MIDDLE EAST TECHNICAL UNIVERSITY
ELECTRICAL – ELECTRONICS ENGINEERING DEPARTMENT
EE300
SUMMER PRACTICE REPORT

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Company Name: Meteksan Savunma Sanayii A.Ş.

Company Division: Radar, RF/Analog Design Department

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1. INTRODUCTION

I have conducted my mandatory summer internship at Meteksan Savunma Sanayii A.Ş. This was my first internship. The company is a defence industry company and conducts research, development, and manufacturing. My internship lasted 20 workdays from 1 August 2023 to 28 August 2023. I wanted to perform my internship at this company because the working field of the company was a field that I was interested in. Furthermore, I wanted to experience a defence industry company and I wanted to make R&D during my internship. Because of these reasons I applied for internship to Meteksan Savunma. I had the opportunity to talk about internship with the engineers at the company and apply for internship during the METU Career Fair.

I was assigned to Radar, RF/Analog Desing department which was under the Radar Systems Vice Presidency. The department consisted of 5 to 10 engineers with 2 to 4 technicians. They were developing new systems related to electronic warfare/EM which I cannot elaborate on due to security concerns. The department was mostly responsible from the design of the products in accordance with required specifications. These products were mostly radar systems or subsystems.

During my internship, I was supervised by an experienced engineer, Yılmaz Kaan Dengizek who has a B.Sc degree in Electrical & Electronics Engineering from Bilkent University. He guided me during my internship. He was a very experienced engineer and helped me a lot during my internship. Most of the engineers there were nice and helping to me.

I started my internship by learning some fundamental concepts about Microwave and Antenna Engineering. I was assigned to read some certain articles and some parts of the book "*Microwave and RF Desing of Wireless Systems*" by David Pozar. Then in the following days I have learned how to conduct some certain measurements by using Vector Network Analyzer and Spectrum Analyzer. After learning basic concepts, I started measurements of some components used in RF design such as filters, amplifiers, and attenuators. I also had the chance to witness some test process of manufactured and developed products. Through the end of my internship, I have learned how to use Keysight GENESYS - which is a tool for microwave simulation, modelling, design, and optimization - and I have developed a RF filter by using that tool. Moreover, I have realized the filter by soldering real components and done a final measurement on it.

I have learned some crucial methods and skills used in RF design during my internship. Also, thanks to the approach of my supervisor, I learned some significant concepts about Microwaves & Antennas field, and I had the chance to see the practical side of this field.

In this report, I will briefly describe the company. Then through the following chapters, I will try to tell and elaborate on the work I have done during my internship. I will use graphics, figures, and images to emphasize what I want to report in a better way.

2. DESCRIPTION OF THE COMPANY

2.1 Company Name

Meteksan Savunma Sanayii A.Ş

2.2 Company Location

Meteksan Savunma Sanayii A.Ş. company is located in Ankara, Türkiye. The company has a research and development facility which is located at Bilkent CYBERPARK.

Address: Cyberpark F Blok Beytepe Lodumlu Köy Yolu No:85/A Bilkent Çankaya Ankara/Türkiye

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2.3 Review of the Company

Meteksan Savunma is a Turkish defence industry company which was established in 2006. The only shareholder of the company is Bilkent Holding and due to this, the company has close connections with Bilkent University in terms of internship and job opportunities. The main establishment goal of the company was to provide high-technology products and systems for the Turkish Armed Forces and other security foundations in Türkiye. Company now designs military based solutions for its local and international clients. The company is in high co-operation with the Presidency of Defence Industries throughout the development and deployment processes of the products. The products and solutions of the company specialize in radar systems, communication systems, laser & electro-optic systems, electronic warfare systems, perimeter surveillance and intelligence systems, platform simulators and underwater acoustic systems.

Meteksan Savunma has advanced technology infrastructure investments which are used in production, test, and design processes. Some of these are:

1) Class-10.000 Clean Room

2) Near Field Antenna Measurement System

3) Underwater Acoustic Laboratory

Meteksan Savunma is also known for its underwater acoustic facilities. The company is often referred as the Underwater Acoustic Excellence Center of Türkiye. With its facilities in Ankara and its collaboration with a shipyard in Antalya, Meteksan Savunma designs and develops advanced underwater acoustic sonars. Furthermore, the company develops high-level platform training simulators for military units such as submarines, ships, and air platforms in accordance with the request and need of Naval Forces.

Meteksan Savunma designed and developed the first indigenous armed unmanned surface vessel (AUSV) which was named “ULAQ”. It is also one of the famous products of the company. ULAQ is an unmanned combat boat equipped with crypto and electronic warfare protected communication infrastructure and state-of-the-art missile/weapon systems. It can operate autonomously, or it can be controlled remotely. As ULAQ’s test phase is coming to an end, it will be used in firefight, search & rescue, patrol, and security missions.

Figure 1 – ULAQ

Meteksan Savunma gained a valuable experience on radar and RF (Radio Frequency) systems since its foundation in 2006. Radar systems are the one of the oldest systems that the company has ever produced. That’s why company is also famous for its radar solutions. “MILSAR” is a radar system developed by the company which can be integrated on UAVs and other aerial platforms. It can provide more precise calculations when compared to the predecessor electro-optic sensors which were used in air platforms. Furthermore, company has recently developed a perimeter surveillance radar system called “Retinar”. It is a mobile radar which is easy to transport and fast to deploy, and it is used for zone and border security.

Figure 2 – MILSAR

Figure 3 – Retinar

2.4 Organization of the Company

Figure 4 – Organization Schematic

The total number of people working for the company is 323. Most of these people are engineers which are responsible for research and development process. Other most significant part consists of technicians who are mainly responsible form testing and manufacturing process.

In the department where I have conducted my internship – which is RF/Analog Design Department- most of the staff were engineers with a B.Sc or M.Sc degree in EE. The others were technicians who were specialized in testing process.

2.5 Brief History of the Company

Meteksan Savunma was founded in 2006 by Bilkent Holding to unify the defence industries related projects and activities of the other members of the Bilkent Holding. The company was firstly developing radar systems and subsystems for Turkish Armed forces and its allies.

3. FUNDAMENTAL CONCEPTS

3.1 Scattering Matrix (S – Parameters)

Scattering matrix (S-Parameters) is known to provide description about a microwave junction or network. Due to high frequency, reflected signal level becomes undeniable. At that point a relation between incident wave and the reflected wave helps to model the network better.

$$\begin{bmatrix} V_1^- \\ V_2^- \\ \vdots \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1N} \\ S_{21} & & & \vdots \\ \vdots & & & \vdots \\ S_{N1} & \cdots & & S_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ \vdots \\ V_N^+ \end{bmatrix}$$

$$[V^-] = [S][V^+].$$

Figure 5 – Scattering Matrix

$$S_{ij} = \left. \frac{V_i^-}{V_j^+} \right|_{V_k^+ = 0 \text{ for } k \neq j}.$$

Figure 6 – Calculation of S parameters

With the help of this modelling matrix of waves through a network, it becomes easier to analyse the microwave junction mathematically. For example, S_{21} means the ratio of the reflected wave from port 2 due to the incident wave form port 1.

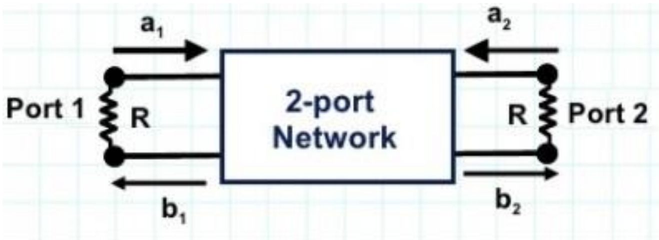

Figure 7 – 2 port network

S_{11} : Voltage of the reflected wave from port 1 over voltage of the incident wave over port 1. This parameter is often referred as "Return loss" which means the part of the signal which fails to be sent from the transmission line.

S_{21}: Voltage of the reflected wave from port 2 over voltage of the incident wave coming from port 1. This is often referred as "Insertion loss" which stands for the portion of the incident wave which succeeded to travel through the transmission line.

For the ease of further calculations, S parameters are generally used in decibels (dB). To apply the previously mentioned ratios displayed in Figure 6 and to find the S-parameters, all the other ports of the network need to be "matched", which is a following key topic.

3.2 VSWR

Voltage Standing Wave Ratio (VSWR) is the ratio of the maximum and minimum voltage on a TL. This parameter is important because RF devices are designed the operate in a certain interval of power and VSWR indicates the peak values of the power over the line.

3.3 Impedance Matching

Nowadays, most of the microwave systems use 50Ω impedance for ports, cables etc. The reasons behind the 50 Ω is maximum transfer and minimum loss. As it can be seen in Figure 8, highest power transform occurs at 30Ω when a TEM (Transverse Electromagnetic) wave travels through a coaxial cable. Furthermore, lowest lost occurs at 77Ω for most of the dielectric-filled coaxial cable. Arithmetic mean of these two values give 53.5Ω, which is considered as 50Ω for ease.

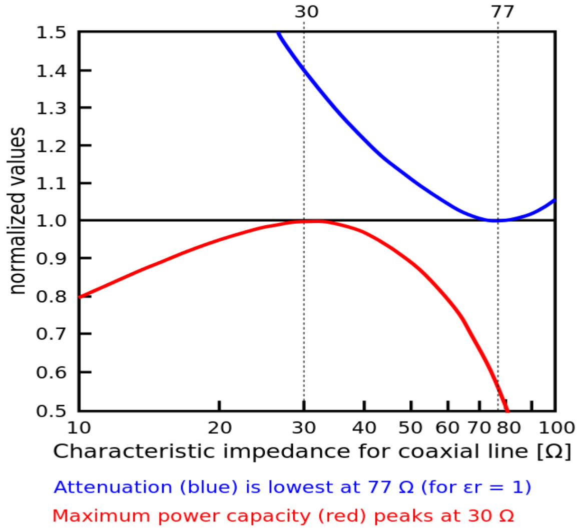

Figure 8 – Attenutation and power capacity versus chracateristic impedance of the cable

When two microwave components meet, for example a coaxial cable is connected to a port, they are expected to have the same impedance to optimize the transmission process. If the two mediums provide the same impedance, then incident wave travels throguh the junction as if it is not a junction but it is still a part of the cable. This situation is called “impedance matching” and it is crucial for systems with high sensitivity.

3.4 Power, dB, dBm

When analysing TEM waves, power of the signals becomes more important than the other properties. This is because insertion, reflection and transmission stages all affect the power level of the output . Thus, a relation between input and output signal power becomes handy. Since a comparison is made between these two signals, using logarithmic scale (decibels) makes calculations easy. The unit “dBm” is the power measured in reference to 1mW. That means if an output power is 10 mW, then it is 20log(10/1) = 20 dBm. Conventionally, dBm is used instead of watts when indicating power.

3.5 Transmission Lines (TL)

Due to the high frequency of microwave signals, a special treatment is required when it comes to transmission. There are several types of transmission lines such as microstrip, strip line and CPWG (Co-planar Waveguide).

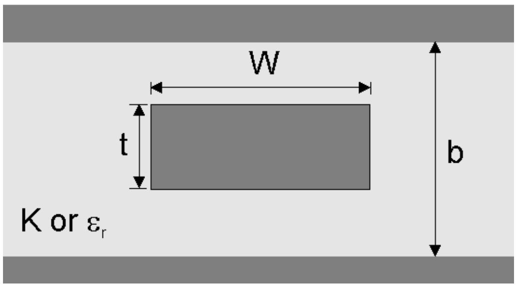

Figure 9 – Stripline

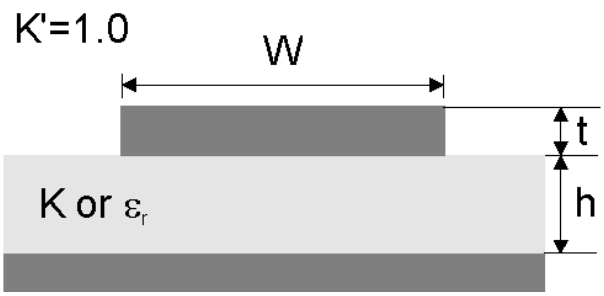

Figure 10 – Microstrip

Stripline: In this TL configuration, TL is sandwiched between a dielectric which has ground planes. These plates can be seen in the top and bottom part of Figure 9. With this configuration, radiation from the TEM wave passing through the TL is minimized and thus reflection loss is less in this case. Moreover, it is more immune to EM interference coming from outside.

Microstrip: In microstrip, TL is on the top, with a dielectric below and a ground plane at the bottom, which can be seen in Figure 10. Due to less interaction with dielectric, dielectric loss is way too less when compared to stripline. Moreover, since the TL is on the top, it can be seen in the surface of the PCB and thus it is easy to design. However, since TL has a direct contact with air, it is prone to be distorted by outside noise.

Coplanar Waveguide (CPWG): This configuration is very similar to microstrip; however, this time TL has ground planes nearby and ground loops can occur faster, which is important for high-speed signals to reduce noise.

SMA: SMA(Sub-Miniature) version A is a type of interface used in RF ports and connectors. It can be considered as the default interface of RF connections.

Figure 11 – SMA Ports

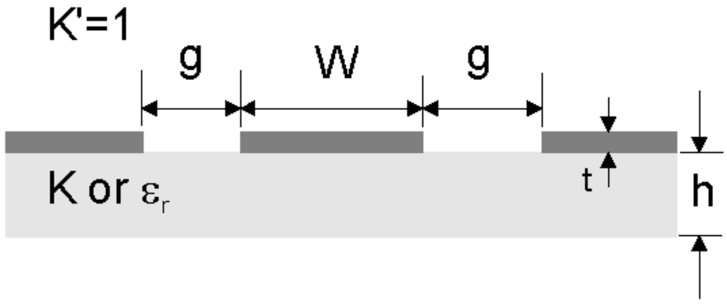

Figure 12 – CPWG

Transmission lines can be designed with different parameters such as width, thickness etc. In Figure 9 and 10, the one can see the physical properties of TL. These parameters affect the impedance value of the TL which is crucial for matching.

4. MEASUREMENT & TEST

During my internship, I had the opportunity to work with different measurement tools. These tools were, Vector Network Analyzer (VNA), Spectrum Analyzer and Phase Noise Analyzer. All devices are used for certain measurements, and they are superior to each other in different measurements. I also had the chance to observe a testing process.

4.1 Vector Network Analyzer

This was the device which I used most. A vector network analyser is generally used to measure transfer properties. A device -which is conventionally called DUT (Device Under Test)- is connected to the two ports of the VNA. VNA sequentially sends signals from its one port and listens from the other port. In this way, S-parameter values can be measured. If one wants to measure S_{21} or S_{12}, VNA would be the best measurement device. I have done measurements on attenuators and filters with VNA. A VNA must be calibrated before the measurement because of the imperfection of the cables connecting the DUT to the device. I also conducted this calibration process a dozen times.

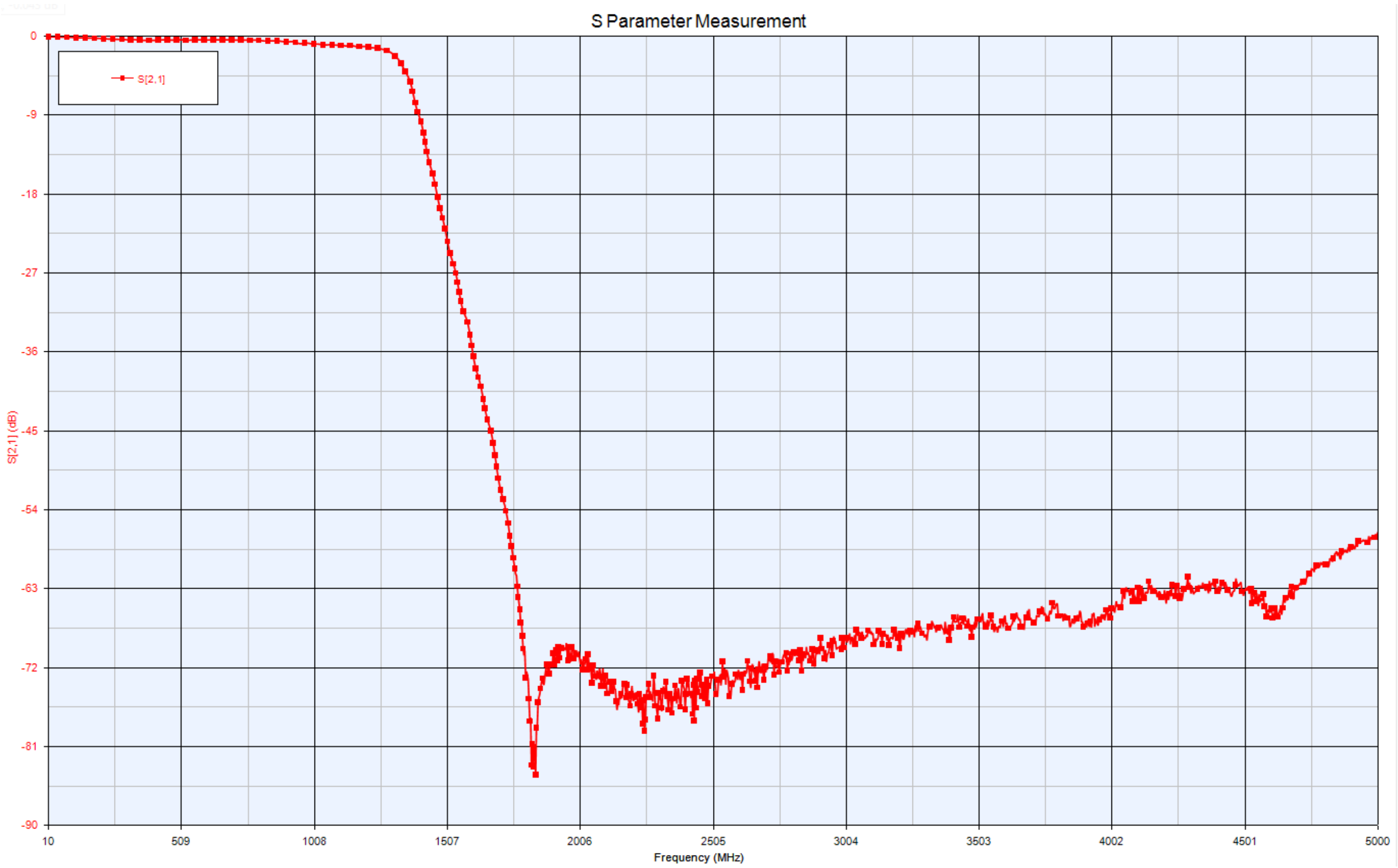

Figure 13 – S_{21} measurement data plot

I have measured a filter with VNA. In Figure 13, the one can see the S_{21} parameter of this filter. The s-parameter values are saved by the VNA and then can be plotted from GENESYS.

4.2 Spectrum Analyzer

Spectrum analzyer is a device that measures and displays signal amplitude as it varies by frequency within its frequency spectrum. With the help of a spectrum analzyer, components of a signal can be observed. I have observed an antenna measurement with spectrum analyzer. The engineer open circuited all the other ports of the antenna then connected the one last port to the analyser and observed S_{11} behaviour.

4.3 Phase Noise Analyzer

As it can be understood from its name, this device is specialized on measuring the phase noise of complex and mixed signals. This device uses XCORR (Cross Correlation Method) to observe the phase noise.

Figure 14 - VNA

Figure 15 – Spectrum Analyzer

4.4 Climatic Chamber Test

I had a chance to observe a climatic chamber test in context of testing part of R&D process of a product X, which I am unable to give details about due to security concerns. Climatic chamber test simply simulates extreme conditions on DUT. Device X was put in a special cabin which is called “Environmental Chamber”. Engineers observed the behaviour of the device X while applying and adjusting different environmental conditions on it. In other words, they tested the device for different levels of temperature and humidity while observing certain parameters about the device such as voltage level.

Figure 16 – Phase Noise Analyzer

Figure 17 – Environmental Chamber

5. NOISE AND DISTORTION

In such high frequencies, a lot of parameters affect the behaviour of a TEM wave. In my internship, I had the chance to get familiar with the concept of noise, how to detect it, how to eliminate it etc. There are several parameters important for the success of microwave systems, which I will explain in this chapter.

5.1 Thermal Noise

Thermal noise is the noise which occurs regardless of the microwave system, but dependent upon the temperature of the environment. In other words, thermal noise always exists in a signal.

$$P = kTB$$

Equation 1 – Thermal Noise Formula

The one can obtain the thermal noise from Equation 1 where P stands for the power of the noise, T stands for the temperature (in Kelvins), B stands for the bandwidth and k stands for the Boltzmann constant. For a 50Ω impedance system, the thermal noise at room temperature is -174 dBm/Hz.

5.2. Noise Figure

In a non-ideal signal wave, there always exist noisy signals. The noise level is often called noise floor. In Figure 18, the one can see the red line as the desired signal at frequency f_1. For all other frequencies, there exists a signal with very low power, which is called noise floor and indicated as brown in the same figure.

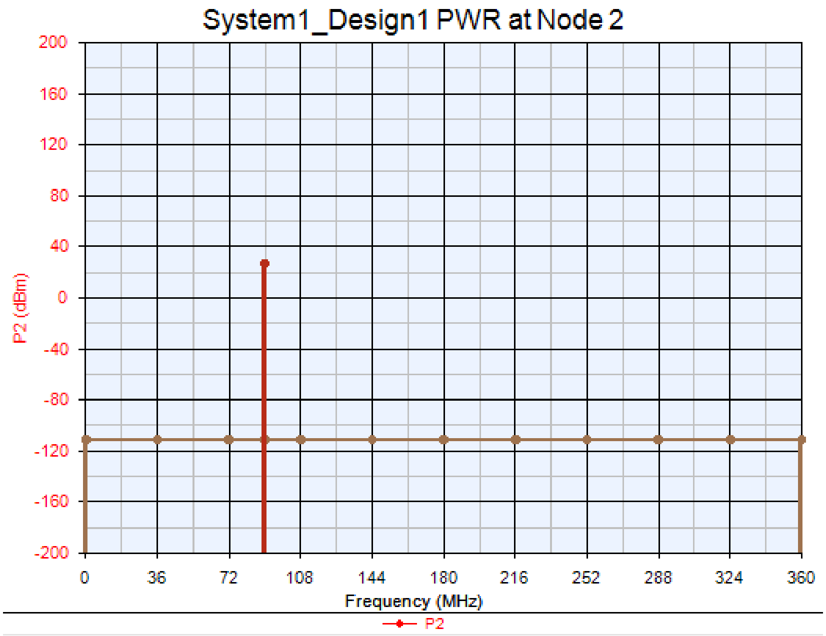

Figure 18 – Thermal Noise Formula

Noise figure is the quantity which indicates the increase in noise floor level. For example, a signal has a noise floor of -150 dBm. This signal is transmitted to an amplifier A with gain G and noise figure of NF. Amplifier would amplify all signals no matter if it was a noise or not. The noise floor would normally result in (-150+G) dBm. However, due to do nonideality of the amplifier A, noise floor increases NF more and becomes (-150+G+NF) dBm. The one can see that as the number of components which the signal pass through increase, the noise floor starts to increase due to Noise Figure of the components, which results in a noisy signal. I have measured the Noise Figure value of different components by using spectrum analyzer with different methods.

5.3. 1 dB Gain Compression Point

There are several parameters to understand the response of an RF component to various microwave excitations. One of the most crucial one among them is 1 dB gain compression point, which is often referred as P1dB.

In a certain frequency interval, some RF components are designed to work linearly. For example, a 20dB gain is expected from an amplifier which has a gain of 20dB. However, as the frequency deviates from that certain interval, the gain behaviour starts to change from its nominal value. P1dB indicates the point where gain value deviates for 1dB from the theoretical value. This parameter is an important parameter for amplifiers and can be found in datasheets.

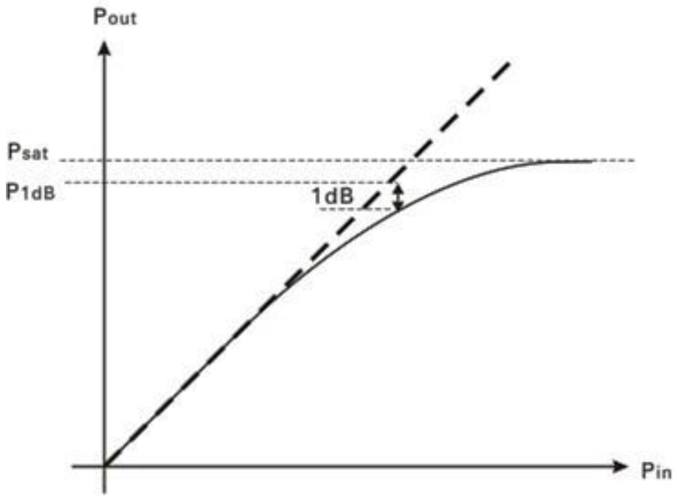

Figure 19 – P1dB diagram

In Figure 19, the deviation from the ideal response can easily be seen. This point is useful to find out the maximum input power level for an ideal response.

5.4 Interception Point (IP2 / IP3)

When a two or more signals are used in a non-linear system-for example a mixer, some unexpected responses occur. These are harmonics and intermodulation products. Harmonic distortion occurs because of the mixing process of the signal with itself. However, intermodulation products occur due to the mixing of two different signals.

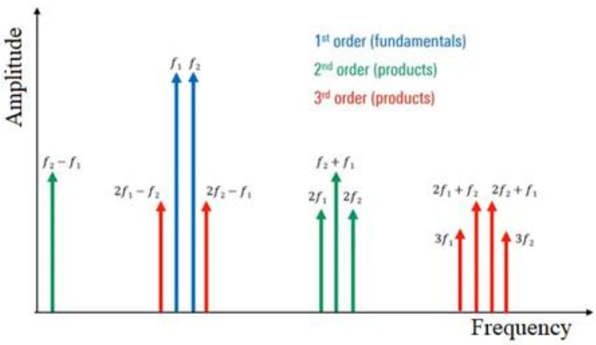

Figure 20 – Harmonics and Intermodulation Products

Say there is an input signal x(t) and output y(t). By Taylor's expansion of the transfer function, y(t) is equal to the linear combination of powers of x(t) which can be shown as $y(t) = a_1.x(t) + a_2.x(t)^2 + a_3.x(t)^3 + \ldots\ldots +$ H.O.T (Higher order terms). Let's say x(t) $= A\cos(wt)$ and H.O.T are eliminated by a low pass filter. If we insert x(t) to previous equation and if we perform trigonometric identities, we obtain gain $G = (a_{1.} + 3a_3.A^2)/4$. For low input power level (lower A value) secondary part of the gain can be neglected and a linear gain can be found. However, for a sufficiently large input power, secondary part of the gain starts to dominate the gain. The coefficient of the 3rd order intercept a_3 gets bigger due to the dominated gain and the power level of the 3rd order interception signals starts to increase. The point intermodulation point IP3 is defined as the point where the input power is sufficiently large and 3rd intermodulation intercepts with fundamental signal and starts to compress it. At this point, the amplification process is unhealthy since the output signal is extremely noisy because of the high-power level intermodulation products. IP2 has the same logic except this time 2nd order intermodulation products are considered. However, since 2nd order product falls far from the fundamental signals in frequency domain, they are easy to filter out. Thus, IP3 is a more decisive parameter for an amplifier.

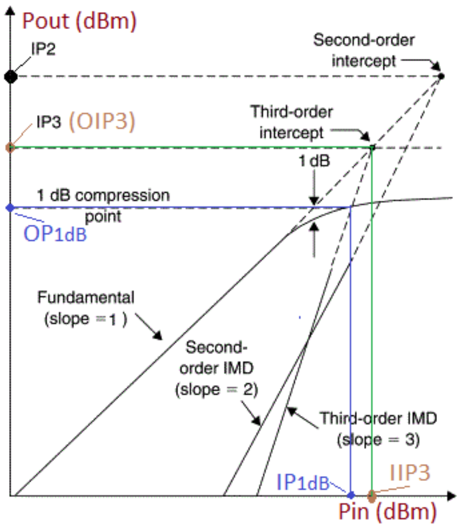

Figure 21 – IP3 and IP2 interception visualized

6. RF COMPONENTS

During my time at Meteksan Savunma, I was able to observe and learn the basics of various components and devices which are frequently used in RF Design field. These were amplifiers, attenuators, filters, mixers, and couplers. I had the chance to measure and test some of them and I also had the chance to simulate some of them with GENESYS. I will give a brief information about the component and share my experience about it.

6.1 Amplifiers

Amplifiers are mainly used to increase the power of a signal. They are an essential part of PCBs used in RF Design. I did some calculations and simulations on GENESYS about amplifiers during a design phase of a small system which I will write about in the following chapters.

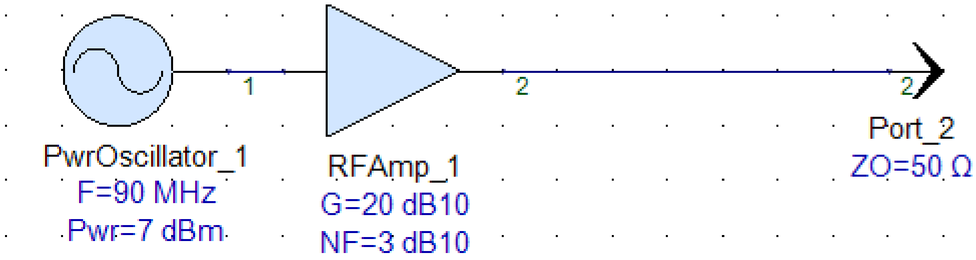

Figure 22 – Amplifier System Example

In Figure 22, there is a basic system which I have simulated from the software. A signal with defined frequency and power level enters the amplifier. Then, amplifier levels up the power of the signal with respect to its gain value G. In the example, the outcome signal power level is 27(7+20)dBm. There are also other crucial parameters of amplifiers such as Noise Figure (NF). The one can see that power is indicated in dBm and the impedance of the output port is 50Ω.

6.2 Attenuators

Attenuators can be considered the device which applies the reverse operation of an amplifier. It attenuates the amplitude of a signal with respect to a defined rate of attenuation.

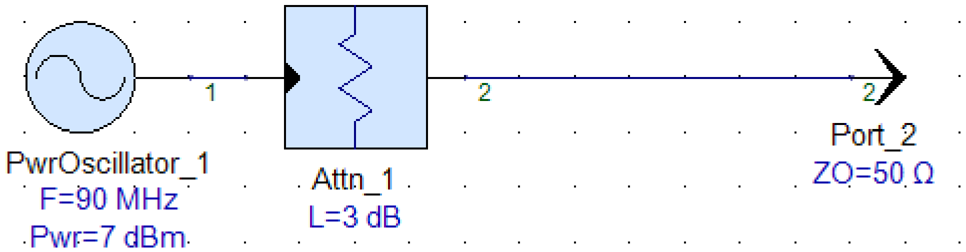

Figure 23 – Attenuator System Example

In the example shown in Figure 23, a signal with 7dBm power enters the attenuator which has a loss rate of 3dB. The one can see that output signal has 4dBm power.

6.3 Mixers

Unlike the two previous components, mixers are used to manipulate the frequency property of a signal. In short, mixer is a 3-port non-linear RF component which produces a signal that has the frequency of the sum (or the difference of) the incoming signals. It is mostly used to transform the frequency of an incoming signal whether to Intermediate Frequency (IF) or Radio Frequency (RF). The outcome always consists of the sum and the difference of the incoming signals. The wanted part can be easily distinguished by the other product by a very simple filter. Generally, a local oscillator with a perfect stability is connected to LO port of a mixer. The other ports are connected with respect to the desired outcome. There two different types of uses of a mixer. These two types are up-conversion and down-conversion. In up-conversion, the frequency of the output signal is higher than the input signal whereas the case is completely opposite in down-conversion process.

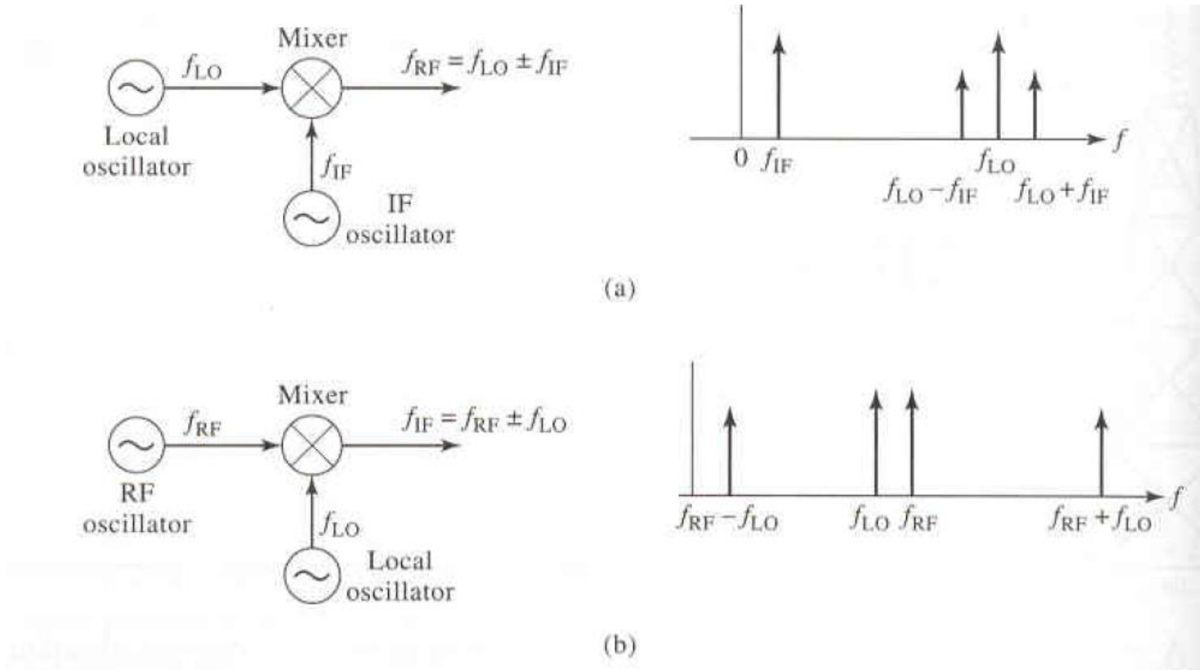

Figure 24 – Representation of up-conversion (a) and down-conversion (b)

Since mixers are non-linear components too, similar parameters were also defined for them like the situation in 6.2 and 6.1. Expected frequency of the output signal of a mixer is $f_1 + f_2$ and $f_1 - f_2$ where f_1 and f_2 are input signals. However, because of the non-linearity of mixers some unwanted products also emerge. These products are intermodulation products which were mentioned in 5.3. Because of this, some parameters like NF and IP3 also applies for mixers too. There also a power dissipation happens in mixers and a conversion loss is an important parameter of a mixer due to this. Isolation is another important property of a mixer. Since two or more signals pass through mixers, it becomes super important if they travel the correct path through the component. This is important because an unwanted coupling would affect the output signal frequency and there also would be more power loss.

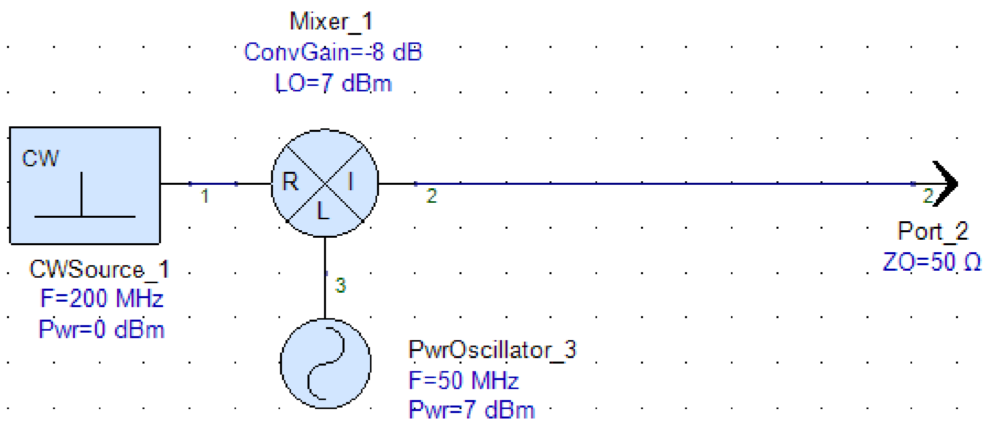

Figure 25 – Basic RF system for mixer operation example

During my internship I have simulated many RF systems by using SPECTRASYS – RF system architecture design and simulation tool- on GENESYS to understand the basics of RF components and build a basic system. In Figure 25, the one can see a basic mixer system. A 200MHz input signal and 50MHz is connected to mixer. The parameters like signal power and conversion loss can be seen from the figure.

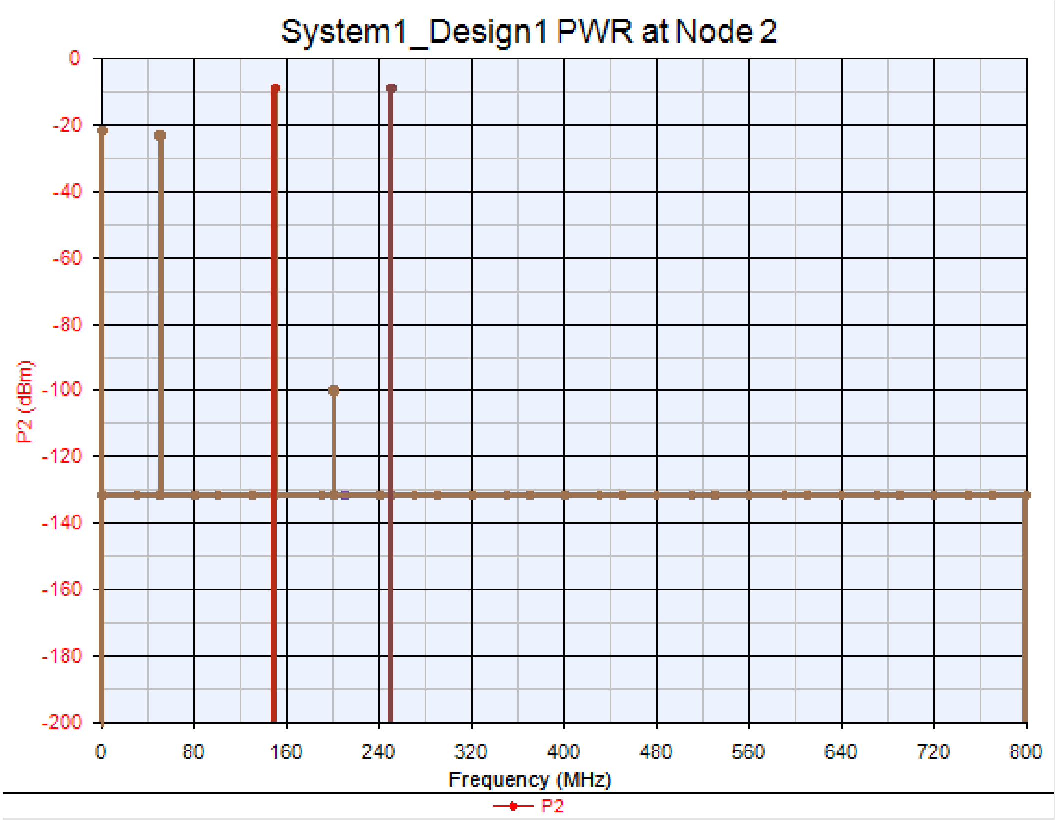

Figure 26 – Output signal in frequency domain

Figure 26 represents the output signal in frequency domain. As expected, output signal contains different signals with different frequencies. For example, 150 MHz and 250 MHz signals are the product of summation and difference operation done by mixers. Due to non-linearity and imperfection, the input signals and thermal noise also show up at output signal.

7. RECEIVER SYSTEM

During my internship, I had the chance to learn the basics of a simple receiver system, namely superheterodyne receiver. I had studied the part related to this topic from the book of David Pozar. Then I tried to mimic a superheterodyne receiver system from Keysight GENESYS and observed the results. I will first talk about a superheterodyne receiver system, then I will elaborate on my work.

7.1 Superheterodyne Receivers

Receivers are special RF circuit systems which are designed to perform the necessary operations between the antenna and the signal processing unit. Some of these operations include amplification, mixing or rarely attenuation. There are very different types of receiver architectures which are useful for different operation conditions. I will only write about superheterodyne receivers. Superheterodyne receivers are the most famous type of receivers all around the world. Different configuration of amplifiers, mixers and filters are used to transform the RF signal coming from the antenna to an IF signal to transmit to the demodulator.

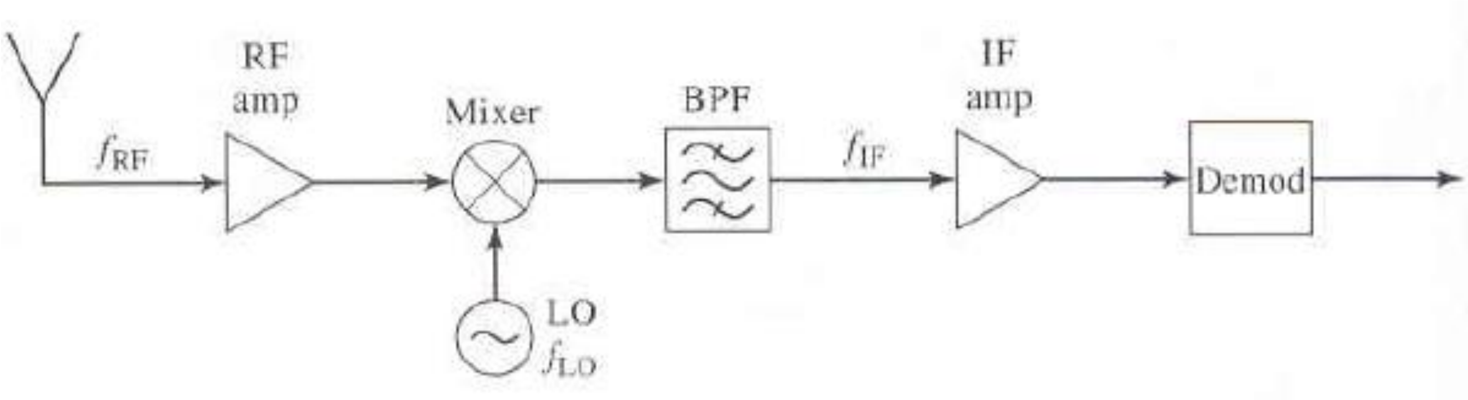

Figure 27 – Diagram of a superheterodyne receiver

In Figure 27 the one can see that the frequency f_{RF} coming from the antenna is converted to am IF signal with frequency f_{IF} thanks to mixer and filter, and sent to the demodulator with a sufficient power level with help of amplifier.

7.2 Low Noise Amplifiers (LNA)

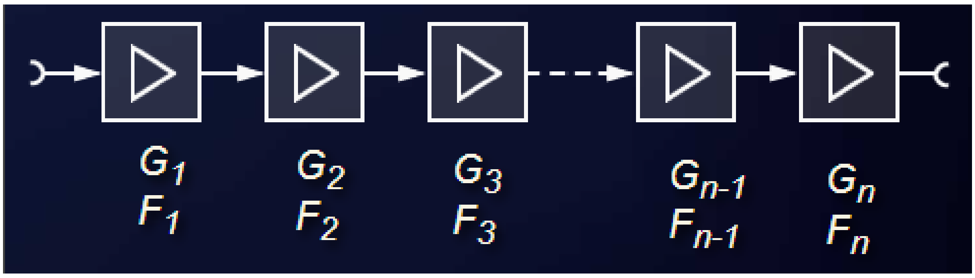

Figure 28 – Cascaded amplifiers

Imagine a system with amplifiers connected to each other like the one shown in Figure 28, which often called cascaded. Structures like the ones in Figure 28 appears a lot in receiver architectures since power level of a signal is very crucial for those systems. An overall noise of all cascaded system can be found with a special relation.

$$F_{total} = F_n + G_n \cdot \{F_{n-1} + G_{n-1} \cdot [\ \ldots\ F_3 + G_3 \cdot (F_2 + G_2 \cdot F_1)]\}$$

Figure 29 – Total noise of cascaded amplifiers

Figure 29 shows the mentioned relation to find the total noise. If the one investigates the equation closely, it is easy to see that as the index n increase, the effect of the noise of n^{th} amplifier decreases since it is divided to previous noise figure and gain. Therefore, the first term F_1 is the decisive factor for the total noise. F_1 stands for the noise figure of the first amplifier in the system. Since F_1 is the most dominant part for total noise, it is generally selected to be low. The low noise concept comes from the previously mentioned fact. A low noise also comes with a trade-off with less amplification. However, this handicap can easily be tolerated with adding amplifiers whereas it is extremely hard to compensate if a system is not equipped with low noise amplifier (LNA). In my system, I have considered this fact and chose my components with respect to this information.

7.3 Overall Process

During this task of my internship, I was given to mimic and design a superheterodyne receiver architecture for given specifications. Then I have realized the system components by entering the real measured parameters of real components in the market by looking their datasheet. Then I finalized my basic superheterodyne receiver system by conducting necessary measurements. All the test, measurement, and optimizations that I have done was done by using Keysight GENESYS.

7.4 Specifications

The main specification was converting a cellular (GSM band) 835 MHz noisy signal into IF band (88 MHz) with a necessary power level.. I had a constraint to use superheterodyne architecture which was more than sufficient for me.

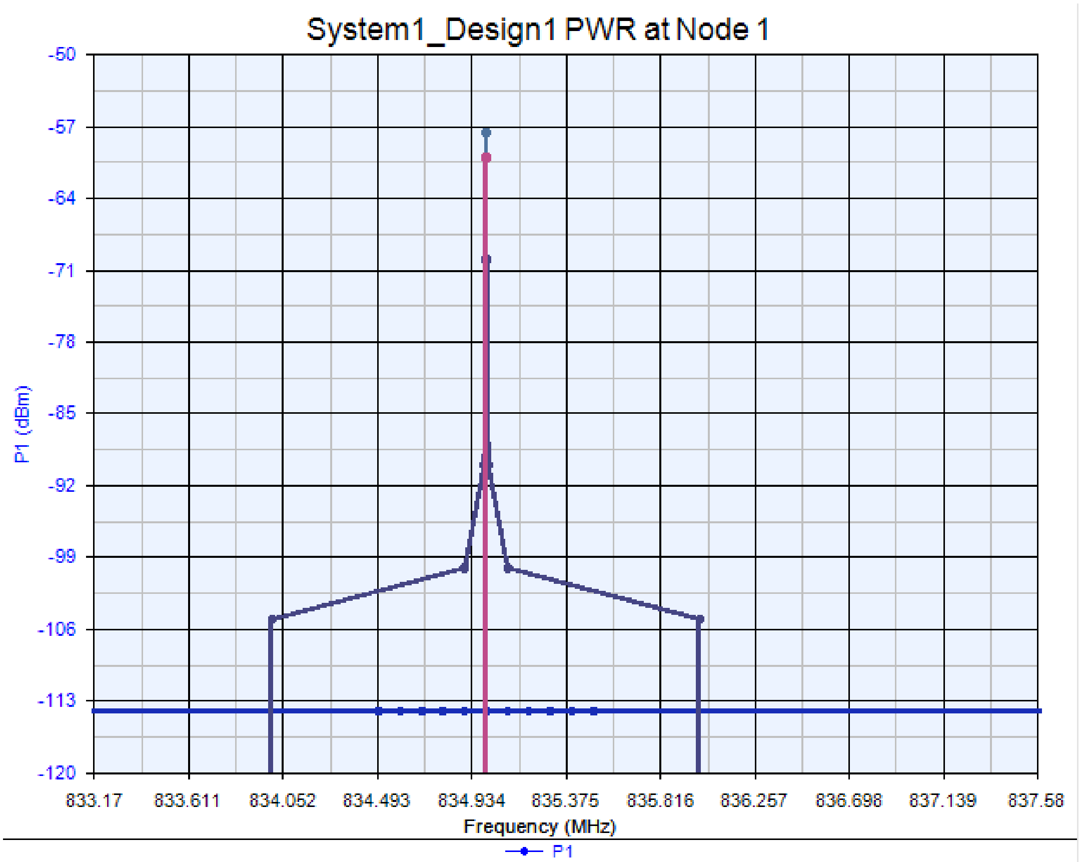

Figure 30 – Noisy 835MHz signal

Figure 30 is the input signal shown in frequency domain with a noise floor, a noisy bandwidth, and the main signal at 835 MHz.

7.5 Receiver Architecture

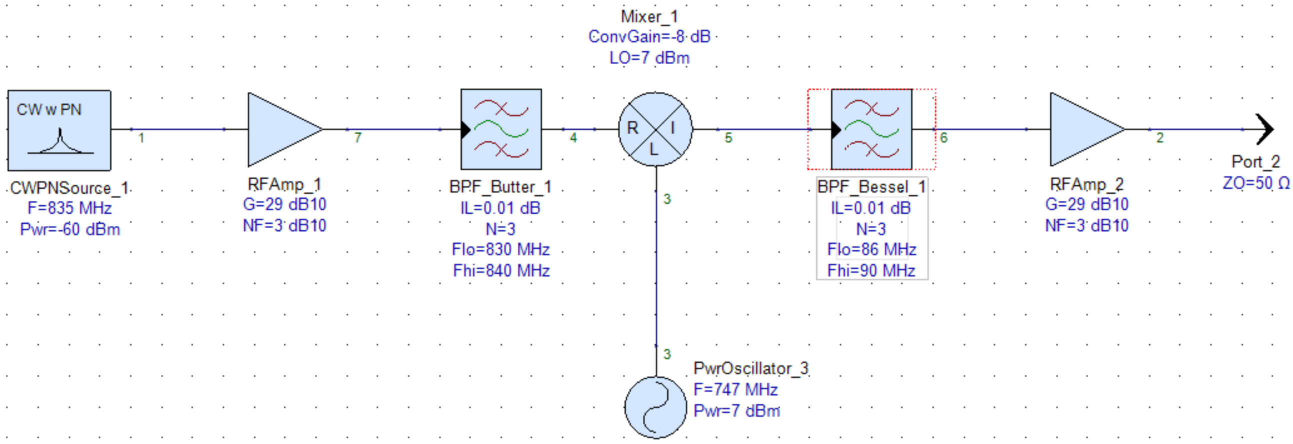

Figure 31 – Receiver system in GENESYS

In Figure 31, the one can see the simple superheterodyne receiver architecture with certain parameters entered to meet the specifications. These components are the ideal components that belongs to the tool SPECTRASYS under GENESYS. Therefore, with this architecture only ideal response can be observed. In this part I will explain the system briefly from the system in Figure 31, then I will give details about real components and component selection.

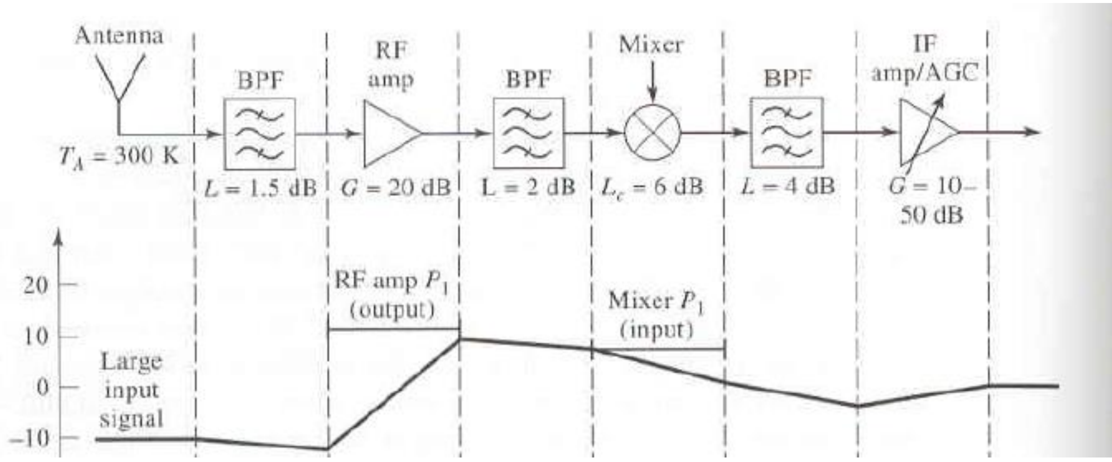

Figure 32 – Diagram of power and noise levels at consecutive stages of a receiver

First component represents the signal coming from an antenna as mentioned. It is a noisy signal since the real signals coming from antennas are extremely noisy. Next, an amplifier is connected to amplify the power of the signal since the signal coming from antennas generally have low power as they travel through mediums such as air. That amplifier is also crucial in terms of the concept of low noise amplifier which was deeply handled in section 7.2. The following component is a Butterworth bandpass filter. Filters are one of the most significant components in RF design. They can “filter out” certain frequencies in a signal, which makes them a very useful tool for RF engineers. Filters will be explained profoundly in the incoming chapter. A bandpass filter is used in the system to eliminate the unwanted signals, namely noise. The signal from antenna contains unwanted frequencies and a bandpass filter can attenuate those signals.

Next component is a mixer, which was explained briefly previously. Mixing process is the process where the signals frequency is transformed. An oscillator with selected frequency is connected to a mixer to do the down-conversion. I have selected the frequency 747MHz to obtain 88 MHz by the operation 835-747 which can be done by mixer.

Although mixer is able to produce 88 MHz signal by taking difference of two signals, it also produces some unwanted products which were mentioned in previous chapters. For example, the sum of the signals with a frequency 747+835 = 1582 MHz also appears in output signal. Moreover, intermodulation and harmonic products also can be observed in output. To eliminate these signals, again a Butterworth bandpass with center frequency 88MHz is used.

As the signal travels through various components, it is known that it loses its initial power level due to power dissipation, reflection, impedance mismatch, etc. In order for the demodulator part to interpret the signal in a healthy way, the signal must have sufficient amplitude. This is achieved by the last amplifier in the system. This amplifier basically amplifies the signal one last time and gets the signal ready to be processed.

In Figure 32, the one can observe the change in the power level of a signal as it travels through a receiver architecture like the one that I have simulated. It is easy to see that the power level decreases during certain components, and it increases again thanks to amplifiers.

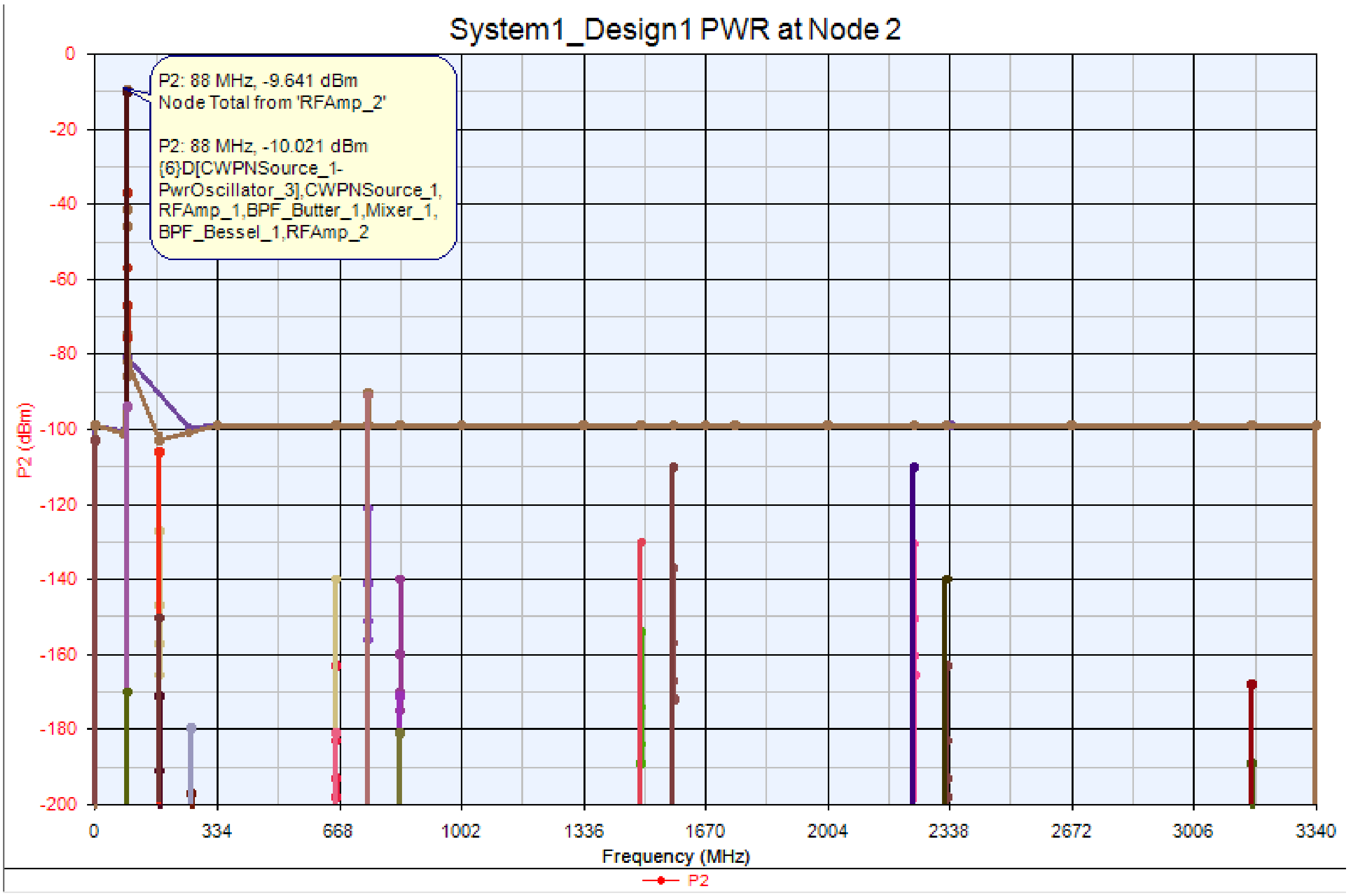

Figure 33 – The final output signal in frequency domain

In Figure 33 the components of the output signal can be seen. There also some unwanted signals exists below and above the horizontal line, which is the noise floor. The strongest signal is 88 MHz with -9dBm which was the result that was desired. With a right configuration of components which was done in Figure 31, the most dominant part of the signal can be obtained as 88 MHz. To sum up, specifications were met thanks to the receiver system. In the following section I will handle the same scenario with real components.

7.6 Component Selection

Most of the commercial RF & Microwave design software have a built-in system which selects suitable real components from the market that have similar parameters to ideal components in the designed system. The tool I used, Keysight GENESYS did not have that kind of a feature. Therefore, I have selected corresponding components by searching. While completing this task, I got more familiar with datasheets of components and gained a little experience on how to read datasheets.

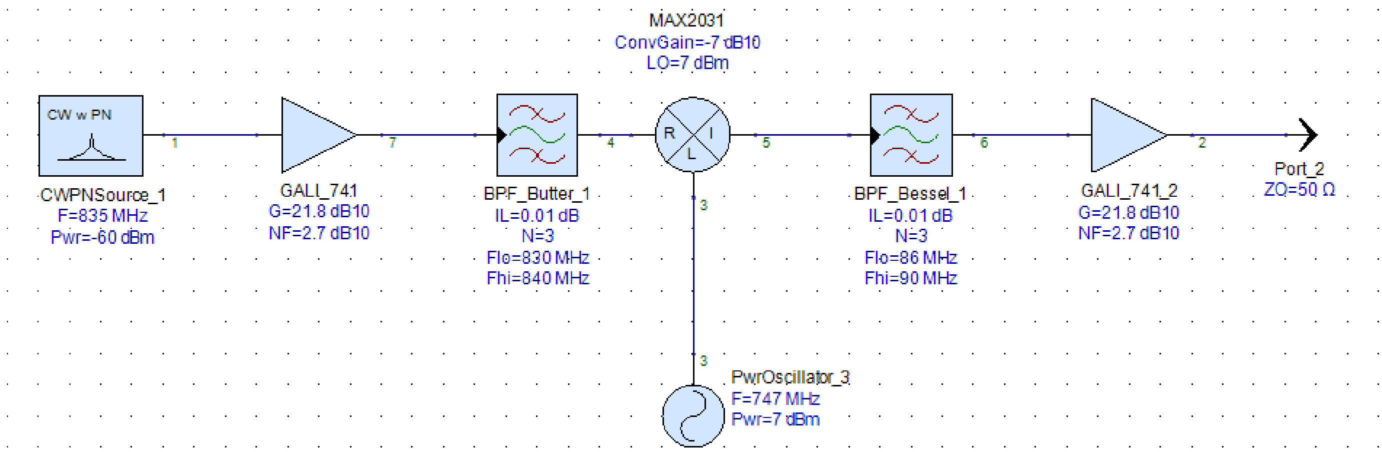

Figure 34 – Receiver system with real components

Component	Name	Manufacturer
Amplifier	MAX2031	Maxim Integrated Products
Mixer	GALI-74+	Mouser Electronics

Table 1 – Real components info table

Since the signal source is implicit as the signal coming from antenna in real systems, we do not select any component for that part. Mixer and amplifiers are selected with respected to the parameters that were set in Figure 31. Moreover, I did not select any real filter because in the next chapter I will talk about filter synthesis.

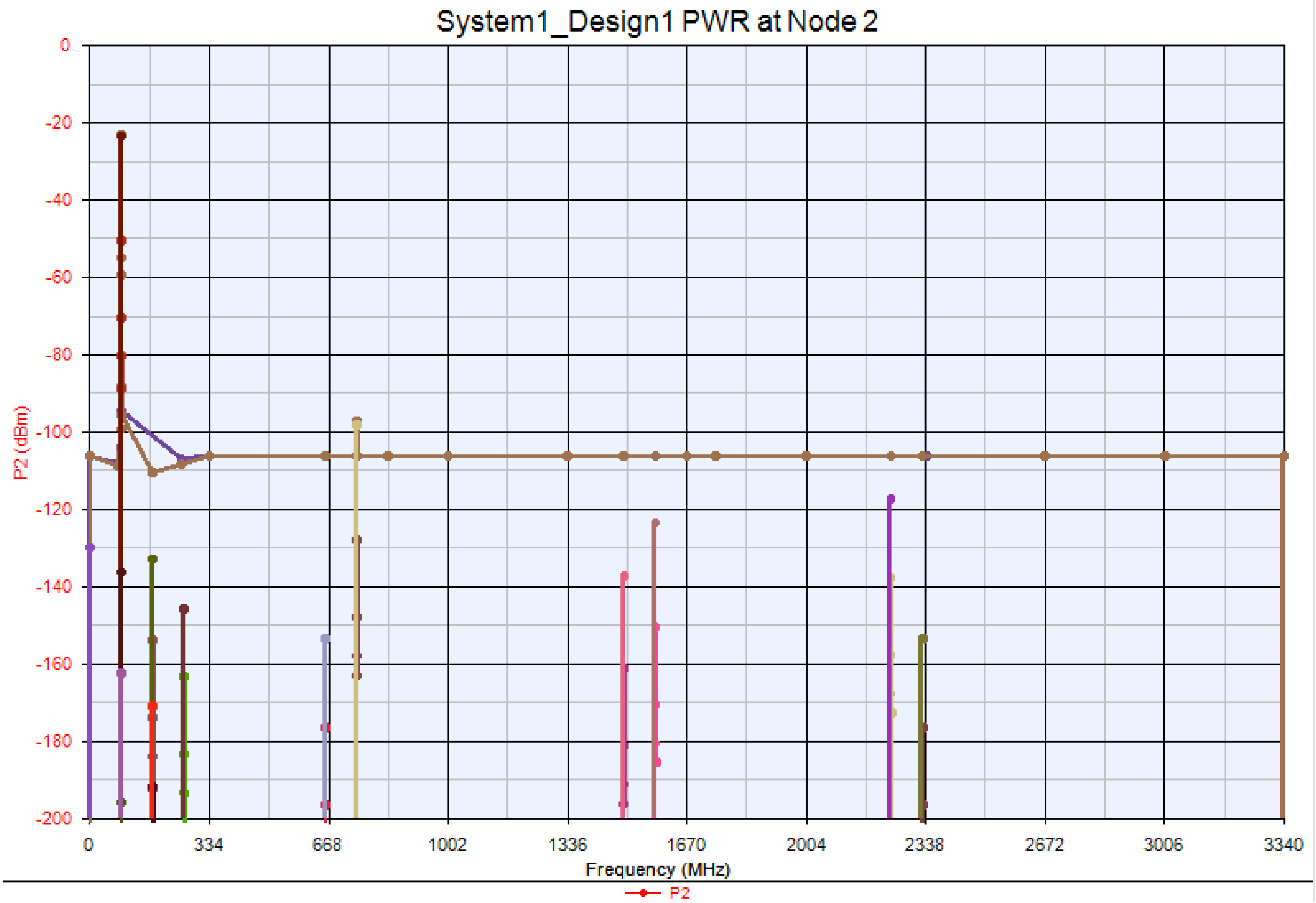

Figure 35 – Output signal in frequency domain for real component simulation

To sum up, I have tried to adjust the component parameters to meet the specifications. I have used superheterodyne receiver architecture and simulated it from GENESYS.

8. RF FILTER DESIGN

As discussed previously, RF Filters are crucial components in RF systems. Their ability to attenuate certain frequencies are extremely utilized by the designers of RF systems. During my internship, I have learned the basics of RF filters and I have learned how to do measurements on filters. As a one final task, I have designed, simulated an optimized an RF filter and then realized it. In this chapter I will briefly explain filter types, filter synthesis and my simple filter project.

8.1 Lumped Filters

As the header indicates, lumped filters are circuits that are built with lumped elements such as resistors, inductors, and capacitors. Different configuration of these elements leads to different responses. Some circuits attenuate the low frequency signals while the other only attenuates the signals in between certain frequencies which are determined by capacitance, resistance, and inductance values in the filter. These filters work very well for lumped case, such as low frequency signals. In that case, the physical dimensions of the circuit are much smaller than the wavelength of the signal. However, their response starts to get worse as the frequency of signal increases and the wavelength becomes comparable with physical dimensions. A different type of filter called

"Distributed Filter" which are generally used in high-speed networks and will be elaborated on next section.

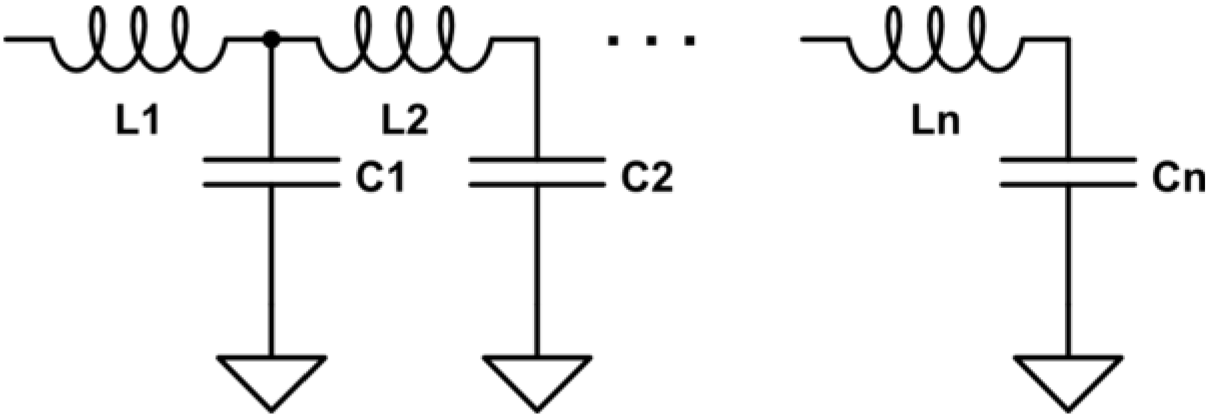

Figure 36 – Generic structure of a lumped filter

As it can be seen from Figure 36, lumped filters are passive simple RLC circuit which filters signals with low frequencies. The filtering characteristics of these filters are independent from physical dimensions of components whereas the case is opposite in distributed element filters.

I had a chance to build a lumped filter in my internship. I will discuss about this simple filter in following sections

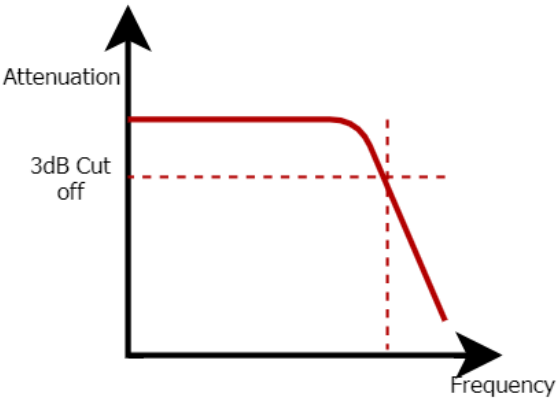

Figure 37 – Lowpass Filter Response

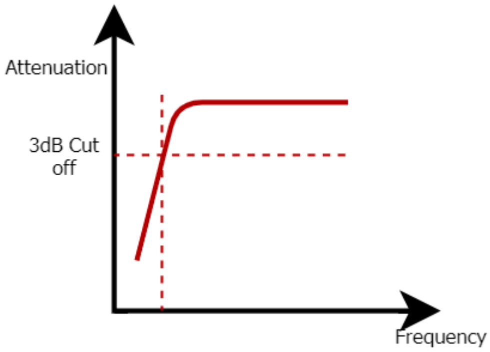

Figure 38 – Highpass Filter Response

8.2 Distributed Element Filters

As the frequency of the signal increase, the response of lumped filter deviates from the ideal case rapidly. That is because capacitors and inductors are capable to work healthy in a certain frequency interval. In other words, lumped filters become useless in high frequencies which is mostly the case in RF systems. Distributed element filters are used for filtering process in high frequency.

Distributed element filters consist of special transmission line segments. In this type of filter, the structure is built with open circuit or short circuit transmission line stubs instead of capacitors or inductors. In other words, the capacitive and inductive properties of filters are obtained from transmission lines. Since the physical dimensions of these stubs are comparable with the wavelength of the signal, a filtering process can be done. The physical properties of stubs such as width or length are determined by the specifications of the filter such as cutoff frequency, attenuation at cutoff, etc.

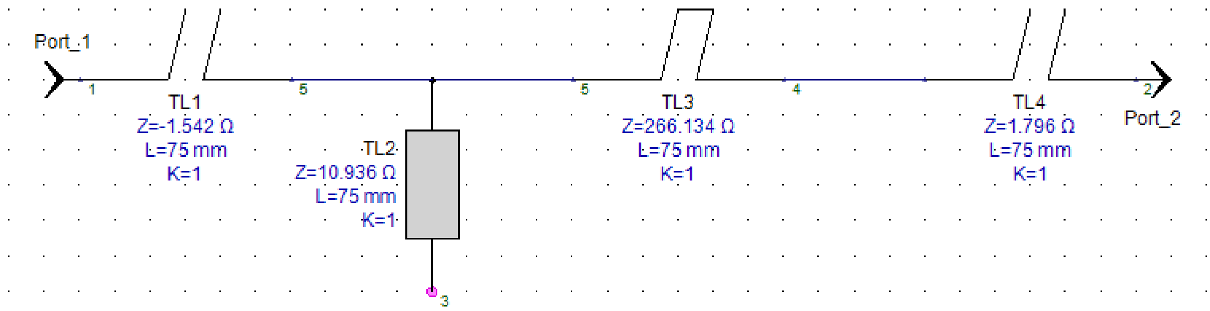

Figure 39 – An example of distributed element filter structure from GENESYS

In Figure 39, the one can see the short circuit stub as S.C and open circuit stub as O.C. The location, width , length, and impedance properties of stubs are all calculated with respect to the goal of the filter. Moreover, the stubs physical dimensions are also dependent to wavelength of the signal since they must be comparable.

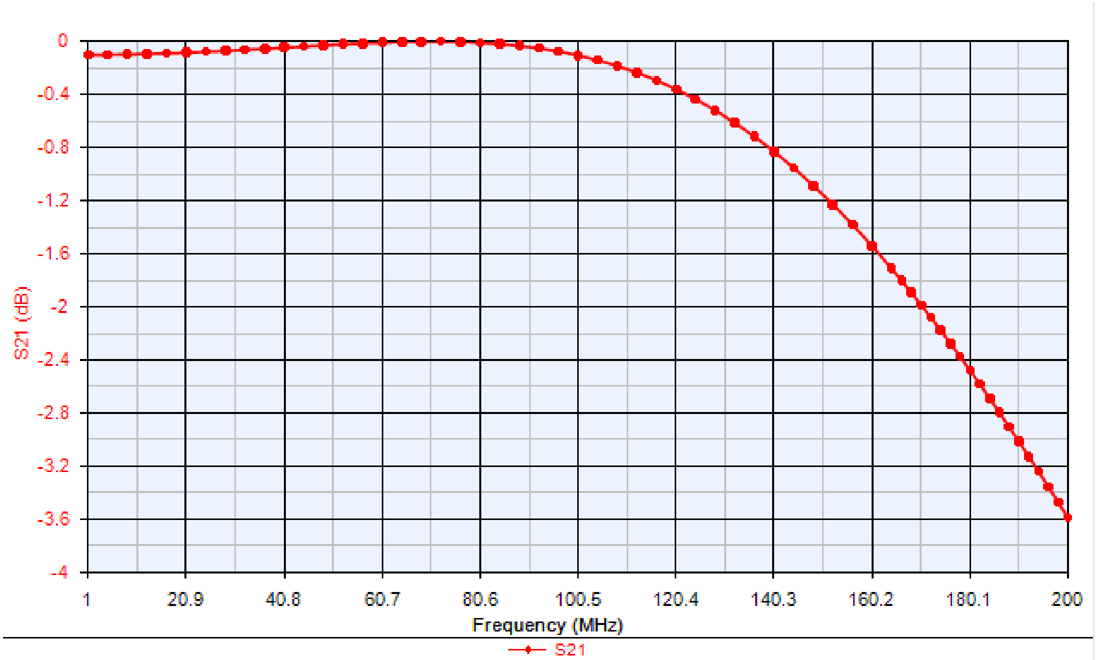

Figure 40 – Response of the filter in Figure 39

From Figure 40, we can see that the special configuration of transmission lines serves as a lowpass filter for high frequency signals.

8.3 Interdigital Filters

Interdigital filters can be considered as a special type of distributed element filters. In this type of filters, signals travel through the structure of filter by resonance unlike distributed element filters. These resonant transmission lines are responsible from the filtering process.

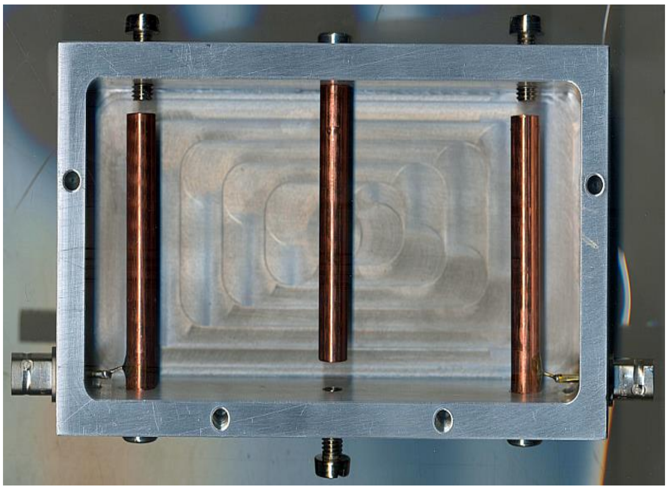

Figure 41 – Interdigital Filter example

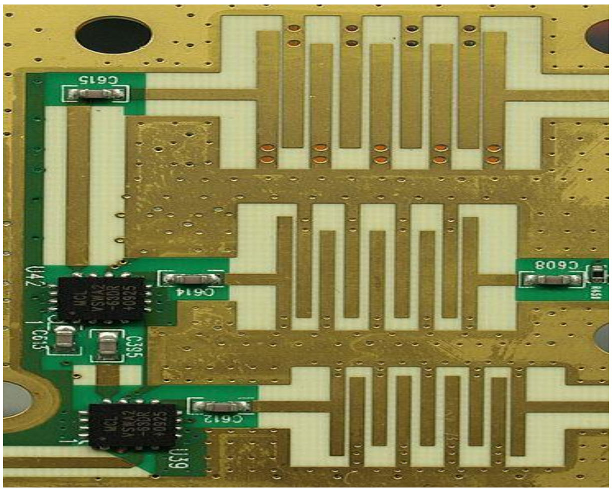

Figure 42 – Interdigital Filter structure

In Figure 41 and 42 different type of interdigital filters can be observed. The width between resonators, the diameter of the rod in Figure 41, the length of elements and that kind of physical properties are calculated with respect to goals like filtering type, center frequency, bandwidth, passband ripple etc.

8.4 Filter Shapes

There are different filtering processes. High-pass, lowpass, band-stop and band-pass filtering are the most used ones. They differ from each other by the frequency of attenuated signals. There is another concept which is called filter shapes which is different from previously mentioned concept.

There are 3 main filter shapes. These are called Butterworth, Chebyshev , Bessel. They all determine the S_{21} characteristics of the filter by really complex mathematical relations. I will discuss about them briefly.

Butterworth filters are often called maximally flat filters. Their aim is to guarantee a smooth S_{21} characteristic in the passband of the filter. If a system requires a robust passband and is intolerant to ripple in passband, a Butterworth filter is the best option.

Next shape to consider is Chebyshev. The behaviour of Chebyshev filters comes from the Chebyshev polynomials. Unlike maximally flat filters, a passband ripple exists in Chebyshev filters. However, due to these ripples in passband, a steeper transition from passband to stopband can be achieved. For example, if a system requires fast and sharp transition around the cutoff frequency, a Chebyshev filter would be the best solution. There is also a filter shape called Chebyshev-II which is much like an ordinary Chebyshev filter, but a ripple exists in stopband this time. Again, thanks to the ripple, a steeper roll-off can be guaranteed.

The next shape is called Bessel filters. The characteristic of these filters comes from the mathematical relation which is called Bessel polynomial. Bessel filters have a roll-off steepness which is even worse than Butterworth filters. However, Bessel filter is the only type of filter shape which shows linear phase response. If group delay is important for a system, Bessel filters are the best option to use. Moreover, the coefficients of Bessel transfer functions are much simpler when compared to other filter types. Therefore they are mostly easy to calculate.

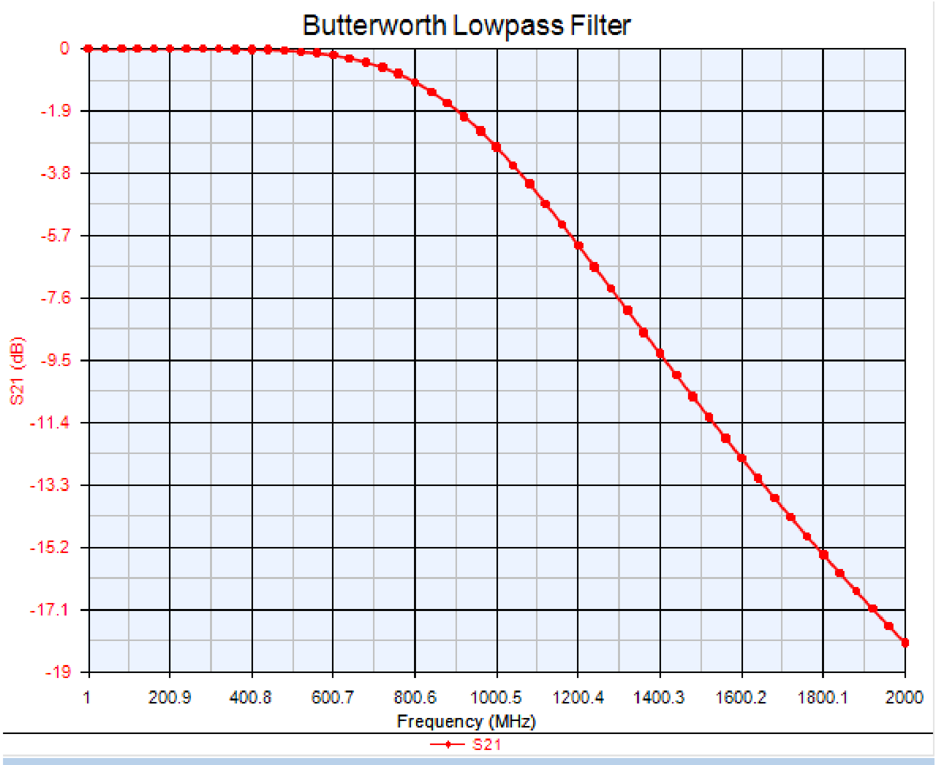

Figure 43 – S_{21} of Butterworth

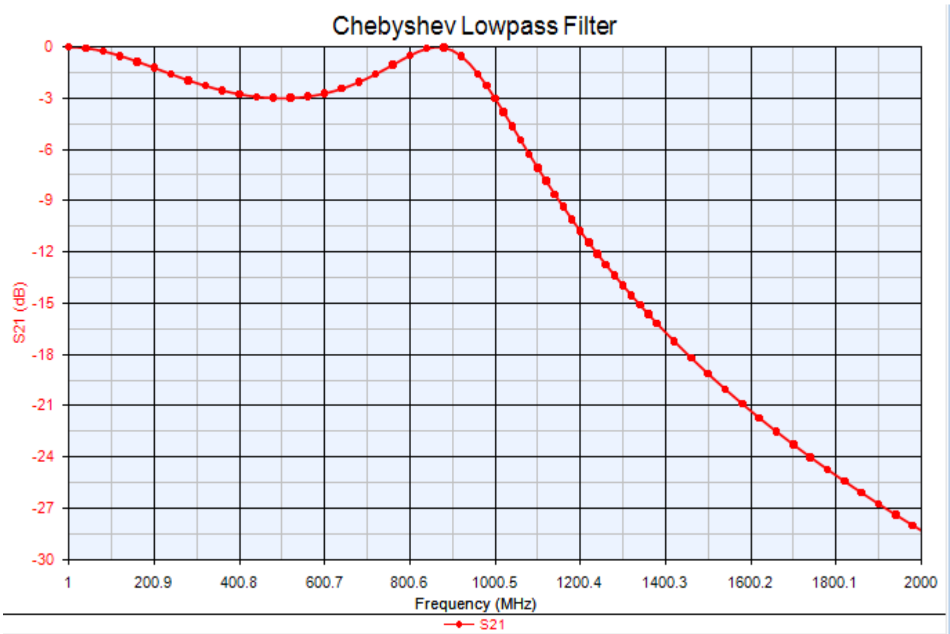

Figure 44 – S_{21} of Chebyshev

In Figure 43 and 44, the one can see the differences between Butterworth filter response and Chebyshev filter response. The two filters have the same order, same cut-off frequency (1 GHz) and same attenuation at cut-off (3dB). If we observe the S_{21} parameter for 2 GHz in each response, we can see that the attenuation is around -30dB for Chebyshev filter while it is around -18dB for Butterworth. Therefore, we can say that the roll-off is much steeper in Chebyshev type of filter. Filters also have a property called “order” which is directly related with number of components inside the filter.

8.5 Filter Synthesis

Before jumping into my design, I want to discuss about filter synthesis methods. There are several methods that filter design tools use to synthesise a filter with respect to given parameters. One of them is prototyping.

In prototyping method, a filter is designed with source impedance of 1Ω and cutoff angular frequency 1 rad/sec. Then a prototype RLC circuit is built by using “g values” for RLC values. G values are often called elemental values and they are just pre-calculated coefficients. Then, this prototype is scaled and converted according to impedance and cut-off frequency. This method is often called insertion loss method.

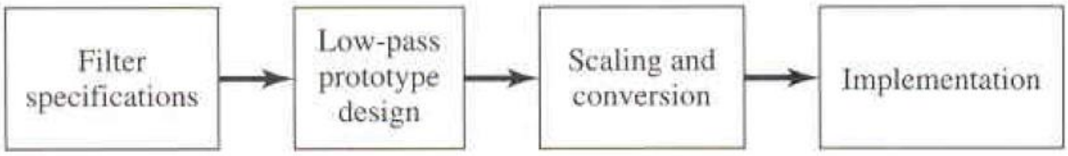

Figure 45 – Insertion Loss Method

N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}
1	2.0000	1.0000									
2	1.4142	1.4142	1.0000								
3	1.0000	2.0000	1.0000	1.0000							
4	0.7654	1.8478	1.8478	0.7654	1.0000						
5	0.6180	1.6180	2.0000	1.6180	0.6180	1.0000					
6	0.5176	1.4142	1.9318	1.9318	1.4142	0.5176	1.0000				
7	0.4450	1.2470	1.8019	2.0000	1.8019	1.2470	0.4450	1.0000			
8	0.3902	1.1111	1.6629	1.9615	1.9615	1.6629	1.1111	0.3902	1.0000		
9	0.3473	1.0000	1.5321	1.8794	2.0000	1.8794	1.5321	1.0000	0.3473	1.0000	
10	0.3129	0.9080	1.4142	1.7820	1.9754	1.9754	1.7820	1.4142	0.9080	0.3129	1.0000

Figure 46 – Elemental values for Butterworth LPF

$$C_1' = \frac{C_1}{R_0\omega_c} = \frac{0.618}{(50)(2\pi)(2 \times 10^9)} = 0.984 \text{ pF},$$

$$L_2' = \frac{R_0 L_2}{\omega_c} = \frac{(50)(1.618)}{(2\pi)(2 \times 10^9)} = 6.438 \text{ nH},$$

$$C_3' = \frac{C_3}{R_0\omega_c} = \frac{2.000}{(50)(2\pi)(2 \times 10^9)} = 3.183 \text{ pF},$$

$$L_4' = \frac{R_0 L_4}{\omega_c} = \frac{(50)(1.618)}{(2\pi)(2 \times 10^9)} = 6.438 \text{ nH},$$

$$C_5' = \frac{C_5}{R_0\omega_c} = \frac{0.618}{(50)(2\pi)(2 \times 10^9)} = 0.984 \text{ pF}.$$

Figure 47 – Scaling

In Figure 47, the capacitance and inductance values are found by scaling the elemental values. Type of the filter changes this scaling process; however, main procedure is almost always same.

Another filter synthesis method is obtaining distributed element filters from lumped element filters by using some mathematical relations. These relations are Richard's Transformation and Kuroda's Identity.

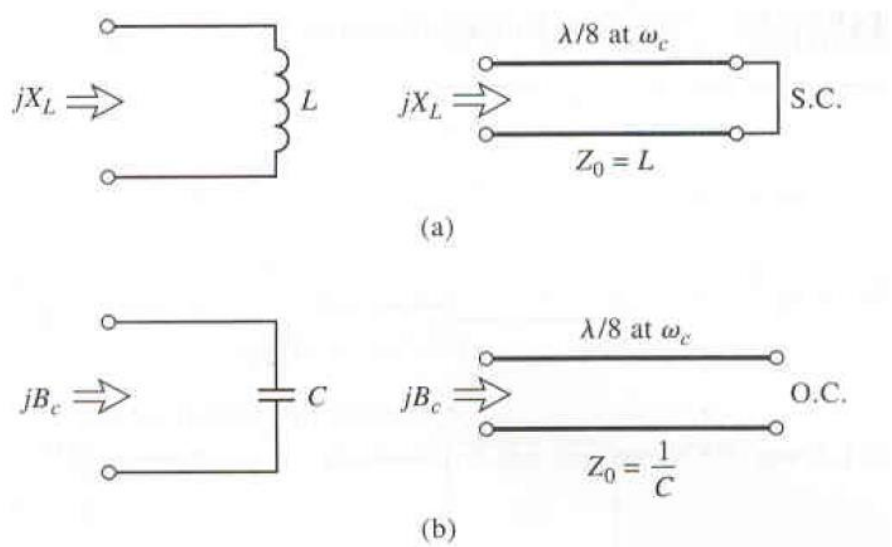

Figure 48 – Richard's transformation

From Figure 48, the capacitive and inductive effects can be provided with stubs by simply applying Richard's transformation on lumped circuits.

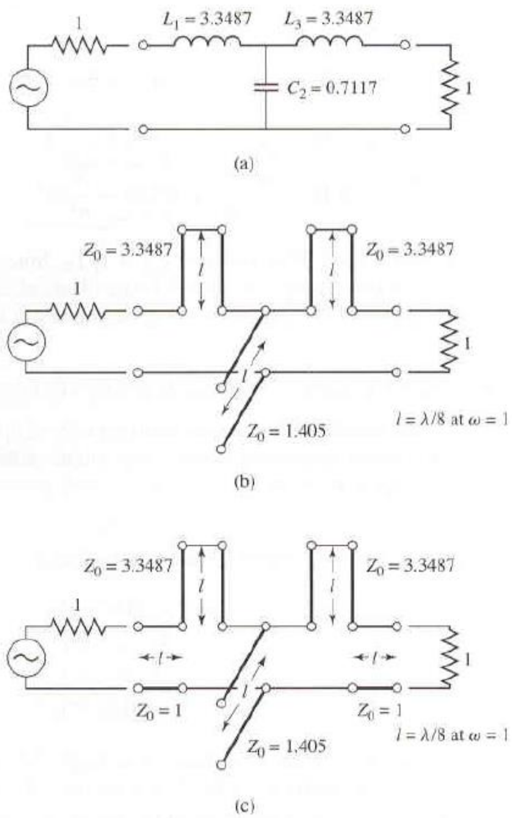

Figure 49 – Transformation from lumped to distributed elements

The transformation from lumped structure to distributed elements can be seen in Figure 49 step by step.

The physical properties, impedance and types of stubs are found by applying Kuroda's Identities and Richard's transformation to the lumped filter in initial step. A lumped prototype can be found by elemental values. Later, it can be converted to a distributed element filter if the signal frequency is high for lumped filters.

This concludes my brief review of filters, and I will explain my filter design experience in following sections.

8.6 Filter Specifications

I chose to design a filter with 1.5 GHz cut-off frequency. Moreover, my filter was a Chebyshev filter with a 0.05 dB ripple in passband. When I did the necessary calculations, I have found that the order of my filter was 12 to meet the desired conditions.

8.7 Filter Prototype

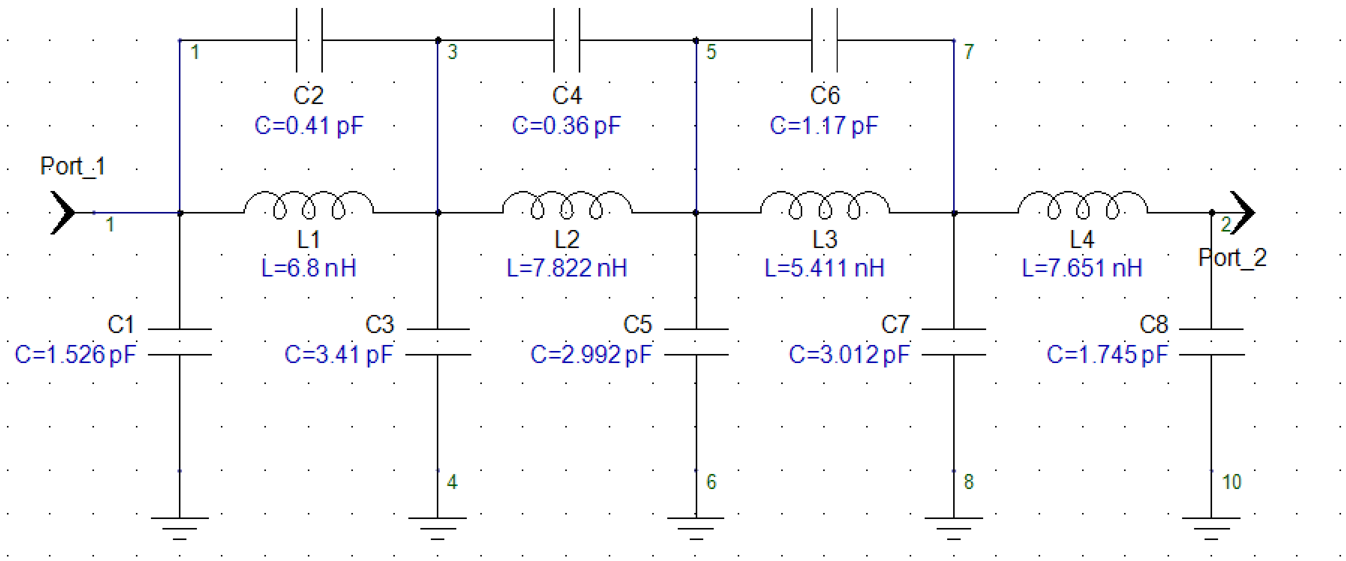

Figure 50 – Prototype

By using filter synthesis from GENESYS, I was able to obtain a filter circuit. This circuit was created by the algorithms in GENESYS which use the methods discussed in section 8.5. The order of the circuit can be seen as 12 in Figure 50 as expected.

I have visualized the response of this prototype filter to catch the problems and see whether the response was correct or not.

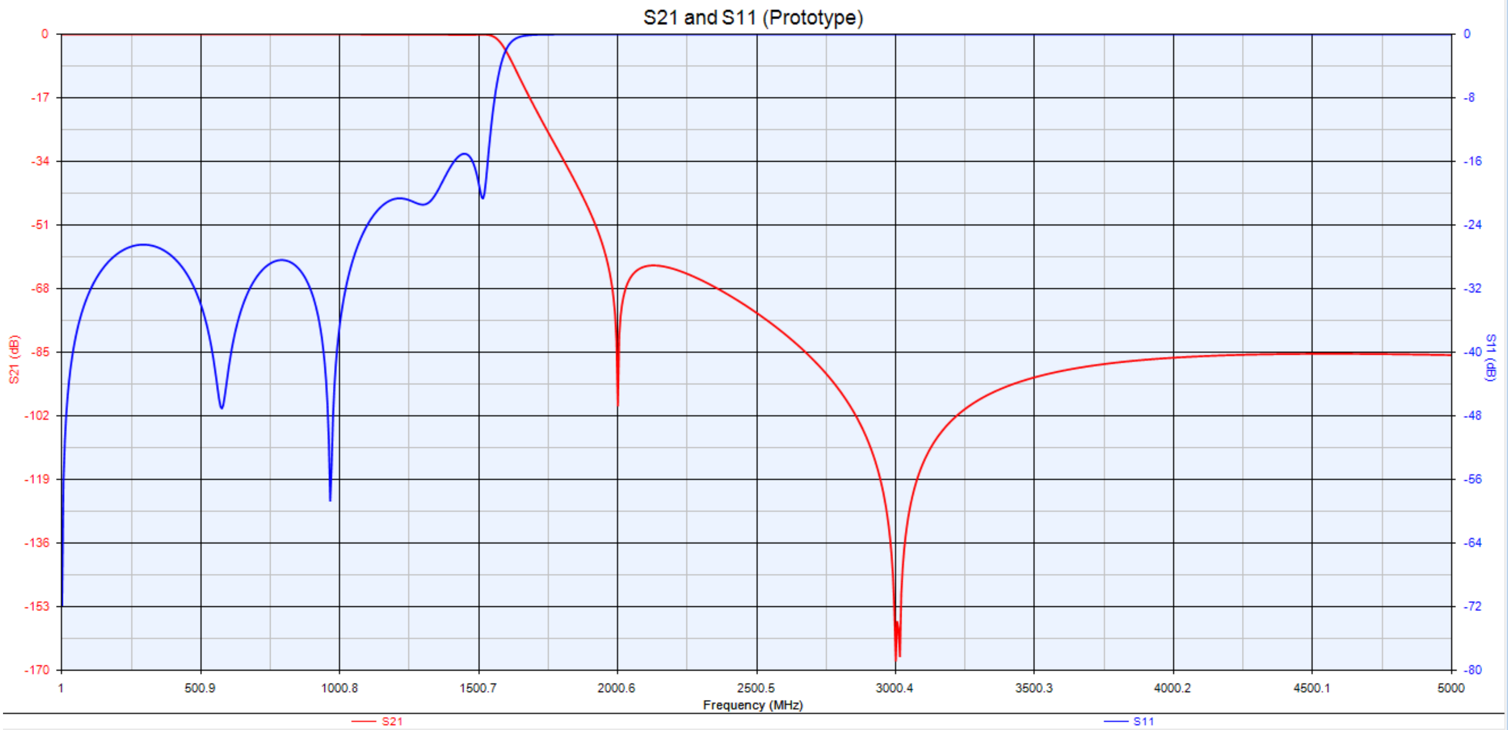

Figure 51 – Frequency Response

The ripple at passband was low as I desired. The ripple also enabled a steep roll-off which can be seen in Figure 51.

Although this filter was meeting the specifications, it was simulating ideal components, and it was neglecting some real facts such as insertion losses. To be able to obtain a real model from this prototype I had to make some optimization and correction.

8.8 Optimization

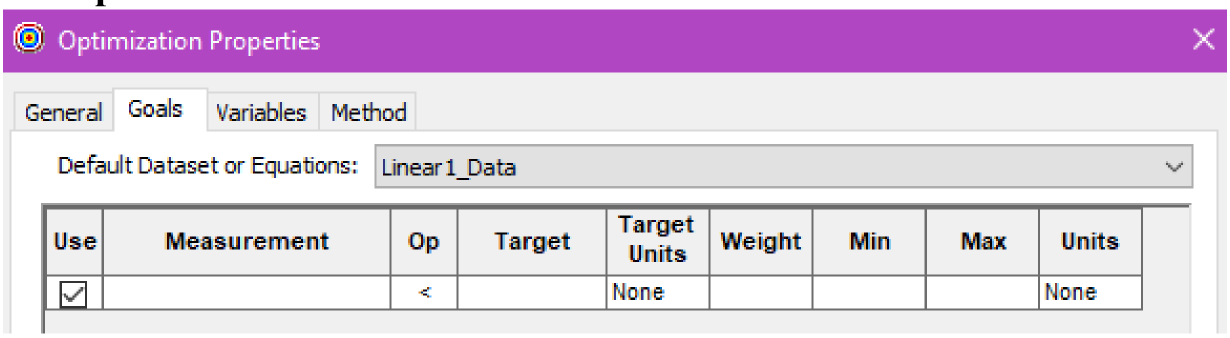

Figure 52 – Optimization Tool

GENESYS had a feature called “Optimization”. The tool was used to add some constraints on the design and re-design the system. The system that was built in Figure 50 was built with some capacitance and inductance values which cannot be provided in a real design. In other words, a 1.526 pF capacitor does not exist. Therefore, I had to convert these calculated capacitance and inductance values into real values where I could find components. I have used the optimization tool which calculates the responses for every change in any of the values in circuit.

Document 195-2

0603CS Series (1608)

Designer's Kit C324 contains 10 each of all 5% values
Designer's Kit C324-2 contains 10 each of all 2% values

Part number[1]	Inductance[2] (nH)	Percent tolerance[3]	Q min[4]	900 MHz L typ	900 MHz Q typ	1.7 GHz L typ	1.7 GHz Q typ	SRF min[5] (GHz)	DCR max[6] (Ohms)	Irms[7] (mA)	Color dot[8]
0603CS-1N6XJR_	1.6 @ 250 MHz	5	24	1.67	49	1.65	63	12.5	0.030	700	Red
0603CS-1N8XJR_	1.8 @ 250 MHz	5	16	1.83	35	1.86	50	12.5	0.045	700	Black
0603CS-2N2XJR_	2.2 @ 250 MHz	5	13	2.22	31	2.24	44	12.5	0.250	100	Yellow
0603CS-3N3X_R_	3.3 @ 250 MHz	5,3,2	35	3.31	75	3.38	88	5.90	0.045	700	Blue
0603CS-3N6X_R_	3.6 @ 250 MHz	5,3,2	22	3.72	53	3.71	65	5.90	0.063	700	Red
0603CS-3N9X_R_	3.9 @ 250 MHz	5,3,2	22	3.95	49	3.96	67	6.90	0.080	700	Brown
0603CS-4N3X_R_	4.3 @ 250 MHz	5,3,2	22	4.32	50	4.33	70	5.90	0.063	700	Orange
0603CS-4N7X_R_	4.7 @ 250 MHz	5,3,2	20	4.72	47	4.75	57	5.80	0.116	700	Violet
0603CS-5N1X_R_	5.1 @ 250 MHz	5,3,2	20	4.93	47	4.95	56	5.70	0.140	700	Green
0603CS-5N6X_R_	5.6 @ 250 MHz	5,3,2	26	5.77	63	6.05	80	4.76	0.075	700	Black
0603CS-6N8X_R_	6.8 @ 250 MHz	5,3,2	27	6.75	60	7.10	81	5.80	0.110	700	Red
0603CS-7N5X_R_	7.5 @ 250 MHz	5,3,2	28	7.70	60	7.82	65	4.80	0.106	700	Brown
0603CS-8N2X_R_	8.2 @ 250 MHz	5,3,2	30	8.25	82	8.37	87	4.20	0.115	700	Orange
0603CS-8N7X_R_	8.7 @ 250 MHz	5,3,2	28	8.86	62	9.32	58	4.60	0.109	700	Yellow
0603CS-9N5X_R_	9.5 @ 250 MHz	5,3,2	28	9.7	59	9.92	61	5.40	0.135	700	Blue
0603CS-10NX_R_	10 @ 250 MHz	5,3,2	31	10.0	66	10.6	83	4.80	0.130	700	Orange
0603CS-11NX_R_	11 @ 250 MHz	5,3,2	30	11.0	53	11.5	56	4.00	0.130	700	Gray
0603CS-12NX_R_	12 @ 250 MHz	5,3,2	35	12.3	72	13.5	83	4.00	0.130	700	Yellow
0603CS-15NX_R_	15 @ 250 MHz	5,3,2	35	15.4	64	16.8	89	4.00	0.170	700	Green
0603CS-16NX_R_	16 @ 250 MHz	5,3,2	34	16.2	55	17.3	52	3.30	0.170	700	White

Figure 53 – Inductor Set Datahseet [1]

I had limited number of choices when selecting inductance values. I was using surface mount inductors from Coilcraft. According to L values shown in Figure 53, I chose the possible inductance value for each of inductors in Figure 50. Moreover, I also had to choose the capacitance values in a same way.

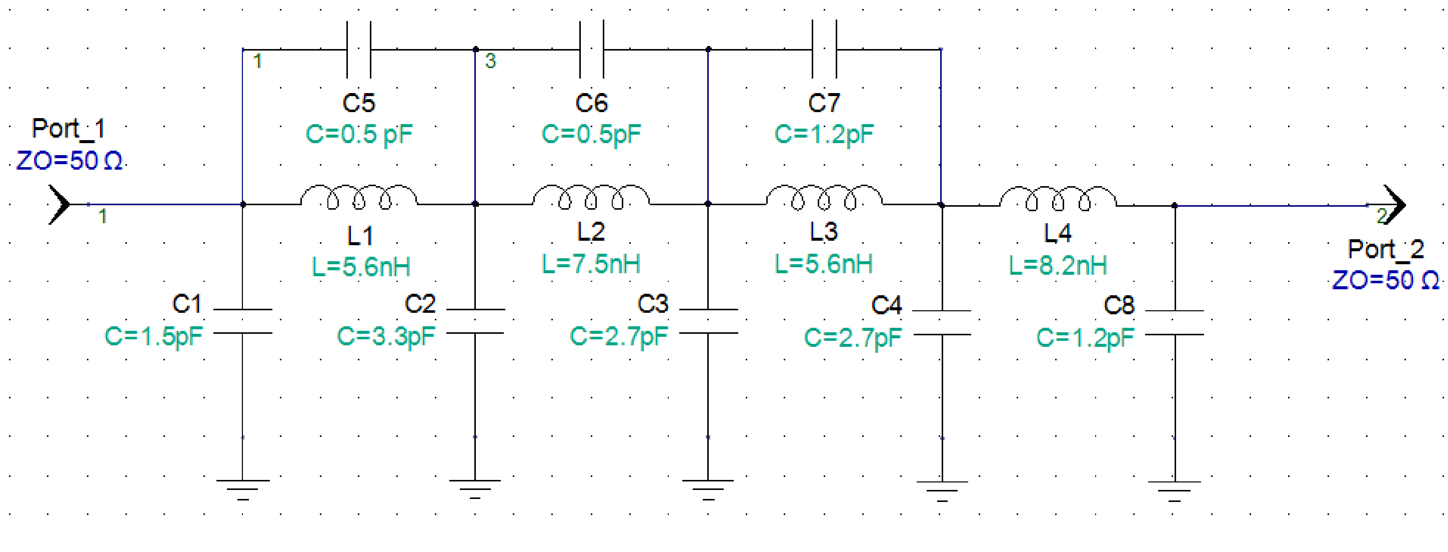

Figure 54 – Final Ideal Design

By running the optimization tool for certain conditions which had the constrain mentioned before, I was able to obtain a final filter structure with L and C values which can be easily found in market. The optimization process was important to minimize the effects on the response while changing the component values. The response of the filter can be seen in Figure 55.

Figure 55 – Frequency response of new design

8.9 Real Parameters

Figure 56 – Frequency response with real parameters

Although the last obtained design had LC values of real components, they were still ideal models for the frequency sweep simulation. Since I was aiming to obtain a real filter design, I had to make to simulation as close as the real scenario. To do this, I have simulated the filter design with real components.

The components in previous section were ideal. Therefore, parameter like their internal resistance, resonant frequency, and quality factor was neglected. From datasheet I found the internal resistance and Q-factors corresponding to each inductor. Then I have simulated the filter again. The response was different from Figure 55. However, it was not completely different. Furthermore, the distortions were much worse for higher frequency, which was an expected outcome. The response was sufficient for the initially given design specifications therefore I did not change the LC values.

8.10 Real S Parameters

At this point, the filter that was being simulated was very far from its ideal prototype, and it had real, non-ideal parameters. However, in microwave concept, the measurements and values are very sensitive with frequency and temperature. I still knew the response was far from the real response. To minimize this, I have used the S parameters of models.

Instead of using a model from GENESYS, I have used the S-parameters of the inductor from Coilcraft. Coilcraft and many other companies supply the S-parameters for the components in market. These parameters are found by measurement therefore no simulation or no idealization are done on these values. In other words, I have modelled the inductor in filter by using the real measurement values.

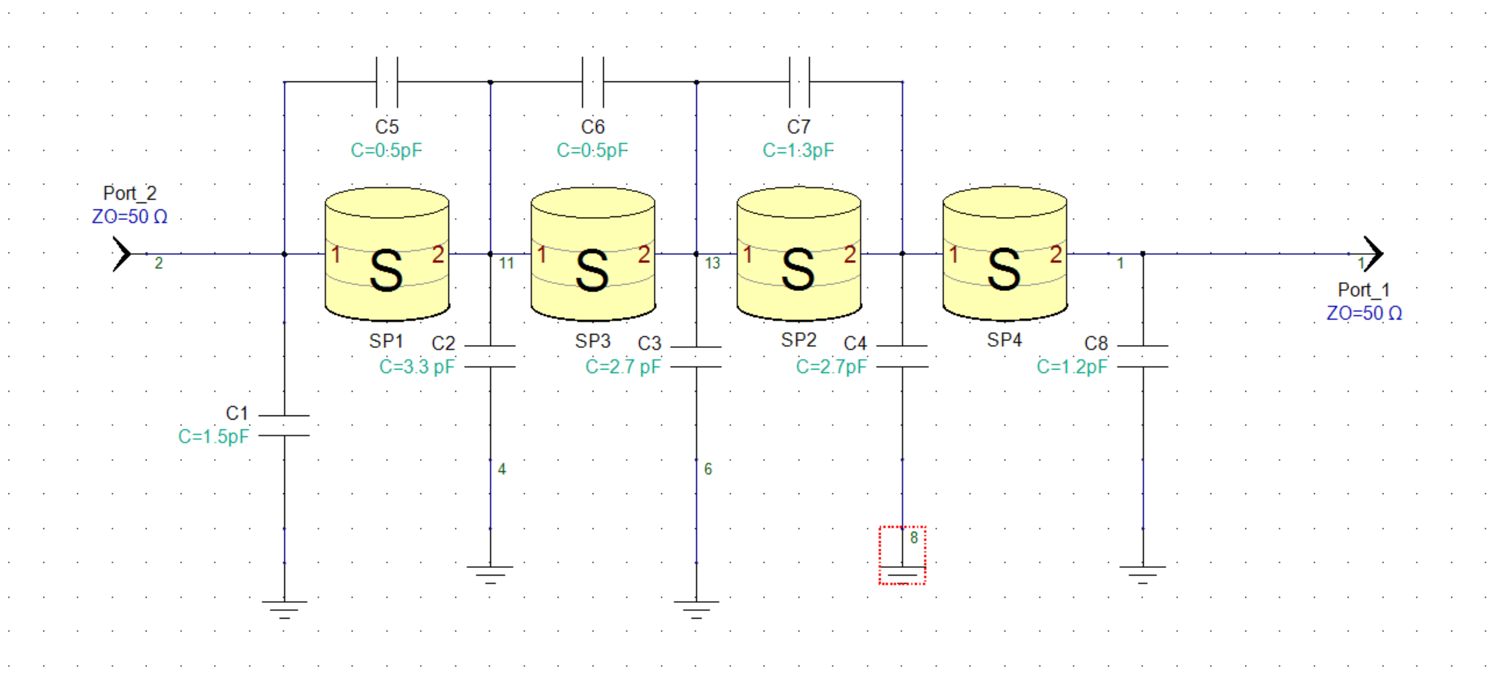

Figure 57 – Filter with new inductor models

As the one can infer from Figure 57, instead of inductors with finite Q-factor, a black-box model is used. The parameters of these black-box components are found from the S parameter measurements, and they are simulated with respected to those measurements.

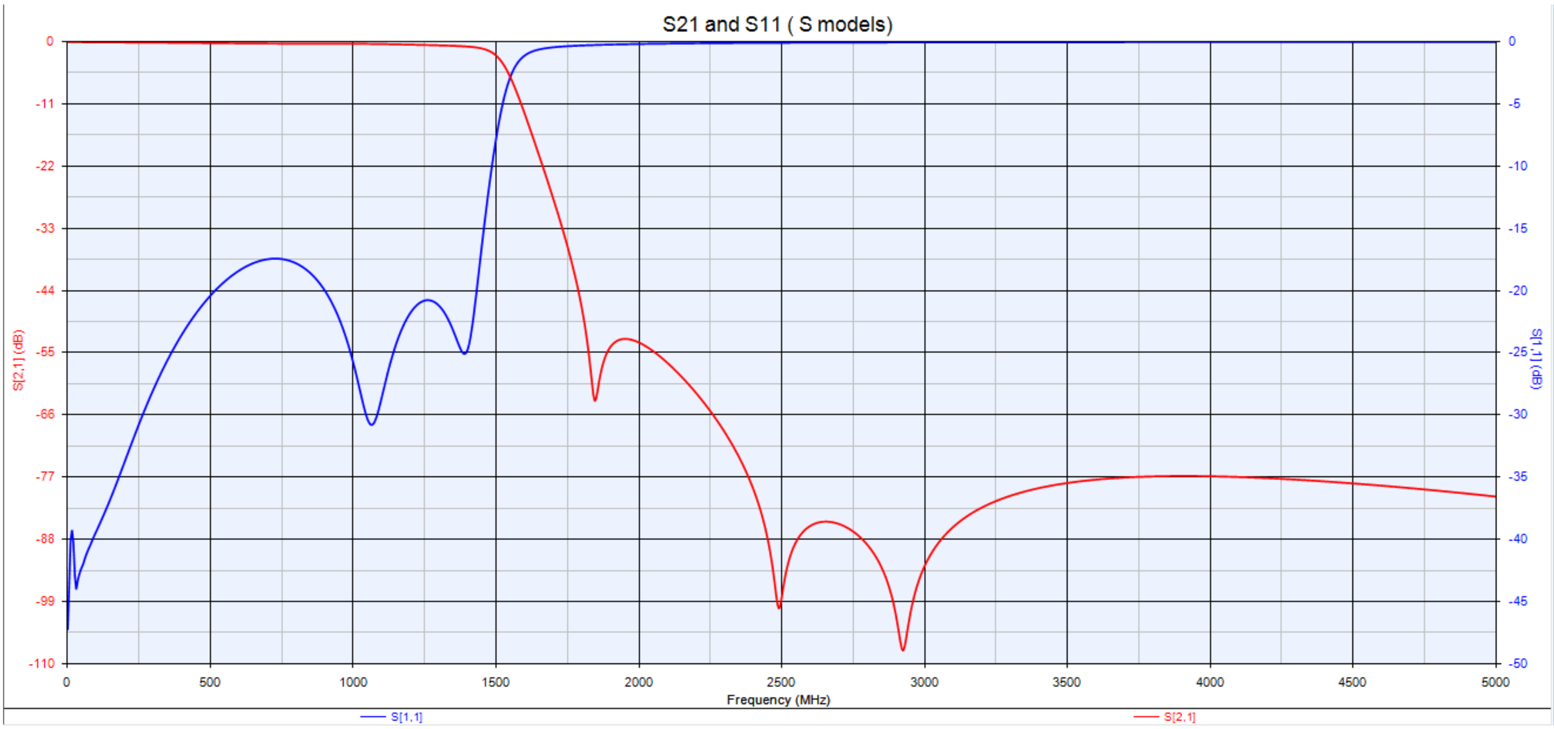

Figure 58 – Frequency response

8.11 Realization

After the simulation process done on GENESYS, the filter was ready to be made in practice. The component values were chosen with respect to the models in the inventory.

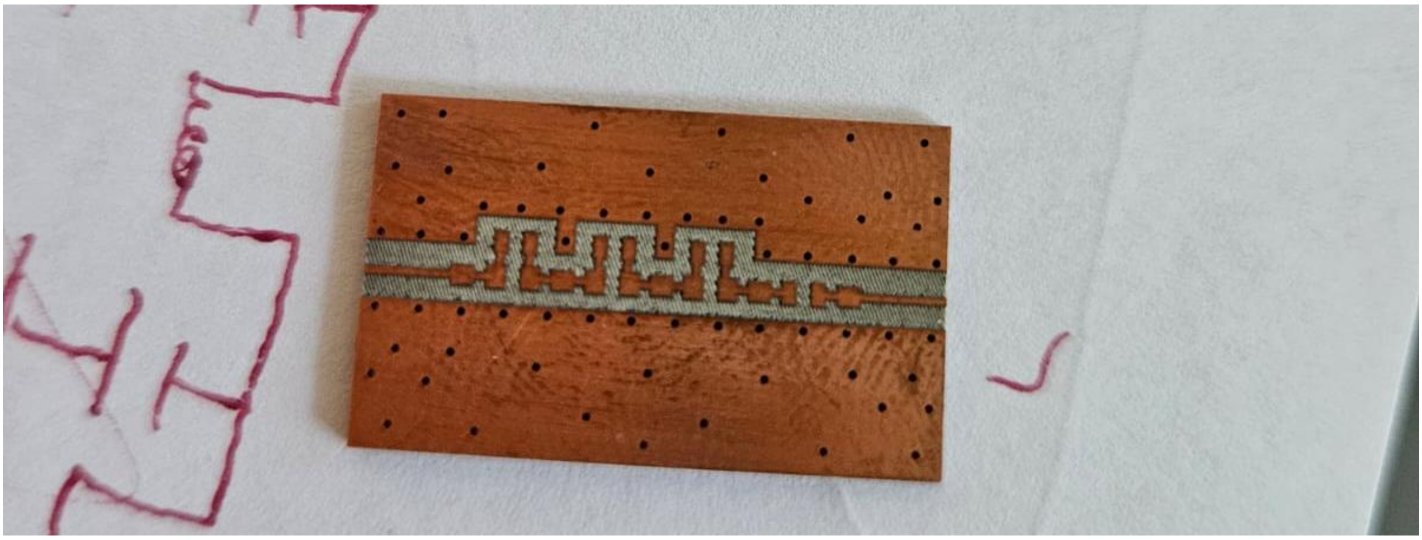

Figure 59 – PCB

The PCB which can be seen in Figure 59 was a previously manufactured empty board. It had the topology of the filter without the components. We have soldered the components in Figure 57 to the board.

After each soldering of a single element, we measured the resistance over that part and tried to observe whether it makes a sense or not according to the nominal internal resistance values of the components. It was a double check method to see if the soldered component is the correct one.

After the soldering of the components completed, we then soldered the SMA connectors at the two end ports of the board.

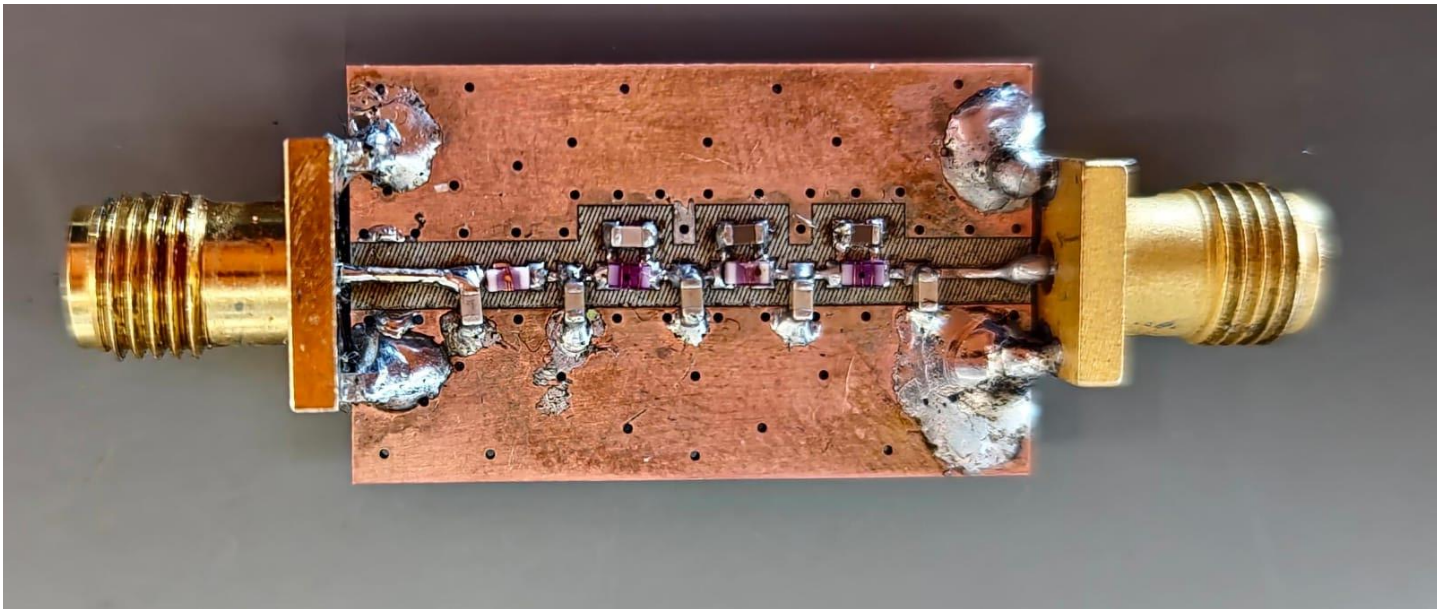

Figure 60 – Filter

Figure 60 is the image of the finalized product. It was designed to be a 12^{th} order lowpass Chebyshev RF filter with 1.5 GHz cut-off frequency and 0.05 dB ripple in the passband.

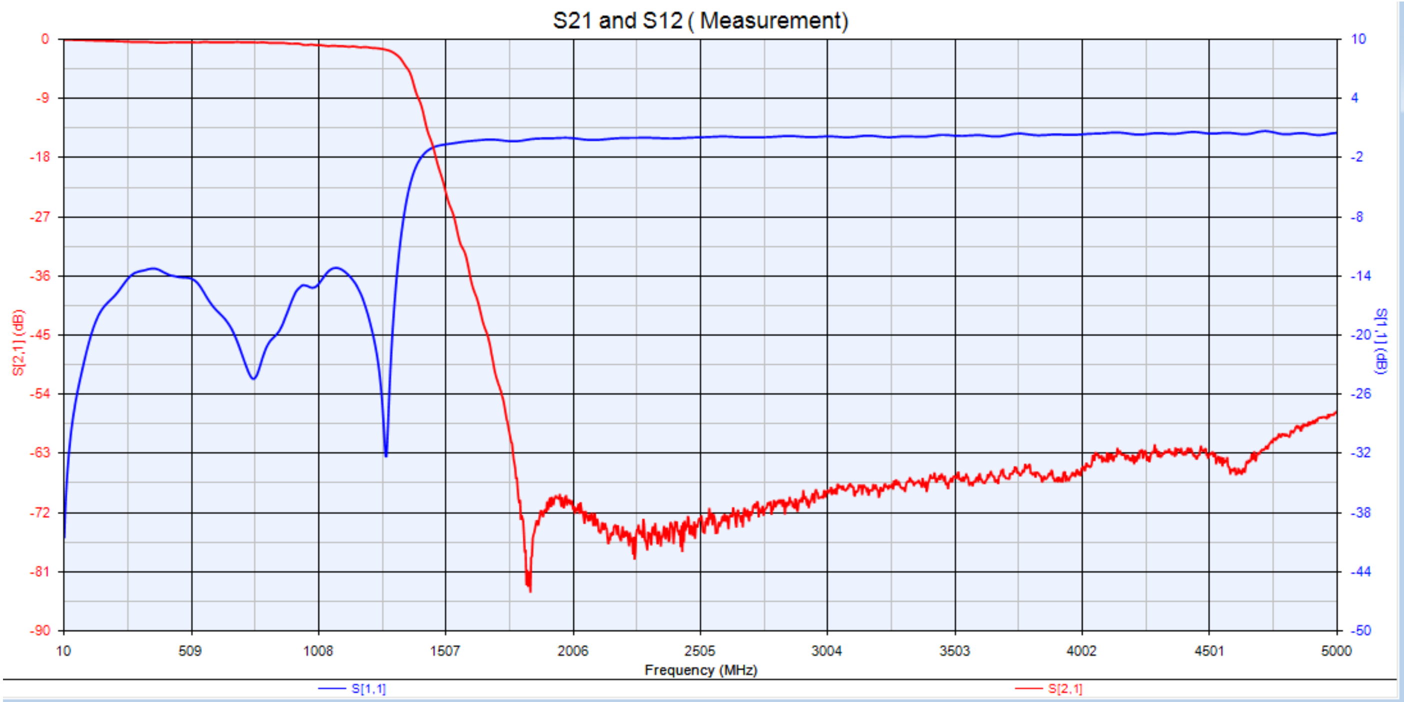

Figure 61 – Frequency response of the real filter

In Figure 61, the one can see the S parameter measurements that I have done on the filter in Figure 60 by using VNA. Then I have plotted these S-parameters by importing them to GENESYS. The pattern of S_{11} and S_{21} was very much similar to the frequency response obtained from the simulation in GENESYS. The one can see the ringing in the S_{21}. That is because since the measurement environment far away from ideal conditions.

There were some major differences between the two main frequency response. The simulation case had a closer cut-off frequency response to 1.5 GHz. However, the other response had a cut-off frequency far from 1.5 GHz. Moreover, the ripple in the passband was higher than 0.05dB.

8.12 Comments

The plots were very similar to each other at the first look. However, when I investigated the two response there were obvious differences. Although the last simulation still was not the perfect model, it should have been very close to the real-world measurement.

The first reason was transmission lines. In GENESYS I had not had the chance to conduct an EM analysis on my filter. By not doing it, I have neglected any effect that is coming from transmission lines. At these frequencies, transmission line effects are not negligible, so it deviated my result.

Second reason was imperfection in manufacturing. I had not measured any SMD component with an LC-meter. Moreover, the soldering was not perfect, and simulation could not have simulated the soldering. Moreover, connectors were not soldered properly, and this may have affected the impedance matching critically. Although all these problems seem like basic and simple, in high-speed networks with little SMD components, they all affect the outcome significantly.

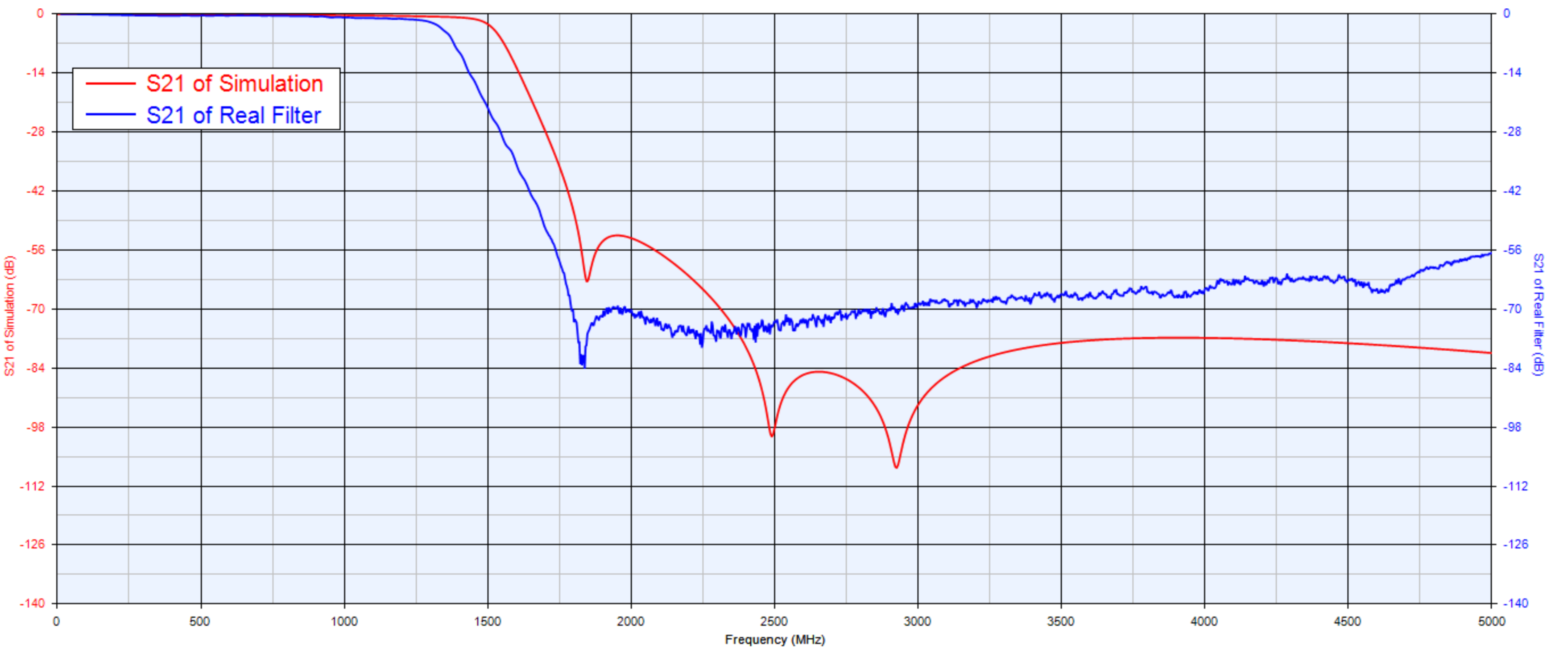

Figure 62 – Frequency responses compared

The differences due to previously mentioned reasons can be seen in a better way in Figure 62 which compares the frequency response and S_{21} of two filters.

8.13 Final Thoughts

At the end of the day, I have developed a RF filter from scratch. It is hard to say that final product has satisfied the specifications. There are numerous reasons behind of this. However, I was able to experience how to develop a project from scratch, what steps are needed and how to execute them. Moreover, I had a very similar pattern of S_{21} parameter which increases the chances that not the designed filter structure, but the transmission lines were responsible from the deviation. It was a perfect experience for me, and I was happy to obtain a real product at the end of this task.

During my internship, I gained experience on the field that I want to work in future. I observed how a R&D company runs; what engineers do in a R&D company. I learned very useful information in Meteksan. I can definitely say that if an engineering candidate wants to work in R&D and defence industry, Meteksan is a perfect company.

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