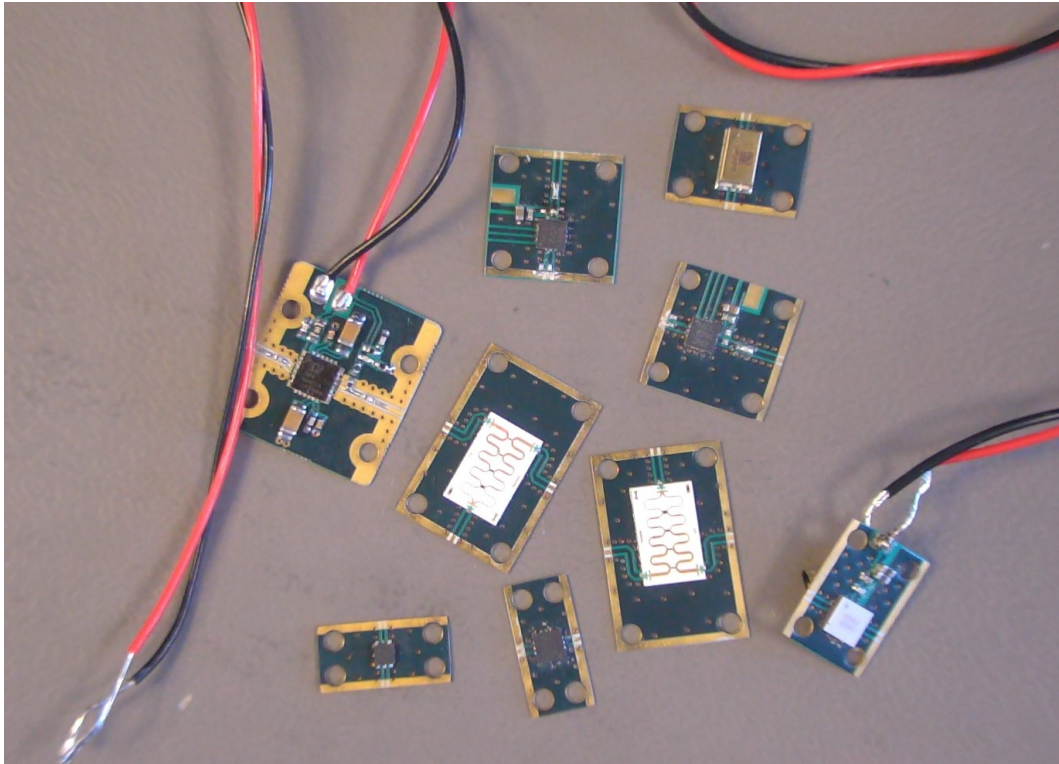




CHALMERS
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Filter Bank Design for Receiver Back Ends of Satellite Constellations

Focus on compact implementation and power optimization of Arctic Weather Satellite.

Master's Thesis in Wireless, Photonics and Space Engineering

MÅNS JAKOBSSON & AMRITHA RAJAN

DEPARTMENT OF MICROTECHNOLOGY & NANOSCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY

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Abstract

Weather forecasting using satellites has been of great interest, since climate change is a global threat. There is also a need to make sustainable designs and reduce power consumption, size etc. This thesis presents the receiver back-end design (IF Block) for faster weather forecasting in satellite constellations. The suggested prototype called Weather Cube, has been able to meet most of the design goals.

The first step of this thesis, was reviewing the existing design of the Arctic Weather Satellite and identifying what could be changed. Certain methods to reduce the power consumption for the back-end of the Arctic Weather Satellite, while maintaining the system performance are presented. Amplifiers present in the RF Section were the main reason of power consumption. There are amplifiers present in each channel for both gain levelling and isolation. Initially, the number of amplifiers were reduced and attenuators were added for gain levelling, but that didn't satisfy the isolation requirements. Different components were explored to test ideas. The final decision was to replace multiple amplifiers used for isolation in the system, with passive isolators. This reduces the power consumption significantly, while fulfilling the requirements for isolation.

Bulky, coaxial components like diplexers are also replaced with a simpler system of a resistive divider and filters. The performance of a diplexer is better than this system, in terms of insertion loss and isolation but the resistive divider and high pass/low pass filters can be surface mounted. The insertion loss due to the resistive divider can be compensated for with more amplification in the system and isolation can be achieved with divider and filters combination. Transmission lines are also tuned to minimize reflections. There are certain trade-offs when design choices were considered, which are also a part of this report.

All components were tested by designing individual PCBs, and the measurements were then simulated in Microwave Office. The transmission lines for channel performance, were optimized in Microwave Office to attain better results. The measurements can be improved further by designing the whole PCB. Another future improvement is linked to one of amplifiers used in the system, ADL9005, this amplifier is now operated at 3 V and 20 mA and has a certain amount of ripple, but it's possible to test it further by changing the bias resistor to vary the current and in turn gain. The isolators are a relatively new component and is not frequently used in space-systems, different mounting strategies could be tested later to see if the performance can be improved.

Keywords: weather forecasting, isolator, diplexer, IF block, amplifiers, power consumption, size, Microwave Office, Weather Cube, Arctic Weather Satellite, resistive dividers.

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Finally, we would like to extend our gratitude to our families and friends, for supporting us throughout our education. This success is as much yours, as it is ours.

Måns Jakobsson & Amritha Rajan, Gothenburg, June 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ADC	Analog to Digital Converter
ADS	Advanced Design System
AWS	Arctic Weather Satellite
BE	Back End
BP	Band Pass
BS	Band Stop
BW	Bandwidth
DC	Direct Current
DD	Diode Detector
ESA	The European Space Agency
FE	Front End
GEO	Geostationary Orbit
GHz	Gigahertz
HP	High Pass
IF	Intermediate Frequency
IO	Input/Output
JPSS	Joint Polar Satellite System
K	Kelvin
LNA	Low Noise Amplifier
LO	Local Oscillator
LP	Low Pass
MetOp	Meteorological Operational Satellite
MHz	Megahertz
MIC	Microwave Integrated Circuits
MMIC	Monolithic Microwave Integrated Circuits
MWO/AWR	Microwave Office
NBW	Noise Bandwidth
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
NRE	Non Recurring Engineering
NTC	Negative Temperature Coefficient
NWC	Nowcasting

NWP	Numerical Weather Prediction
PCB	Printed Circuit Board
RF	Radio Frequency
SAW	Surface Acoustic Wave
SEU	Single Event Upset
SF	Shape Factor
SHM	Sub-Harmonic Mixer
SMT	Surface Mount Technology
SSB	Single Side Band
TEM	Transverse Electromagnetic
VSWR	Voltage Standing Wave Ratio
VNA	Vector Network Analyzer
WC	Weather Cube

Contents

List of Acronyms	ix
List of Figures	xiii
List of Tables	xvii
1 Introduction	1
1.1 Mission Requirements	2
1.2 Summary of Current Satellite Generation & Goals	2
1.3 Purpose and Scope	3
1.4 Ethical Considerations	3
1.5 Thesis Outline	3
2 Theory	5
2.1 Total Power Microwave Radiometer	5
2.2 Filter Bank	6
2.3 Atmospheric Properties	8
2.3.1 Brightness Temperature	8
2.3.2 183 GHz Water Vapour Spectral Line	8
2.3.3 54 GHz Oxygen Spectral Line	9
2.4 System Layout & Performance Parameters	11
2.5 Front End Components	15
2.5.1 Low Noise Amplifier	15
2.5.2 Mixer & LO	15
2.5.3 IF Amplifier	16
2.6 Back End Components	16
2.6.1 Power Splitter	16
2.6.2 Amplifier	16
2.6.3 High Pass/Low Pass Filter	17
2.6.4 Attenuator	17
2.6.5 Isolator	17
2.6.6 Equalizers	17
2.6.7 Diode Detectors	18
2.7 Filter Technologies	19
2.7.1 Surface Acoustic Wave Filter	22
2.7.2 Lumped Element Filter	22
2.7.3 Cavity Filter	22

2.7.4	Thin Film Filter	23
3	Circuit Design	25
3.1	Design Requirements	25
3.2	183 GHz	26
3.2.1	Front End Design for 183 GHz.	26
3.2.2	Previous Design for Back End of 183 GHz	27
3.2.3	Proposed Design for Back End of 183 GHz	29
3.2.3.1	Key Changes	29
3.2.3.2	Solutions	29
3.3	54 GHz	31
3.3.1	Front End for 54 GHz	31
3.3.2	Previous Design for Back End of 54 GHz	32
3.3.3	Proposed Design for Back End of 54 GHz	32
3.3.3.1	Key Changes & Solutions	33
3.4	Component List	34
4	Results & Discussions	35
4.1	RF Power Budget	35
4.1.1	183 GHz RF Power Budget	36
4.1.2	54 GHz RF Power Budget	40
4.2	Circuit Improvements	42
4.3	Simulations for 183 GHz	46
4.3.1	Channel Response	48
4.3.2	Cross-talk	49
4.4	Simulations for 54 GHz	52
4.4.1	Cross-talk	54
4.4.2	Channel Response	55
4.5	Measurements	56
4.5.1	Printed Circuit Boards	56
4.5.2	Channel Measurements	58
4.6	Power Comparison	62
5	Conclusion	63
	Bibliography	65
A	Appendix	I
A.1	Amplifiers	I
A.2	Power Splitters	III
A.2.1	Equalizer	V
A.2.2	Filters	VI
A.3	RF Power Budgets	X
A.4	Measurement Layouts	XIV

List of Figures

2.1	Filter mask to describe how the filters frequency response have to be constrained to follow given specifications. The shaded regions in the figure are not allowed/rejected [5].	7
2.2	Water vapour Line at 183 GHz. The brightness temperature of Earth at the Arctics is assumed as 270K or 0° C. The temperature decreases as the height of the atmosphere increases and resonances/peaks occur at 183 GHz, at around 240 K.	9
2.3	Filter mask to describe how the filter’s frequency response has to be constrained to follow given specifications.	10
2.4	Layout of the system that is used in the AWS project [15].	11
2.5	Y-factor measurement graph [17].	12
2.6	The measured Allan variance curve is the detector curve. The theoretical curve shows an ideal linear system.	13
2.7	Noise bandwidth illustration to show the difference between noise bandwidth and 3 dB bandwidth [20].	14
2.8	Noise figure calculation of a cascaded system [12].	15
2.9	Gain slope of a system.	18
2.10	Circuit of diode detector [27].	19
2.11	The most common filter types.	20
3.1	183 GHz FE design [37].	26
3.2	Previous design for 183 GHz Filter Bank [9].	28
3.3	Prototype design for 183 GHz filter bank.	29
3.4	54 GHz FE design [38].	31
3.5	Previous design for 54 GHz BE.	32
3.6	Proposed design for 54 GHz Filter Bank.	32
4.1	Size comparison between diplexer (left) and power splitter setup with filters (right).	42
4.2	Transmission through a diplexer. Port 2 represents the window channel and Port 3 represents the other channels.	43
4.3	Transmission through a resistive divider with LP filters (XLF-73+ and LFCW-5000+).	43
4.4	Transmission through a resistive divider with HP filter (XHF14M+).	44
4.5	Isolators for 183 GHz. KTMI-2002A (left) and KTMI-1502A16 (right). Isolators are bigger for lower frequencies.	45

4.6	First part of the 183 GHz layout, which shows the setup of the resistive divider, LP and HP filter.	46
4.7	Second part of the 183 GHz layout, which shows channel 31.	47
4.8	Third part of the 183 GHz layout, which shows the amplifier chain leading up to channel 32 to 36.	47
4.9	Fourth part of the 183 GHz layout, which shows channel 32 to 36.	47
4.10	Channel response for WC32-WC36.	48
4.11	Channel response for WC31.	48
4.12	Cross-talk simulations between channel 31 with channel 32 to 36 with the final layout.	49
4.13	Cross-talk simulations between channel 32 with channel 33 to 36 in the final layout.	50
4.14	Cross-talk simulations between channel 33 with channel 32 to 36 in the final layout.	50
4.15	Cross-talk simulations between channel 34 with channel 32 to 36 in the final layout.	51
4.16	Cross-talk simulations between channel 35 with channel 32 to 36 in the final layout.	51
4.17	Cross-talk simulations between channel 36 with channel 32 to 36 in the final layout. Channel 32 and 33 overlap each other in the graph, and Channel 34 and 35 overlap each other.	52
4.18	First part of the 54 GHz layout, which shows the amplifier chain leading up to channel 11 to 18.	52
4.19	Second part of the 54 GHz layout, which shows channel 11 to 14.	53
4.20	Third part of the 54 GHz layout, which shows channel 15 to 18.	53
4.21	Cross-talk without the isolator for WC15 and WC16.	54
4.22	Cross-talk with the isolator for WC15 and WC16.	54
4.23	Channel response for WC11 and WC12.	55
4.24	PCB design.	56
4.25	The isolator mounted two different ways. The isolator tested is KTMI-1502A16 which operates between 12-17 GHz.	57
4.26	Measurements of KTMI-702A5 for the designed frequency band.	57
4.27	Measurements of KTMI-1502A16 for the designed frequency band.	58
4.28	Measurements of KTMI-2002A for the designed frequency band.	58
4.29	Measured cross-talk between channel 33 and channel 32 to 36 for the final layout.	59
4.30	Measured cross-talk between channel 34 and channel 32 to 36 for the final layout.	59
4.31	Channel response for channel WC32 to WC36 with measured components and having the lengths of the transmission lines the same as in the ideal scenario.	60
4.32	Channel response for channel WC32 to WC36 with measured components and having the lengths of the transmission lines tuned for better performance.	60

4.33	Channel response for channel WC31 with measured components and having the lengths of the transmission lines tuned for better performance.	61
A.1	S parameters of PMA3-83LN+.	I
A.2	S parameters of HMC342LC4.	II
A.3	S parameters of ADL9005.	II
A.4	Power splitter Transmission.	III
A.5	Power splitter input reflection.	III
A.6	Power splitter output reflection.	IV
A.7	Power splitter isolation.	IV
A.8	Power splitter Characteristics for PDW06038.	V
A.9	EQY-4-63+ equalizer.	V
A.10	Filter response for WC11 with Knowles filter and showcasing the 3 dB points.	VI
A.11	Filter response for WC12 with Knowles filter and showcasing the 3 dB points.	VI
A.12	Filter response for WC31 with Knowles filter and showcasing the 3 dB points.	VII
A.13	Filter response for WC32 with Knowles filter and showcasing the 3 dB points.	VII
A.14	Filter response for WC33 with Knowles filter and showcasing the 3 dB points.	VIII
A.15	Filter response for WC34 with Knowles filter and showcasing the 3 dB points.	VIII
A.16	Filter response for WC35 with Knowles filter and showcasing the 3 dB points.	IX
A.17	Filter response for WC36 with Knowles filter and showcasing the 3 dB points.	IX
A.18	Soldering machine.	XIV
A.19	Component measurement with VNA.	XIV
A.20	Power splitter measurement circuit.	XV
A.21	Resistive divider, LP and HP Filter setup tested on the Prototype X-Microwave circuit.	XV

List of Tables

2.1	54 GHz filter mask response. Centre RF & all frequencies are in GHz [5].	7
2.2	183 GHz filter mask response. Centre RF & frequencies listed in the frequency response mask are in GHz [9].	7
3.1	Components in the circuit design.	34
4.1	Instruments used to obtain the measurements in the report.	35
4.2	Estimated FE power while observing cold load and observed temperature.	35
4.3	Input power due to cold load and observed temperature, to detector diode for all the channels.	36
4.4	RF power budget for WC32.	37
4.5	Dynamic range calculations for WC32.	38
4.6	RF power budget for WC31.	38
4.7	Dynamic range calculations for WC31.	39
4.8	RF power budget for WC11.	40
4.9	Dynamic range calculations for WC11.	41
4.10	RF power budget for WC12.	41
4.11	Dynamic range calculations for WC12.	42
4.12	Power comparison between previous and suggested prototype for BE183.	62
4.13	Power comparison between previous and suggested prototype for BE183.	62
A.1	RF power budget for WC33.	X
A.2	RF power budget for WC34.	XI
A.3	RF power budget for WC35.	XII
A.4	RF power budget for WC36.	XIII

1

Introduction

Accurate weather forecasting is important and complements routine based land activities such as managing resources, routing of ships etc [1]. Satellites, in geostationary and polar orbits, are an important tool for forecasting the weather [1]. It has become possible to foresee potential disasters before they arrive and prepare for them, especially because environmental issues and climate change are global threats [1]. The day to day weather forecasting and global coverage has also improved, due to better technology and sustainable designs [1].

The satellites present in the Geostationary orbit (GEO) follow Earth's rotation and circle the Earth from west to east [2]. They travel at exactly the same rate as Earth, thereby appearing stationary [2]. This orbit is used by weather satellites, so that they can continuously observe certain areas of the Earth [2]. Europe's Meteosat satellites are located in the GEO, 36000 km above the equator. Weather images are returned every 15 minutes but they cannot be used for forecasting weather in the Arctics, as they cannot view very high latitudes, near the poles [3]. While Meteorological Operational (MetOp) Satellite can view the poles, as they are present in a lower orbit but it takes 24 hours to achieve the coverage needed [3]. Therefore, the need of the hour is to obtain more frequent data over the Arctics, particularly data related to the water vapour, as it changes rapidly [3].

The Arctic Weather Satellite (AWS) will be polar orbiting and has to supply a constant flow of temperature and humidity data [3].

The absorption features of some atmospheric gases can be studied in the microwave range through their rotational lines (spectral lines) [4]. The frequencies, 183 GHz is used for water vapour profiling under dry conditions [4]. Oxygen is uniformly distributed in the atmosphere and its spectral line at 54 GHz is used to derive temperature profiles of the atmosphere [4]. Similarly, 89 GHz is used for cloud/ice detection and as a window channel for temperature soundings and 325 GHz is used for cloud detection and humidity sounding [4].

1.1 Mission Requirements

The aim of weather satellites mentioned in this report, is to provide a more frequent and faster weather forecasting in the Arctics, mainly using water vapour and oxygen profiling. These measurements of the satellites will be used as part of Numerical Weather Predictions (NWP) and Nowcasting (NWC) [5].

- NWP includes weather predictions that run over longer forecast periods. A set of equations that describe liquid flow are employed which translate into computer code and use governing equations, numerical methods etc [6].
- NWC is meteorology that involves predictions between 0-6 hours. This involves details that can't be solved by using NWP. It can be referred to as short range weather forecasting [7].

The measurements are processed by a microwave radiometer, with 19 frequency channels [8]. The data points observed at the output of the radiometer can be interpreted to find the water vapour or oxygen lines [8]. This report only addresses 14 channels, at the 183 and 54 GHz frequency bands. The total power microwave radiometer will be the single payload in the satellite. The overall mission requirements are to provide global measurements of the atmosphere and ground [5].

The following requirements will be delivered by the satellite:

- Water-vapour profiles in clear and cloudy conditions [5].
- Temperature profiles in clear and cloudy conditions [5].
- Information on cloud ice and ground emissivity [5].
- Sharp gradients in the atmosphere water vapour profiles [5].

1.2 Summary of Current Satellite Generation & Goals

The aim of this project is to complement the measurements by the existing satellites in the Arctics; like MetOp, MetOp-SG, National Oceanic and Atmospheric Administration (NOAA), National Polar-orbiting Partnership (NPP) and Joint Polar Satellite System (JPSS) series [5]. Their revisit times are limited and can't support regional/nowcasting users [5].

For the current generation, Receiver Back Ends (BEs) were designed to convert the measurements at 54 and 183 GHz to 2-20 GHz, as components are readily available at those frequencies. A review of the existing design was conducted and the following goals were decided upon:

1. The focus is to reduce power consumption from the existing design.
2. The focus is a more compact implementation of the back-end and exploring possibilities to reduce filter size.

A more detailed description of the existing design is presented in Chapter 3.

1.3 Purpose and Scope

With the previous generation design as a starting point, the purpose of this project is to examine the various possibilities to reduce the power consumption. Most of the power consumption is from the RF section of the design rather than the DC section, so the power reduction is focused on the RF section [9].

The scope of the thesis is to design and optimize the filter bank design or BEs of a 183 and 54 GHz radiometers, that are more compact and consume less power. Different amplifiers, power detectors are tested and design changes may be implemented, if required.

1.4 Ethical Considerations

There are several possible ethical, societal and ecological aspects that are taken into consideration for this project. The aim of the prototype is to reduce the power consumption and still achieve the same performance. There is also an aim to make the system more compact which could lead to lower production costs and decrease the material used. This could also lead to fitting more equipment in one launch, so as to reduce the number of launches and thereby, fuel burnt.

Considering the societal aspects of the project, it would help in improving weather forecasting over the Arctics and track storms, and extreme weather conditions. Weather forecasting can also used in day to day life for many fields.

1.5 Thesis Outline

This report addresses the prototype of the receiver BE design for a weather satellite, which is an optimized version of the AWS. The prototype is titled Weather Cube (WC).

Initially, the theoretical concepts related to the circuit design, system layout and component definitions are explained, along with the performance parameters. Subsequently, the circuit design is presented for the Front End (FE) & BE in depth along with key changes and solutions for the BE. Simulations and measurements to support the design choices are presented in the end. Some trade-offs have also been mentioned.

2

Theory

In this chapter, the theory of the problem in question will be examined and explained. The reader can therefore understand how the system is built and its function. The system as a whole and the components, will be explained separately and in later sections, the parts will be connected.

The report describes an optimization of the Filter Bank Design (BE) of two receivers with frequency channels at different points on the spectral lines, at 183 and 54 GHz, in a total power microwave radiometer. The 183 GHz receiver has 6 channels called WC31-36 and the 54 GHz has 8 channels called WC11-18.

The first section of this chapter explains the basic principle of working of a total power microwave radiometer, as it is the key concept for the design.

2.1 Total Power Microwave Radiometer

A total power microwave radiometer is a sensitive instrument that measures the power of the thermal noise emitted by bodies at a physical temperature, which is greater than 0 Kelvin (K) [4].

All bodies at a nonzero Kelvin temperature emit electromagnetic radiation [4]. Gases also emit and absorb radiation, similar to solids and liquids [4]. According to quantum theory, each spectral line can correspond to the transition of an electron from an atomic energy level E1 to another one E2 [4]. Alternatively, if a photon at a certain frequency is absorbed, an electron is excited from energy level E2 to energy level E1 [4].

When there is higher interaction due to increased kinetic energy at high temperature, the energy levels split and the emission is no longer at a single frequency but a band around the frequency F1-2 (at energy levels E1 and E2, respectively) [4].

Values at these frequency bands are used for measurements of atmospheric gases to evaluate atmospheric humidity and temperature [8]. Filter banks or spectrum analyzers can be used to obtain the data points at these frequency bands.

Spectrum analyzers are used when a fine spectral resolution is required. A large number of frequency points are observed but only a few are required to obtain the water vapour and oxygen curves [10].

The allowed bandwidths in the specifications, mentioned in table 2.1 and 2.2, and the windows allowed for the down link to view the ground, are both limited [5]. Therefore, it is easier to analyze compact data points in the short time span. Spectrum analyzers also consume more power when compared to a filterbank. Therefore it is useful to use a total power microwave radiometer with a filterbank, for this application [10].

A filter bank has multiple detection channels and all of them are processed in parallel. Each channel has its own filter and the number of data points are limited [10]. It is explained further in section 2.2.

2.2 Filter Bank

A filter bank is a circuit that divides a wide band signal into different frequency channels by utilizing filters that pass certain frequencies, and reject the other frequencies [11].

Filter banks also consists of amplifiers, attenuators, power splitters, equalizers and other microwave components which are used to change the strength of the signal, remove slopes and split it into different channels [12]. The band pass filters are used to decrease the unwanted number of data points to an acceptable level by limiting the bandwidth of the channels [12]. Custom Radio Frequency (RF) filters are designed and specifications are to be fulfilled regarding allowed ripple, central frequency, filter mask, bandwidth, and good isolation between channels [5].

The frequency specifications for AWS are quite strict, as the customer wants to have a system that is as ideal as possible and to obtain very specific points on the spectral curves shown in section 2.3. The 3 dB and 40 dB points are critical for the filter bank. The 3 dB points are used as a standard definition for the filter bandwidth and 40 dB points are used as rejection specifications, as the channel frequencies are quite close and overlap must be avoided [5]. The WC will have similar specifications as well.

The filter shape required for AWS is presented in figure 2.1 and table 2.1 and 2.2, which mention the frequency requirements of the AWS and the Weather Cube [5]. In table 2.1 and 2.2, the RF is converted to Intermediate Frequency (IF) using a Local Oscillator (LO) frequency of 48 GHz for the 54 GHz system and 162.575 GHz for the 183 GHz system.

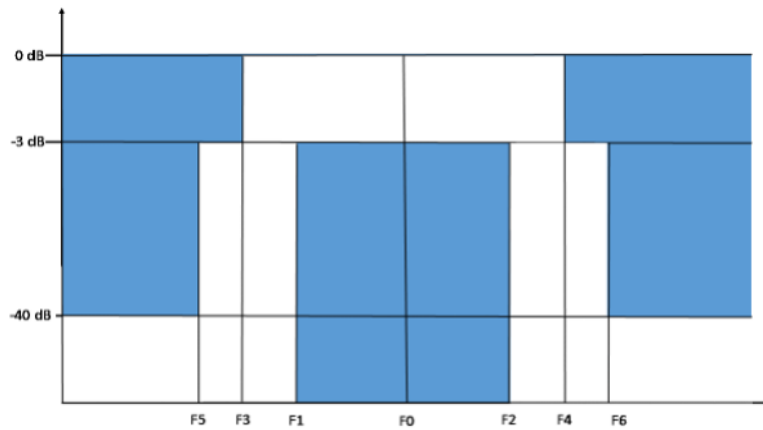


Figure 2.1: Filter mask to describe how the filters frequency response have to be constrained to follow given specifications. The shaded regions in the figure are not allowed/rejected [5].

Table 2.1: 54 GHz filter mask response. Centre RF & all frequencies are in GHz [5].

Filter	Centre RF [GHz]	BW [MHz]	Frequency response mask						
			Normalized S_{21}						
			F5	F3	F1	F0	F2	F4	F6
WC11	50.3	180	2.162	2.21	2.223	2.3	2.377	2.39	2.438
WC12	52.8	400	4.494	4.6	4.63	4.8	4.97	5	5.106
WC13	53.246	300	5.017	5.096	5.119	5.246	5.374	5.396	5.476
WC14	53.596	370	5.313	5.411	5.439	5.596	5.753	5.781	5.879
WC15	54.4	400	6.094	6.2	6.23	6.4	6.57	6.6	6.706
WC16	54.94	400	6.634	6.74	6.77	6.94	7.11	7.14	7.246
WC17	55.5	330	7.248	7.335	7.36	7.5	7.64	7.665	7.752
WC18	57.29	330	9.038	9.125	9.15	9.29	9.431	9.455	9.543

Table 2.2: 183 GHz filter mask response. Centre RF & frequencies listed in the frequency response mask are in GHz [9].

Filter	Centre RF [GHz]	BW [MHz]	Frequency response mask						
			Normalized S_{21}						
			F5	F3	F1	F0	F2	F4	F6
WC31	165.5	2800	0.783	1.525	1.735	2.925	4.115	4.325	5.067
WC32	176.311	2000	12.206	12.736	12.886	13.736	14.586	14.736	15.266
WC33	178.811	2000	14.706	15.236	15.386	16.236	17.086	17.236	17.766
WC34	180.311	1000	16.971	17.236	17.311	17.736	18.161	18.236	18.501
WC35	181.511	1000	18.717	18.436	18.511	18.936	19.361	19.436	19.701
WC36	182.311	500	19.354	19.486	19.524	19.736	19.949	19.986	20.118

The data from each channel of the filterbank is interpreted to estimate the spectral lines to extract accurate weather data over the Arctics.

2.3 Atmospheric Properties

The frequency bands presented in this report are 166-183 GHz and 50.3-57.2 GHz, as displayed in table 2.1 and 2.2. The atmosphere is quite transparent at certain frequencies and this can be defined as 0% opaque [13]. The opacity increases as the height increases and therefore, the absorption increases [4], [13].

2.3.1 Brightness Temperature

Brightness temperature is the value of radiance of microwave radiation which travels upwards from the top of Earth's atmosphere [14]. The spectral lines are plotted as a function of brightness temperature in K and Frequency in GHz. The spectral lines for the mentioned frequency bands and the atmospheric properties are mentioned in the below sections.

2.3.2 183 GHz Water Vapour Spectral Line

The 183 GHz channels are used for water vapour profiling/humidity sounding [8]. The spectrum is strongly opaque at 183 GHz [13]. The center frequencies of the channels (WC31-36) included are 165.5, 176.311, 178.811, 180.311, 181.511 and 182.311 GHz, as shown in table 2.2. The window channel (165.5 GHz) is used to find the point closest to the ground and has a lower frequency than the rest of the channels. The other channels are strategically placed on the water vapour line, shown in the figure 2.2.

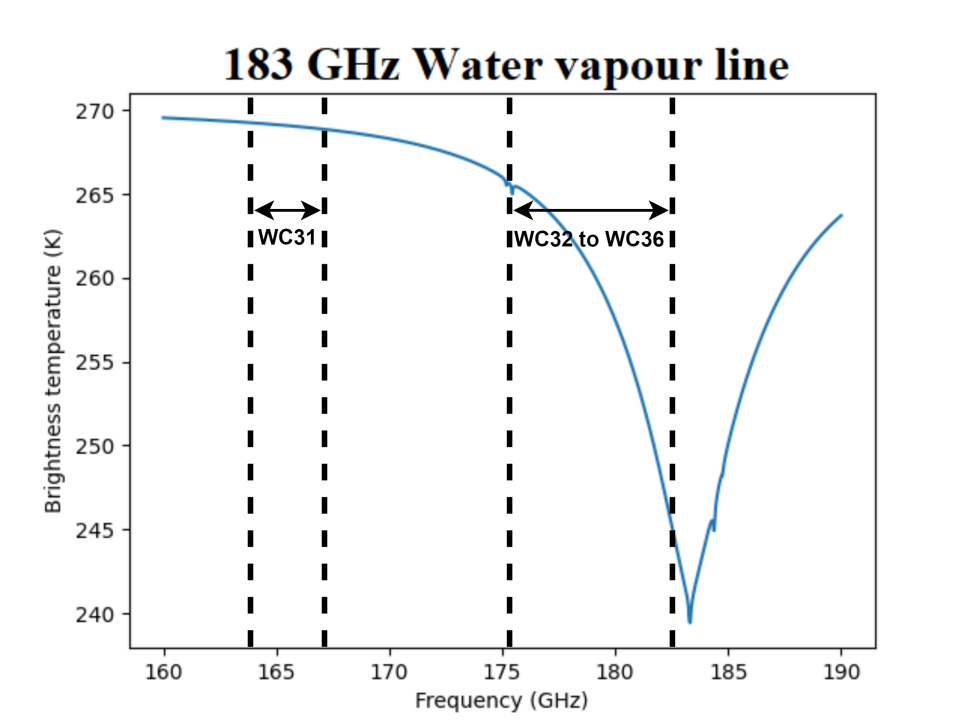


Figure 2.2: Water vapour Line at 183 GHz. The brightness temperature of Earth at the Arctics is assumed as 270 K or 0°C . The temperature decreases as the height of the atmosphere increases and resonances/peaks occur at 183 GHz, at around 240 K.

Most of the time, the atmosphere is too opaque near this line due to the strong absorption by tropospheric water vapour [13]. Therefore, it is difficult to detect the stratospheric signal from the ground at 183 GHz, but it is easily detectable from the satellite [13].

2.3.3 54 GHz Oxygen Spectral Line

The oxygen line is strongly opaque at 54 and 118 GHz, and provides data about temperature profiles related to oxygen [8]. Only channels at 54 GHz have been used for this design. The 54 GHz channels (WC11-18) includes the following center frequencies 50.3, 52.8, 53.246, 53.6, 54.4, 54.94, 55.5 and 57.3 GHz. These frequencies can be seen in table 2.1. The 54 GHz line has some peaks due to the presence of ozone molecules [4]. Initially, only 4 channels were used for the oxygen spectral line but increasing the number of channels could make the interpreted weather data more accurate. Similarly to the 183 GHz case, there is a window channel while other channels are strategically placed on the oxygen line, shown in the figure 2.3.

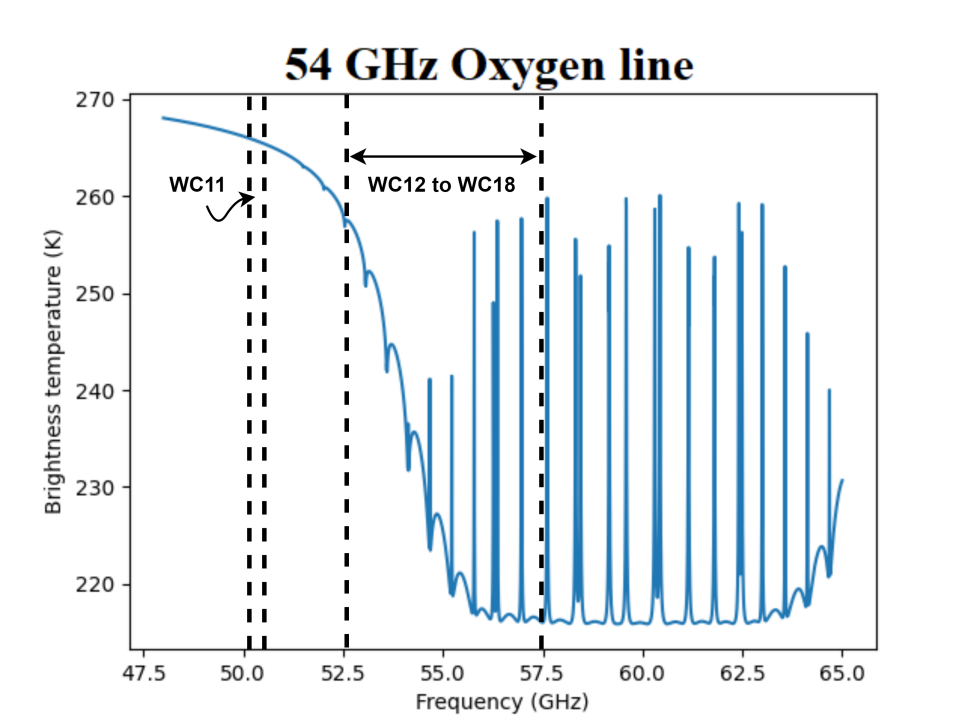


Figure 2.3: Filter mask to describe how the filter’s frequency response has to be constrained to follow given specifications.

Only the lower half of the line is used for both 183 and 54 GHz to reduce the number of filters and points as it still gives an accurate model, since the lines are approximately symmetrical in their shape. The following section presents how the satellite measures the data that it receives and what parameters are important for the system.

2.4 System Layout & Performance Parameters

There are a set of sub-systems which form the entire layout; a feed horn antenna, FE, BE, ADC and the user system, as displayed in figure 2.4.

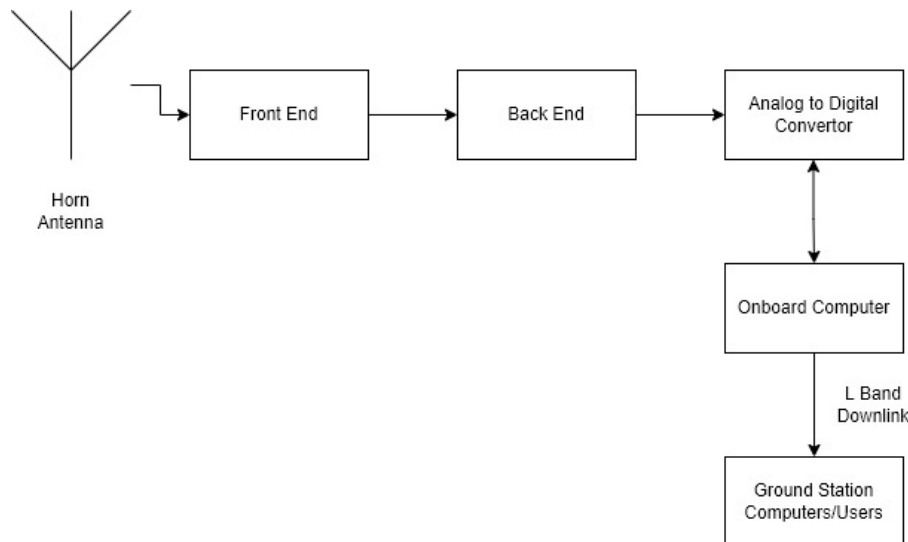


Figure 2.4: Layout of the system that is used in the AWS project [15].

The radiometer consists of a rotating antenna which sends the incoming signals to the feed horn. The feed horn, in turn, transfers the signal to a Low Noise Amplifier (LNA) [15]. The LNA is the first component of the FE circuit and determines the noise figure of the entire circuit [12]. The signal is down converted in the FE to an IF and sent to the BE, which is divided into channels based on the frequency bands. Thereafter, it is sampled by the ADC and sent to the user system through an L band down link. The L band refers to frequencies in the 1-2 GHz range in the spectrum [16], [15].

For every antenna rotation, the receiver noise and gain are calibrated using Y factor measurements of a hot load (which is onboard the satellite) and cold space [5]. Calibration is important due to gain drifts in space and it makes the measurements more accurate and improves the quality, this is also based on the accuracy requirements of the customer. The receiver temperature, T_{rec} is determined by the values of temperatures of hot load and cold space [5]. This is done by extrapolating the line between the cold and hot measurement down to where the output temperature is zero degrees Kelvin. The slope of the line is the gain of the receiver, these parameters are shown in figure 2.5. The value of T_{rec} determines the noise figure of the circuit.

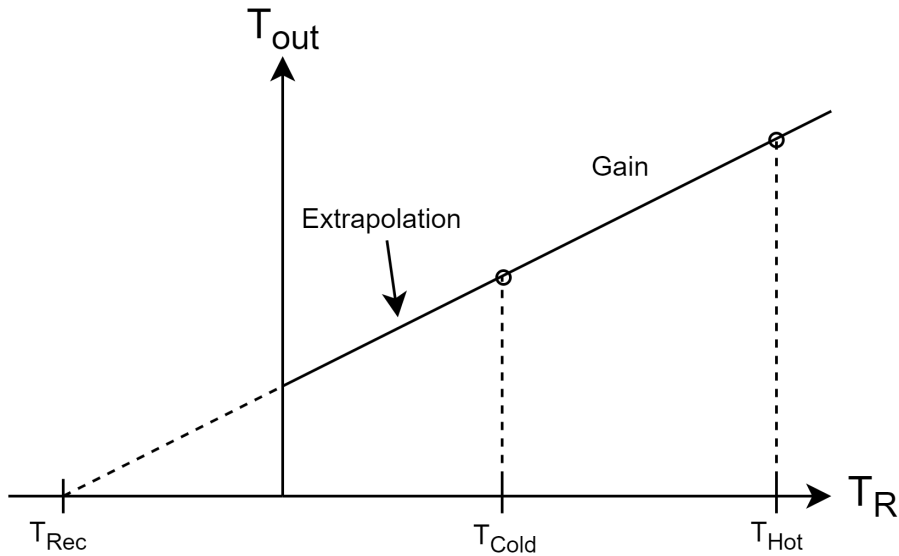


Figure 2.5: Y-factor measurement graph [17].

Below are some performance parameters which are important to consider for the system design.

- **Gain Levelling**

The gain of the system determines the absolute signal level for each channel. The gain is levelled in each channel to improve the readability of the output [9].

- **Filter Bandwidth**

The filter bandwidth defines the bandwidth of each channel. The data from each channel is used to obtain the set of sample points interpreted into the spectral line. The bandwidth is set differently for each channel and requires custom filters to meet the requirements, which is explained in section 2.9 [9].

- **Noise Equivalent Delta Temperature**

It is a measure of the radiometric resolution and tells the user what amount of noise to expect in the system. For the manufacturer, it is an important specification which is essential to be met. It is also defined as the standard deviation of the data series when everything is calibrated. The input to the detector diode is dependent on the Nedt value.

Below is the approximate Nedt equation, without considering gain fluctuations:

$$Nedt = \frac{T_{Sys}}{\sqrt{BW_{RF} * \tau}} \quad (2.1)$$

In equation 2.1, τ is the integration time. T_{Sys} can be calculated using the T_{rec} shown in figure 2.5 added to the antenna temperature.

The higher the temperature difference is between the hot and cold body, the lower the receiver temperature is since the line from these measurements will have a larger difference in temperature. The integration time is not big as the satellite is in constant motion [18].

- **Integration Time**

Integration time (τ) in digital signal processing is the amount of time that samples are accumulated, in order to get lesser noise in the output data, based on the following equation:

$$Noise = \frac{1}{\sqrt{(BW_{RF} * \tau)}} \quad (2.2)$$

- **Allan Variance/Stability**

The Allan variance, also known as two-sample variance, is a measure of frequency stability in clocks, oscillators and amplifiers [19]. The Allan variance is intended to estimate stability due to noise processes and not that of systematic errors or imperfections such as frequency drift or temperature effects [19]. The graph is stable until the linear part and becomes unstable once the curve rises, which is shown in figure 2.6 [19]. The y axis in figure 2.6 shows the time during which the uncertainty of the system is measured [19]. This value can be modified by adding white noise to the system, which may make it seem infinitely stable but is not [19].

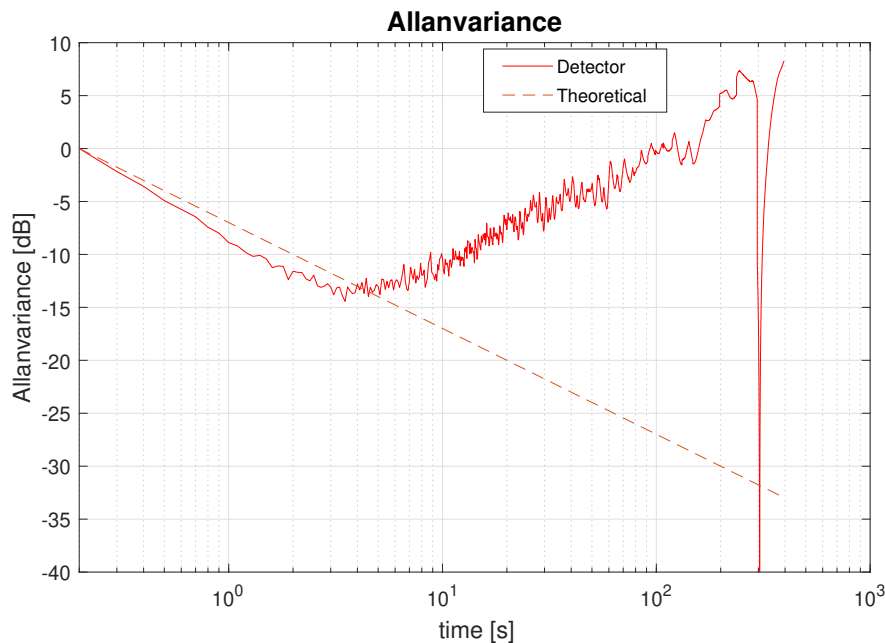


Figure 2.6: The measured Allan variance curve is the detector curve. The theoretical curve shows an ideal linear system.

- **Equivalent Noise Bandwidth**

Equivalent noise bandwidth is the bandwidth of a perfect rectangular filter that allows the same amount of power to pass as the cumulative bandwidth of the channel selective filters. It can be found by integrating the area in the filter mask. It is more accurate to use this value than the 3 dB bandwidth when calculating the power in the channel [20].

The minimum and maximum bandwidth refer to the bandwidth the filter can measure based on its tolerances. This is shown in figure 2.7.

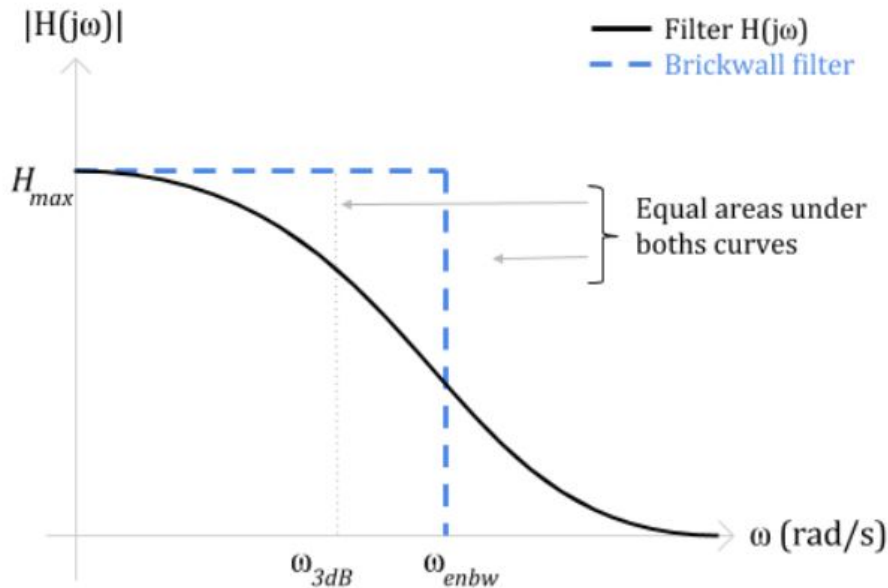


Figure 2.7: Noise bandwidth illustration to show the difference between noise bandwidth and 3 dB bandwidth [20].

- **Power Consumption**

Majority of the power is consumed by the RF section of the BE rather than the Direct Current (DC) section [9]. Therefore, power optimization is important for the RF section [9].

- **Size/Mass of the BE**

This design is expected to be compact. Therefore, the components selected must not be bulky nor heavy.

- **Cross-Talk**

Cross-talk is the unwanted leakage or coupling between the channels [9]. Cross-talk is simulated between the channels.

- **Ageing of Components**

Most components in space are expected to sustain for a long life span. There can be accelerated ageing due to radiation like Total Dose, Single Event Upsets (SEUs), which are unpredictable [5], [21]. It is expected to test the device/satellite through accelerated ageing conditions to ensure that it can survive in space.

These parameters are very important to consider while choosing components for the circuit.

The FE and BE circuit consist of some active and passive components, which are fundamental to microwave engineering. The upcoming sections describe them in detail.

2.5 Front End Components

The working of components used in the FE and their requirement in the system are presented in this section.

2.5.1 Low Noise Amplifier

The LNA takes a weak signal from the feedhorn antenna and amplifies the strength of the signal to a value that is useful for the system [12]. LNA's usually have high gain, so as to reduce the noise contribution from the rest of components in the system based on equation 2.3, where n is the number of components in the system, which is shown in figure 2.8 [12].

$$F_n = F_1 + \frac{F_2}{G_1} + \frac{F_3}{G_1 * G_2} + \dots \quad (2.3)$$

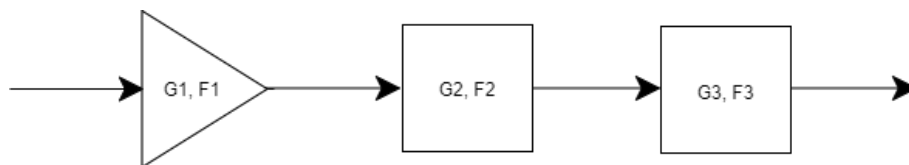


Figure 2.8: Noise figure calculation of a cascaded system [12].

Based on equation 2.3, if the gain of the first component is high, it can neutralize the noise from all the other components and dominate the noise figure in the circuit. LNAs must be highly linear as the received signal can be corrupted by intermodulation products and higher order harmonics [12].

Linearity of an amplifier is quantified by defining a parameter called the 1 dB compression point or P1dB [12]. This is a measurement of when an amplifier gives 1 dB less in gain compared to an ideal linear amplifier, where a high value is desirable [12]. It is important that the LNA is stable at a large range of temperatures, since it is an essential component.

2.5.2 Mixer & LO

Mixers are used to down-convert the RF or up-convert the IF [12]. They are important components as it is difficult to assess the signal at very high frequencies and it is important to down-convert it. Components are more easily available to study at IF frequencies.

The mixer used in this design is a Sub-Harmonic Mixer (SHM), which is a passive mixer and a sub-harmonically pumped LO. This setup can pump the LO frequency to a different tone. Therefore, it is required to use only half the LO frequency, which makes it easier to design.

2.5.3 IF Amplifier

The IF amplifier used in this system, is an amplifier at 2-20 GHz. It is present to amplify the mixer's output and to improve the strength of the signal that is transferred to the BE.

2.6 Back End Components

How the components work and what purpose they have in the system in the back end is presented here.

2.6.1 Power Splitter

A power splitter is used to split a signal into multiple channels. A resistive divider & Wilkinson power splitter are used in this circuit and below are the reasons and explanation of their working [22].

1. Resistive Divider: A resistive divider is used at the input of the circuit for the first splitting into the window channel and other channels. They operate over a very large frequency band compared to other power splitters and therefore, are the preferred option in spite of their large insertion loss. They are very small in size but their isolation is low [22].
2. Wilkinson Power Splitter: Wilkinson power splitter split an input port into two equal output ports which are equal in phase. They have lesser loss than the resistive dividers but have lower operational bandwidth. However, they provide good isolation between the output channels [22].

2.6.2 Amplifier

An amplifier is a device that magnifies its input signal [23]. Some of the parameters that are important for amplifier selection are listed as follows.

1. Gain or S_{21} : Gain is the difference between the amplitude of the input and output of the amplifier. It's preferred to have a gain/amplification of 15-20 dB, based on the required input and output values of the system.
2. Return Loss or S_{11} : Return loss is preferred to be below -15 dB to attenuate any reflections from the signal, to avoid interference with other components.
3. Current/Voltage: Since this is a low power application, an amplifier with low current and voltage values are preferred to lower the power consumption.

4. Reverse Isolation or S_{12} : Amplifiers are also used for isolation of channels from each other. It is important to have a good isolation value as it prevents any reverse transmission through the amplifier.
5. P1dB: P1dB requirements are set by the customer, and it describes the non linearities in the circuit. It is usually required to back-off by a certain amount of decibels from the P1dB point.

2.6.3 High Pass/Low Pass Filter

High Pass (HP) and Low Pass (LP) filters are included in the system to separate the window channel (WC31) from channel WC32 to WC36. This will also reduce the bandwidth for each component which in turn will decrease the amount of power that is passing through the components.

2.6.4 Attenuator

Attenuators are used to reduce the power of a signal in a system, which is the opposite function of an amplifier [24]. Another implementation that an attenuator can be used for is to improve matching between components. It can reduce improper matching between the output and input of two cascaded components, by having a low Voltage Standing Wave Ratio (VSWR) [24]. By attenuating the signal between two consecutive amplifiers, oscillation can be suppressed as there can be positive feedback at certain frequencies [24]. The oscillation wastes power, heats up the system and can make it unstable [24]. For lower frequencies it is possible to build an attenuator with passive components such as resistors, in a pi or T schematic [24]. This is not possible at higher frequencies due to parasitic inductance and capacitance in the resistors that are used to build the attenuators [24].

2.6.5 Isolator

An isolator is a passive component which is composed of a ferrite and only allows a signal or energy to pass in one direction and attenuates the reflected signal travelling in the opposite direction [25]. The usage of an isolator is to route a signal in a desired direction in a RF circuit [25]. There are two main types of isolators depending on the layout of the circuit which are coaxial based and drop-in [25]. The drop-in isolator is mainly used in designs that use microstrip technology and both the input and output of the isolator is matched to the PCB that is used [25]. The coaxial based isolator is used in test equipment due to the ease of connecting it with a cable [25].

2.6.6 Equalizers

One common problem with RF circuits is that the components could have a gain slope, where the gain is either decreasing or increasing with frequency [26]. The principle is the same for passive components where the insertion loss of the component causes a gain slope instead [26]. The main cause of this problem is the gain slope in RF amplifiers, which is decreasing with frequency, as depicted in figure 2.9 [26].

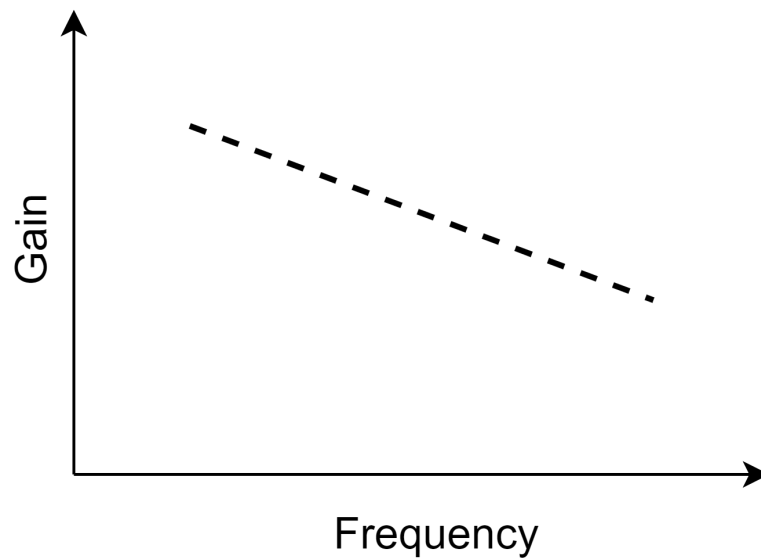


Figure 2.9: Gain slope of a system.

This can be a problem in a communication system as this would amplify different frequencies unevenly, which in turn would mean that the effective centre frequency of a filter for a channel is moved [26]. In order to solve this problem a component called gain equalizer is used, which attenuates the signal differently for different frequencies to counter this problem [26]. Equalizers can be divided into different categories, which are mainly positive slope and negative slope equalizers [26]. For the positive slope equalizer, the insertion loss increases with frequency, and the opposite is true for negative slope equalizers [26].

2.6.7 Diode Detectors

The Diode Detectors (DDs) are placed after the BPF. They convert the RF power to voltage, so that the signal can be measured by the ADC [27]. A zero bias Schottky diode has been used for this application [27]. This component has not been optimized in this design but is explained briefly for understanding [27].

The zero bias Schottky diode detector is used for RF applications where there is no standby DC power available [27]. It is operated in the square law region, as that is ideal for the radiometer [27]. The square law region is where the output voltage proportional to the square of input power [27]. The circuit of the diode detector is shown in figure 2.10.

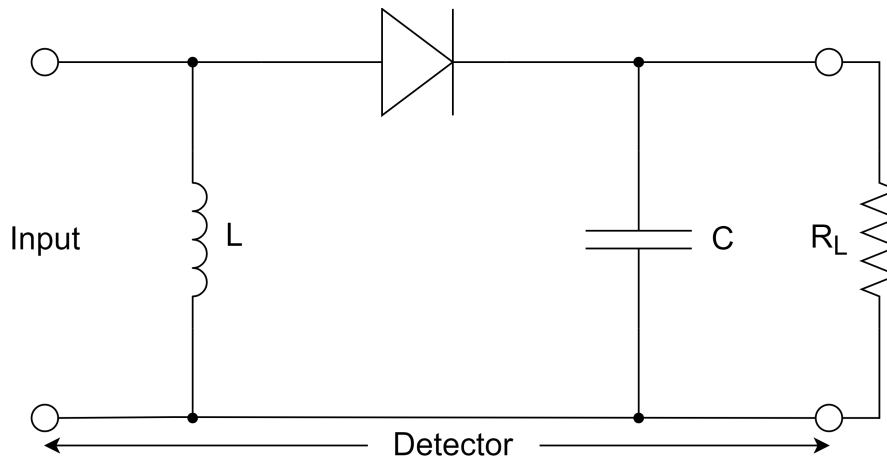


Figure 2.10: Circuit of diode detector [27].

R_L is the video load resistance. L , the shunt inductance is a current return path for the diode. The bypass capacitance, C must be large enough to have appropriate isolation between the RF and DC circuit [27].

The advantage of these detector diodes, is that a very wide range of power that can be detected, but the detector diodes have a minimum input power that they can detect. The detector diodes can operate well in the square law region at a minimum input power of -55 dBm and a maximum of -15 dBm [28].

2.7 Filter Technologies

Filters are very important components in high frequency systems. They are used to pass only the required data signal and reject the unwanted signals. Therefore, it is very important to use filters with high rejection. Cross coupled structures where there is cross coupling between the nonadjacent resonators improves the amplitude roll-off of the filter [29].

Filters come in different packages to meet different requirements such as integrability, size and cost. The main distinction is whether the package of the component can be integrated on a PCB or not. In that case, a die or a Surface-Mount Technology (SMT) is used, which provides a smaller and simpler package, which in turn will reduce the price compared to other technologies. If robustness and ease of connectivity is a priority, a component with coaxial connections can be preferable since they are usually shielded in a robust metal case with the drawback of size and weight compared to the die and SMT solutions [29]. Important parameters for filters are listed as follows.

- **Size**

Sending a satellite or any component into space is very expensive and is usually measured as a cost per weight. A larger filter would require a larger PCB and shielding box, which in turn entails that a larger filter would increase the total price of sending the system into orbit.

- **Cost**

As with most components, the cost of the filters has to be taken into consideration. Depending on if the filters are commercialized or customized, the cost will vary greatly, as with the customized filters, they have to be specifically designed and will then most likely introduce a Non Recurring Engineering (NRE) cost.

- **Types and Frequency Bands**

There are four main types of filters that describe the basic principles of a filter, which are shown in figure 2.11. Figure (a) is a LP filter, where its function is to attenuate or filter out the higher frequencies, this part is called the stop band, a frequency band where the signal is stopped from propagating through the filter. The part where the frequencies are able to pass through the filter is called the pass band, also shown in figure (a). The part, in between the pass band and the stop band, is called the transition band and is shown in figure (a). Another type of filter is the HP filter, which attenuates signals of low frequencies and passes through high frequency signals and is shown in figure 2.11 (b). In figure 2.11 (c), a BP filter is depicted which only let through a signal for a specific range frequency in a band. The opposite of the BP filter is the Band Stop (BS) filter, which will attenuate the signal for a specific band of frequencies, shown in figure 2.11 (d).

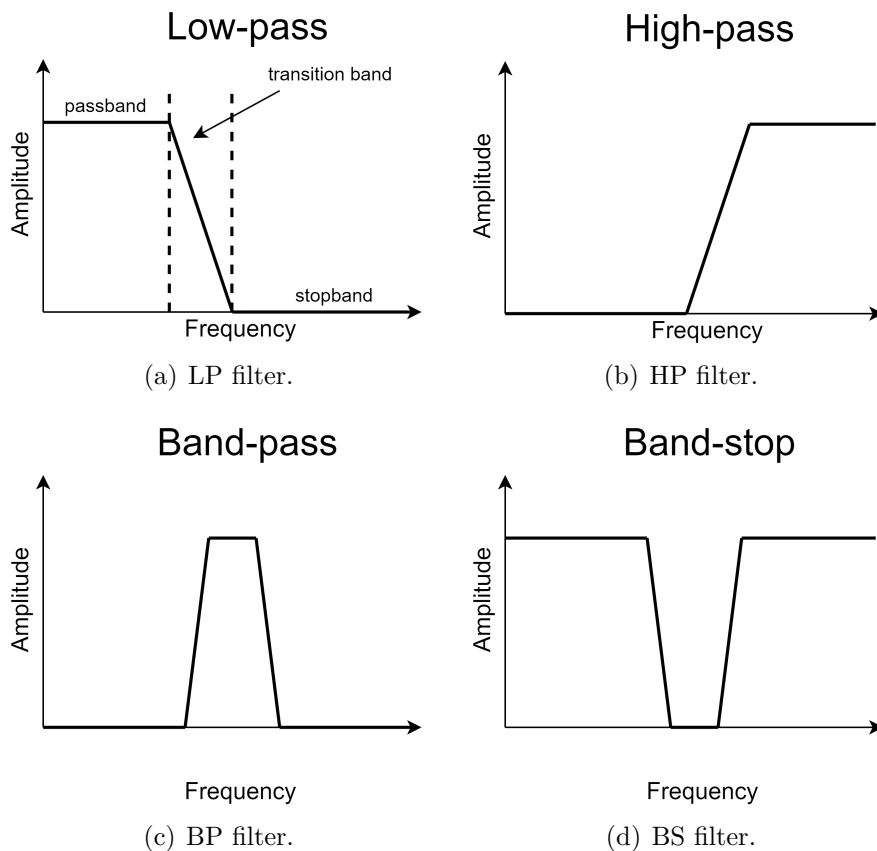


Figure 2.11: The most common filter types.

- **Insertion Loss**

The insertion loss of the filters will impact the gain budget of the system in the way that a higher insertion loss requires a higher gain out of the amplifiers in the system.

- **Bandwidth**

The bandwidth of a filter is the span of frequencies for the pass band shown in figure 2.11 (a). With a filterbank system such as AWS, it is important to not have any overlap between the channels as this would cause the measurements to be ambiguous. This can be minimized by having the correct bandwidth for the filters. A common measurement is the 3 dB bandwidth. This is determined to be the bandwidth when the signal has been attenuated to have half its power, i.e 3 dB compared to the maximum power of the pass band. Another common bandwidth is the 40 dB bandwidth, which represents the rejection points of the filter.

- **Sharpness of the Filter Response**

Ideally, a filter would have no transition band where the step between the pass band and the stop band is a discrete step. However, for a real filter the transition band is not a discrete step and looks like what is shown in figure 2.11 (a). With a sharper or higher slope of the transition band, the bandwidth ambiguity is decreasing. The steepness of the transition band is called roll-off and depends on the number of poles in the system. Poles are roots in the denominator of the transfer function of the filter. A filter with more poles will have a higher roll-off factor [30], [31].

Filter specifications may also include a Shape Factor (SF) requirement, which describes how fast signals roll-off during transition. The SF represents the ratio between the cutoff/ripple frequency and where the filter achieves a desired attenuation level.

- **Ripple**

An ideal filter would have a flat pass band but in reality, a filter will exhibit a characteristic called ripple. This means that the levels of the pass band are not constant and will vary for different frequencies. Ripple can be defined in different ways depending on the information the end user needs from the simulations or measurements of the filter. But, the general idea is that ripple is a measurement of the variation of the pass band level.

- **Shape of the Filter Response**

The shape of the filter response is of utmost importance for the design of the filter bank. When taking the previous points into consideration a shape for how the response of the filter should look like can be constructed, called a filter mask which is shown in figure 2.1.

Some common filter technologies are listed as follows, for an overall understanding about the various filters.

2.7.1 Surface Acoustic Wave Filter

The operational principles of a Surface Acoustic Wave (SAW) filter is that it converts electrical energy into acoustic or mechanical energy on a piezoelectric material [32]. The transducer at the input generates an acoustic wave from the electrical signal, that is incident at the input, then propagates, and is received at the output [33]. The wave is generated equally in both directions so that only half of the power will reach the output, which is called a bidirectional transversal filter [33]. With the input and output transducer together the total insertion loss is 6 dB [33]. SAW filters are used for frequencies up to 3 GHz where the selectivity of the filter declines after 1.5 GHz [33].

2.7.2 Lumped Element Filter

With lumped elements, there are two main categories of capacitors and inductors, which are SMT parts and thin-film lumped elements [34]. The SMTs are most suitable for PCB design while the thin-films are used for Microwave Integrated Circuits (MICs) and Monolithic Microwave Integrated Circuits (MMIC) [34]. SMT capacitors are used up to the Ku band which ranges from 12 to 18 GHz, while the inductors have resonance below 10 GHz [34].

For frequencies up to 100 GHz, thin-film capacitors can be used in MMICs, while the inductors are limited to the Ku band [34]. When the frequency is increased, lumped elements become less and less ideal until a certain point where lumped elements can't be used at all to build a filter [34]. This is due to the parasitic elements that are introduced at higher frequencies including resonances of inductors and capacitors and additional resistive losses [34]. If a filter is designed for higher frequencies, these parasitic elements need to be included in the simulations [34].

2.7.3 Cavity Filter

A cavity filter is a RF filter that works by using resonances, like a cavity resonator [35]. The practical way that a cavity filter works is that it has a screw that is used to fine tune the resonant frequency inside the resonator [35]. The resonator is a metallic construction which is a waveguide where the ends of the resonator is short circuited [35]. The resonator resonates with a higher amplitude at the resonance frequency [35]. The cavity works as a band pass filter at specific frequencies and passes the signals at and around the resonance frequency, while attenuating other frequencies [35]. The frequencies at which the resonator exhibits the resonant frequency is dependent on the physical size of the resonator, dielectric constant ϵ_r , magnetic permeability μ_r and the number of the modes as well as the material of the resonator [35]. The resonator screw is used to change the physical length of the inner part of the resonator as well as changing the capacitance to the ground, which in turn will change the resonant frequency [35].

2.7.4 Thin Film Filter

Thin film technology is made by a microstrip line, which is a conducting strip with thickness t and width W_0 [36]. This strip is placed on top of a dielectric substrate, that has a relative dielectric constant ϵ_r , with a thickness of h and which has a bottom ground plane [36]. The transmission lines are described by two parameters which are the characteristic impedance Z_c and the effective dielectric constant ϵ_{re} [36].

The structure of a thin film filter is inhomogeneous since the dielectric surrounding the conductor is inhomogeneous and the microstrip extends into two medias, the air above and the dielectric below [36]. Due to this, the microstrip does not support a Transverse Electromagnetic (TEM) wave [36]. Since the microstrip is in two mediums, the longitudinal components can be neglected as they are much smaller than the transverse components [36]. If the dielectric substrate under the strip is removed and filled with air, the dielectric that is surrounding the transmission line would be homogeneous, which entails that a true TEM mode can propagate on the line [36].

Filters can be created as traces on PCB materials, stubs, coupled line elements etc. The drawback is that they become big or impossible to manufacture if the filter requirements are too strict. The advantage of thin film is that ϵ_{re} is much higher, more consistent and controlled. The photolithic processes are very accurate, so the traces can be narrow and/or close together. The higher the value of ϵ_{re} , the smaller the traces.

The band pass filters used in this system are custom designed, and are mostly thin film or cavity based. The main focus was to reduce the size and maintain the filter mask shape.

3

Circuit Design

The following section lists the requirements that form the basis for designing the circuit.

3.1 Design Requirements

1. Filter frequency and bandwidth specifications are mentioned in tables 2.1 and 2.2 in Section 2.2. The frequencies are as per the filter mask presented in figure 2.1 [9].
2. The current power consumption in the RF section of the BE is around 2.38 W and must be halved [9].
3. Cross-talk between channels must be around -40 dB to prevent the signal from interfering with signals in other channels. Therefore, sufficient isolation must be achieved between the channels, particularly between neighbouring channels in the 54 and 183 design.
4. The design must be compact and bulky components can be eliminated.
5. Temperature compensation is important for some components, so that the device is unaffected by large temperature changes.
6. Establish margin in the dynamic range of power by adding contingencies, temperature drifts, affects due to ageing etc.
7. Maintain an input power around -30 dBm to be in a good operating range of the detector diode.

In the introduction, a short summary of the goals of the circuit design based on the current design was presented. This section will further explain how those goals were formulated and expand on the previous and proposed designs. The designs, at 183 GHz and 54 GHz, are presented in the upcoming sections.

3.2 183 GHz

The signals at 183 GHz are used for water vapour profiling. Below mentioned are the designs for the FE and BE at 183 GHz.

3.2.1 Front End Design for 183 GHz.

Figure 3.1 presents the FE of the 183 GHz circuit.

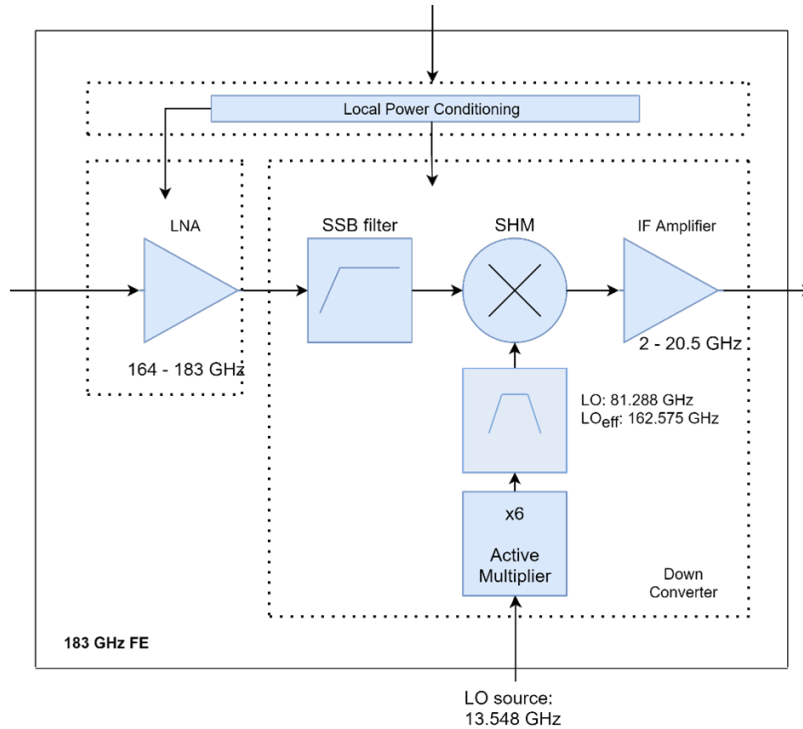


Figure 3.1: 183 GHz FE design [37].

A horn antenna captures the signals and transfers it to the LNA [37]. The LNA is followed by the down converter unit [37]. The down converter consists of the Schottky sub-harmonic mixer, IF amplifier, matching network, LO multiplier, LO waveguide BP filter and an RF waveguide filter for Single Side Band (SSB) filter [37]. A short description of the FE components is presented below.

1. **LNA:** The LNA is the first component of the FE, and its performance is critical. It is placed in the beginning so as to dominate the noise figure of the entire circuit. The current of the LNA is maintained constant by the local power conditioning circuit, so that the system is stable and can handle temperature changes [37].
2. **SSB Filter:** The SSB filter is used to select only the upper side band signals in the slope of the water vapour line [37]. The signals below 165 GHz are removed.

3. **SHM & LO Circuit:** The received signal is between 165.5-183 GHz, which is too high for any useful data analysis. Therefore, the signal is down converted by a SHM and LO Source as depicted in figure 3.1.

The LO Source inputs a frequency of 13.548 GHz, which is multiplied by an active multiplier six times. The filter present in the LO circuit filters out the unwanted harmonics from the multiplier [37]. Therefore, the LO frequency is 13.54×6 , that is 81.288 GHz, which is converted by the SHM into a different frequency tone. This leads to an effective LO frequency of 162.575 GHz [37]. Thus, the RF frequencies are down converted to IF frequencies of 2-20 GHz.

4. **IF Amplifier:** The IF amplifier is present in the circuit to increase the gain of the signal to control the power entering the BE [37]. There is a matching circuit between the IF amplifier and the mixer. This amplifier also provides the required isolation between the mixer and the BE [37].

3.2.2 Previous Design for Back End of 183 GHz

Figure 3.2 represents the previous BE design of 183 GHz channels [9]. There are 6 channels for the 183 GHz design (WC31-36) [9]. Channel WC31 functions as the window channel, which sets the starting point of the output curve of the water vapour line. The design consists of one power Input/Output (IO), filterbank and an external diplexer [9]. The diplexer is used to isolate the water vapour channel WC31 to the other water vapour channels WC32 to WC36 [9]. The window channel frequencies are 2-4 GHz and the other channels are 12-20 GHz [9].

1. **Diplexer:** The diplexer is the ZDSS-7G10G-1 from Mini-Circuits. It separates the window channel from the other water vapour channels. The advantage of the diplexer is that it has very low insertion loss and good isolation [9].
2. **Amplifier:** The first amplifier, HMC7950LS6 in the circuit is used for providing gain and also for isolation and is connected to the power splitters in the circuit. It is temperature compensated [9]. HMC7950LS6 was selected as it has a very flat gain response of around 15 dB and good return loss which is below -15 dB. The amplifier's gain can be controlled by varying the gate voltage (V_{gg2}), which makes it a good amplifier choice. There are 7 amplifiers in the system to provide sufficient isolation for each channel to avoid cross-talk and for gain control in each channel. The window channel uses an amplifier called SBB3089-Z, which can be temperature controlled as well [9].
3. **Power Splitter:** The power splitter used is PD-0530SMG, a Wilkinson power splitter, which has around 25 dB isolation. The power splitter is used to split the channels [9].
4. **Attenuators:** 3 dB attenuators are used in the system to lower the power, so as to not damage the components. They are also used to improve the matching in the circuit.

3. Circuit Design

5. **Equalizers:** They are used to flatten the negative gain slopes due to the amplifiers in the circuit. The equalizer used is EQ-10-24+ from Mini-Circuits.

6. **Filters:** The bandpass filters are custom designs by Knowles Capacitors and are designed based on the frequency specifications of each channel and the filter shape. The initial design included filters by K&L which were resonant cavity filters. They generally have good performance and provide high rejection, but these filters used produced large standing waves when they were tested in the circuit. They were also bulky and that affected the compactness of the design [9].

 These were then replaced by cavity and planar filters from Knowles. Planar filters are smaller but they have higher insertion loss, which is the trade off with compactness.

7. **Detector Diodes:** The detector diodes are used to convert the RF power to voltage [9].

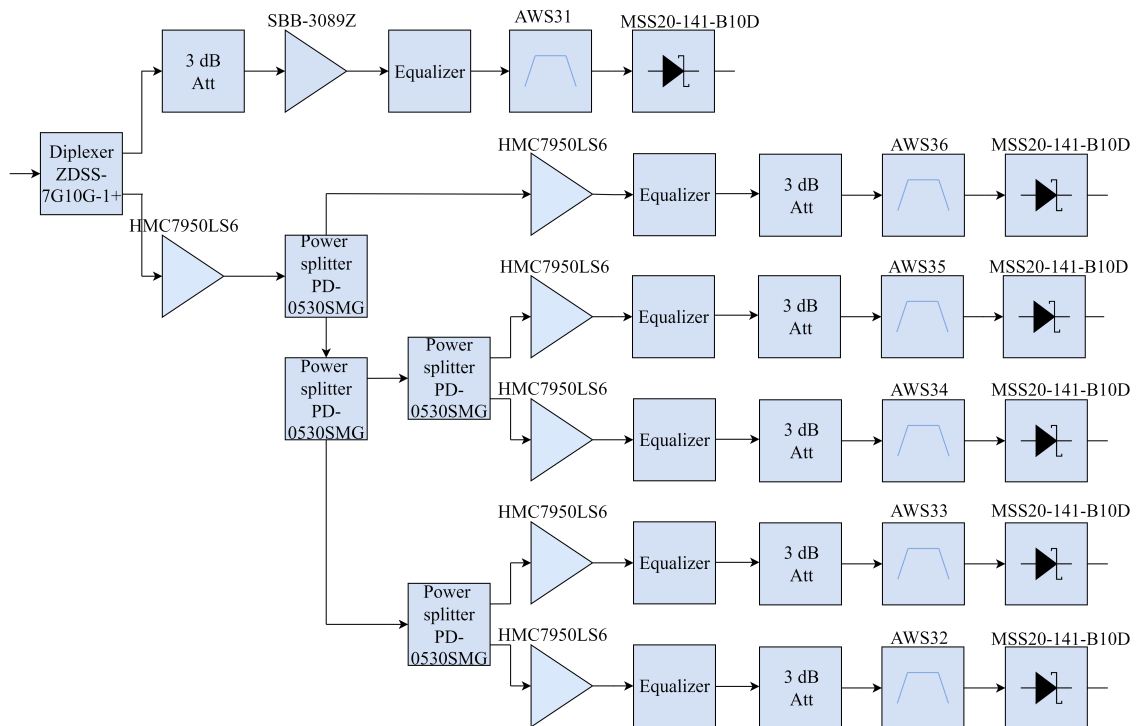


Figure 3.2: Previous design for 183 GHz Filter Bank [9].

3.2.3 Proposed Design for Back End of 183 GHz

The below subsections describe the key changes identified and suggested solutions for the changes.

3.2.3.1 Key Changes

Some of the problems that were identified with the previous design are listed below.

1. The diplexer isolates the window channel and the other channels very well and has a low insertion loss, but it is a bulky component and affects the compactness of the design. It is also coaxial and external to the circuit, which can be modified to a surface mounted configuration.
2. There are many amplifiers in the system which increase the overall power consumption on the IF side. These amplifiers are present to isolate the channels from each other. So, it is necessary to find other methods of isolation, while maintaining the gain in every channel.
3. Since the gain per channel needs to be levelled, attenuators with different values could be introduced in the system, while having a different solution for isolation.
4. Amplifiers with higher gain and lower values of voltage and current can be used instead of HMC7950LS6.

3.2.3.2 Solutions

Different configurations were tested to check for optimum performance and the following solutions were formulated. Figure 3.3 displays the suggested prototype layout for 183 GHz.

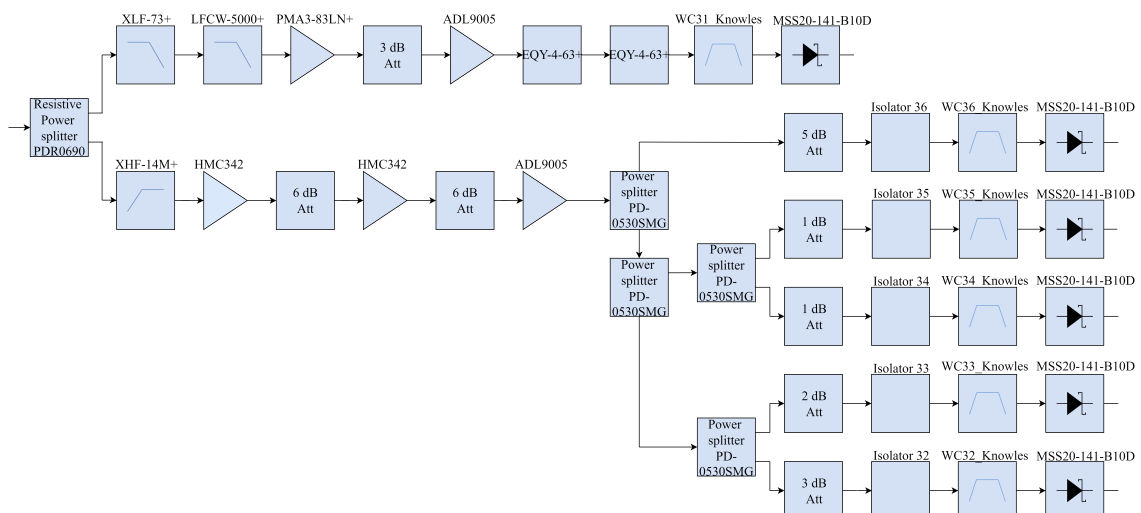


Figure 3.3: Prototype design for 183 GHz filter bank.

The suggested circuit improvements are listed below.

1. The diplexer is replaced with a simple configuration of a resistive divider with a LP and HP filter, to isolate the window channel (2-4 GHz) from the other channels (12-20 GHz). The resistive divider is picked, in spite of its high insertion loss as it has a large operational bandwidth. The length of transmission lines between the resistive divider and LP/HP filter are also optimized, so as to avoid reflections. It was observed that the length of these transmission lines are quite sensitive.
2. For the window channel, two LP filters are used after the resistive divider. The first filter (XLF-73+) is a reflection-less filter, to optimize for reflections. The second ceramic filter (LFCW-5000+) is used to limit the bandwidth of XLF-73+ and increase the attenuation at higher frequencies, due to higher order harmonics at 12 GHz. LFCW-5000+ can not be used on it's own as it is not reflection-less.
3. The amplifiers are placed after the HP filter, instead of in the channels. They are cascaded with attenuators in between, so as to reduce oscillations due to improper matching. Five amplifiers are used instead of seven to lower power consumption. We lose the isolation and gain levelling in the channels due to this, but this is compensated for using isolators and attenuators for the two problems, respectively.
4. Most amplifiers used can be operated at 3 V instead of 5 V, to lower the power.
5. The amplifiers in each channel are replaced with isolators, to provide sufficient isolation between the channels. The isolators used are from Kete-Microwave and provide an isolation of around 20 dB. They also have a very low insertion loss. The only drawback is that they are a bit expensive but the cost can be decreased when ordered in bulk.
6. The solutions were decided on while aiming for an input of around -30 dBm into the detector diodes, which are the components present after the filter. These values are in a good operating range of the detector diodes.

3.3 54 GHz

The signals at 54 GHz are used for humidity profiling. Below mentioned are the designs for the FE, BE of 54 GHz, problems identified and solutions to the problems of the design.

3.3.1 Front End for 54 GHz

Figure 3.4 presents the FE of the 54 GHz circuit. The FE of the 54 GHz is quite similar to the circuit design at 183 GHz. The difference being the LO circuit, which consists of attenuators for power correction, since the power measurement seems very high and a LP filter to remove high order harmonics.

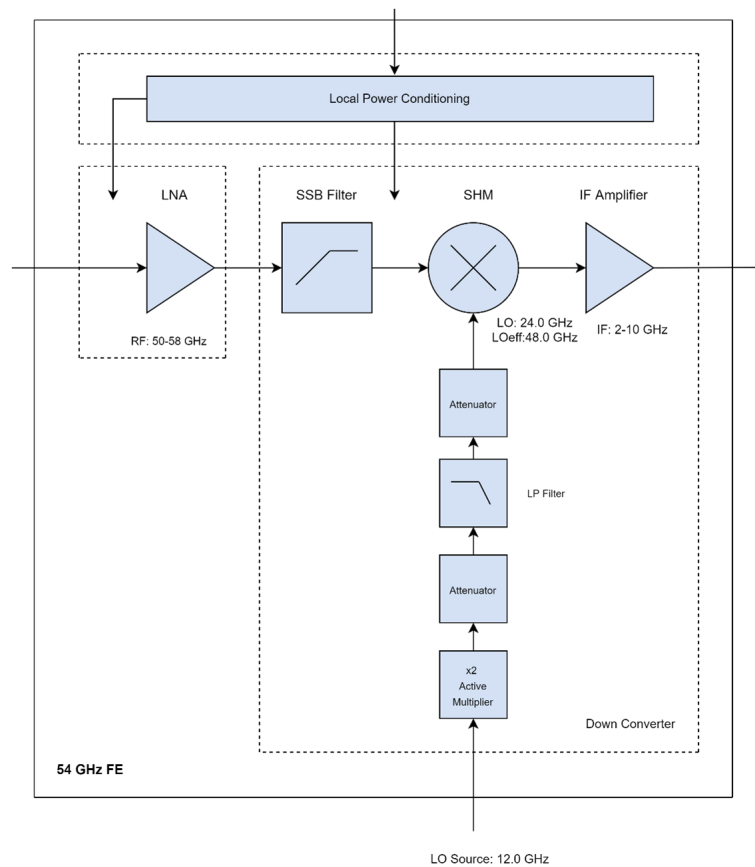


Figure 3.4: 54 GHz FE design [38].

RF frequencies are between 50.3-57.29 GHz and a SHM is used similar to 183 GHz case. LO source gives out a frequency of 12 GHz, which is multiplied by an active multiplier to $12 \times 2 = 24$ GHz, and the effective LO frequency is $24 \times 2 = 48$ GHz [38]. This results in IF frequencies at 2-10 GHz. The IF amplifier provides gain sufficient to control the power into the BE. The FE inputs power over a dynamic range of -33 to -29 dBm over a noise bandwidth of 8 GHz to the BE [38].

3.3.2 Previous Design for Back End of 54 GHz

There are eight channels for the 54 GHz design (WC11-18). The previous design uses eight amplifiers and consumes a lot of power. The design is quite symmetrical and the channels are identical. The working is similar to the design at 183 GHz. The layout of the previous design is shown in figure 3.5.

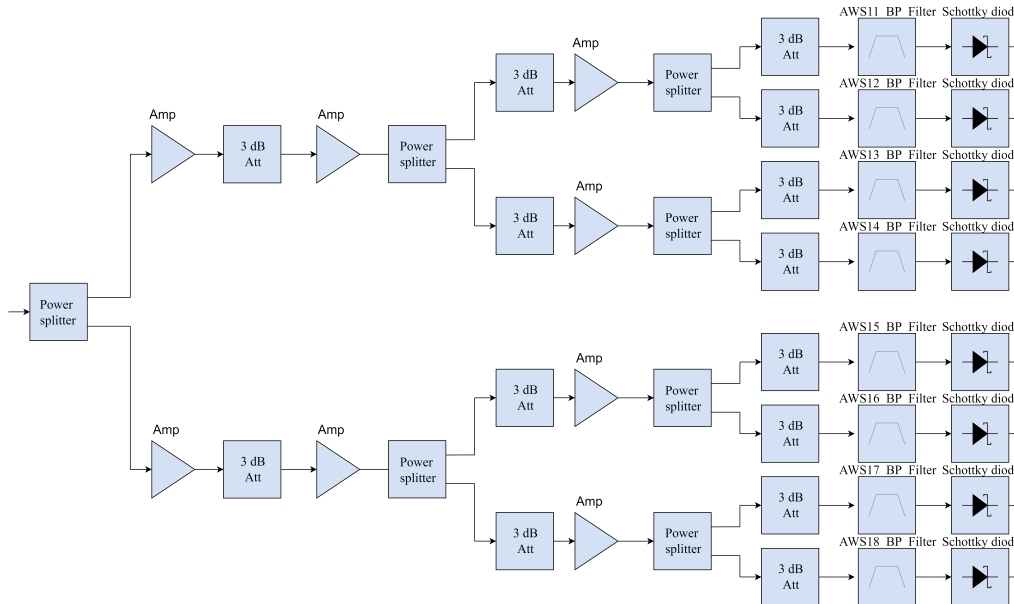


Figure 3.5: Previous design for 54 GHz BE.

3.3.3 Proposed Design for Back End of 54 GHz

Figure 3.6 presents the suggested prototype layout for the 54 GHz BE.

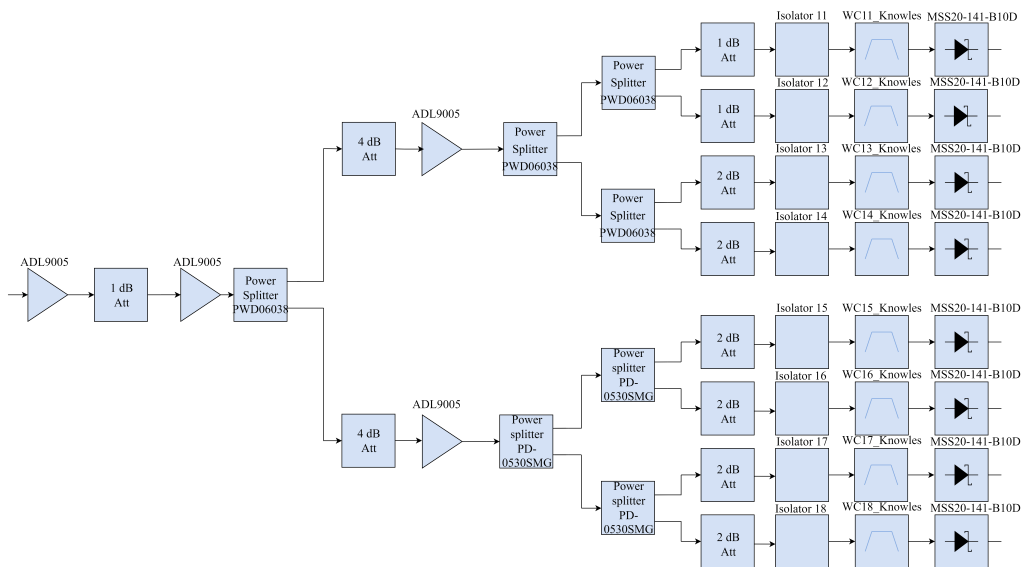


Figure 3.6: Proposed design for 54 GHz Filter Bank.

3.3.3.1 Key Changes & Solutions

Some of the problems that were identified and solutions with the previous design are listed below.

1. The 54 GHz BE design consists of eight amplifiers which are used for isolation but this increases the power consumption in the whole circuit. This could be solved by placing amplifiers in the start of the chain, so that equal gain is supplied to the channels, while reducing the power consumption.
2. There is more chance for inter channel cross-talk in the 54 GHz channels, as the RF frequencies are very close to each other. This is solved using the isolators in all the channels.
3. The 54 GHz works solely on 3 V now, as the amplifiers are operated at 3 V.
4. The amplifier used for 54 GHz channel is ADL9005. The current that the amplifier operates in can be controlled by changing the bias resistor. It's also possible to temperature compensate this amplifier using Negative Temperature Coefficient (NTC) resistors in parallel with the bias resistor. The return loss is also an acceptable value when the current is changed.
5. Some of the power splitters (PDW06038) are replaced with PD-0530SMG to reduce the size of the design as PDW06038 is bigger than PD-0530SMG.

3.4 Component List

Table 3.1 contains the final list of components that are used for 183 and 54 GHz designs. These components have been finalized based on the requirements and after testing them in simulation tools such as Microwave Office (MWO).

Table 3.1: Components in the circuit design.

Component	183 GHz	54 GHz
Amplifier	PMA3-83LN+ ADL9005 HMC342	ADL9005
Power splitter	PDR06390 PD-0530SMG	PD-0530SMG PDW06038
Low Pass filter	XLF-73+ LFCW-5000+	
High Pass Filter	XHF-14M+	
Attenuator	KAT-3+	KAT-3+
Equalizer	EQY-4-63+	
Isolators	KTMI-1502A16 KTMI-2002A	KTMI-702A5 KTMI-702A7 KTMI-502A11 KTSI-202S05 KTMI-902A
Band Pass Filters	Custom Knowles	Custom Knowles

4

Results & Discussions

The results of the studies and measurements have been presented below. Circuit simulations along with RF power budget and important circuit parameters are mentioned. Simulations of selected components are listed in the Appendix. The simulations are performed in Microwave Office (MWO) and the graphs have been plotted in Matlab. The measurements of the components were obtained by using a Vector Network Analyzer (VNA), power supplies and multimeters, which are shown in table 4.1.

Table 4.1: Instruments used to obtain the measurements in the report.

Model number	Instrument type
Wiltron 37269B	VNA
Anritsu MS4647A	VNA
Fluke 179	Multimeter
Agilent E3631A	Power supply

The RF power budget for some channels are presented below.

4.1 RF Power Budget

The RF power budget has been calculated with a value of estimated power from the FE, while observing a cold load at 3 K (minimum temperature) and observed temperature (max temperature) at 300 K, to obtain the possible range of values [9]. Table 4.2 represents the values of the estimated FE Power along with the Noise Bandwidth (NBW).

Table 4.2: Estimated FE power while observing cold load and observed temperature.

Frequency [GHz]	Load	FE NBW [GHz]	P_{in} [dBm/FE NBW]
183	Cold	20	-36.54
183	Observed Temp.	20	-35.12
54	Cold	8	-33
54	Observed Temp	8	-29

Initial dynamic range between the observed temperatures is also estimated from the RF power budget and margins are added for temperature drift, ageing, contingencies and temperature drifts in the FE to calculate the final dynamic range. These are estimates based on the current design [9].

The RF power budget provides the power level into and out of each component, while taking into account the NBW at every step. Min/Max bandwidth of the filters are used for calculations, which simply represent the bandwidth allowances for each channel i.e. the maximum and minimum bandwidth allowed.

The power is maintained so that the input to the detector diode is around -30 dBm, due to the sensitivity of the detector diode and for the values to lie in a good operating range of the detector diode.

4.1.1 183 GHz RF Power Budget

The 183 GHz RF power budget is shown for channel WC32 and WC31 in table 4.4 and 4.6. The RF power budget for the other channels will be displayed in the appendix, as they are calculated in a similar way. The filters values are based on simulated parameters and haven't been measured, as they haven't arrived yet.

In 4.4 and 4.6, P_{in} refers to the power over the bandwidth and P_{out} is calculated by dividing the power in the channel by the bandwidth of the channel. Gain refers to the amplification of the component. Amplifiers have a positive gain and all the other components have a negative gain. The components in the table have been listed as abbreviations i.e. Amp (Amplifier), Att (Attenuator) and P.S. (Power splitter).

The input power to the detector diode for all the channels, based on the RF power budget calculations in table 4.4 and 4.6 in this section and table A.1, A.2, A.3 and A.4 in the appendix, is listed in table 4.3.

Table 4.3: Input power due to cold load and observed temperature, to detector diode for all the channels.

Channel	P_{in} [dBm/FE NBW] Obs. Temp	P_{in} [dBm/FE NBW] Cold Load
WC31	-28.96	-30.38
WC32	-29.56	-30.38
WC33	-30.36	-30.98
WC34	-30.01	-31.43
WC35	-29.36	-30.78
WC36	-28.21	-29.63

This is a brief summary of the RF Power Budget calculations. The input power from the FE was received as a value and the power budget is calculated component wise by including the bandwidth and gain/loss of the component. Pout is calculated by adding gain of the component with the P1dB value, if it exists (for example: an amplifier) and adding the logarithmic value, with a base of ten of the NBW divided by the NBW of the previous component. It starts with the FE NBW as 20 GHz, for the 183 GHz BE. P1dB back-off for an amplifier is calculated by subtracting P1dB with Pout. The Pout of this component becomes the Pin of the next component and the process continues. All RF Power Budgets are calculated in this manner.

Table 4.4: RF power budget for WC32.

Component	Type	P_{in} [dBm] [FE NBW]	Gain [dB]	P1dB _{Out} [dBm]	Noise BW [GHz]	P_{out} [dBm] [BW]	P1dB back-off [dB]
PDR06390	P.S.	-35.12	-6.30	-	20	-41.42	-
XHF14M+	HPF	-41.42	-0.92	-	10	-45.35	-
HMC342	Amp	-45.35	21	7	10	-24.35	31.35
6 dB	Att	-24.35	-6	-	10	-30.35	-
HMC342	Amp	-30.35	21	7	10	-9.35	16.35
6 dB	Att	-9.35	-6	-	10	-15.35	-
ADL9005	Amp	-15.35	12	13.50	10	-3.35	16.85
PD-0530SMG	P.S.	-3.35	-4.30	-	10	-7.65	-
2 PD-0530SMG	P.S.	-7.65	-8.60	-	10	-16.25	-
3 dB	Att	-16.25	-3	-	10	-19.25	-
KTMI-1502A16	Isolator	-19.25	-0.8	-	10	-20.05	-
Filter Min	BPF	-20.05	-2.40	-	1.8580	-29.76	-
Filter Max	BPF	-20.05	-2.40	-	1.945	-29.56	-
MSS20-141-B10D	DD	-29.56	-	-15	-	-	-14.56
PDR06390	P.S.	-36.54	-6.30	-	20	-42.84	-
XHF14M+	HPF	-42.84	-0.92	-	10	-46.77	-
HMC342	Amp	-46.77	21	7	10	-25.77	32.77
6 dB	Att	-25.77	-6	-	10	-31.77	-
HMC342	Amp	-31.77	21	7	10	-10.77	17.77
6 dB	Att	-10.77	-6	-	10	-16.77	-
ADL9005	Amp	-16.77	12	13.50	10	-4.77	18.27
PD-0530SMG	P.S.	-4.77	-4.30	-	10	-9.07	-
2 PD-0530SMG	P.S.	-9.07	-8.60	-	10	-17.67	-
3 dB	Att	-17.67	-3	-	10	-20.67	-
KTMI-1502A16	Isolator	-20.67	-0.8	-	10	-21.47	-
Filter Min	BPF	-21.47	-2.40	-	1.8580	-31.18	-
Filter Max	BPF	-21.47	-2.40	-	1.945	-30.98	-
MSS20-141-B10D	DD	-30.98	-	-15	-	-	-15.98

The dynamic range for WC32, displayed in table 4.5, is calculated based on table 4.4 by adding contingencies and other factors, obtained from [9]. Dynamic range at observed temperatures is calculated by subtracting the maximum value at the output of the filters and the minimum value at the output of the filters. The contingency factors are then added to this value.

Table 4.5: Dynamic range calculations for WC32.

	Power [dB]
Dynamic range, observed temperatures	1.02
Temp. drift BE	1
Contingency BE+FE	1
Ageing	0.2
FE temp	0.2
Dynamic range inc ageing, temp, cont	3.42

Table 4.6: RF power budget for WC31.

Component	Type	P_{in} [dBm] [FENBW]	Gain [dB]	P1dB _{Out} [dBm]	Noise BW [GHz]	P_{out} [dBm] [BW]	P1dB back-off [dB]
PDR06390	P.S.	-35.12	-6.30	-	20	-41.42	-
XLF73+	LPF	-41.42	-0.54	-	7	-46.52	-
LFCW-5000+	LPF	-46.52	-1.6	-	5	-49.58	-
PMA3-83LN+	Amp	-49.58	21.5	15	5	-28.08	43.08
3 dB	Att	-28.08	-3	-	5	-31.08	-
ADL9005	Amp	-31.08	12	13.50	5	-19.08	32.58
EQY-4-63	Equalizer	-19.08	-5.5	-	5	-24.58	-
Filter Min	BPF	-24.58	-1.85	-	2.725	-29.07	-
Filter Max	BPF	-24.58	-1.85	-	2.79	-28.96	-
MSS20-141-B10D	DD	-28.96	-	-15	-	-	-13.96
PDR06390	P.S.	-36.54	-6.30	-	20	-42.84	-
XLF73+	LPF	-42.84	-0.54	-	7	-47.94	-
LFCW-5000+	LPF	-47.94	-1.6	-	5	-51	-
PMA3-83LN+	Amp	-51	21.5	15	5	-29.5	44.50
3 dB	Att	-29.50	-3	-	5	-32.50	-
ADL9005	Amp	-32.50	12	13.50	5	-20.50	34
EQY-4-63	Equalizer	-20.50	-5.5	-	5	-26	-
Filter Min	BPF	-26	-1.85	-	2.725	-30.49	-
Filter Max	BPF	-26	-1.85	-	2.79	-30.38	-
MSS20-141-B10D	DD	-30.38	-	-15	-	-	-15.38

Similarly the dynamic range for WC31 is calculated in table 4.7, based on values from [9] and table 4.6.

Table 4.7: Dynamic range calculations for WC31.

	Power [dB]
Dynamic range, observed temperatures	1.42
Temp. drift BE	1
Contingency BE+FE	1
Ageing	0.2
FE temp	0.2
Dynamic range inc ageing, temp, cont	3.82

4.1.2 54 GHz RF Power Budget

The 54 GHz RF power budget is complete for channel WC11 & WC12, as filter characteristics were received for these channels. But the other channels have been designed based on some assumptions for the filters, as some of the components were unable to be procured.

The designs will be tested later based on the suggested circuit prototype. The RF power budgets for channel 11 and 12 are listed below in table 4.8 and 4.10.

Table 4.8: RF power budget for WC11.

Component	Type	P_{in} [dBm] [FENBW]	Gain [dB]	P1dB _{Out} [dBm]	Noise BW [GHz]	P_{out} [dBm] [BW]	P1dB back-off [dB]
ADL9005	Amp	-29	12	13.50	8	-17	30.50
1 dB	Att	-17	-1	-	8	-18	-
ADL9005	Amp	-18	12	13.50	8	-6	19.50
PDW06038	P.S.	-6	-3.3	-	8	-9.30	
4 dB	Att	-9.30	-4	-	8	-13.30	-
ADL9005	Amp	-13.30	12	13.50	8	-1.30	14.80
PDW06038	P.S.	-1.30	-3.30	-	8	-4.60	-
PDW06038	P.S.	-4.60	-3.30	-	8	-7.90	-
1 dB	Att	-7.90	-1	-	8	-8.90	-
DPVMI18A	Isolator	-8.90	-0.80	-	8	-9.70	-
Filter Min	BPF	-9.70	-4	-	0.15	-30.97	-
Filter Max	BPF	-9.70	-4	-	0.18	-30.18	-
Diode Detector	Detector	-30.18	-	-15	-	-	-15.18
ADL9005	Amp	-33	12	13.50	8	-21	34.50
1 dB	Att	-21	-1	-	8	-22	-
ADL9005	Amp	-22	12	13.50	8	-10	23.50
PDW06038	P.S.	-10	-3.30	-	8	-13.30	
4 dB	Att	-13.30	-4	-	8	-17.30	
ADL9005	Amp	-17.30	12	13.50	8	-5.30	18.80
PDW06038	P.S.	-5.30	-3.30	-	8	-8.60	-
PDW06038	P.S.	-8.60	-3.30	-	8	-11.90	-
1 dB	Att	-11.90	-1	-	8	-12.90	-
DPVMI18A	Isolator	-12.90	-0.80	-	8	-13.70	-
Filter Min	BPF	-13.70	-4	-	0.15	-34.97	-
Filter Max	BPF	-13.70	-4	-	0.18	-34.18	-
DD	DD	-34.18	-	-15	-	-	-19.18

Dynamic range calculations for table 4.8 are presented in table 4.9.

Table 4.9: Dynamic range calculations for WC11.

	Power [dB]
Dynamic range, observed temperatures	4.79
Temp. drift BE	1
Contingency BE+FE	1
Ageing	0.2
FE temp	0.2
Dynamic range inc ageing, temp, cont	7.19

Table 4.10: RF power budget for WC12.

Component	Type	$\frac{P_{in}}{[FE NBW]}$ [dBm]	Gain [dB]	P1dB _{Out} [dBm]	Noise BW [GHz]	$\frac{P_{out}}{[BW]}$ [dBm]	P1dB back-off [dB]
ADL9005	Amp	-29	12	13.50	8	-17	30.50
1 dB	Att	-17	-1	-	8	-18	-
ADL9005	Amp	-18	12	13.50	8	-6	19.50
PDW06038	P.S.	-6	-3.30	-	8	-9.30	
4 dB	Att	-9.30	-4	-	8	-13.30	-
ADL9005	Amp	-13.30	12	13.50	8	-1.30	14.80
PDW06038	P.S.	-1.30	-3.30	-	8	-4.60	-
PDW06038	P.S.	-4.60	-3.30	-	8	-7.90	-
1 dB	Att	-7.90	-1	-	8	-8.90	-
KTMI-502A11	Isolator	-8.90	-0.80	-	8	-9.70	-
Filter Min	BPF	-9.70	-6.50	-	0.1530	-33.38	-
Filter Max	BPF	-9.70	-6.50	-	0.4	-29.21	-
DD	DD	-29.21	-	-15	-	-	-14.21
ADL9005	Amp	-33	12	13.50	8	-21	34.50
1 dB	Att	-21	-1	-	8	-22	-
ADL9005	Amp	-22	12	13.50	8	-10	23.50
PDW06038	P.S.	-10	-3.30	-	8	-13.30	
4 dB	Att	-13.30	-4	-	8	-17.30	
ADL9005	Amp	-17.30	12	13.50	8	-5.30	18.80
PDW06038	P.S.	-5.30	-3.30	-	8	-8.60	-
PDW06038	P.S.	-8.60	-3.30	-	8	-11.90	-
1 dB	Att	-11.90	-1	-	8	-12.90	-
KTMI-502A11	Isolator	-12.90	-0.80	-	8	-13.70	-
Filter Min	BPF	-13.70	-6.50	-	0.1530	-37.38	-
Filter Max	BPF	-13.70	-6.50	-	0.4	-33.21	-
DD	DD	-33.21	-	-15	-	-	-18.21

Dynamic range calculations for table 4.10 are presented in table 4.11.

Table 4.11: Dynamic range calculations for WC12.

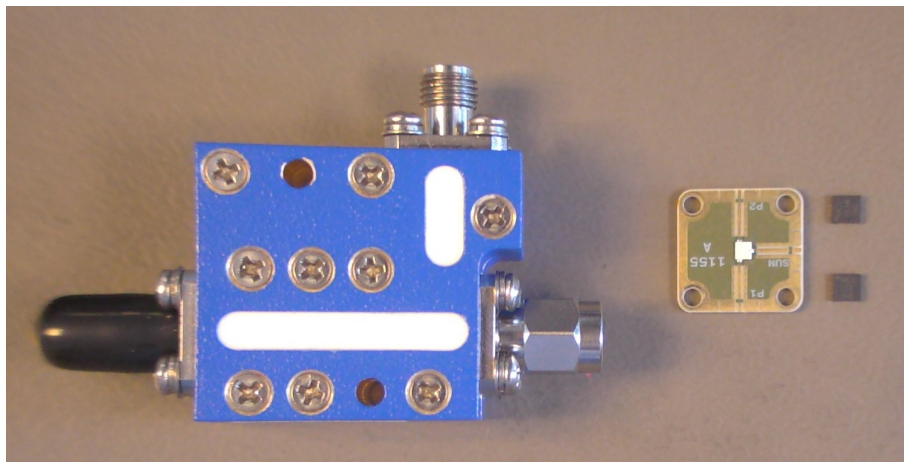
	Power [dB]
Dynamic range, observed temperatures	8.17
Temp. drift BE	1
Contingency BE+FE	1
Ageing	0.2
FE temp	0.2
Dynamic range inc ageing, temp, cont	10.57

As observed in the RF power budgets seen in table 4.6, 4.4, 4.8 and 4.10, some trade offs were made. It was difficult to maintain a 20 dB back-off for all amplifiers, while maintaining the input to the detector diodes. Therefore, some amplifiers have a lower value of back-off, so as to maintain the input in a good operating range of the detector diodes.

4.2 Circuit Improvements

1. Diplexer v/s Resistive Divider, LP and HP Filter

The diplexer is replaced by the resistive divider and filter combination, to eliminate the bulkiness and size of both components are compared in figure 4.1. The diplexer is also a coaxial component and must be connected external to the circuit, whereas the resistive divider and filters can be surface mounted, within the circuit. Performance of the diplexer is seen in figure 4.2 and is compared to the resistive divider and LP/HP filter combination seen in figure 4.3 and 4.4.

**Figure 4.1:** Size comparison between diplexer (left) and power splitter setup with filters (right).

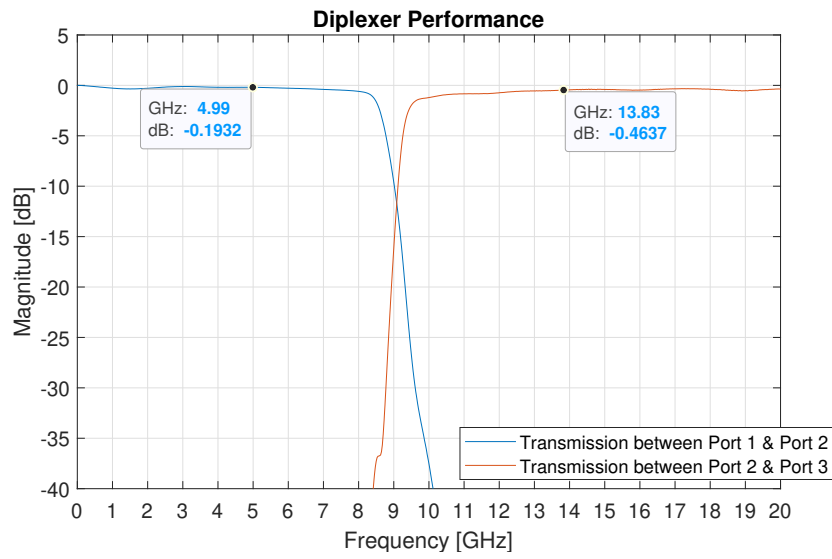


Figure 4.2: Transmission through a diplexer. Port 2 represents the window channel and Port 3 represents the other channels.

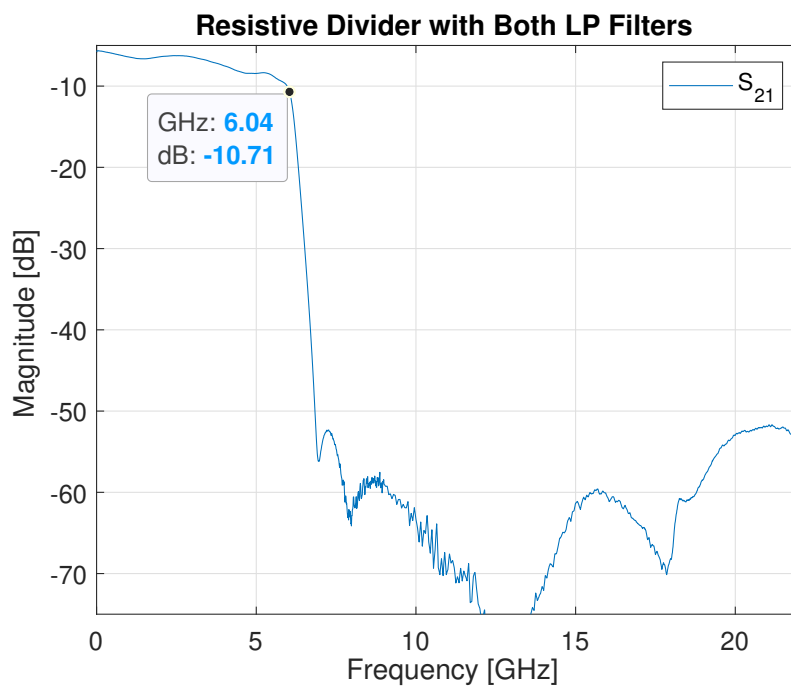


Figure 4.3: Transmission through a resistive divider with LP filters (XLF-73+ and LFCW-5000+).

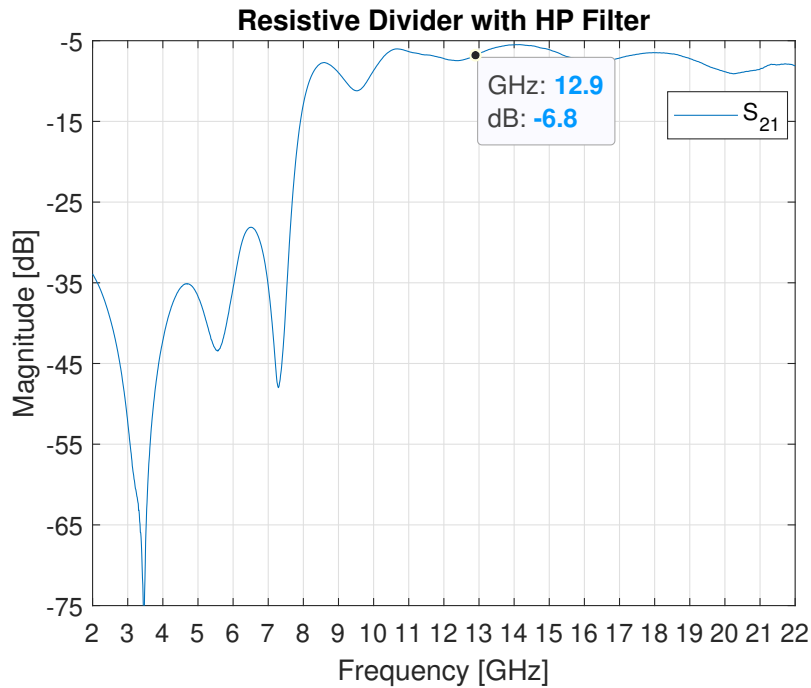


Figure 4.4: Transmission through a resistive divider with HP filter (XHF14M+).

The LP filters used are XLF-73+ and LFCW-5000+ and therefore, the frequencies passed through WC31 are 0-6 GHz. The first filter, XLF-73+ is selected as it is a reflectionless filter and the other filter is selected to attenuate higher harmonics present due to the BP filter. Similarly, the HP Filter used is XHF-14M+ and it passes frequencies from 9.9 to 20 GHz. The resistive divider has a loss of 6 dB and the filters have an insertion loss of 0.5-0.8 dB, therefore the loss of the system is 6.5 to 6.8 dB at the initial frequencies. This loss is accounted for in the RF power budget and compensated for using amplifiers.

The diplexer has a very low insertion loss and very good isolation, but since it is coaxial and bulky, the solution of using a resistive divider with LP and HP filter, seems to be more fitting for the requirements.

2. Number of Amplifiers

The number of amplifiers was a concern, as more amplifiers lead to increased power consumption. The initial solution was removing the amplifiers from the channels and implementing them in the beginning of the circuit, so that the gain of the amplifier is supplied equally to all the channels. Gain levelling is carried out by attenuators in individual channels, for 183 GHz. There was a concern that cascading three amplifiers would cause oscillation due to improper matching between the circuits, this was tested and attenuators were added in between, to improve the matching between the amplifiers.

The 54 GHz follows a similar idea, but attenuators are not implemented channel wise, as a trade off was made with the P1dB back-off of the amplifiers and input to the detector diode. The design for the 54 GHz is not final yet as filters have not been received for all the channels, and the insertion loss of the filters would vary the channel wise performance.

This solution increased the cross-talk between channels as amplifiers were no longer present to isolate the channels and reduce coupling. The 183 GHz uses only five amplifiers and 54 GHz uses four amplifiers. Therefore, the next solution was to improve the isolation. Isolators are implemented channel wise to improve the isolation/cross-talk between the channels. The window channel for 183 GHz does not have an isolator as it is sufficiently isolated from the other channels with the power splitter and filter solution. This is seen in the cross-talk simulations which are presented in section 4.3.2. The isolators used for 183 GHz are seen in figure 4.5.

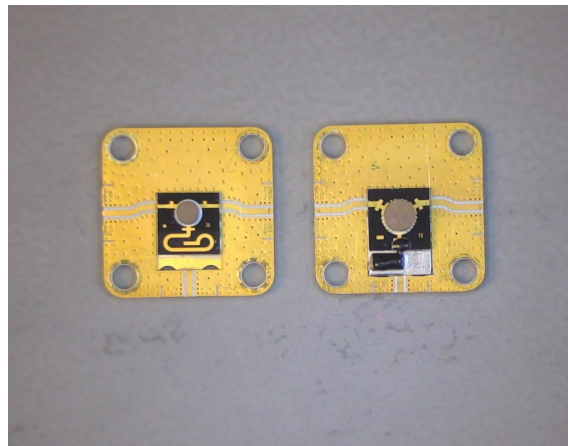


Figure 4.5: Isolators for 183 GHz. KTMI-2002A (left) and KTMI-1502A16 (right). Isolators are bigger for lower frequencies.

3. Power Splitter Selection for 54 GHz

This is a very small design change for 54 GHz. The earlier design used power splitters that were relatively big. The prototype design includes two power splitters PD-0530SMG and PDW06038. PDW06038 operates between 0-20 GHz and is satisfactory for all the channels, and PD-0530SMG operates between 5-30 GHz. But for some of the channels at higher frequencies, PD-0530SMG is implemented instead of PDW06038 as it is smaller in size and the performance is very similar.

4.3 Simulations for 183 GHz

In this section, the most important simulation results are presented. The simulation layout in MWO has been included in figure 4.6-4.9. Due to the size of the layout, it has been divided into four different parts in order to be readable.

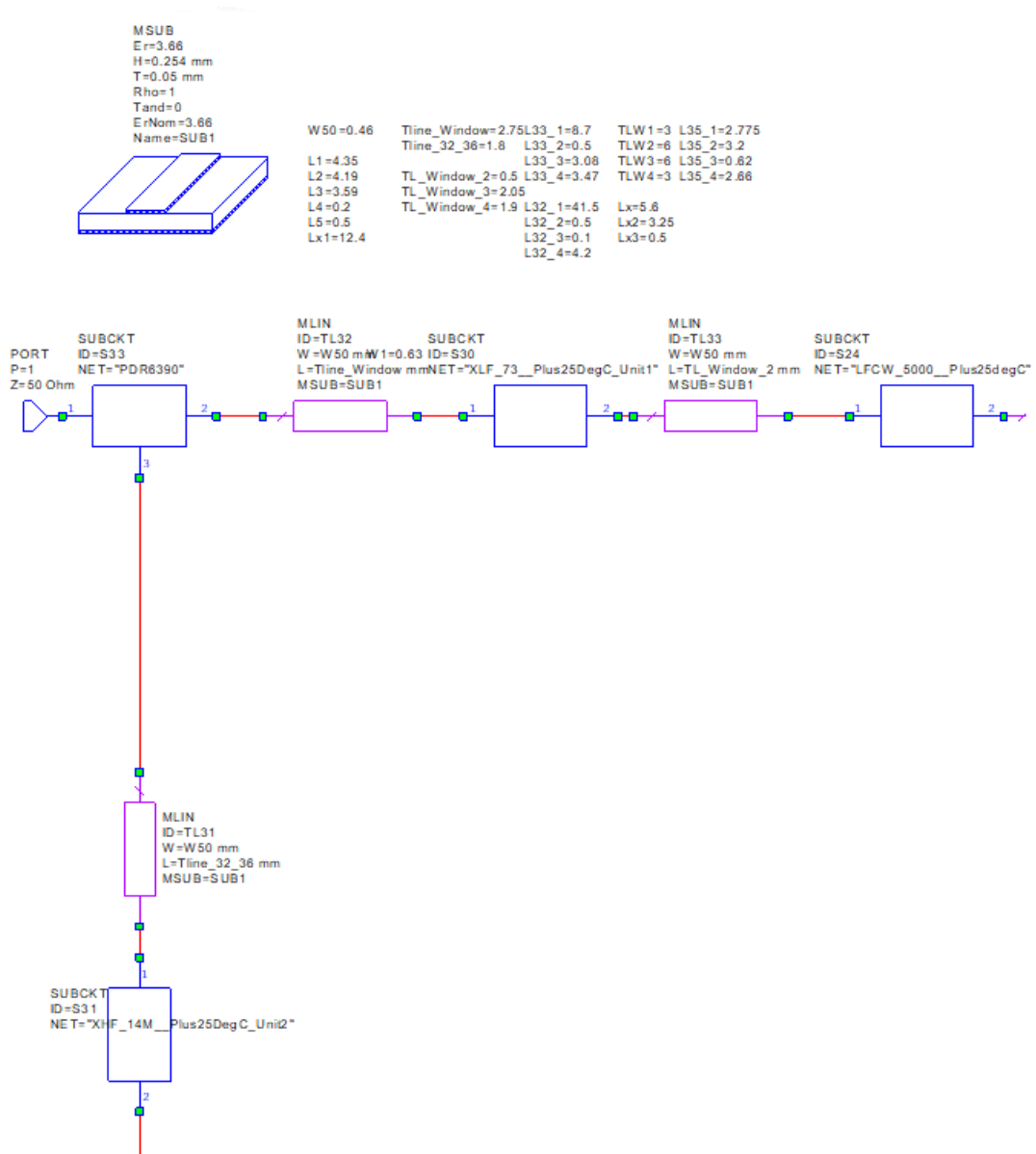


Figure 4.6: First part of the 183 GHz layout, which shows the setup of the resistive divider, LP and HP filter.

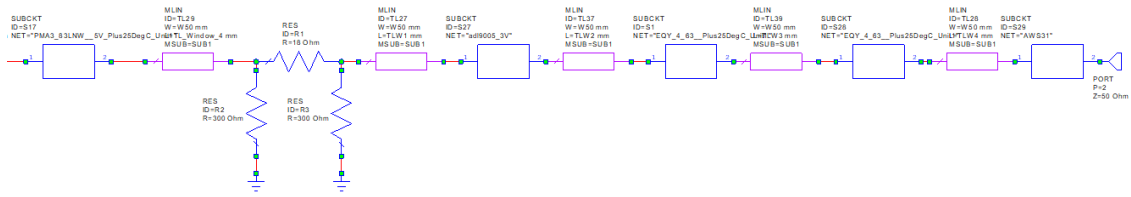


Figure 4.7: Second part of the 183 GHz layout, which shows channel 31.



Figure 4.8: Third part of the 183 GHz layout, which shows the amplifier chain leading up to channel 32 to 36.

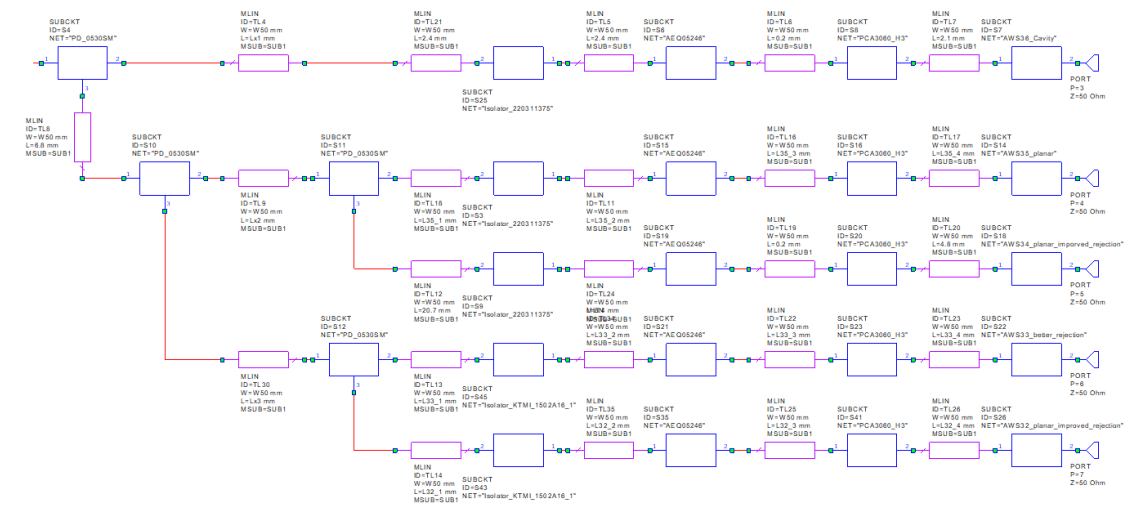


Figure 4.9: Fourth part of the 183 GHz layout, which shows channel 32 to 36.

The channel response and cross-talk between the channels are seen in the following subsections.

4.3.1 Channel Response

The channel response for all the channels is seen in figure 4.10 and 4.11. This is the output of the entire system layout. The transmission lines played a very important part while optimizing the curves, in this scenario and they were optimized to modify the shape of the curves.

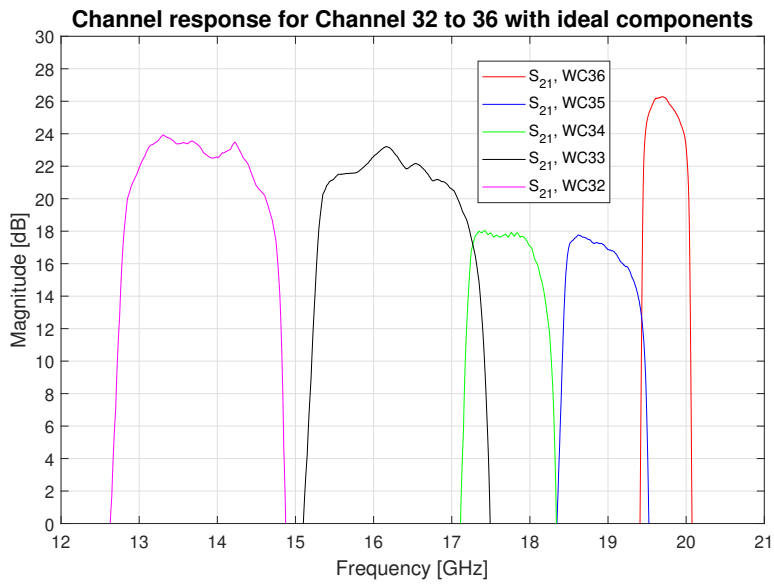


Figure 4.10: Channel response for WC32-WC36.

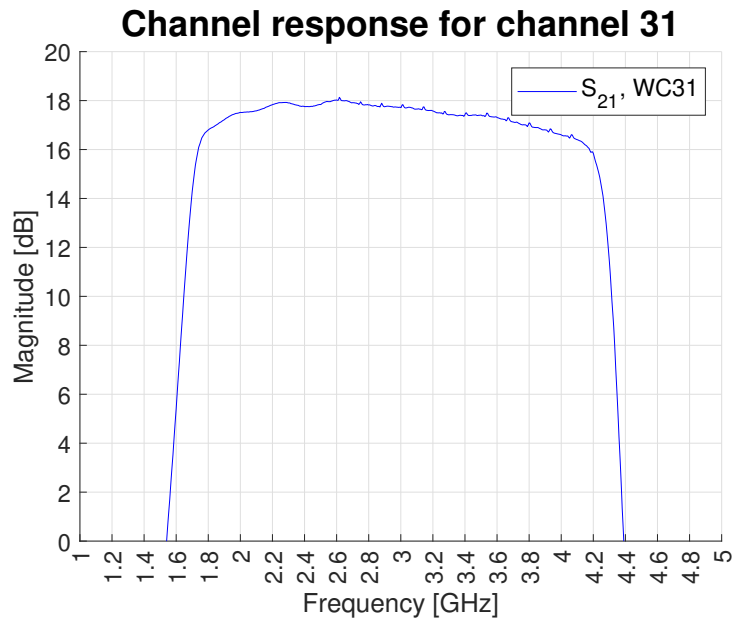


Figure 4.11: Channel response for WC31.

4.3.2 Cross-talk

These simulations represent how the channels interact with each other and as seen, it fulfills the requirements by maintaining the interactions between the channels to less than -40 dB. This is achieved by the isolators present in each channel. The isolator KTMI-1502A16 is used for channels WC32-34 and KTMI-2002A for channels WC35-36.

Figure 4.12 shows the cross-talk between the window channel (WC31) with the other channels. As observed from the figure, the window channel is well isolated from all the other channels due to the resistive divider and LP filters.

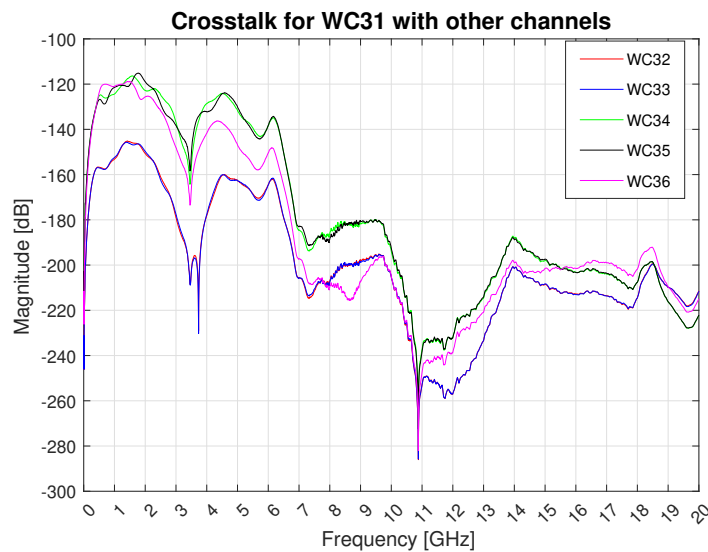


Figure 4.12: Cross-talk simulations between channel 31 with channel 32 to 36 with the final layout.

Figure 4.13-4.17 represent the cross-talk between the other channels in the layout. As seen in figure 3.3, Channel WC32 and WC33 are close to each other in the layout. Similarly, Channel WC34 and WC35 are close to each other. By principle, cross-talk or coupling is higher between the neighbouring channels, as they are quite close in frequency and affect each other's performance.

But if the figures are observed carefully, it is noticed that the lowest cross-talk is between the neighbouring channels, in the operating frequency band when compared to the others. This is a very useful result, which shows that the isolators function very well in isolating neighbouring channels.

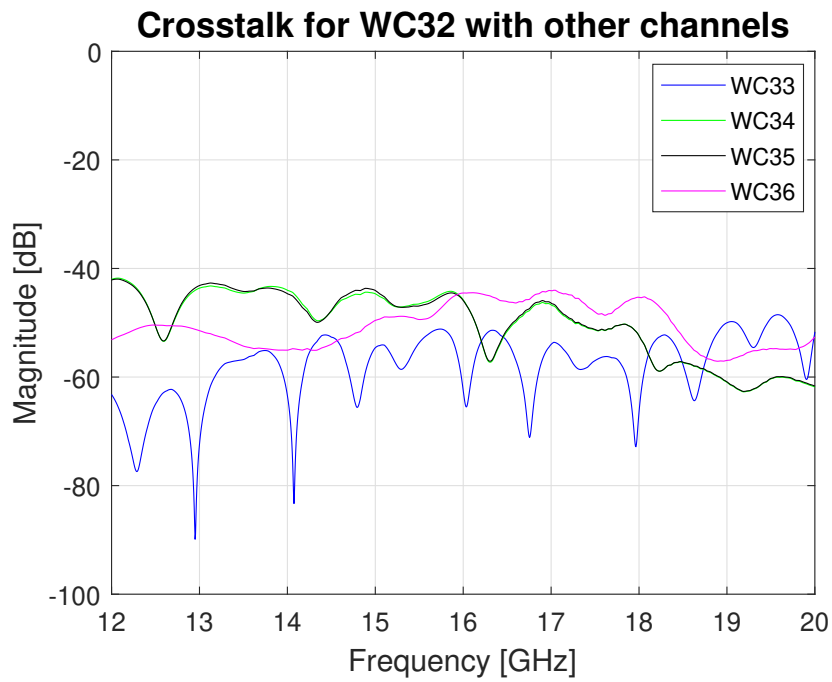


Figure 4.13: Cross-talk simulations between channel 32 with channel 33 to 36 in the final layout.

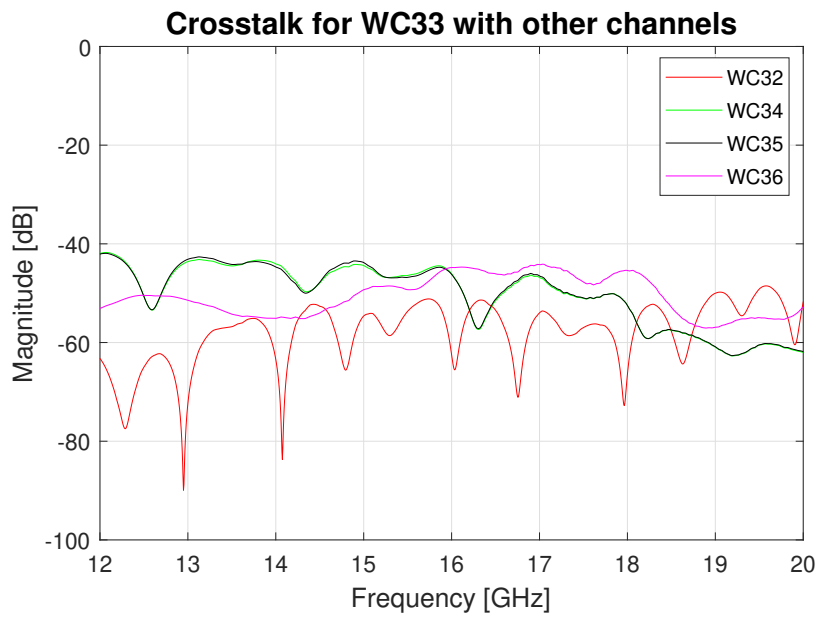


Figure 4.14: Cross-talk simulations between channel 33 with channel 32 to 36 in the final layout.

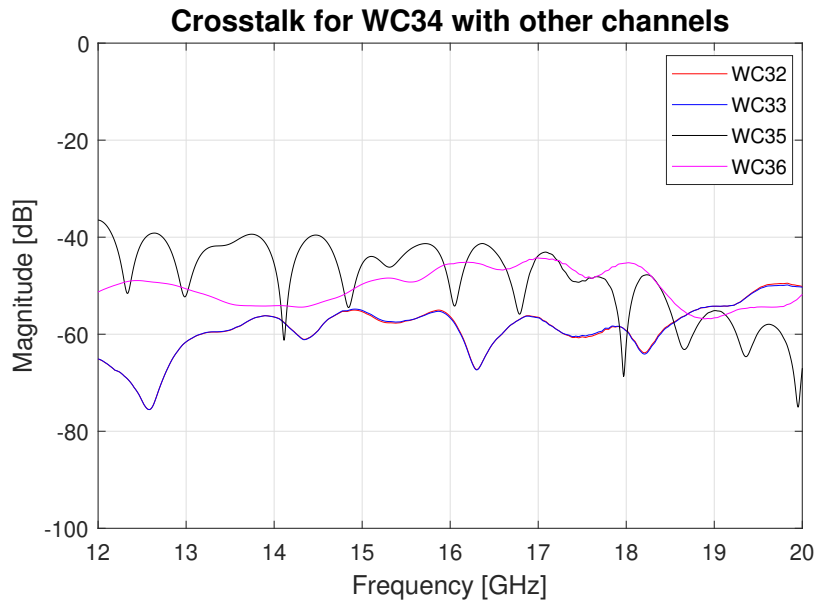


Figure 4.15: Cross-talk simulations between channel 34 with channel 32 to 36 in the final layout.

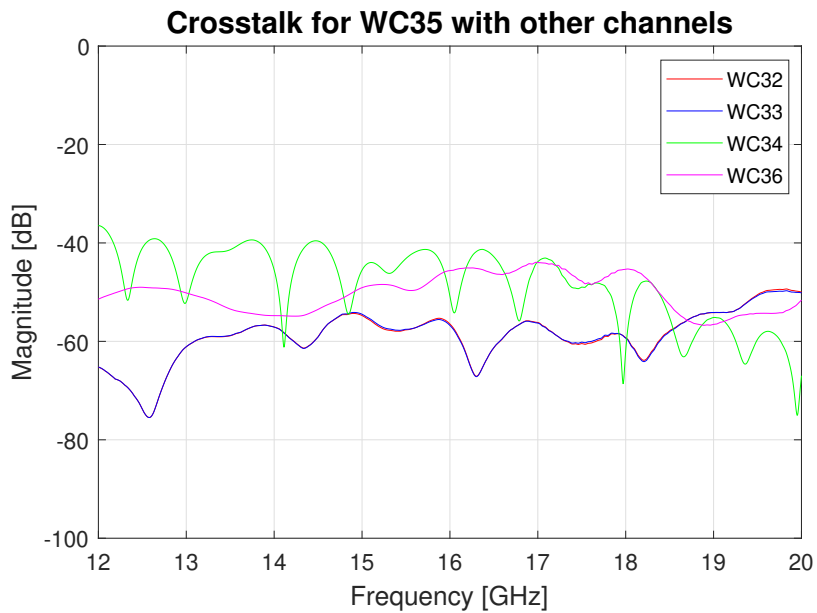


Figure 4.16: Cross-talk simulations between channel 35 with channel 32 to 36 in the final layout.

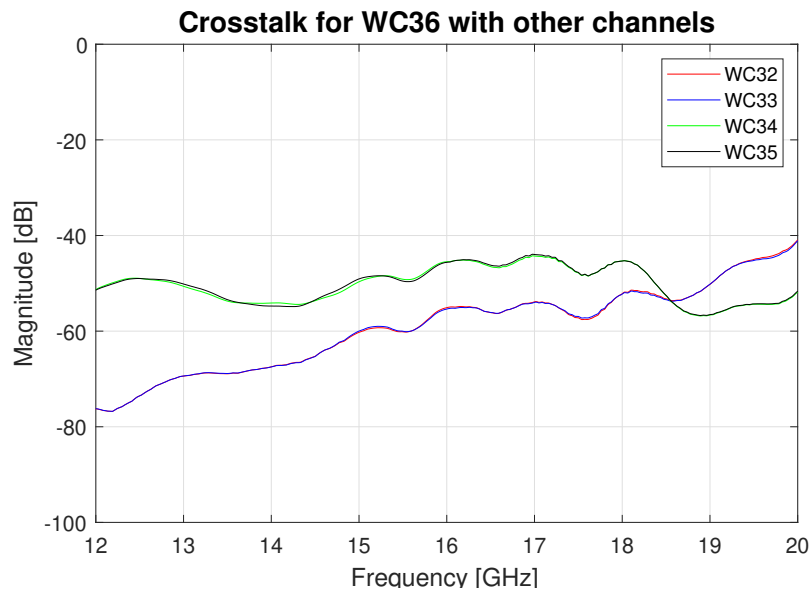


Figure 4.17: Cross-talk simulations between channel 36 with channel 32 to 36 in the final layout. Channel 32 and 33 overlap each other in the graph, and Channel 34 and 35 overlap each other.

4.4 Simulations for 54 GHz

The simulations for the 54 GHz channels are presented below. The 54 GHz layout has channels quite close to each other in frequency, making the isolation very important. The schematic that has been used for the simulations of the 54 GHz BE is shown in figure 4.18-4.20.

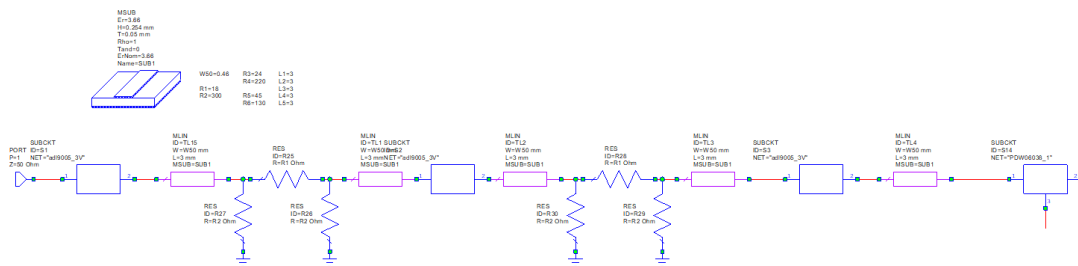


Figure 4.18: First part of the 54 GHz layout, which shows the amplifier chain leading up to channel 11 to 18.

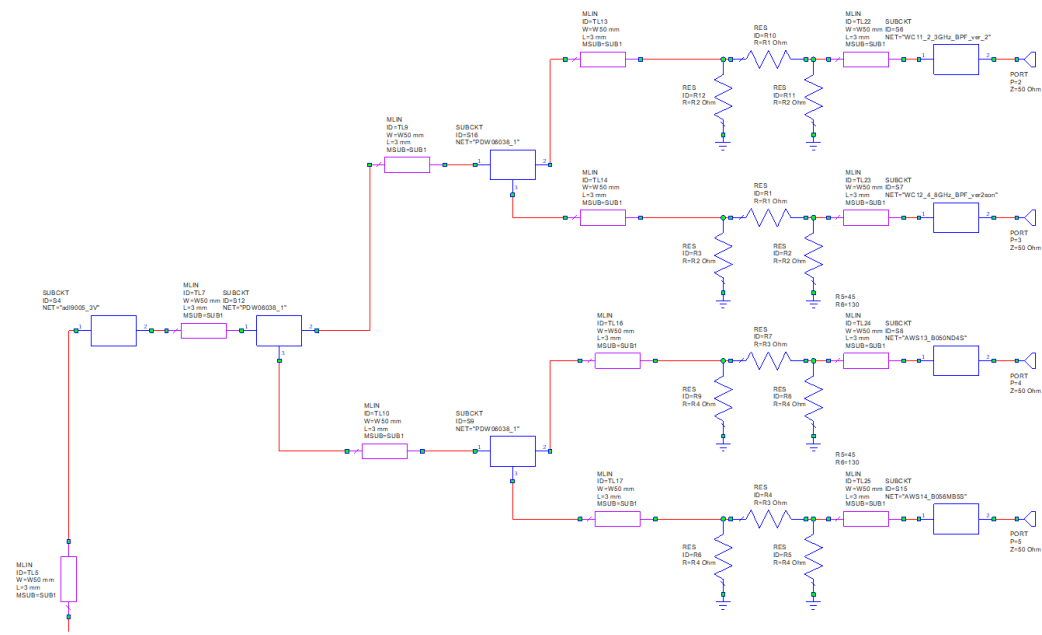


Figure 4.19: Second part of the 54 GHz layout, which shows channel 11 to 14.

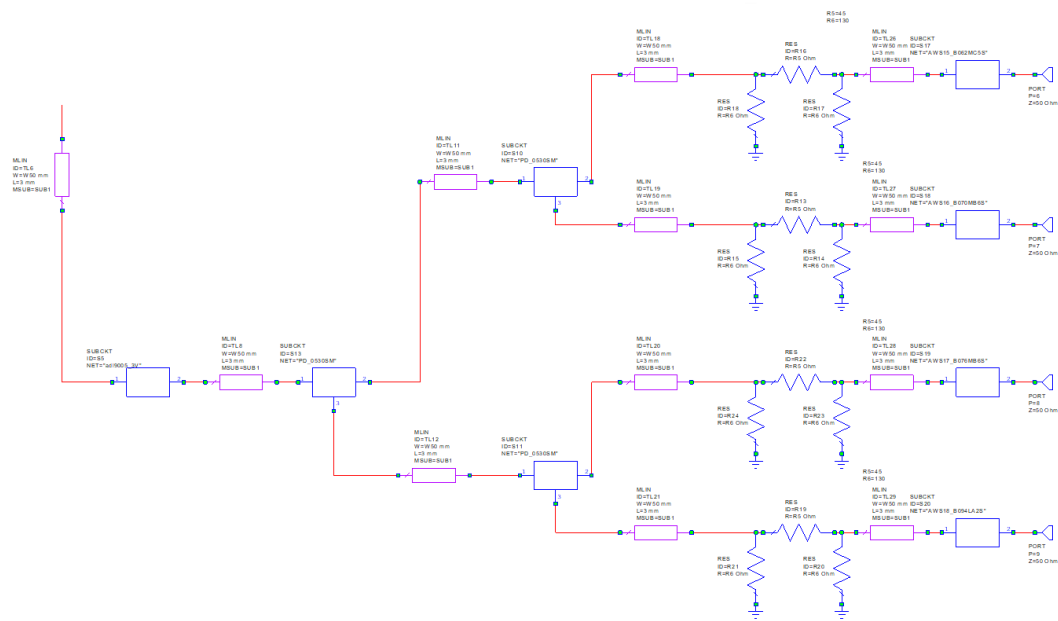


Figure 4.20: Third part of the 54 GHz layout, which shows channel 15 to 18.

4.4.1 Cross-talk

The cross-talk between Channel WC15 and WC16 is simulated before and after implementing the isolators. For 54 GHz, isolators were only received for WC15 and WC16. Therefore, the performance of these two channels were evaluated. When figure 4.21 and 4.22 are compared, it is clear that the isolators improve the cross-talk between the neighbouring channels to a great extent.

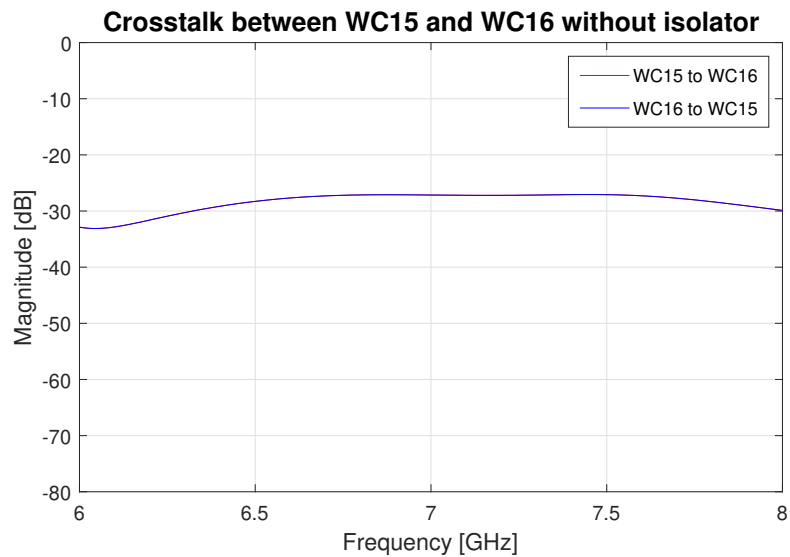


Figure 4.21: Cross-talk without the isolator for WC15 and WC16.

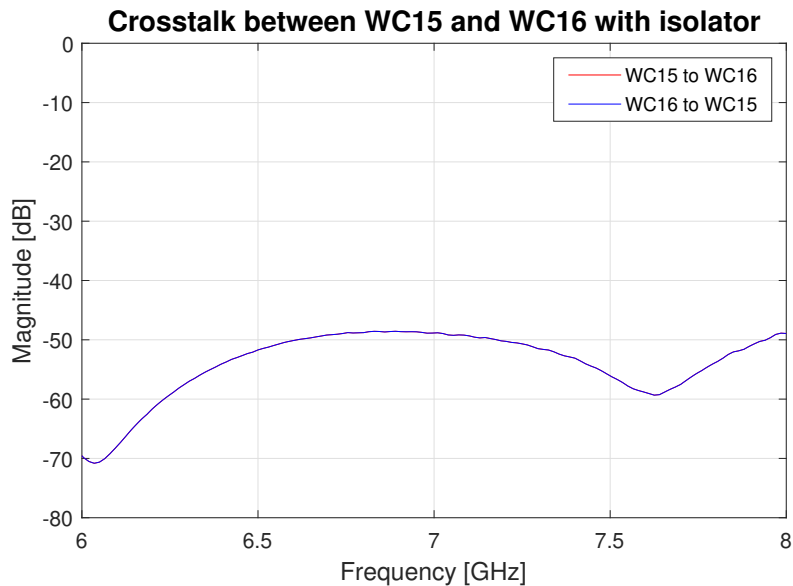


Figure 4.22: Cross-talk with the isolator for WC15 and WC16.

4.4.2 Channel Response

The channel response for WC11 and WC12 are presented in figure 4.23. Filters were received for these channels and hence, these are simulated.

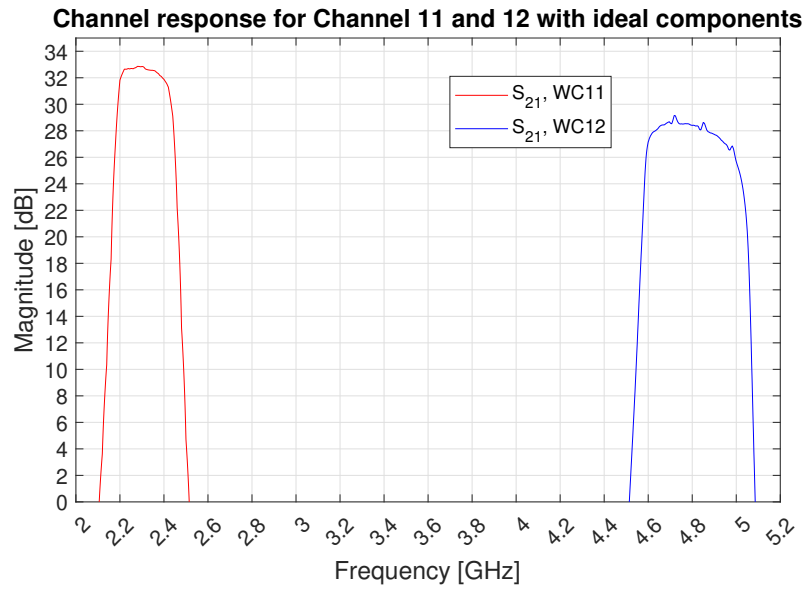


Figure 4.23: Channel response for WC11 and WC12.

4.5 Measurements

The following subsections represent the measurements for the 183 GHz design.

4.5.1 Printed Circuit Boards

Printed Circuit Boards (PCBs) for some of the components were designed in Path-Wave Advanced Designed System (ADS) and some in Altium Designer. Some of the PCBs are displayed in figure 4.24.

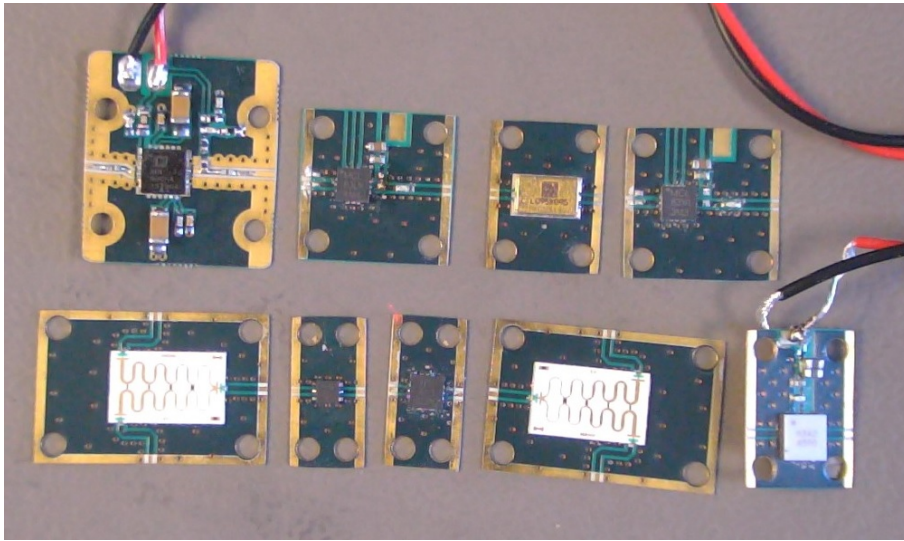


Figure 4.24: PCB design.

Some of the components were also procured from X-Microwave, for test measurements. The PCBs of most components were relatively straightforward to design except the isolators. The isolators are a less explored component and it is difficult to mount them, they are quite thick components and mounting them directly on the PCB lead to more reflections. Mounting them by making a small cutout in the board seemed to improve the performance. This is done to reduce mechanical stress on the PCB. The performance of both configurations is measured and displayed in figure 4.25. The isolation or S_{12} is displayed in dB.

Mounting of the isolators could be a topic that can be explored in the future, as the performance could be improved further. Time constraints limited the design of a PCB of the complete system and that would definitely change the performance.

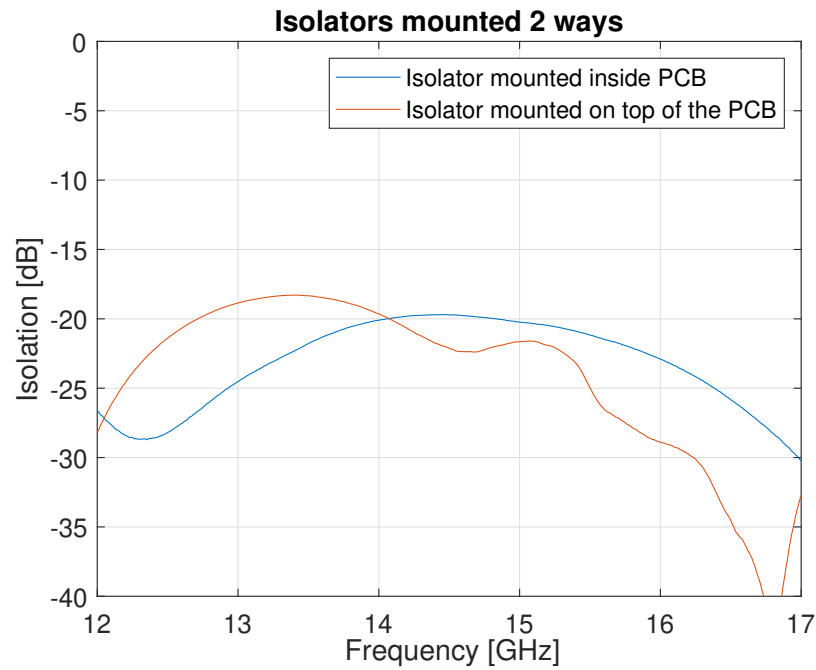


Figure 4.25: The isolator mounted two different ways. The isolator tested is KTMI-1502A16 which operates between 12-17 GHz.

The isolators that has been used in the simulations and measurements if the 183 and 54 GHz BE are shown in figure 4.26-4.28, where it is simulated for the designed frequencies of the isolators.

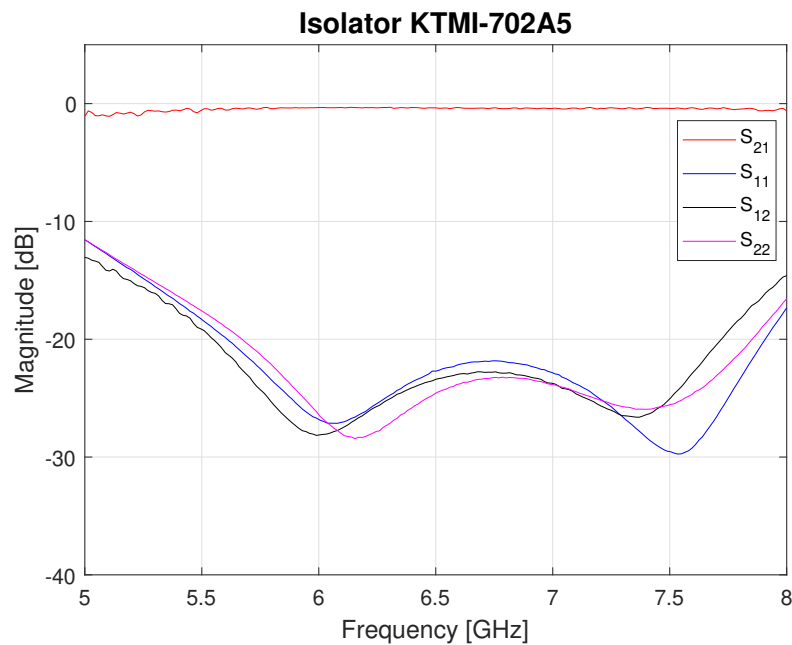


Figure 4.26: Measurements of KTMI-702A5 for the designed frequency band.

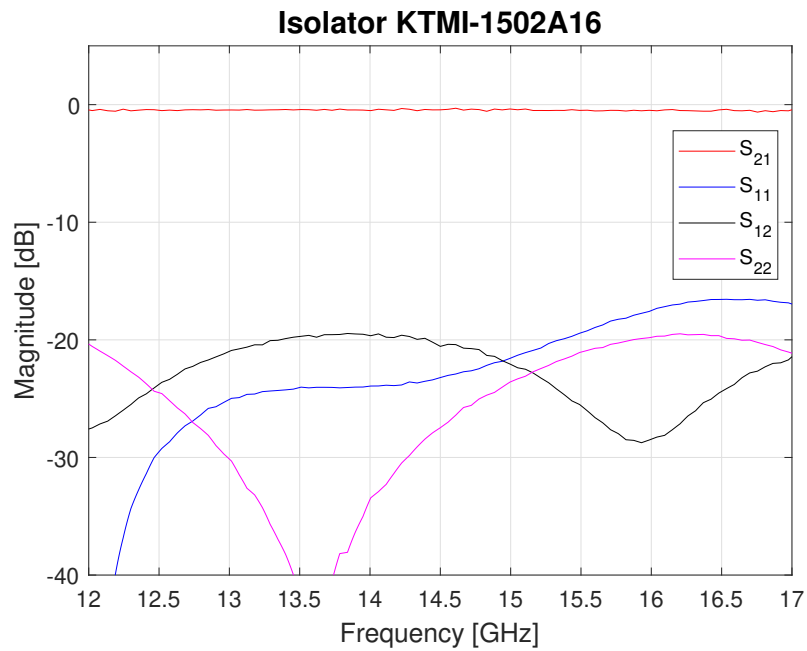


Figure 4.27: Measurements of KTMI-1502A16 for the designed frequency band.

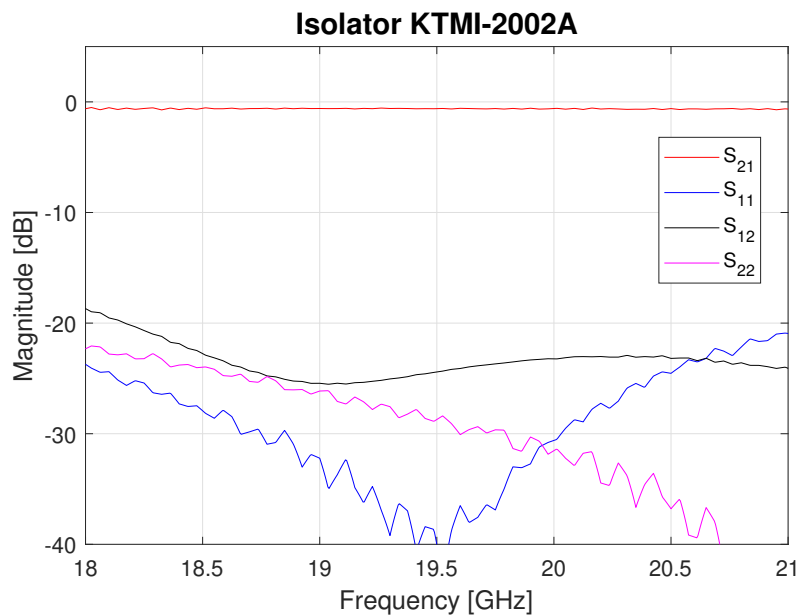


Figure 4.28: Measurements of KTMI-2002A for the designed frequency band.

4.5.2 Channel Measurements

The cross-talk with measured components has been simulated for channel WC33 and WC34 and is shown in figure 4.29 and 4.30. Comparing these measurements with the simulated ones in figure 4.14 and 4.15 shows that they are quite similar in the amount that they isolate the other channels, with the difference between them being the shape of the curves.

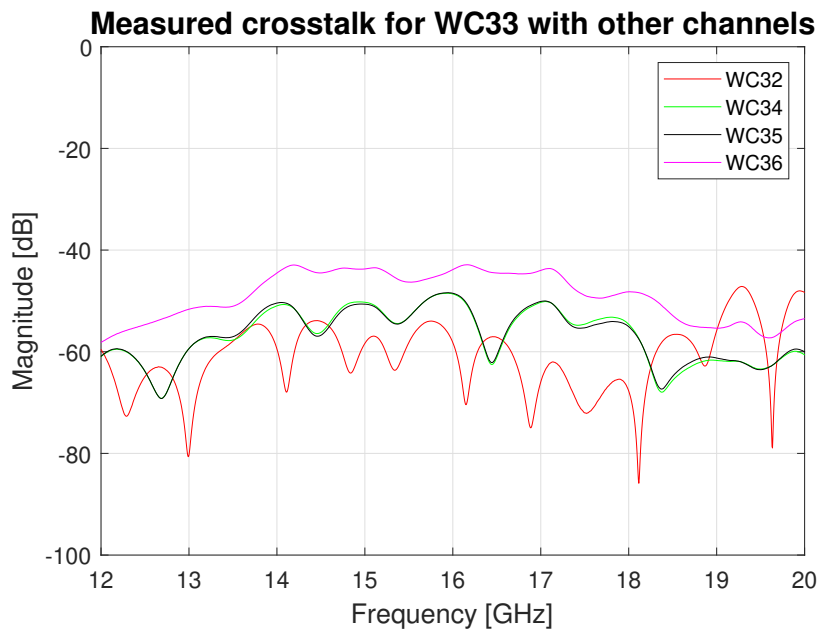


Figure 4.29: Measured cross-talk between channel 33 and channel 32 to 36 for the final layout.

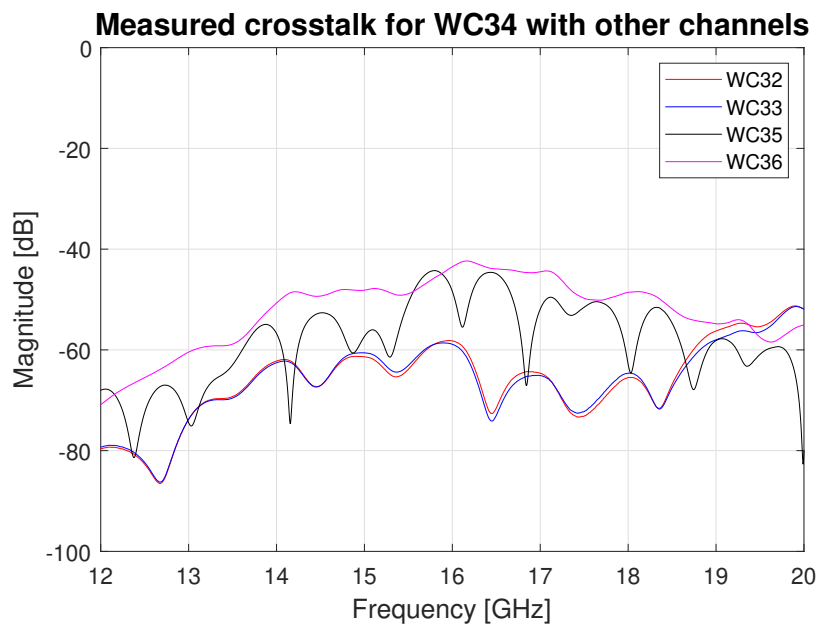


Figure 4.30: Measured cross-talk between channel 34 and channel 32 to 36 for the final layout.

The measured channel response for the 183 GHz BE when using the same lengths of the transmission lines are shown in figure 4.31. When compared to figure 4.10 it clearly shows that either the length of the transmission lines or the measured components makes a big difference. Therefore the transmission lines were tuned for the measured components which are shown in figure 4.32. When compared to the simulated channel response it is now more similar except for that the measured components induces more ripple in the channels.

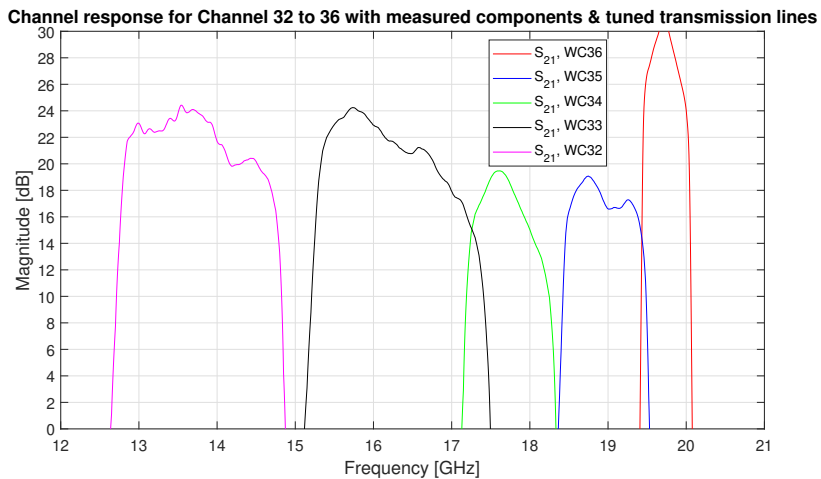


Figure 4.31: Channel response for channel WC32 to WC36 with measured components and having the lengths of the transmission lines the same as in the ideal scenario.

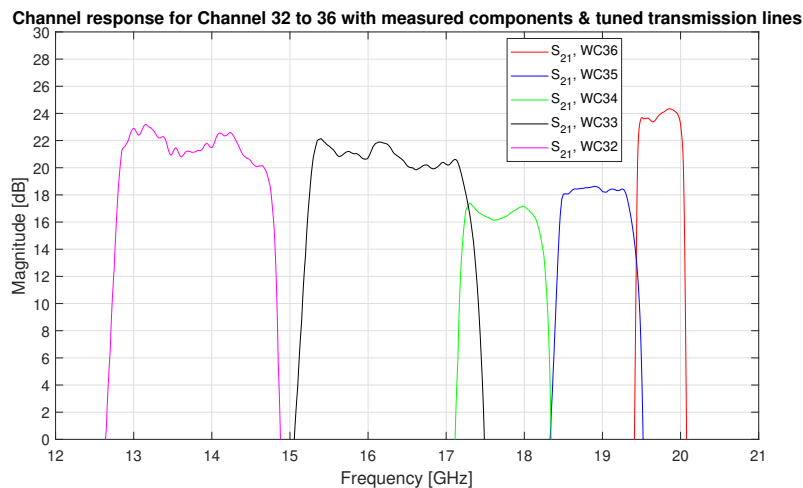


Figure 4.32: Channel response for channel WC32 to WC36 with measured components and having the lengths of the transmission lines tuned for better performance.

Similarly channel WC31 is simulated with measured components which is shown in figure 4.33. When compared to the case with the ideal components in figure 4.11, section 4.3.1, the magnitude of the measured one is about the same with the difference being that there is more ripple in the measured one.

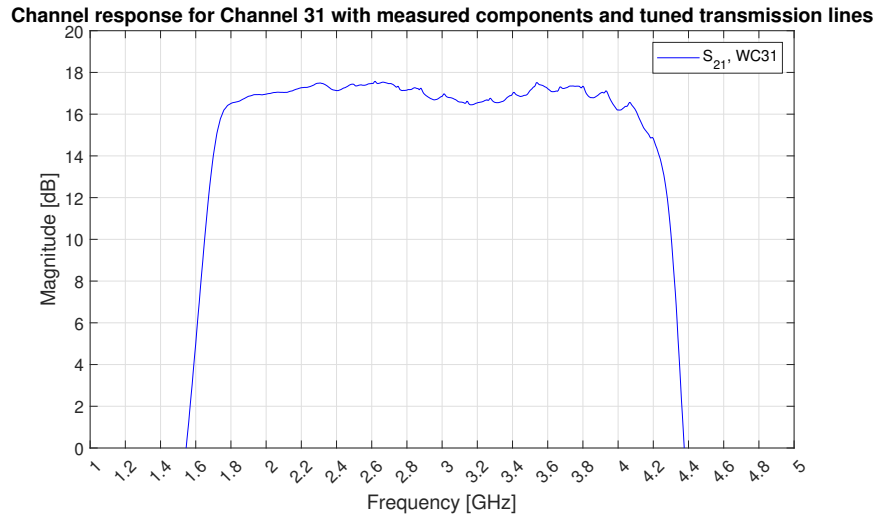


Figure 4.33: Channel response for channel WC31 with measured components and having the lengths of the transmission lines tuned for better performance.

4.6 Power Comparison

Table 4.12 represents the power comparison between the previous and prototype design for 183 GHz BE. The power is decreased by a factor of three compared to the original value for the 183 GHz design. The values for the rail voltages are preliminary values for the both prototype designs.

Table 4.12: Power comparison between previous and suggested prototype for BE183.

Component	Number	Supply Voltage [V]	Current [mA]	Total Current [mA]	Rail [V]	Power [W]
Previous design						
HMC7950LS6	6	5	60	360	5.5	1.98
HMC7950LS6 Gate	6	-1.41	5	30	-5.5	0.165
SBB3089Z	1	5	42	42	5.5	0.231
Total	7	-	-	432	-	2.38
Prototype design						
HMC342LC4	2	3	42	84	3.5	0.294
ADL9005	2	3	20	40	3.5	0.14
PMA3-83LN+	1	5	58	58	5.5	0.319
Total	5	-	-	182	-	0.753

Table 4.13 represents the power comparison between the previous and prototype design for 54 GHz BE. The power is reduced by a factor of six for the 54 GHz design.

Table 4.13: Power comparison between previous and suggested prototype for BE183.

Component	Number	Supply Voltage [V]	Current [mA]	Total Current [mA]	Rail [V]	Power [W]
Previous design						
ADL9005	8	5	40	320	5.5	1.76
Prototype design						
ADL9005	4	3	20	80	3.5	0.28

5

Conclusion

This report shows that significant change in the power consumption, of the previous generation BE, is achievable by optimizing and changing components. When a system is designed as the one in the report, multiple factors have to be taken into consideration such as how the components will affect each other and other less pronounced factors such as if components really work as promised. The performance of the same component can vary between different units, as manufacturing does not yield exactly ideal components. Components work a bit differently in space and experience a large range of temperatures, so temperature compensation is important. Stability is quite essential as well, which is measured by the Allan variance of the system. Compact and devices that consume less power are preferred, as material costs are saved and it is sustainable for the environment as well. There are also a lot of variations and noise introduced in the system when it is measured rather than simulated.

The system mentioned in the report is used for weather measurements for the Arctics. Currently, the satellites over the Arctics have limited revisit times and more short-term measurements are required. This is for supporting now casting users across the region. The filter banks designed in this report are at 183 and 54 GHz, the data is processed through the entire layout seen in figure 2.4 and sampled by the ADC, the signal is sent to the users through a L band down link. The received data is then processed by the users and interpreted to form the spectral lines, which are studied.

There were certain design changes implemented while keeping the requirements in mind, and they were tested and measured. The main change in the system was to replace some amplifiers with isolators to reduce the power consumption, with the drawback of having worse cross-talk between channels. The total power consumption of the 183 GHz BE was improved from 2.38 W down to 0.753 W, while the isolation improved by about 15 dB. For the 54 GHz BE the previous power consumption were 1.76 W and was improved to 0.28 W, as for the cross-talk no comparison can be made as isolators were only received for two of the channels. With an acceptable level of cross-talk less than -40 dB on all channels, and a major decrease in power, this proves that the concept of replacing amplifiers with isolators is a reasonable suggestion. This helps to improve the performance of a system, where power consumption is of major importance. Isolators are relatively new and have not been used in their fullest extent in space systems previously.

5. Conclusion

Challenges were faced with respect to mounting them on PCBs but it was solved by placing them inside the PCB rather than on top of the PCB. This idea could be tested further to improve the performance of the isolator and minimize reflections.

The other concept to be tested in this project was the replacement of the diplexer with a simple power splitter and a LP and HP filter. The working principle of both systems is the same. This came at the cost of higher insertion loss but the full BE can now be integrated into a PCB. The entire system is surface mountable and that is an excellent selling point to the customer.

As with any system, there can always be improvements. The ADL9005 amplifier can be more thoroughly tested to see how it works when using different values for the bias resistor, and using a different PCB layout to see if the ripple could be reduced. Two layouts were tested for the same amplifier but it is probably possible to make the measurements better. In the report, measurements of both individual components and channels have been presented. The results are then simulated in MWO, to identify the optimum length of transmission lines for a good performance and to compare the simulations and measurements. In order to correctly understand how the different parts affect each other a complete PCB has to be constructed and measured in a lab.

Overall, most of the design requirements have been fulfilled while encountering some trade-offs while making design choices. The performance can be improved by further research or investigations.

Bibliography

- [1] M. Tjernström, G. Svensson, L Magnusson, *Arctic weather forecasting – in the high Arctic*, Jul. 2019, [Online], Available: <https://www.ecmwf.int/en/newsletter/160/meteorology/arctic-weather-forecasting-high-arctic>
- [2] "Types of orbits," *European Space Agency*, [Online], Available: https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits#GEO
- [3] "Better Arctic and global weather forecasts," *European Space Agency*, [Online], Available: https://www.esa.int/Applications/Observing_the_Earth/Meteorological_missions/Arctic_Weather_Satellite/Better_Arctic_and_global_weather_forecasts
- [4] W. Emery and A. Camps, *Introduction to Satellite Remote Sensing*, Amsterdam, NL: ELSEVIER, 2017.
- [5] AWS system team, "Satellite and Instrument Requirements Specification Arctic Weather Satellite," OHB Sweden, Sweden, AWS-OSE-RQ-0096.
- [6] National Oceanic and Atmospheric Administration, U.S. Department of Commerce, "Numerical Weather Prediction (Weather Models)" [Online] Available: <https://www.weather.gov/media/ajk/brochures/NumericalWeatherPrediction.pdf>
- [7] K. Wapler, E.d. Coning and M. Buzzi, *Nowcasting, Reference Module in Earth Systems and Environmental Sciences*, Elsevier, 2019.
- [8] "The instrument," *European Space Agency*, [Online], Available: https://www.esa.int/Applications/Observing_the_Earth/Meteorological_missions/Arctic_Weather_Satellite/The_instrument?fbclid=IwAR0_fTRyngxlqdRnfp31lSZK1fsXbccjTHux8ACxYTfbn8RidWo3ABaNCA
- [9] U. Krus and E. Ryman, "BE183 Design Report," Omnisys Instruments, Sweden, AWS-OMN-RP-0003, 2021.
- [10] T. L. Rose, "Spectrum Analyzer (MP-3000) versus Filter Bank (RPGHAT-PRO) Receiver Design for Profiling of Earth's Atmosphere" *Radiometer Development and System Engineering Radiometer Physics GmbH*, May, 2009. [Online], Available: <https://www.radiometer-physics.de/download/Radiometer/references/Filter%20Bank%20versus%20Spectrum%20Analyzer.pdf>
- [11] "Filter Bank: What is it? (DCT, Polyphase, Gabor, Mel And FBMC)," *Electrical 4 u*, [Online], Available: <https://www.electrical4u.com/filter-bank/>

- [12] D. M. Pozar, *Microwave AND RF Design OF Wireless Systems*, 1st ed., Hoboken, NJ: John Wiley & Sons, 2001.
- [13] A. Siegenthaler, O. Lezeaux, D. G. Feist and N. Kampfer, "First water vapor measurements at 183 GHz from the high alpine station Jungfrauoch," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 39, no. 9, pp. 2084-2086, Sept. 2001, doi: 10.1109/36.951108.
- [14] "Brightness Temperature," *Remote Sensing Systems*, Aug, 2014. [Online] Available: <https://tinyurl.com/222drc6p>
- [15] K.E. Kempe, "Algorithm Theoretical Basis Document," Omnisys Instruments, Sweden, AWS-OMN-TN-0003, 2021, (*Restricted Report by Omnisys Instruments AB).
- [16] "What is the L Band?," *everythingRF*, [Online], Available: <https://www.everythingrf.com/community/l-band>
- [17] J. Dunn, "Y-factor and antenna testing," *EDN*, May. 24, 2016, [Online] Available: <https://www.edn.com/y-factor-and-antenna-testing/>
- [18] N. Atkinson, "NE Δ T specification and monitoring for microwave sounders," *Met Office.*, 2017, [Online] Available: <https://www.semanticscholar.org/paper/NE%E2%88%86T-specification-and-monitoring-for-microwave-Atkinson/00749d3ceb945d7cb8e5a4f8787dc88c61245fe3#citing-papers>
- [19] "Allan variance," *Home Engineering*, [Online] Available: <https://home.engineering.iastate.edu/shermanp/AERE432/lectures/Rate%20Gyros/Allan%20variance.pdf>
- [20] Radio Geek, "Equivalent Noise Bandwidth," *Analog/RF IntgCkts*, [Online] Available: <https://analog.intgckts.com/equivalent-noise-bandwidth/>
- [21] M. Thomasson "THE SPACE ENVIRONMENT AND ITS EFFECTS ON SPACECRAFT," 2009. [Online] Available:
- [22] D.M. Pozar, *Microwave Engineering*, 4th ed., Hoboken, NJ: Wiley, 2012.
- [23] "Introduction to the Amplifier," *Electronics Tutorials*, [Online], Available: https://www.electronics-tutorials.ws/amplifier/amp_1.html
- [24] "Attenuators," *Electronics Tutorials*, [Online], Available: <https://www.electronics-tutorials.ws/category/attenuators>
- [25] "How RF Isolator Works | How does an RF Isolator work," *RF Wireless World*, [Online], Available: <https://www.rfwireless-world.com/Terminology/How-RF-Isolator-Works.html>
- [26] J. S. Kim, "What is a Gain Equalizer?," *everythingRF*, [Online], Available: <https://www.everythingrf.com/community/what-is-a-gain-equalizer>
- [27] Hewlett Packard, "The Zero Bias Schottky Diode Detector at Temperature Extremes – Problems and Solutions Application Note 1090," 2000 [Online] Available: http://www.hp.woodshot.com/hprfhel/4_downld/lit/diodelit/an1090.pdf
- [28] E. Nash "Understanding, Operating, and Interfacing to Integrated Diode-Based RF Detectors," *Analog devices*, [Online], Available: <https://www.analog.com/en/technical-articles/integrated-diode-based-rf-detectors.html>

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- [29] J. S . Hong, M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*, 1st ed., Wiley, 2001. [Ebook] Available: <https://onlinelibrary.wiley.com/doi/book/10.1002/0471221619>
- [30] "DIGITIZING SIGNALS AND ALIASING," *Frequency Devices inc*, [Online], Aug, 2003. Available: <http://www.freqdev.com/guide/analog.html>
- [31] "Understanding Poles and Zeros," *MASSACHUSETTS INSTITUTE OF TECHNOLOGY DEPARTMENT OF MECHANICAL ENGINEERING*, [Online], Available: <https://web.mit.edu/2.14/www/Handouts/PoleZero.pdf>
- [32] "Introduction to SAW Filter Theory & Design Techniques," Apitech, 2022, [Online] Available: <https://www.apitech.com/globalassets/documents/rf2m-us/white-paper—saw-filter-2018.pdf>
- [33] "What is a SAW Filter?," *everythingRF*, Apr. 4, 2019. [Online] Available: <https://www.everythingrf.com/community/what-is-a-saw-filter>
- [34] "Lumped Element Filters," *microwaves101*, 2022. [Online] Available: <https://www.microwaves101.com/encyclopedias/lumped-element-filters>
- [35] "What are Cavity Filters?," *everythingRF*, Jan. 9, 2022. [Online] Available: <https://www.everythingrf.com/community/what-are-cavity-filters>
- [36] M. Radulescu, "APPLICATION NOTE USM 104," *US MICROWAVES*, Jul. 1, 2019 [Online] Available: http://www.usmicrowaves.com/appnotes/usm_an_104_thin_film_micro_strip_transmission_lines.htm
- [37] J. Embretsén, "FE 183 Design Report," Omnisys Instruments, Sweden, AWS-0MN-RP-0005, 2021, (*Restricted Report by Omnisys Instruments AB).
- [38] J. Embretsén, "FE 54 Design Report," Omnisys Instruments, Sweden, AWS-0MN-RP-0004, 2021, (*Restricted Report by Omnisys Instruments AB).

A

Appendix

The components from 183 and 54 GHz were simulated individually and the results are included here. The results have been simulated on MWO and the graphs are plotted in Matlab.

A.1 Amplifiers

The S parameters of the amplifiers used in the 183 GHz design are presented below. The amplifier PMA3-83LN+ and ADL9005 are used in the window channel, WC31, and ADL9005 and HMC342 are used in the other channels, WC32-36.

The gain and frequencies at some important frequency points are marked in the figures in this section.

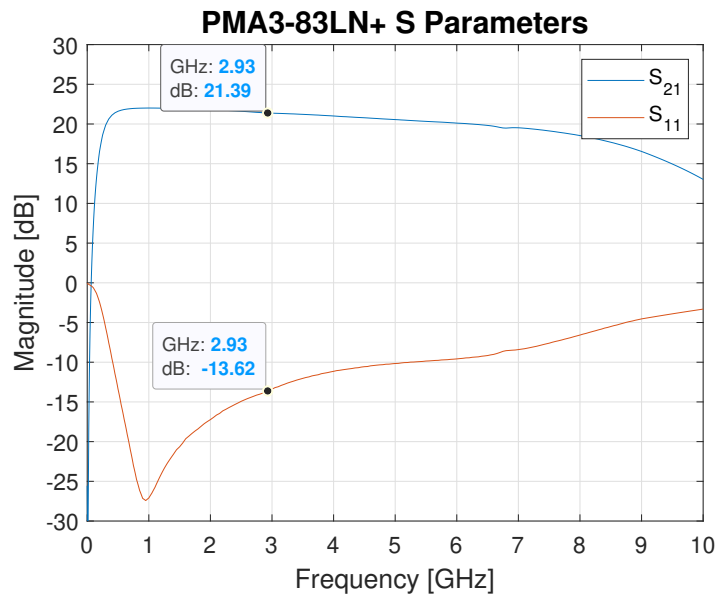


Figure A.1: S parameters of PMA3-83LN+.

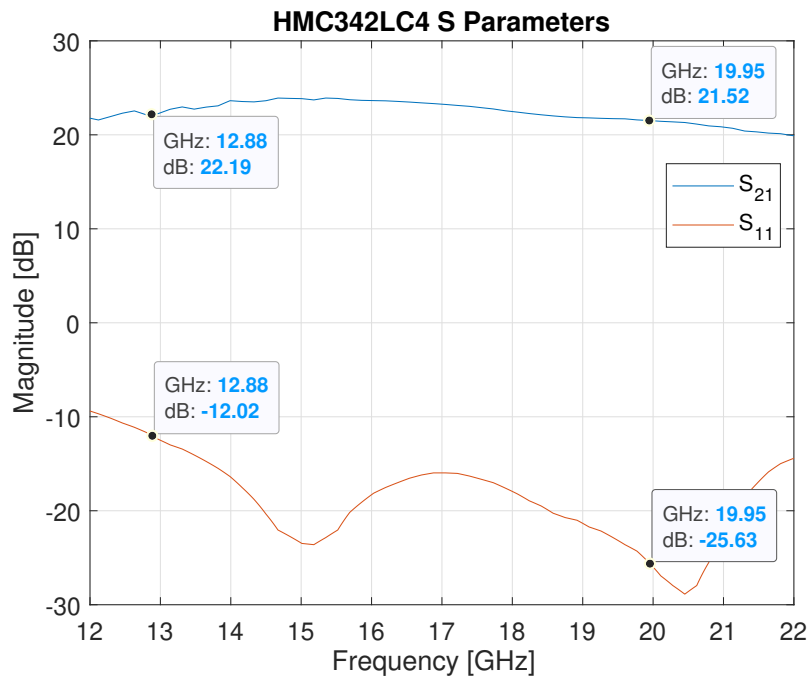


Figure A.2: S parameters of HMC342LC4.

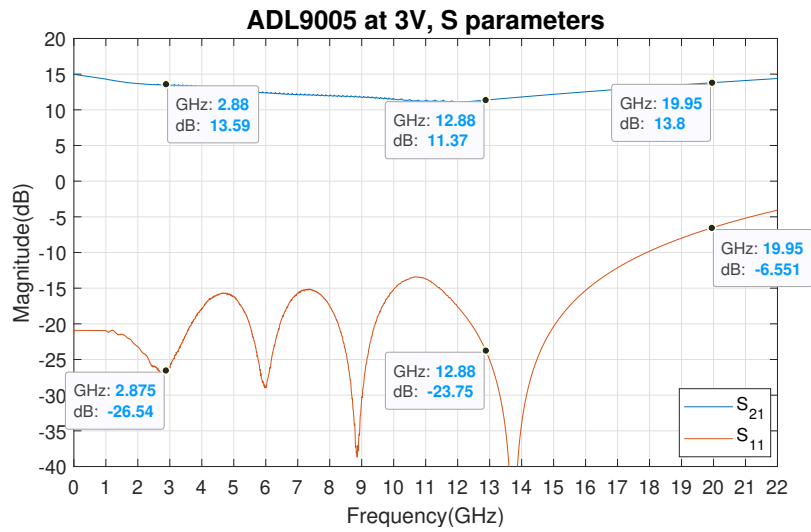


Figure A.3: S parameters of ADL9005.

A.2 Power Splitters

The same power splitter, PD-0530SMG is used for all the channels of 183 GHz and for some channels of 54 GHz. Different parameters of the power splitter are tested, by making a combination circuit.

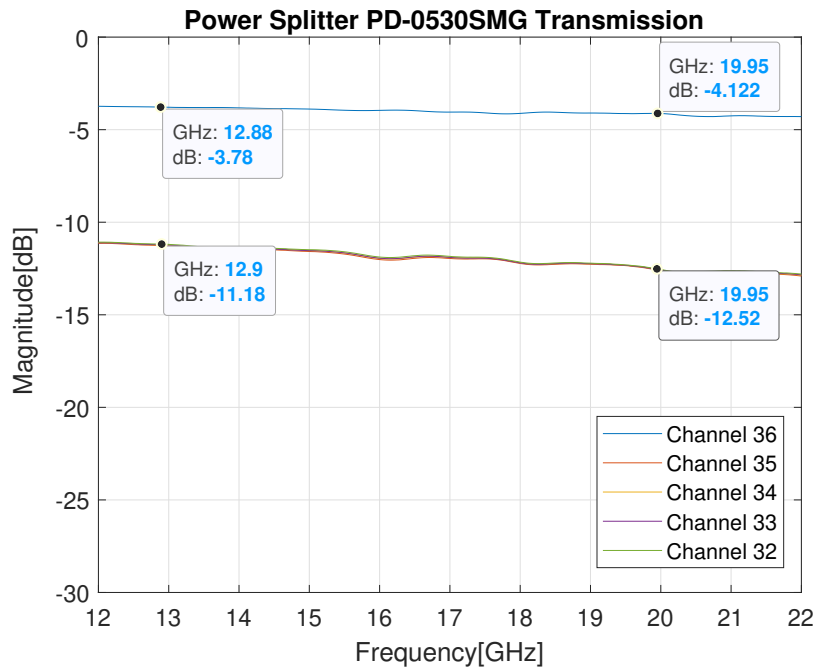


Figure A.4: Power splitter Transmission.

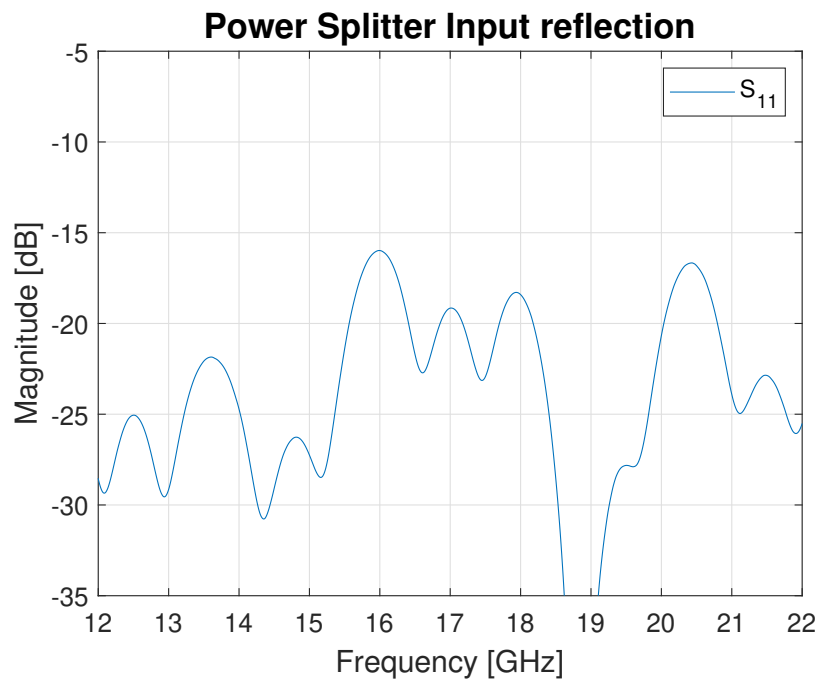


Figure A.5: Power splitter input reflection.

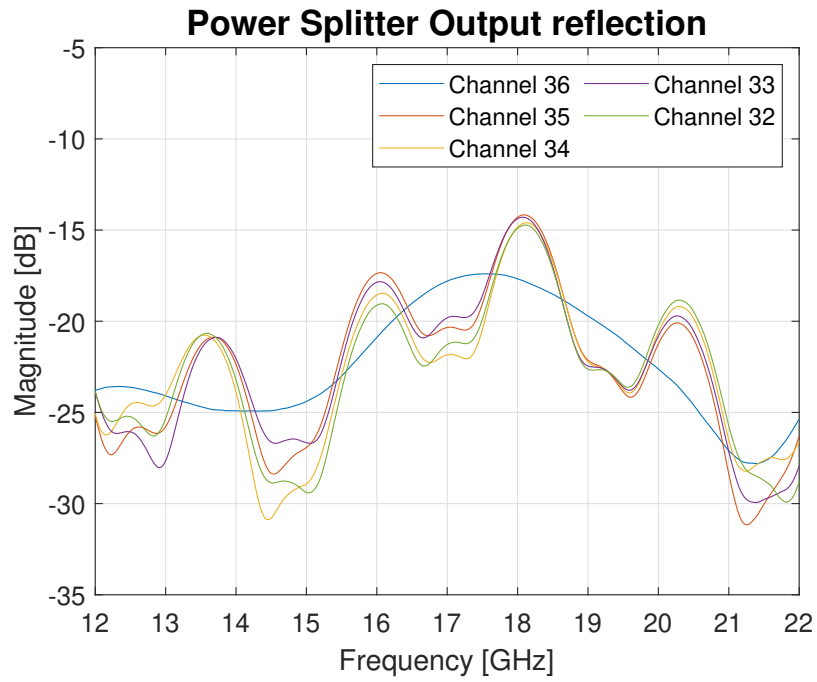


Figure A.6: Power splitter output reflection.

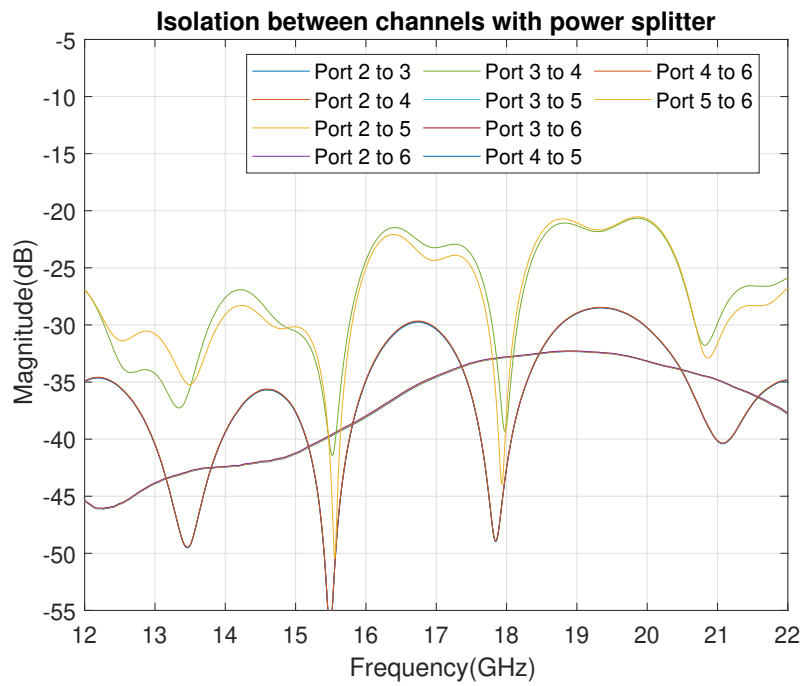


Figure A.7: Power splitter isolation.

The characteristics of PDW06038 are also tested.

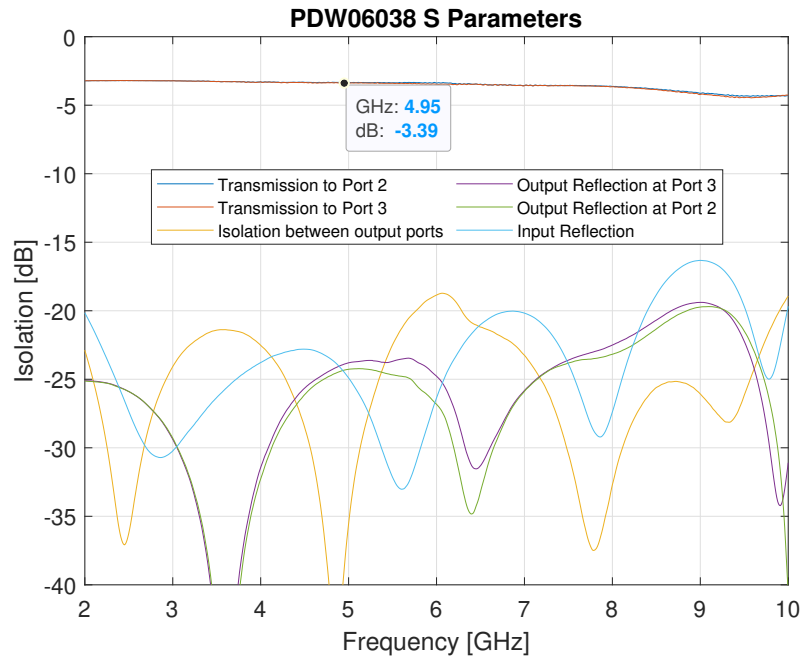


Figure A.8: Power splitter Characteristics for PDW06038.

A.2.1 Equalizer

The equalizer is used for the window channel of 183 GHz and is simulated in the figure below.

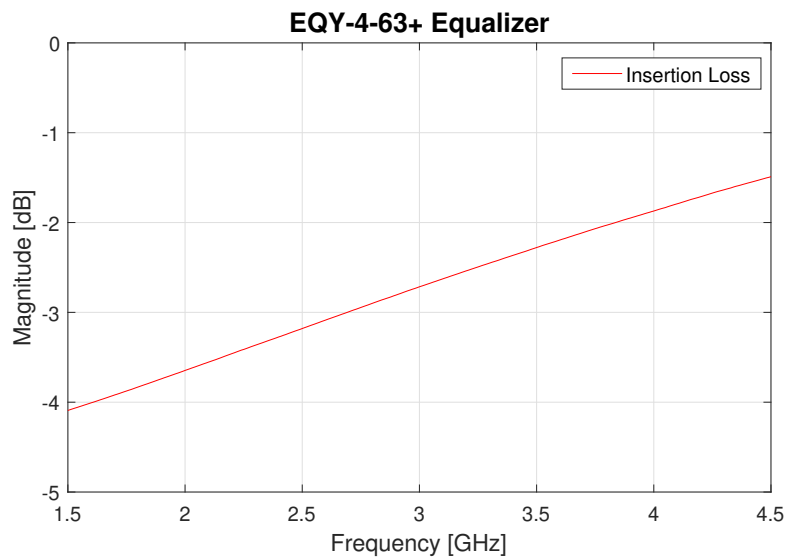


Figure A.9: EQY-4-63+ equalizer.

A.2.2 Filters

Individual filter responses are presented for all channels of 183 GHz, and Channel WC11 and WC12 FOR 54 GHz.

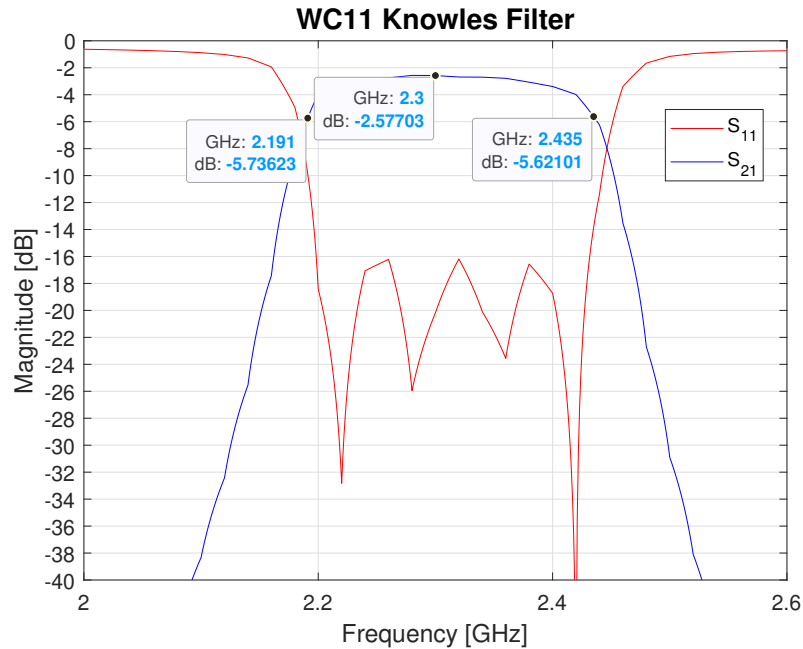


Figure A.10: Filter response for WC11 with Knowles filter and showcasing the 3 dB points.

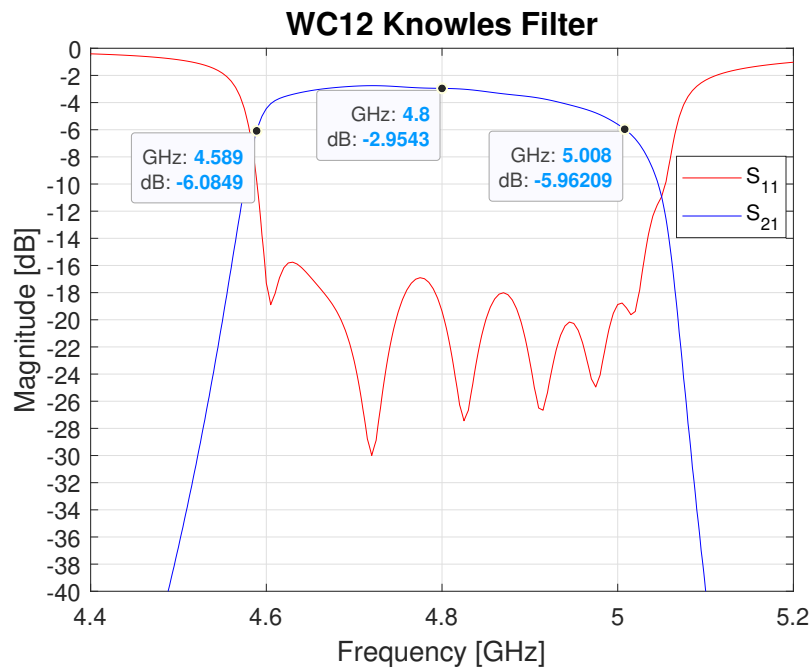


Figure A.11: Filter response for WC12 with Knowles filter and showcasing the 3 dB points.

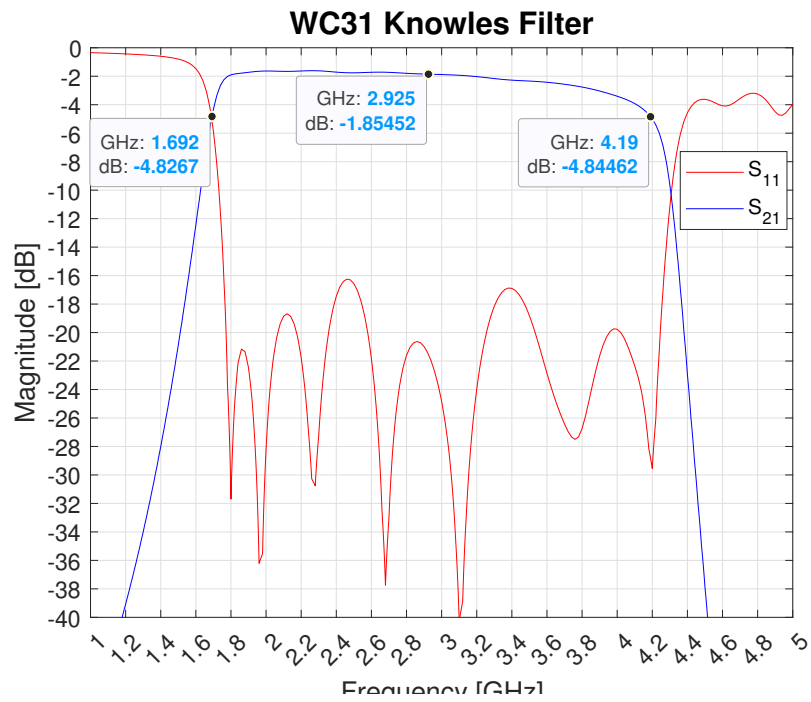


Figure A.12: Filter response for WC31 with Knowles filter and showcasing the 3 dB points.

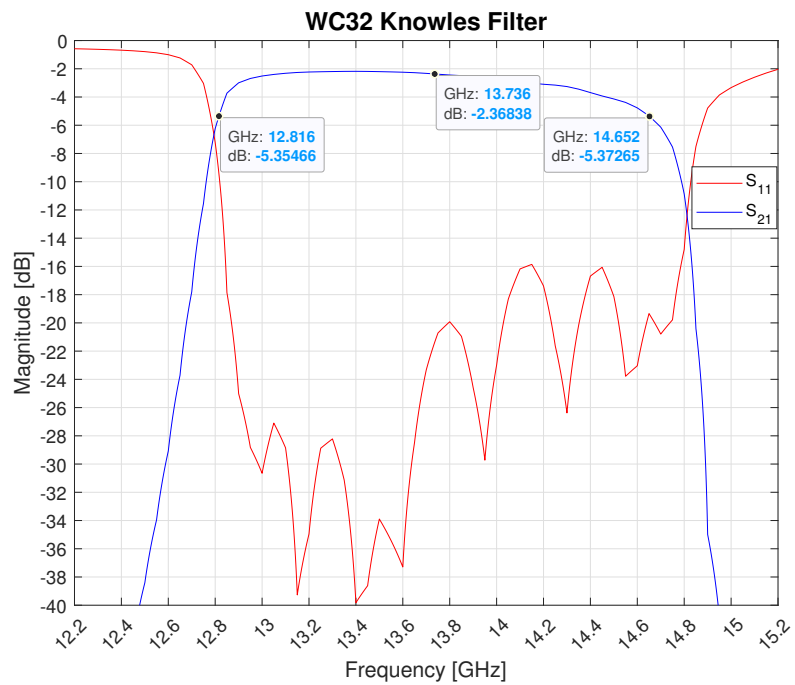


Figure A.13: Filter response for WC32 with Knowles filter and showcasing the 3 dB points.

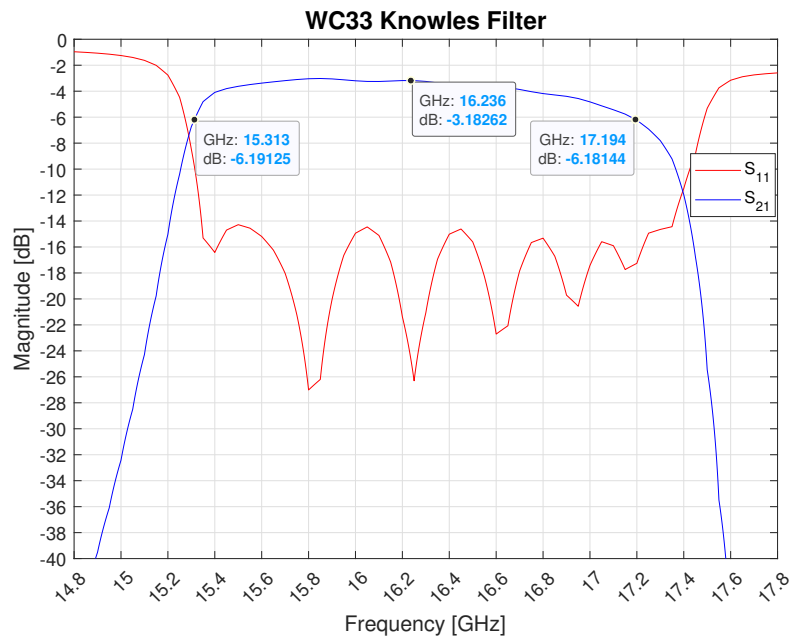


Figure A.14: Filter response for WC33 with Knowles filter and showcasing the 3 dB points.

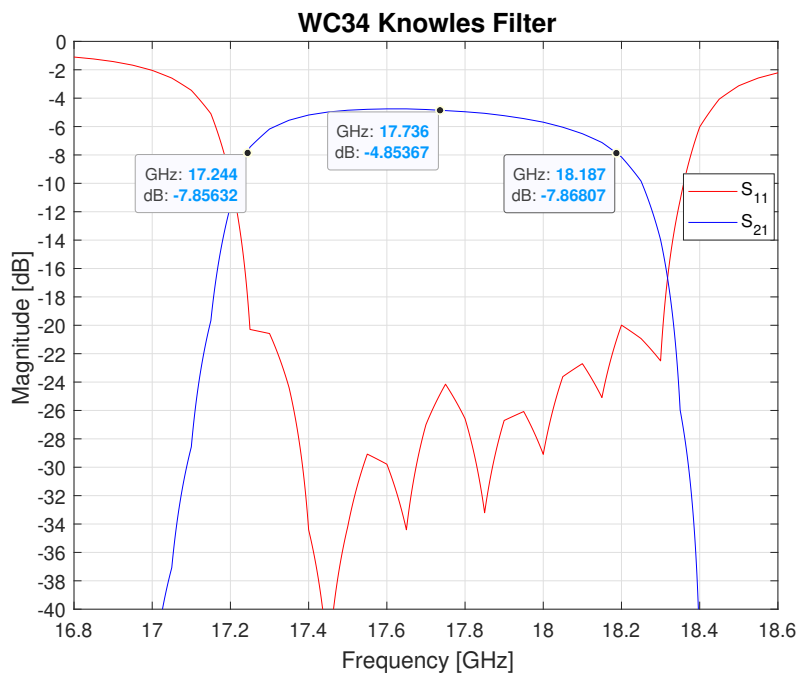


Figure A.15: Filter response for WC34 with Knowles filter and showcasing the 3 dB points.

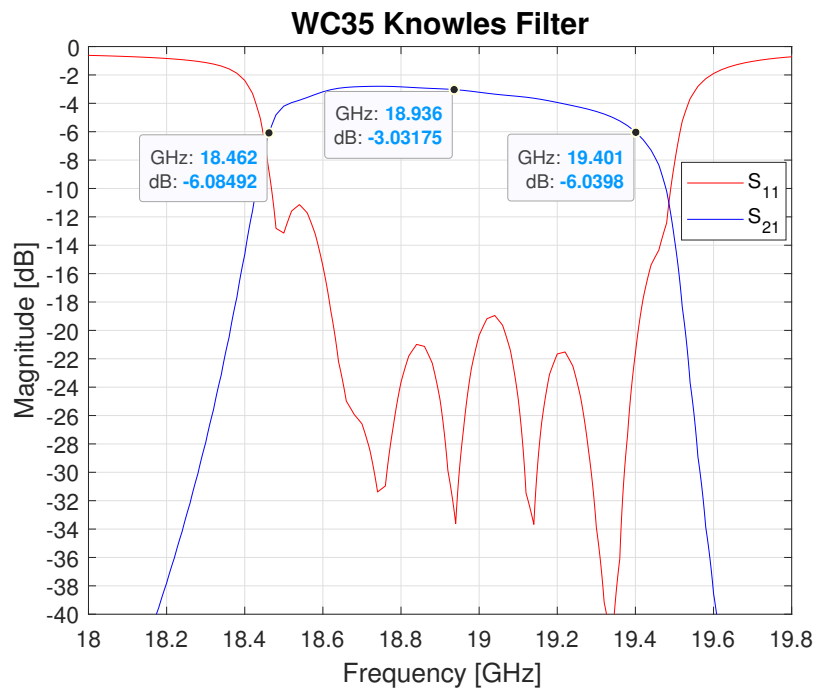


Figure A.16: Filter response for WC35 with Knowles filter and showcasing the 3 dB points.

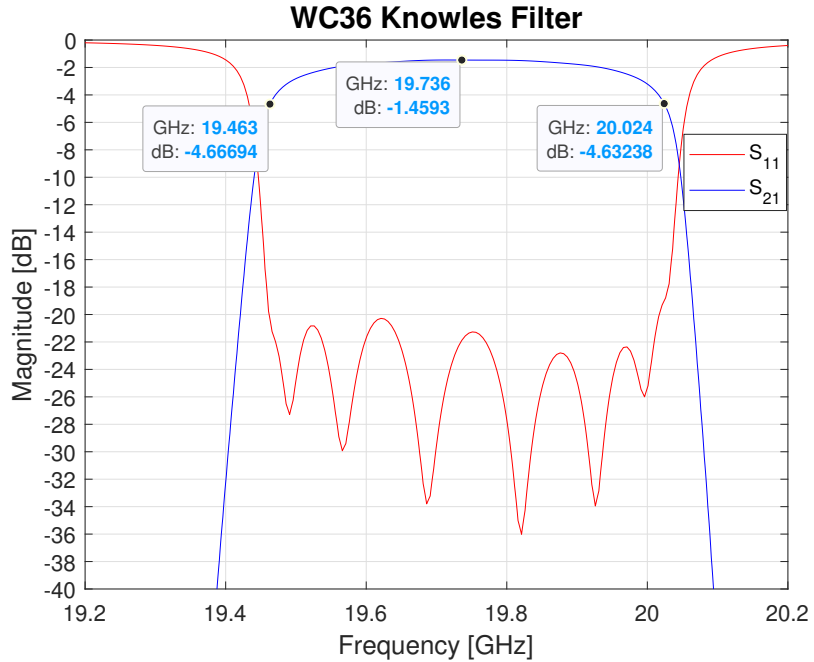


Figure A.17: Filter response for WC36 with Knowles filter and showcasing the 3 dB points.

A.3 RF Power Budgets

RF power budgets for other channels of 183 GHz are presented here. The channels are WC33-36.

Table A.1: RF power budget for WC33.

Component	Type	P_{in} [dBm] [FENBW]	Gain [dB]	P1dB _{Out} [dBm]	Noise BW [GHz]	P_{out} [dBm] [BW]	P1dB back-off [dB]
PDR06390	P.S.	-35.12	-6.30	-	20	-41.42	-
XHF14M+	HPF	-41.42	-0.92	-	10	-45.35	-
HMC342	Amp	-45.35	21	7	10	-24.35	31.35
6 dB	Att	-24.35	-6	-	10	-30.35	-
HMC342	Amp	-30.35	21	7	10	-9.35	16.35
6 dB	Att	-9.35	-6	-	10	-15.35	-
ADL9005	Amp	-15.35	12	13.50	10	-3.35	16.85
PD-0530SMG	P.S.	-3.35	-4.30	-	10	-7.65	-
2 PD-0530SMG	P.S.	-7.65	-8.60	-	10	-16.25	-
2 dB	Att	-16.25	-2	-	10	-18.25	-
KTMI-1502A16	Isolator	-18.25	-0.8	-	10	-19.05	-
Filter Min	BPF	-19.05	-3.20	-	1.8740	-29.52	-
Filter Max	BPF	-19.05	-3.20	-	1.9090	-29.44	-
MSS20-141-B10D	DD	-29.44	-	-15	-	-	-14.44
PDR06390	P.S.	-36.54	-6.30	-	20	-42.84	-
XHF14M+	HPF	-42.84	-0.92	-	10	-46.77	-
HMC342	Amp	-46.77	21	7	10	-25.77	32.77
6 dB	Att	-25.77	-6	-	10	-31.77	-
HMC342	Amp	-31.77	21	7	10	-10.77	17.77
6 dB	Att	-10.77	-6	-	10	-16.77	-
ADL9005	Amp	-16.77	12	13.50	10	-4.77	18.27
PD-0530SMG	P.S.	-4.77	-4.30	-	10	-9.07	-
2 PD-0530SMG	P.S.	-9.07	-8.60	-	10	-17.67	-
2 dB	Att	-17.67	-2	-	10	-19.67	-
KTMI-1502A16	Isolator	-19.67	-0.8	-	10	-20.47	-
Filter Min	BPF	-20.47	-2.40	-	1.8740	-30.14	-
Filter Max	BPF	-20.47	-2.40	-	1.9090	-30.06	-
MSS20-141-B10D	DD	-30.06	-	-15	-	-	-15.06

Table A.2: RF power budget for WC34.

Component	Type	P_{in} [dBm] [FENBW]	Gain [dB]	P1dB _{Out} [dBm]	Noise BW [GHz]	P_{out} [dBm] [BW]	P1dB back-off [dB]
PDR06390	P.S.	-35.12	-6.30	-	20	-41.42	-
XHF14M+	HPF	-41.42	-0.92	-	10	-45.35	-
HMC342	Amp	-45.35	21	7	10	-24.35	31.35
6 dB	Att	-24.35	-6	-	10	-30.35	-
HMC342	Amp	-30.35	21	7	10	-9.35	16.35
6 dB	Att	-9.35	-6	-	10	-15.35	-
ADL9005	Amp	-15.35	12	13.50	10	-3.35	16.85
PD-0530SMG	P.S.	-3.35	-4.30	-	10	-7.65	-
2 PD-0530SMG	P.S.	-7.65	-8.60	-	10	-16.25	-
1 dB	Att	-16.25	-1	-	10	-17.25	-
KTMI-2002A	Isolator	-17.25	-0.8	-	10	-18.05	-
Filter	BPF	-18.05	-4.85	-	1	-32.90	-
MSS20-141-B10D	DD	-32.90	-	-15	-	-	-17.90
PDR06390	P.S.	-36.54	-6.30	-	20	-42.84	-
XHF14M+	HPF	-42.84	-0.92	-	10	-46.77	-
HMC342	Amp	-46.77	21	7	10	-25.77	32.77
6 dB	Att	-25.77	-6	-	10	-31.77	-
HMC342	Amp	-31.77	21	7	10	-10.77	17.77
6 dB	Att	-10.77	-6	-	10	-16.77	-
ADL9005	Amp	-16.77	12	13.50	10	-4.77	18.27
PD-0530SMG	P.S.	-4.77	-4.30	-	10	-9.07	-
2 PD-0530SMG	P.S.	-9.07	-8.60	-	10	-17.67	-
1 dB	Att	-17.67	-1	-	10	-18.67	-
KTMI-2002A	Isolator	-18.67	-0.8	-	10	-19.47	-
Filter	BPF	-19.47	-4.85	-	1.8740	-34.32	-
MSS20-141-B10D	DD	-34.32	-	-15	-	-	-19.32

Table A.3: RF power budget for WC35.

Component	Type	P_{in} [dBm] [FENBW]	Gain [dB]	P1dB _{Out} [dBm]	Noise BW [GHz]	P_{out} [dBm] [BW]	P1dB back-off [dB]
PDR06390	P.S.	-35.12	-6.30	-	20	-41.42	-
XHF14M+	HPF	-41.42	-0.92	-	10	-45.35	-
HMC342	Amp	-45.35	21	7	10	-24.35	31.35
6 dB	Att	-24.35	-6	-	10	-30.35	-
HMC342	Amp	-30.35	21	7	10	-9.35	16.35
6 dB	Att	-9.35	-6	-	10	-15.35	-
ADL9005	Amp	-15.35	12	13.50	10	-3.35	16.85
PD-0530SMG	P.S.	-3.35	-4.30	-	10	-7.65	-
2 PD-0530SMG	P.S.	-7.65	-8.60	-	10	-16.25	-
1 dB	Att	-16.25	-1	-	10	-17.25	-
KTMI-2002A	Isolator	-17.25	-0.8	-	10	-18.05	-
Filter	BPF	-18.05	-3	-	0.9470	-31.29	-
MSS20-141-B10D	DD	-31.29	-	-15	-	-	-16.29
PDR06390	P.S.	-36.54	-6.30	-	20	-42.84	-
XHF14M+	HPF	-42.84	-0.92	-	10	-46.77	-
HMC342	Amp	-46.77	21	7	10	-25.77	32.77
6 dB	Att	-25.77	-6	-	10	-31.77	-
HMC342	Amp	-31.77	21	7	10	-10.77	17.77
6 dB	Att	-10.77	-6	-	10	-16.77	-
ADL9005	Amp	-16.77	12	13.50	10	-4.77	18.27
PD-0530SMG	P.S.	-4.77	-4.30	-	10	-9.07	-
2 PD-0530SMG	P.S.	-9.07	-8.60	-	10	-17.67	-
1 dB	Att	-17.67	-1	-	10	-18.67	-
KTMI-2002A	Isolator	-18.67	-0.8	-	10	-19.47	-
Filter	BPF	-19.47	-3	-	0.9470	-32.71	-
MSS20-141-B10D	DD	-32.71	-	-15	-	-	-17.71

Table A.4: RF power budget for WC36.

Component	Type	P_{in} [dBm] [FENBW]	Gain [dB]	P1dB _{Out} [dBm]	Noise BW [GHz]	P_{out} [dBm] [BW]	P1dB back-off [dB]
PDR06390	P.S.	-35.12	-6.30	-	20	-41.42	-
XHF14M+	HPF	-41.42	-0.92	-	10	-45.35	-
HMC342	Amp	-45.35	21	7	10	-24.35	31.35
6 dB	Att	-24.35	-6	-	10	-30.35	-
HMC342	Amp	-30.35	21	7	10	-9.35	16.35
6 dB	Att	-9.35	-6	-	10	-15.35	-
ADL9005	Amp	-15.35	12	13.50	10	-3.35	16.85
PD-0530SMG	P.S.	-3.35	-4.30	-	10	-7.65	-
5 dB	Att	-7.65	-5	-	10	-12.65	-
KTMI-2002A	Isolator	-12.65	-0.8	-	10	-13.45	-
Filter	BPF	-13.45	-1.45	-	0.46	-28.27	-
MSS20-141-B10D	DD	-28.27	-	-15	-	-	-13.27
PDR06390	P.S.	-36.54	-6.30	-	20	-42.84	-
XHF14M+	HPF	-42.84	-0.92	-	10	-46.77	-
HMC342	Amp	-46.77	21	7	10	-25.77	32.77
6 dB	Att	-25.77	-6	-	10	-31.77	-
HMC342	Amp	-31.77	21	7	10	-10.77	17.77
6 dB	Att	-10.77	-6	-	10	-16.77	-
ADL9005	Amp	-16.77	12	13.50	10	-4.77	18.27
PD-0530SMG	P.S.	-4.77	-4.30	-	10	-9.07	-
5 dB	Att	-9.07	-5	-	10	-14.07	-
KTMI-2002A	Isolator	-14.07	-0.8	-	10	-14.87	-
Filter	BPF	-14.87	-1.45	-	0.46	-29.69	-
MSS20-141-B10D	DD	-29.69	-	-15	-	-	-14.69

A.4 Measurement Layouts

Some of the measurement pictures are presented here.

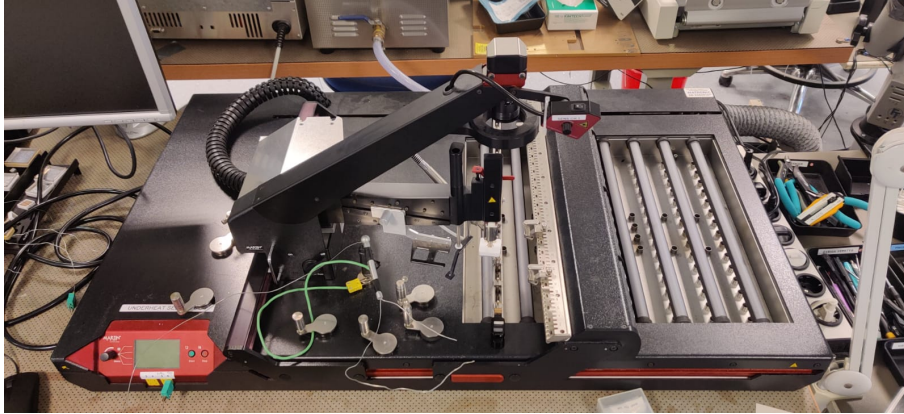


Figure A.18: Soldering machine.

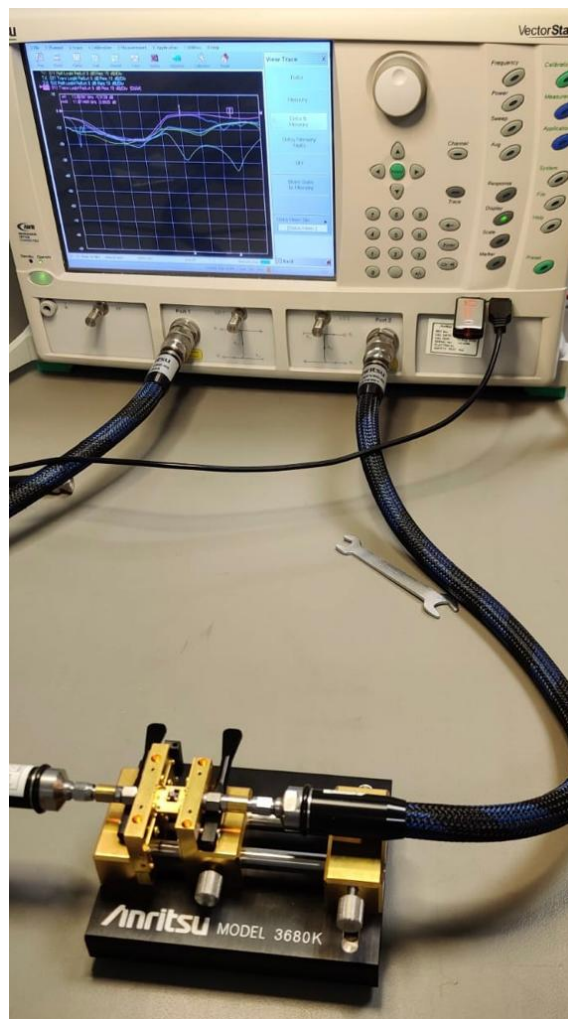


Figure A.19: Component measurement with VNA.

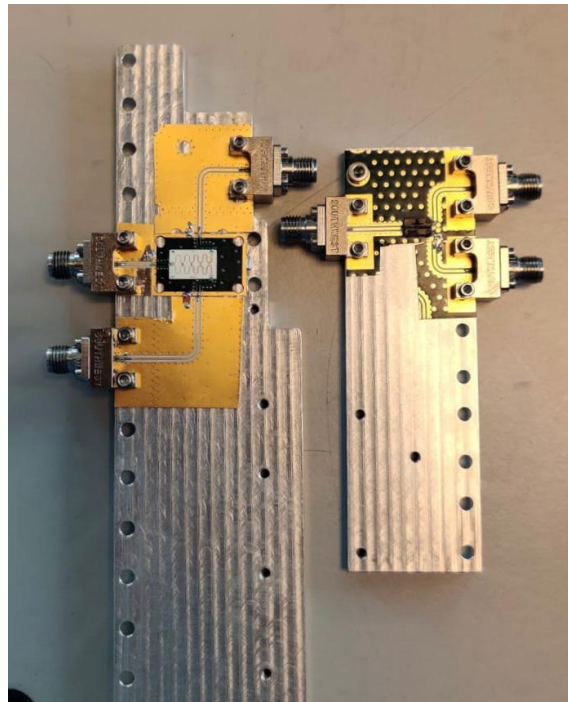


Figure A.20: Power splitter measurement circuit.

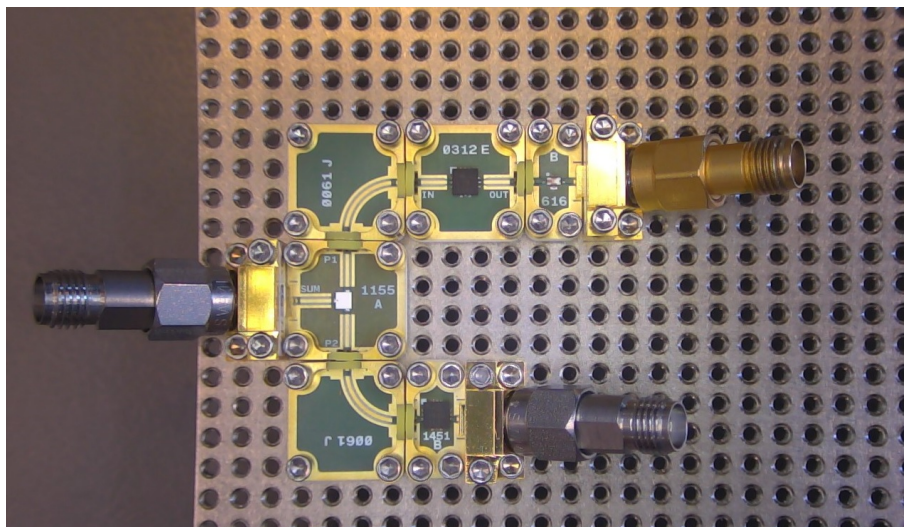


Figure A.21: Resistive divider, LP and HP Filter setup tested on the Prototype X-Microwave circuit.

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