</td>
<td>2360 – 2395</td>
<td>Telemetry is the primary service in the USA(^1)</td>
</tr>
<tr>
<td>Lower C-Band</td>
<td>4400 – 4940</td>
<td>WRC 2007 allocation to telemetry(^2)</td>
</tr>
<tr>
<td>Middle C-Band</td>
<td>5091 – 5150</td>
<td>WRC 2007 allocation to telemetry(^3)</td>
</tr>
<tr>
<td>Upper C-Band</td>
<td>5925 – 6700</td>
<td>WRC 2007 allocation to telemetry(^4)</td>
</tr>
</tbody>
</table>

\(^1\) Prior to 1997, the Upper S-band extended from 2310 to 2390 MHz. The lower portion of Upper S-band was reallocated in two separate auctions in 1997: 2320–2345 MHz was assigned to digital audio radio (today’s Sirius-XM satellite radio) and 2305–2320 MHz and 2345–2360 MHz were assigned to wireless communication services.

\(^2\) Prior to WRC 2007, lower C-band was available for aeronautical telemetry by federal government users in the USA. The WRC 2007 allocation extended use of this band for aeronautical telemetry to all of ITU Region 2. Non-federal-government users will not be allowed to use this band for time being, but may be in the future.

\(^3\) In the USA, the NTIA and FCC made middle C-band available to aeronautical telemetry by both federal government and non-federal government users.

\(^4\) The WRC 2007 allocation allows aeronautical telemetry on a non-interfering basis. Upper C-band is home to point-to-point microwave links by users such as railroads, oil companies, gas companies, etc. and VSAT satellite terminals used to link convenience stores, fast-food chains, etc.
Chapter II

Design of a triple-band dual polarization mono-pulse feed antenna

Monopulse is also called simultaneous multi-beam. The monopulse system is developed on the basis of conical scanning and sequential beam switching systems. Because the beam conical scanning and beam switching techniques are sensitive to the amplitude of the echo, the tracking error is large. The monopulse antenna provides required beam that is sensitive to angular error and is carried on a single pulse, and compares the output of each beam at the same time. Therefore, the amplitude changes over time of echo is eliminated.

2.1 Principle of monopulse antenna

The monopulse antenna system is mainly used to target measure and to track the angle. The information on the target angular position is determined by comparison of signals received in two or more simultaneous beams. The term "mono-pulse" comes from the ability of this system to extract the angular position from only one pulse. However, in practice the angular position of the target is obtained from multiple pulses in order to improve target detection probability and further improve angle measurement accuracy.

The main advantage of a monopulse system in comparison to standard angle measurement methods like conical scanning and beam switching is that it is not affected by amplitude fluctuations of the target echo because the angle information is acquired by comparing signals received by several simultaneous beams and produced by a single echo pulse.
There are three main monopulse techniques for angle sensing. These techniques are: amplitude-comparison, phase-comparison and the combination of the amplitude and phase comparison.[19]-[21] The applied monopulse technique determines the nature of information in the received signal prior to any processing. This means that the choice of a certain Monopulse technique will determine the construction of the radar antenna system.

Angle measurement in a monopulse antenna system is performed by an angle discriminator. If the angle discriminator is non-coherent and the angle-sensing response is produced only by amplitude relations, it is called amplitude discriminator. Angle discriminators responding only to phase relations are called phase angle discriminators, while angle discriminators responding to both amplitude and phase relations are called sum-and-difference angle discriminators. The type of angle discriminator determines the nature of the processing used to extract the angle information from the received signals.

To measure angular errors in the azimuth direction, here we choice azimuth difference pattern as shown in Figure 2. The azimuth difference pattern has two main beams with a null between them. Reflected or received signal's response of each beam can be defined as functions $f_1(\theta)$ and $f_2(\theta)$ given by

\begin{align}
  f_1(\theta) &= f(\theta_1) = f(\theta_0 - \theta_k) \\
  f_2(\theta) &= f(\theta_2) = f(\theta_0 + \theta_k)
\end{align}

(2.1a)  

(2.1b)
Figure 3 shows the signal amplitude response of each beam (amplitude versus angle).

Received signals from each beam are subtracted to form a difference response or error signal as shown in Figure 4(a). This error signal or difference response is given by:

\[ \Delta(\theta) = f_1(\theta) - f_2(\theta) \quad (2.2) \]

This difference response is used as a feedback signal in the closed-loop system of monopulse tracking. A null is formed in the middle of the two beams. The monopulse tracking system keeps its target within the null of the difference pattern. When the target is within the null, the error signal becomes very small due to the subtraction of signal
responses. This type of the system is called a "null tracker". The error signal becomes very small when the target enters the null region or gets out from the radar range or enters the null region that is not in the tracking direction. These conditions could lead to a wrong tracking direction. In order to overcome this situation, one more signal response is used which is the sum response. The sum response is a summation of signal responses of each beam. The sum response is given by

$$\Sigma(\theta) = f_1(\theta) + f_2(\theta)$$  \hspace{2cm} (2.3)

The sum response function is shown in Figure 4 (b).

![Fig.4 Sum and difference signal response (a) difference and (b) sum](image)

The sum response is actually used for target detection and to avoid unambiguous tracking conditions.

If the offset $\theta_k$ is very small, the difference pattern expression can also be written as follows.

$$\Delta(z) \approx 2\theta_k f'(\theta_0) = 2\theta_k \frac{df}{d\theta}$$  \hspace{2cm} (2.4)
The difference response normalized by the sum response is given by:

\[
\frac{\Delta}{\Sigma} = \frac{f_1(\theta) - f_2(\theta)}{f_1(\theta) + f_2(\theta)} \approx \frac{\theta_k df / d\theta}{f(\theta_0)} \tag{2.5}
\]

In the difference response shown in Figure 4 (a), the slope crossing the zero point on the measurement axis is called the difference slope of the monopulse measurement. The rate of change in the slope of the curve at this point expresses the relative measurement sensitivity of the system. A sharply rising slope indicates a high sensitivity, and a slow rising slope indicates a low sensitivity. The normalized difference slope as a differential function is given by:

\[
k_m = -\frac{d(\Delta / \Sigma)}{d(\theta / \theta_3)} \bigg|_{\theta = \theta_0} \tag{2.6}
\]

where \( \theta_3 \) is the 3-dB beamwidth.

The equation (2.8) expresses the fundamental relationship of the RMS position error of the monopulse estimate in a thermal noise environment.

\[
\sigma_\theta = \frac{\theta_3}{k_m \sqrt{2E / N_0}} = \frac{\theta_3}{k_m \sqrt{2(S / N)_n}} \approx \frac{\theta_3}{2\sqrt{(S / N)_n}} \tag{2.7}
\]
2.2 Antenna structure and design goals

Figure 5 shows the structure of L/S/C triple-band dual-polarization mono-pules antenna designed. The designed antenna consist of L-band elements, S-band elements, C-band elements, circular ground plane, five small cavities, dielectric cap, outer cavity and radome. The five small cavities used to improve isolation of each C-band elements and the axial ratio of C-band difference channel. A dielectric cap set on the C-band sum element for improving the axial ratio of C-band sum channel and impedance matching. The outer cavity is used to improve the gain pattern of S-band sum channel and reducing the side lobe of L-band. Finally a circular radome used to protect antenna elements far from dust and external interference.
This antenna can be used at a auto tracking antenna system for remote data receiving, tracking and controlling. And it is designed to use for a 4.6m or 11mm reflector with the F/D=0.4. It can work at L-band(1.435-1.535GHz), S-band(2.25-2.35GHz) and C-Band(5.09-5.15GHz) and it has dual-circular polarization(LHCP: Left Hand Circular Polarization, RHCP: Right Hand Circular Polarization) performance. The design gials are
shown in Table 2.

Table 2: Design target of the triple-band monopulse feed antenna

<table>
<thead>
<tr>
<th>Item</th>
<th>L-band</th>
<th>S-band</th>
<th>C-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1.435-1.535GHz</td>
<td>2.2-2.4GHz</td>
<td>5.09-5.15GHz</td>
</tr>
<tr>
<td>Reflection Coefficient</td>
<td></td>
<td>-10dB</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>Dual-circular</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>polarization(1.HCP/RHCP)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge taper @ ±64°</td>
<td>20dB</td>
<td>20dB</td>
<td>20dB</td>
</tr>
<tr>
<td>Axial ratio on-axis</td>
<td>2 dB</td>
<td>2 dB</td>
<td>2 dB</td>
</tr>
<tr>
<td>Maximum gain</td>
<td>12dBi</td>
<td>12dBi</td>
<td>9dBi</td>
</tr>
<tr>
<td>Difference channel</td>
<td>Null level</td>
<td>-25dB</td>
<td>-25dB</td>
</tr>
</tbody>
</table>
2.3 L-band elements

Figure 6 shows the structure of L-band element. L-band element uses the printed cross dipoles to get the dual circular polarization. It is formed from two erect crossed dielectric substrate. The dipoles, transformation parts for impedance matching, feed line ground patch are printed on the front of the L-band erect boards. And there is a balun structure used on the front of dielectric substrate for feed line to dipole transformation. The feed line is printed on back of the dielectric substrate for excitation current. At the end of feed line a open stub is used for impedance matching. For getting the same phase delay the length of feed line which printed on two L-band dielectric substrate have to secure uniformity. There is a printed ground joint used for connecting with ground plane of antenna. Because of that the two erect dielectric substrate are 90 degree crossed there are two complementary cutting part on each substrate. There is another cutting part at the bottom of dielectric substrate used for connecting SMA connector. The dielectric substrate of L-band element uses FR-4(ԑr=4.3, tanδ=0.0002, 2.25mm thickness) boards.
Fig. 6 Structure of L-band element

(a) 3D structure, (b) dielectric substrate(i), (c) dielectric substrate(ii)
Figure 7 shows the simulation results of single L-band radiation element. The results was simulated in the situation of a 300mm diameter’s ground plane. The reflection coefficients of both two ports are less than -10dB in the frequency range of 1.435 to 1.535 what the target was set. Fig xb and xc shows the axial ratios and gain pattern at center frequency(1.485GHz) of both LHCP and RHCP. It shows that the axial ratio is less than 2dB at the center of L-band component, the maximum gain is about 8.3dB.
Fig. 7 Design result of L-band radiation element

(a) Reflection Coefficient, (b) Gain pattern, (c) Axial Ratio
Figure 8 shows the parameters of L-band element. The thickness of printed metal is 0.035mm. The parameters have considered the case of machining precision, it is less than 0.1mm. It applies to all antenna structure.
Fig. 8 Design parameters of L-band element

(a) Substrate(i), (b) Substrate(ii)
2.4 S-band elements

A printed crossed dipoles also used at S-band radiation element. Figure 9 shows the structure of S-band element. The dipole, transformation part, feed line ground are printed on the front of both two erect dielectric substrate. A balun is used to transform the feed line transmission to dipole. At the bottom of substrate there is a SMA connection space cut. There are two complementary cutting part on each substrate used for making the two dielectric substrate erect. On the back of the dielectric substrate there is a feed line printed. A short bar is used through the via hole from feed line end to dipole. The ground joint is printed on the bottom of substrate back. The dielectric substrate of S-band element uses FR-4($\varepsilon_r=4.3$, $\tan\delta=0.0002$, 1.5mm thickness) boards.
Fig. 9 Structure of S-band element

(a) 3D structure, (b) dielectric substrate(i), (c) dielectric substrate(ii)
Figure 10 shows the simulation results of S-band radiation element. The S-band element is simulated with a ground plane of 300mm diameter. The reflection coefficient of two ports covered 2.2GHz to 2.4GHz frequency band based on less than -10dB. The gain pattern shows the total gain is about 6.7dB and the axial ratio is less than 1dB at the center of S-band element in both LHCP and RHCP.
Fig. 10 Design result of S-band element

(a) Reflection Coefficient, (b) Gain pattern, (c) Axial Ratio
Figure 11 shows the parameters of S-band element. The thickness of printed metal is 0.035mm. The parameters have considered the case of machining precision, it is less than 0.1mm. It applies to all antenna structure.
Fig. 11 Design parameters of S-band element

(a) Substrate(i), (b) Substrate(ii)
2.5 C-band elements

Figure 12 shows the structure of C-band radiation element. C-band radiation element used crossed dipole to get dual polarization. A completed C-band element consists of horizontal circular substrate and two erect substrates. The crossed dipole is printed on the circular dielectric substrate. And the feed lines are printed on the erect crossed substrate. The crossed dipole substrate has 4 slots on the printed dipoles to connect with feed line substrates. On the front of feed line substrate feed line, protruding part and ground joint are printed. The feed line uses open stub to making dipoles to work. There is a feed line ground with a balun on the back of feed line substrate. SMA connecting space is cut at the bottom of feed line. Both crossed dipole substrate and feed line substrate of S-band element uses RF-35(\(\varepsilon_r=3.5, \tan\delta=0.0002, 0.76\text{mm thickness}\)) boards.
Figure 13 shows the simulation results of single C-band radiation element for difference channel. The C-band radiation element of difference channel is simulated in a cavity set on ground plane of 300mm diameter. The reflection coefficient of both ports less than -10dB from 5.01GHz to 5.29GHz. The maximum gain is about 8dB and the minimum axial ratio is less than 1dB in the cases of both LHCP and RHCP.
Fig. 13 Design results of C-band difference channel element

(a) Reflection Coefficient, (b) Gain pattern, (c) Axial Ratio

Figure 14 shows the effect of the cavity on C-band gain pattern and axial ratio. From figure 16 we can see that when the cavity is removed the gain fell and the axial ratio increased. And it is obvious that the axial ratio angle is narrowed down.
Fig. 14 The effect of the cavity on design results of C-band element

(a) Gain pattern, (b) Axial ratio
Figure 15 shows the simulation results of C-band radiation element for sum channel. Because of C-band sum channel used just one element, the gain pattern and axial ratio should be improved for suit to the 4.6m reflector. A dielectric cap is used for improving gain pattern and axial ratio. The impedance matching is also done by the dielectric cap. The result shows that the reflection coefficient is less than -10dB in frequency range 5.09GHz to 5.15. It achieved the target. The maximum gain is improved to 9.3dB and the axial ratio is improved to less than 1.5dB in the edge taper(+/−64°) of a 4.6m reflector.

(a)
Fig. 15 Design results of C-band sum channel element

(a) Reflection Coefficient, (b) Gain pattern, (c) Axial Ratio
Figure 16 shows the parameters of C-band element. The feed substrate of C-band sum channel element and difference channel element used the same. The crossed dipole substrate has some size difference at the printed dipoles between sum channel element and difference channel element. The thickness of printed metal is 0.035mm. The parameters have considered the case of machining precision, it is less than 0.1mm. It applies to all antenna structure.
Fig. 16 Design parameters of C-band element

(a) Difference channel crossed dipole substrate, (b) Sum channel crossed dipole substrate, (c) Feed substrate(i), (d) Feed substrate(ii)
2.6 L/S/C triple-band dual polarization feed antenna

This part predicts the sum and difference radiation pattern of L/S/C triple band and finally determines the distance between elements of each band. In the calculation of the radiation pattern, the similar method to array antenna is used. There are some important parameters in radiation pattern calculation. The number of units(N) decide the number of lobes in one cycle time. The distance(d) between units decides the radius of polar. The phase difference(α) between units decide the central location of polar.

N: number of units

βd: radius of polar

(-α,0): central location of polar

In the cases of L/S-band sum/difference channel and the C-band difference channel the number of units is 2 by 2, N=2 in a straight line. The waveform is like following Figure17.

![Antenna radiation waveform](image)

**Fig.17 Antenna radiation waveform**

If the distance between units is less than 1/2λ, there will be no side lobe. But if the distance larger than 1/2λ, the side lobes will appear. Figure 18 shows the sum channel
radiation pattern in the cases of $D=1/2\lambda$ and $D=\lambda$.

Fig. 18 Sum channel antenna radiation pattern in polar

(a) $D=1/2\lambda$, (b) $D=\lambda$
In the cases of difference radiation pattern there is a $180^\circ$ phase delay between the azimuth or elevation units. The central point of polar will move to $-\pi$. The radiation pattern of difference channel is shown as the following Figure 19. Because of the reflection of ground plane has not be considered for the calculation of the radiation pattern, the actual simulation results of radiation pattern will more upward and there will less radiation at $-z$ direction.

![Difference channel antenna radiation in polar](image)

**Fig.19 Difference channel antenna radiation in polar**

The increased gain by combine antenna units can be calculated with the following formula.

$$G=10\log(N)$$ (3.1)

In the case of L/S-band sum channel the antenna units is 4, the increased gain is 6dB by calculation. Because of 4 units are used for forming 2 difference channel lobe, each lobe has just 2 units. The increased gain will be 3dB in the case of L/C-band difference channel. In the case of the simulation results of L/S/C-band are 8.3dB, 6.7dB and 8dB, the predicted combined antenna gain of L-band sum channel, L-band difference channel,
S-band sum channel and C-band difference channel will be 14.3dB, 11.3dB, 12.7dB, 11dB through calculations. In the cases of S-band difference channel and C-band sum channel, just one antenna unit used for each lobe formation, so the predicted difference channel gain of S-band is same as the element simulation result and the sum channel gain of C-band is same as the C-band sum channel element results.

Taking into account the size of antenna units and impact between the elements of different band, the distance between units of every band has reduced as much as possible to reduce side lobes. Figure 20 shows the final design structure parameters of cavities and distance between elements. The designed antenna set on a ground plane with a 288mm diameter. The inner diameter of outer cavity is same as ground plane, and the thickness of outer cavity is 5mm. Height of the outer cavity is 63mm from ground plane. The inner cavities consist of five. The inner diameter of inner cavity is 35mm and the thickness is 4mm. The distance between two C-band difference channel elements arranged vertically or horizontally is 52.32mm. The C-band sum channel element is placed at the center of the circular ground plane. The distance between two S-band difference channel elements arranged vertically or horizontally is 102mm and the distance of L-band is 133.5mm. C-band sum channel element has a dielectric cap. The design parameters of C-band dielectric cap are shown on Figure 22(c). The designed antenna is covered a radome which used the UHMW-PE(εr=2.3, tanδ=0.0002, 2mm thickness).
Fig. 20 Final designed antenna parameters.

(a) C-band, (b) Entirety, (c) Dielectric cap

From this section the final designed results of the triple-band monopulse feed antenna will be introduced. Figure 21 shows the reflection coefficients of L-band. L-band element A and L-band element B used the same arrangement, the L-band element C and L-band element D used another arrangement. So the same arrangement gives the same reflection coefficients. From Figure 21 we can see the reflection coefficient of L-band are less than -10dB in the frequency band from 1.435GHz to 1.535GHz.
Figure 22 shows the reflection coefficients of S-band. The same elements are used in S-band. S-band element A and S-band element B used the same arrangement, the S-band element C and S-band element D used another arrangement. So the same arrangement gives the same reflection coefficients. Figure 22 shows the reflection coefficients are less than -10dB from 2.2GHz to 2.4GHz.
In the case of C-band the same elements are used for sum channel and difference channel. But even the cavities are same the dielectric cap is used for only sum element. So the reflection coefficients of sum channel and difference channel are different. From figure 23 we can see the reflection coefficients of sum channel and difference channel from 5.09GHz to 5.15GHz are less than -10dB.
Table 3, table 4, table 5 are the phase delay of final designed antenna for simulation. The port position of each band element with a physical phase difference is shown in the figure 24 to figure 26. In chapter 2.7, the design of monopulse synthesis circuit for feed antenna will be introduced. The monopulse synthesis circuit is designed according to these tables.
Fig. 24 Port position of L-band

Fig. 25 Port position of S-band
Fig. 26 Port position of C-band

Table 3: Simulation phase delay setting of L-band.

<table>
<thead>
<tr>
<th>Port</th>
<th>( \Sigma \text{RHCP} )</th>
<th>( \Sigma \text{LHCP} )</th>
<th>( \Delta \text{RHCP (EL)} )</th>
<th>( \Delta \text{LHCP (EL)} )</th>
<th>( \Delta \text{RHCP (AZ)} )</th>
<th>( \Delta \text{LHCP (AZ)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>180°</td>
<td>360°</td>
<td>270°</td>
<td>270°</td>
<td>450°</td>
<td>450°</td>
</tr>
<tr>
<td>A2</td>
<td>270°</td>
<td>270°</td>
<td>360°</td>
<td>180°</td>
<td>540°</td>
<td>360°</td>
</tr>
<tr>
<td>B1</td>
<td>180°</td>
<td>360°</td>
<td>270°</td>
<td>270°</td>
<td>270°</td>
<td>270°</td>
</tr>
<tr>
<td>B2</td>
<td>270°</td>
<td>270°</td>
<td>360°</td>
<td>180°</td>
<td>360°</td>
<td>180°</td>
</tr>
<tr>
<td>C1</td>
<td>270°</td>
<td>270°</td>
<td>180°</td>
<td>360°</td>
<td>360°</td>
<td>540°</td>
</tr>
<tr>
<td>C2</td>
<td>360°</td>
<td>270°</td>
<td>180°</td>
<td>270°</td>
<td>450°</td>
<td>450°</td>
</tr>
<tr>
<td>D1</td>
<td>270°</td>
<td>270°</td>
<td>180°</td>
<td>360°</td>
<td>180°</td>
<td>360°</td>
</tr>
<tr>
<td>D2</td>
<td>360°</td>
<td>180°</td>
<td>270°</td>
<td>270°</td>
<td>270°</td>
<td>270°</td>
</tr>
</tbody>
</table>
Table 4: Simulation phase delay setting of S-band.

<table>
<thead>
<tr>
<th>Port</th>
<th>$\Sigma$ RHCP</th>
<th>$\Sigma$ LHCP</th>
<th>$\Delta$ RHCP (EL)</th>
<th>$\Delta$ LHCP (EL)</th>
<th>$\Delta$ RHCP (AZ)</th>
<th>$\Delta$ LHCP (AZ)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>×</td>
<td>×</td>
</tr>
<tr>
<td>A2</td>
<td>270°</td>
<td>270°</td>
<td>360°</td>
<td>180°</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>B1</td>
<td>270°</td>
<td>270°</td>
<td>×</td>
<td>×</td>
<td>180°</td>
<td>360°</td>
</tr>
<tr>
<td>B2</td>
<td>360°</td>
<td>180°</td>
<td>×</td>
<td>×</td>
<td>270°</td>
<td>270°</td>
</tr>
<tr>
<td>C1</td>
<td>270°</td>
<td>270°</td>
<td>180°</td>
<td>360°</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>C2</td>
<td>360°</td>
<td>180°</td>
<td>270°</td>
<td>270°</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>D1</td>
<td>180°</td>
<td>360°</td>
<td>×</td>
<td>×</td>
<td>270°</td>
<td>270°</td>
</tr>
<tr>
<td>D2</td>
<td>270°</td>
<td>270°</td>
<td>×</td>
<td>×</td>
<td>360°</td>
<td>180°</td>
</tr>
</tbody>
</table>

* × Represents the port is not used.

Table 5: Simulation phase delay setting of C-band.

<table>
<thead>
<tr>
<th>Port</th>
<th>$\Sigma$ RHCP</th>
<th>$\Sigma$ LHCP</th>
<th>$\Delta$ RHCP (EL)</th>
<th>$\Delta$ LHCP (EL)</th>
<th>$\Delta$ RHCP (AZ)</th>
<th>$\Delta$ LHCP (AZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
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<td>450°</td>
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<tr>
<td>A2</td>
<td>×</td>
<td>×</td>
<td>360°</td>
<td>180°</td>
<td>540°</td>
<td>360°</td>
</tr>
<tr>
<td>B1</td>
<td>×</td>
<td>×</td>
<td>180°</td>
<td>360°</td>
<td>180°</td>
<td>360°</td>
</tr>
<tr>
<td>B2</td>
<td>×</td>
<td>×</td>
<td>270°</td>
<td>270°</td>
<td>270°</td>
<td>270°</td>
</tr>
<tr>
<td>C1</td>
<td>×</td>
<td>×</td>
<td>180°</td>
<td>360°</td>
<td>450°</td>
<td>450°</td>
</tr>
<tr>
<td>C2</td>
<td>×</td>
<td>×</td>
<td>270°</td>
<td>270°</td>
<td>540°</td>
<td>360°</td>
</tr>
<tr>
<td>D1</td>
<td>×</td>
<td>×</td>
<td>270°</td>
<td>270°</td>
<td>540°</td>
<td>360°</td>
</tr>
<tr>
<td>D2</td>
<td>×</td>
<td>×</td>
<td>360°</td>
<td>180°</td>
<td>360°</td>
<td>180°</td>
</tr>
<tr>
<td>E1</td>
<td>90°</td>
<td>180°</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>E2</td>
<td>180°</td>
<td>90°</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

* × Represents the port is not used.
The simulation results will be introduced from this part. These results reflect the phase delay shown in the above table. Due to the LHCP pattern and RHCP pattern, the azimuth pattern and the elevation pattern are similar, only the RHCP sum channel pattern and elevation difference channel pattern are listed here.

Figure 27 shows the S-band sum channel gain pattern and axial ratio according to different frequencies. The circular polarization gain pattern shows that the maximum gain is $12.4\text{dBic}$, the edge taper($\pm 64^\circ$) is $-18.8\text{dB}$ minimum. The axial ratio at the center of antenna is near to 0.
(a)

(b)
Figure 27 shows the difference channel pattern and axial ratio according to different frequencies. The maximum gain is 9.8 dBic and the null depth is less than -30 dB. The edge taper is -4.9 dB at central frequency can be determined. The axial ratio in edge taper is less than 2.8 dB.
Fig. 28 Design results of L-band difference channel

(a) Gain pattern, (b) Axial ratio
Figure 29 shows the gain pattern and axial ratio pattern of S-band according to different frequencies. The gain pattern shows that the maximum gain is 12.5dBi and the edge taper(+/−64°) is 19.1dB. The axial ratio at the center of antenna is near to 0.
Fig. 29 Design results of S-band sum channel

(a) Gain pattern, (b) Axial ratio
Figure 30 shows the difference channel pattern and axial ratio according to different frequencies. The maximum gain is 7.9dBi and the null depth is less than -30dB. The edge taper is -8dB can be determined. The axial ratio in edge taper is less than 3.2dB.
Fig. 30 Design results of S-band difference channel

(a) Gain pattern, (b) Axial ratio
Figure 31 shows the gain pattern and axial ratio pattern of C-band according to different frequencies. The gain pattern shows that the maximum gain is 9.2dBi and the edge taper(+/−64°) is 8.9dB. The axial ratio at the center of antenna is less than 0.5dB.
Fig. 31 Design results of C-band sum channel

(a) Gain pattern, (b) Axial ratio
Figure 32 shows the difference channel pattern and axial ratio according to different frequencies. The maximum gain is 11.3dBi and the null depth is less than -30dB. The edge taper is -17.1dB can be determined. The minimum axial ratio in edge taper is less than 2dB.
Fig. 32 Design results of C-band difference channel

(a) Gain pattern, (b) Axial ratio
2.7 Monopules synthetic circuit

This part shows the components of the monopules synthetic circuit and formation process of antenna pattern.

All three bands use the 90° hybrid coupler. Figure 33 shows the ports of a 90° hybrid coupler. 90° hybrid coupler can combine the signals of two input ports and give the signals 90° and 180° phase delay each other. The 90° hybrid coupler gives the same side of input and output ports a 90° phase delay, and it gives the different side of input and output ports a 180° phase delay thru the circular polarization pattern is obtained.

![90° Hybrid Coupler Diagram](image)

Fig.33 90° hybrid coupler

The 90° hybrid coupler, RF switch, power combiner and modulator make up the monopulse synthetic circuit together. Figure 34 shows the 90° hybrid coupler circuit of L-band. The dual polarization pattern can be outputted from this circular. Through this circular sum channel and azimuth difference channel RHCP/LHCP signal 2pairs outputted.
Fig. 34 90° hybrid coupler circuit of L-band

Table 6 shows the phase delay at 8 hybrid coupler in the cases of each S-band port. The figure 35 shows the total phase delay of each port for L-band sum channel.
Table 6: 90° hybrid coupler/port phase delay of L-band sum channel

<table>
<thead>
<tr>
<th>90° Hybrid Coupler</th>
<th>Ports of L-band elements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
</tr>
<tr>
<td>1</td>
<td>90° (180°)</td>
</tr>
<tr>
<td>2</td>
<td>×</td>
</tr>
<tr>
<td>3</td>
<td>90°</td>
</tr>
<tr>
<td>4</td>
<td>(180°)</td>
</tr>
<tr>
<td>5</td>
<td>×</td>
</tr>
<tr>
<td>6</td>
<td>×</td>
</tr>
<tr>
<td>7</td>
<td>×</td>
</tr>
<tr>
<td>8</td>
<td>×</td>
</tr>
</tbody>
</table>

| Total phase delay | 180° (360°) | 270° (270°) | 270° (270°) | 360° (180°) | 180° (360°) | 270° (270°) | 270° (270°) | 360° (180°) |

* 1. × Represents the port didn’t through the 90° hybrid coupler.
2. RHCP(LHCP)
The signal output from 90° hybrid coupler through the power combiner shown on Figure 36 to get the final phase delay for L-band sum channel. The total phase delay of L-band sum channel is shown in Figure 35.
Table 7 shows the phase delay at 90° hybrid coupler of each port during S-band difference channel signal formation. From the 90° hybrid coupler only the +EL signal is outputted. Figure 37 shows the total phase delay of the +EL difference channel signal which outputted from the 90° hybrid coupler circuit.
Table 7: 90° hybrid coupler/port phase delay of S-band difference channel(+EL)

<table>
<thead>
<tr>
<th>90° Hybrid Coupler</th>
<th>Ports of L-band elements</th>
<th>A₁</th>
<th>A₂</th>
<th>C₁</th>
<th>C₂</th>
<th>B₁</th>
<th>B₂</th>
<th>D₁</th>
<th>D₂</th>
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<td>1</td>
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<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>×</td>
<td>×</td>
<td>90° (180°)</td>
<td>180° (90°)</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>180°</td>
<td>180°</td>
<td>90°</td>
<td>90°</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>(90°)</td>
<td>(90°)</td>
<td>(180°)</td>
<td>(180°)</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>90° (180°)</td>
<td>90° (180°)</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>90° (180°)</td>
<td>180° (90°)</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>180°</td>
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<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>(90°)</td>
<td>(90°)</td>
<td>(180°)</td>
<td>(180°)</td>
</tr>
<tr>
<td>Total phase delay</td>
<td></td>
<td>270° (270°)</td>
<td>360° (180°)</td>
<td>180° (360°)</td>
<td>270° (270°)</td>
<td>270° (270°)</td>
<td>360° (180°)</td>
<td>180° (360°)</td>
<td>270° (270°)</td>
</tr>
</tbody>
</table>

* 1. × Represents the port didn’t through the 90° hybrid coupler.
   2. RHCP(LHCP)
Figure 38 shows the modulator which composed of switch and power combiner. The +EL difference channel signal output from 90° hybrid coupler circuit control through the switch to get the +AZ, -AZ, +EL, -EL difference channel pattern.
In order to be able to control the generated difference channel signal in sequence, the following table 8 shows the control signal and phase delay of the RF switch(modulator) which shown in Figure 38.
Table 8: RF switch control signal and phase delay of L-band difference channel

<table>
<thead>
<tr>
<th>RF Switch</th>
<th>L-band difference pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+EL</td>
</tr>
<tr>
<td>A (Modulator)</td>
<td>0(0°)</td>
</tr>
<tr>
<td>B (Modulator)</td>
<td>0(0°)</td>
</tr>
<tr>
<td>C (Modulator)</td>
<td>0(0°)</td>
</tr>
<tr>
<td>D (Modulator)</td>
<td>0(0°)</td>
</tr>
</tbody>
</table>

*Control signal (phase delay)*

According to the control signal (phase delay) the C-band difference pattern shows like figure 39.
Fig. 39 Pattern of L-band difference channel controlled by RF switch

(a)+EL, (b)-EL, (c)+AZ, (d)-AZ

The monopulse synthetic circuit of S-band is designed like figure 40. The $90^\circ$ hybrid coupler, RF switch, power combiner and modulator make up the monopulse synthetic circuit together.
Fig. 40 Monopulse synthetic circuit diagram of S-band
Figure 41 shows the hybrid coupler circuit of S-band. The dual polarization (LHCP, RHCP) sum channel and difference channel (azimuth, elevation) pattern of S-band can be obtained from this circuit. There are 4 sum channel signals (2 for LHCP, 2 for RHCP) outputted from this hybrid coupler circuit. The power combiner shown in Figure 42 is used to combine the sum channel signals of the same polarization ($\Sigma_{LHCP1}/\Sigma_{LHCP2}$, $\Sigma_{RHCP1}/\Sigma_{RHCP2}$) to get the dual polarization patterns of S-band sum channel ($\Sigma_{LHCP}$, $\Sigma_{RHCP}$).

![Fig.41 90° hybrid coupler diagram of S-band sum/difference channel](image-url)
Table 9 shows the phase delay at 8 hybrid coupler of each S-band port. The Figure 43 shows the total phase delay of each port for S-band sum channel.
Table 9: 90° hybrid coupler/port phase delay of S-band sum channel

<table>
<thead>
<tr>
<th>90° Hybrid Coupler</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
<td>A2</td>
<td>B1</td>
<td>B2</td>
<td>C1</td>
<td>C2</td>
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<td>D2</td>
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<td>×</td>
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<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>2</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>90° (180°)</td>
<td>180° (90°)</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>3</td>
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</tr>
<tr>
<td>4</td>
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<td>(180°)</td>
<td>×</td>
<td>×</td>
<td>(90°)</td>
<td>(90°)</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>5</td>
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<tr>
<td>6</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>90° (180°)</td>
<td>180° (90°)</td>
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<tr>
<td>7</td>
<td>×</td>
<td>×</td>
<td>180°</td>
<td>180°</td>
<td>×</td>
<td>×</td>
<td>90°</td>
<td>90°</td>
</tr>
<tr>
<td>8</td>
<td>×</td>
<td>×</td>
<td>(90°)</td>
<td>(90°)</td>
<td>×</td>
<td>×</td>
<td>(180°)</td>
<td>(180°)</td>
</tr>
<tr>
<td>Total phase delay</td>
<td>180° (360°)</td>
<td>270° (270°)</td>
<td>270° (270°)</td>
<td>360° (180°)</td>
<td>270° (270°)</td>
<td>360° (180°)</td>
<td>180° (360°)</td>
<td>270° (270°)</td>
</tr>
</tbody>
</table>

*1. × Represents the port didn't through the 90° hybrid coupler.
2. RHCP(LHCP)
Table 10 shows the phase delay at 90° hybrid coupler of every port during S-band difference channel signal formation. Figure 44 shows the total phase delay of every S-band port during difference(-AZ, +EL pattern) channel signal formation.
Table 10: 90° hybrid coupler/port phase delay of S-band difference channel(-AZ, +EL)

<table>
<thead>
<tr>
<th>90° Hybrid Coupler</th>
<th>Ports of S-band elements</th>
<th>A₁</th>
<th>A₂</th>
<th>B₁</th>
<th>B₂</th>
<th>C₁</th>
<th>C₂</th>
<th>D₁</th>
<th>D₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>90° (180°)</td>
<td>180° (90°)</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>180° (90°)</td>
<td>180° (90°)</td>
<td>×</td>
<td>×</td>
<td>90° (180°)</td>
<td>90° (180°)</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>90° (180°)</td>
<td>180° (90°)</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>90° (180°)</td>
<td>180° (90°)</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>90° (180°)</td>
<td>90° (180°)</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Total phase delay</td>
<td></td>
<td>270° (270°)</td>
<td>360° (180°)</td>
<td>180° (360°)</td>
<td>270° (270°)</td>
<td>180° (270°)</td>
<td>270° (360°)</td>
<td>270° (270°)</td>
<td>360° (180°)</td>
</tr>
</tbody>
</table>

* 1. × Represents the port didn't through the 90° hybrid coupler.
2. RHCP(LHCP)
3. [Pattern] Represents the +AZ pattern.
Fig. 44 Total phase delay of S-band difference channel

(a) +AZ, (b) +EL
The switches (figure 45) and modulators (figure 46) are used to combine the same polarization signal of difference channel.

The difference channel signals output from coupler circuit are controlled by RF switch. The fig shows that the signals output from the coupler circuit connect to the High($\Delta$RHCP$_{AZ}$, $\Delta$LHCP$_{AZ}$) and Low($\Delta$RHCP$_{EL}$, $\Delta$LHCP$_{EL}$) port. The direction of difference channel pattern can be decided by changing the RF switch. The modulator is composed of RF switch, power combiner and 180° phase delay cable. The direction of difference channel pattern can be reversed by this modulator.

![Fig.45 RF switch for S-band](image)
In order to be able to control the generated difference channel signal in sequence, the following table 11 shows the control signal and phase delay of the RF switch (modulator) which shown in figure 46 and figure 47.
Table 11: RF switch control signal and phase delay of S-band difference channel

<table>
<thead>
<tr>
<th>RF Switch</th>
<th>S-band difference pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+ EL</td>
</tr>
<tr>
<td>A</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
</tr>
<tr>
<td>B (Modulator)</td>
<td>0(0°)</td>
</tr>
<tr>
<td>D (Modulator)</td>
<td>0(0°)</td>
</tr>
</tbody>
</table>

* Control signal (phase delay)

According to the control signal (phase delay) the S-band difference pattern shows like figure 48.
Fig. 48 Pattern of S-band difference channel controlled by RF switch (modulator)

(a)+EL, (b)-EL, (c)-AZ, (d)+AZ

Figure 49 shows the circuit diagram of the final design of the C-band monopulse synthesis circuit. The monopulse synthesis circuit is composed of 90° hybrid coupler, RF switch and modulator.
Fig. 49 Monopulse synthetic circuit diagram of C-band
Figure 50 shows the 90° hybrid coupler circuit of C-band. It is used to combine sum channel and difference channel (+EL) signal of C-band. The sum channel of C-band is different from L-band and S-band, it used only one element and one 90° hybrid coupler to get the sum channel pattern ($\Sigma_{RHCP}$, $\Sigma_{LHCP}$).

Eight 90° hybrid couplers are used for C-band difference channel. From the 90° hybrid coupler circuit, two pairs of difference channel signal ($\Delta_{RHCP1 \text{ EL}}$, $\Delta_{RHCP2 \text{ EL}}$, $\Delta_{LHCP1 \text{ EL}}$, $\Delta_{LHCP2 \text{ EL}}$) outputted. The unused output ports of 90° hybrid coupler connected with 50Ω terminals.

![Fig.50 90° hybrid coupler circuit diagram of C-band sum/difference channel](image)
Table 12 shows the phase delay of the 90° hybrid coupler during C-band sum channel pattern formation at each port. The figure 51 shows the sum channel total phase delay of each port.

Tabel 12: Table: 90° hybrid coupler/port phase delay of C-band sum channel

<table>
<thead>
<tr>
<th>90°Hybrid Coupler</th>
<th>Ports of C-band elements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E1</td>
</tr>
<tr>
<td>9</td>
<td>90°(180°)</td>
</tr>
<tr>
<td>Total phase delay</td>
<td>90°(180°)</td>
</tr>
</tbody>
</table>

Fig.51 Total phase delay of C-band sum channel
Table 13 shows the ports phase delay of C-band difference channel during through 90° hybrid coupler. Figure 52 shows the difference channel(+EL pattern) total phase delay of each port.

Tabel 13: Table: 90° hybrid coupler/port phase delay of C-band difference channel(+EL )

<table>
<thead>
<tr>
<th>90° Hybrid Coupler</th>
<th>Ports of C-band elements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
</tr>
<tr>
<td>1</td>
<td>90° (180°)</td>
</tr>
<tr>
<td>2</td>
<td>×</td>
</tr>
<tr>
<td>3</td>
<td>180°</td>
</tr>
<tr>
<td>4</td>
<td>(90°)</td>
</tr>
<tr>
<td>5</td>
<td>×</td>
</tr>
<tr>
<td>6</td>
<td>×</td>
</tr>
<tr>
<td>7</td>
<td>×</td>
</tr>
<tr>
<td>8</td>
<td>×</td>
</tr>
<tr>
<td>Total phase delay</td>
<td>270° (270°)</td>
</tr>
</tbody>
</table>

* 1. × Represents the port didn't through the 90° hybrid coupler.
   2. RHCPLHCP
At first there is just +EL pattern output from 90° hybrid circuit, then through the 4 modulators like figure 53 the C-band difference pattern is changed to +EL, -AZ, -EL, +AZ in order.
Fig. 53 RF switch (modulator) for C-band difference channel

The phase delay of RF switch (modulator) output signal is showed on table 14.
Table 14: RF switch control signal and phase delay of C-band difference channel

<table>
<thead>
<tr>
<th>RF Switch</th>
<th>C-band difference pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Modulator)</td>
<td>+AZ 0(0°)</td>
</tr>
<tr>
<td>B (Modulator)</td>
<td>+AZ 0(0°)</td>
</tr>
<tr>
<td>C (Modulator)</td>
<td>+AZ 0(0°)</td>
</tr>
<tr>
<td>D (Modulator)</td>
<td>+AZ 0(0°)</td>
</tr>
</tbody>
</table>

*Control signal (phase delay)*

According to the control signal (phase delay) the C-band difference pattern shows like Figure 54.
Fig. 54 Pattern of C-band difference channel controlled by RF switch (modulator)

(a) +EL, (b) -EL, (c) +AZ, (d) -AZ
2.8 Simulation results for a 4.6m reflector antenna.

The final design of this thesis simulated with a 4.6m diameter reflector antenna. F/D of the 4.6m reflector antenna is 0.4. The relationship of reflector and feed antenna is like figure 55.

![Figure 55](image)

Fig.55 Structure of a 4.6m reflector antenna

Figure 56, 57 show the L-band simulation results for a 4.6m reflector antenna. The radiation pattern shows that the sum channel maximum gain is 32.7dBic and the difference channel maximum gain is 30.8dBic. Based on the maximum gain of difference channel the null depth more than 26dB. The minimum axial ratio of sum channel and difference channel is near to 0.
Fig. 56 L-band sum channel radiation pattern of a 4.6m reflector antenna

(a) Gain pattern, (b) Axial ratio
Fig. 57 L-band difference channel radiation pattern of a 4.6m reflector antenna

(b) Gain pattern, (b) Axial ratio

Figure 58, 59 show the S-band simulation results for a 4.6m reflector antenna. The radiation pattern shows that the sum channel maximum gain is 37.9dBic and the difference channel maximum gain is 36.5dBic. Based on the maximum gain of difference
channel the null depth more than 26.5dB. The minimum axial ratio of sum channel and difference channel is near to 0.
Fig. 58 S-band sum channel radiation pattern of a 4.6m reflector antenna

(c) Gain pattern, (b) Axial ratio
Fig. 59 S-band difference channel radiation pattern of a 4.6m reflector antenna

(d) Gain pattern, (b) Axial ratio

Figure 60, 61 show the C-band simulation results for a 4.6m reflector antenna. The radiation pattern shows that the sum channel maximum gain is 46.5dBiC and the difference channel maximum gain is 38.3dBiC. Based on the maximum gain of difference
channel the null depth more than 30dB. The minimum axial ratio of sum channel and difference channel is near to 0.
Fig. 60 C-band sum channel radiation pattern of a 4.6m reflector antenna

(e) Gain pattern, (b) Axial ratio
Fig. 61 C-band difference channel radiation pattern of a 4.6m reflector antenna

(f) Gain pattern, (b) Axial ratio
Conclusion

This thesis proposed a triple-band (L/S/C) dual-polarization (LHCP/RHCP) monopulse feed antenna. This antenna can work separately at L-band (1.435GHz-1.535GHz), S-band (2.2GHz-2.4GHz) and C-band (5.09GHz-5.15GHz) to tracking and receiving. Monopulse synthesis circuit is used to achieve dual circular polarization.

Designed antenna used different arrangement for L/S/C-band element. The L-band took a horizontal and vertical 2 by 2 arrangement on the outermost side. 4 elements of L-band are used to get the sum and difference channel signal together. 4 elements of S-band took the X arrangement inside of L-band elements. And all S-band elements are used for forming the sum channel and difference channel signal. C-band sum channel used one element set on the center of ground plane. Around the C-band sum channel element, 4 C-band difference channel elements were used with the arrangement of horizontal and vertical 2 by 2. 5 small cavities used for improving isolation of each C-band elements and the axial ratio of C-band difference channel. A dielectric cap set on the C-band sum element for improving the axial ratio of C-band sum channel and impedance matching. The outer cavity is used for improving the gain pattern of S-band sum channel and reducing the side lobe of L-band. Finally a circular radome used for protecting antenna elements far from dust and external interference.

The elements of L/S/C-band were separately designed. L-band element used 2 crossed substrates which vertical to the ground plane. Printed dipole, translation part, feed line ground plane were printed on the front of substrates. Feed line, open stub were printed on the back of substrates.

S-band element used 2 crossed substrates that are also perpendicular to the circular
ground plane. Printed dipole, translation part, feed line ground plane were printed on the front of substrates. Feed line was printed on the back of substrates. And a short bar was used for each substrate.

C-band element used 3 substrates including a circular crossed dipole substrate and 2 vertically intersected feed line substrates. The dipole was printed on the circular substrates, the feed line and a open stub were printed on the front of feed line substrates and the feed line ground plane was printed on the back of feed line substrates.

For sum channel and difference channel formation, 90° hybrid coupler was used to get the dual circular polarization. Power combiner was used to combine two signals. RF switch was used to select the path and modulator(RF switch + 0°,180° phase delay cable) was used to reverse phase. The simulation was based on the phase delay produced by the final design of the monopulse synthesis circuit.

This thesis described the design process of a multi-band dual circular polarization monopulse feed antenna that can be operated by a monopulse synthesis circuit. In this thesis, different dual polarization antenna elements, arrangement for sum and difference channel pattern, monopulse synthesis circuit were introduced in detail.
REFERENCES


APPENDIX

1. Design diagram of L-band
2. Design diagram of S-band
3. Design diagram of C-band