DESIGN OF NOVEL GENERALIZED LOW PASS FILTER CASCADED WITH PASSBAND NOTCH FOR MRI APPLICATIONS

by

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Dissertation submitted in partial fulfillment of the requirements for the
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CERTIFICATION OF APPROVAL

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Approved by,

____

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

MAY 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MAIMOUNA ABDERAMANE TAHIR

AKNOWLEDGEMENTS

First and foremost, all praise to Allah, the Almighty, the Benevolent, for His blessings and guidance and for granting me the strength to complete successfully the project.

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Last but not least, I would like to express my deepest gratitude to my family and friends for providing moral support. Their great support has given me the courage to fulfill my work with relaxation and peace of mind.

Abstract

Synthesis and design of a lumped-element low-pass filter cascaded with passband notch are done in this project. The filter synthesis and design are stringently carried out using Maple and done based on exact computations involving mainly the determination of the elements specifications. The design of the filter consisted of utilization of inductors and capacitors with Chebyshev approximation in which the elements values are obtained through insertion loss method and the resulting circuit is simulated via Advanced Digital Systems (ADS). The resulting frequency response of the filter is conforming to the given specifications with a total filter order of less than 15 in order to allow a better selective response and also avoid high power loss, high cost and complication in prototype fabrication later on. The main advantage of the cascaded filter is its better ability to increase the signal to noise ratio in Magnetic Resonance Imaging (MRI) equipment.

Table of Contents

List of Figures

CHAPTER 1

INTRODUCTION

1. BACKGROUND OF STUDY

Ideal filters are linear 2-port networks with ability to provide perfect frequency signal transmission within a pass-band interval and infinite frequency attenuation in the stop-band region. Within their performance, filters can also reduce signal degradation by providing accurate linear phase response in the pass-band. Moreover, filters are designed in order to approximate special requirements with tolerable loss in circuits and systems composed of lumped-element, planar, coaxial, cavity, dielectric, electroacoustic or waveguide components.

The classical filter types widely used nowadays are:

- Low Pass Filter: blocks all frequencies higher than its cut-off frequency.
- High Pass Filter: eliminates all frequencies below the cut-off frequency.
- Band-Pass Filter: selects only a band of frequencies desired to pass.
- Band-Stop Filter: blocks a band of frequencies within the frequency region.

However, all filters with the above mentioned functions have limited behavior with respect to the steady-state sinusoidal excitation. Explicitly, when any of these four filters is supplied with sine voltage or current source, it can be clearly noticed that the output displayed has individual frequency response.

This project will focus on designing a lumped element Low-Pass Filter cascaded with Band-Stop Filter to produce notch at the pass-band. The notch will be used for Magnetic Resonance Imaging applications.

2. PROPLEM STATEMENT

The current filter topologies do not comply with the modern requirements due to their limitation to single frequency response. A more complex filter topology with special performance can be the solution for getting an integrated response.

3. OBJECTIVES

The main objective of this project consists of synthesizing and designing a Low Pass Filter with Pass-band Notch.

4. SCOPE OF STUDY

The scope of study for this project is described as per the following points:

- To performance synthesis and analysis of a lumped element Low Pass Filter and a Band-Stop Filter.
- To cascade the two filters and produce notch at the pass-band.
- To model and simulate the design circuit.

5. PROJECT FEASIBILITY

Considering the confirmation of all relevant tools availability in term of software and hardware, the technical feasibility of the project is most likely practical. With reference to the methodology formulation and the project Gantt-chart, the completion of the project within the timeframe can be ensured.

CHAPTER 2

LITERATURE REVIEW

1. MAGNETIC RESONANCE IMAGING AND USE OF FILTERS

The severity of certain diseases and injuries are examined at hospitals using the Magnetic Resonance Imaging machine. It is a procedure of scanning patients for localizing or determining any suspected illness that cannot just be observed through blood analysis over the laboratory. The machine works on basis of high magnetic field generated by the passage of an electric current through the wire loops of its magnet. The magnetic coils produce radio waves that have the ability to pass through the patient's body and send an energetic signal which is further processed into a 3-D image representation by a computer.

The Magnetic Resonance Imaging is qualified by its generated magnetic field strength that is mostly in the range of 0.1-to-1.5 Tesla (T). The strength of its magnetic field is thousands times higher than the entire earth's magnetic field, which is 0.00007 T at the poles and 0.00003 T at the Equator. Its strength of the magnetic field that determines the accuracy of the machine's performance; MRI systems with larger magnetic field strength have much greater utility and higher signal to noise ratio. Whereas, systems with lower magnetic strength have weaker ability to distinguish signal from noise due to their smaller signal to noise ratio. For instance, the image processing gets very difficult and requires specific method for increasing the signal to noise ratio as discussed in [1].

Moreover, filters are commonly used for noise reduction on the basis that they have the ability to block unwanted frequency elements. For example, An Infinite Impulse Filter with special cut-off frequencies requirements can be practically used for cleaning electrical humming sound. In addition, the increase in the signal to noise ratio is related to adjustment in the radio frequency components of the MRI machine. Hence, filtering technique is the proposed solution for image recovering [2].

2. RELATED WORKS

Filter design needs specific requirements for getting the desired performance with less radiation loss. In fact, for designing a Low Pass Filter that needs a wide fractional bandwidth, the defected ground structure can be used for frequency response with a sharp cut-off frequency and an expended stop-band resulted from introducing a microstrip in the design procedure. This technique, which is also called Double-Sided Microwave Integrated Circuit technology, improves the filter's performance and gives it the credit to be integrated in various microwave circuits. Furthermore, this method of using microstrip on both parts of the substrate has the advantages of reducing the prototype fabrication cost, enhancing high-power handling capability and also increasing the flexibility of the design [3]-[6].

Moreover, those Double-Sided Microwave Integrated Circuits have the utility to operate on the basis of various transmission media including coplanar waveguide. Waveguide filters topology can be subjected to some modifications in the filter structure for the purpose of improving the power threshold of the multipactor effect. For instance, the rounded shape was introduced in the waveguide Low Pass Filters for the aim of minimizing the risk of the multipactor and the findings showed greater threshold level as compared to rectangular shaped filters [7]. Whereas, [8] and [9] ensured that rectangular waveguide filters are capable of enhancing the power-handling and reducing the circuit size for better performance in the case of high-power satellite communication.

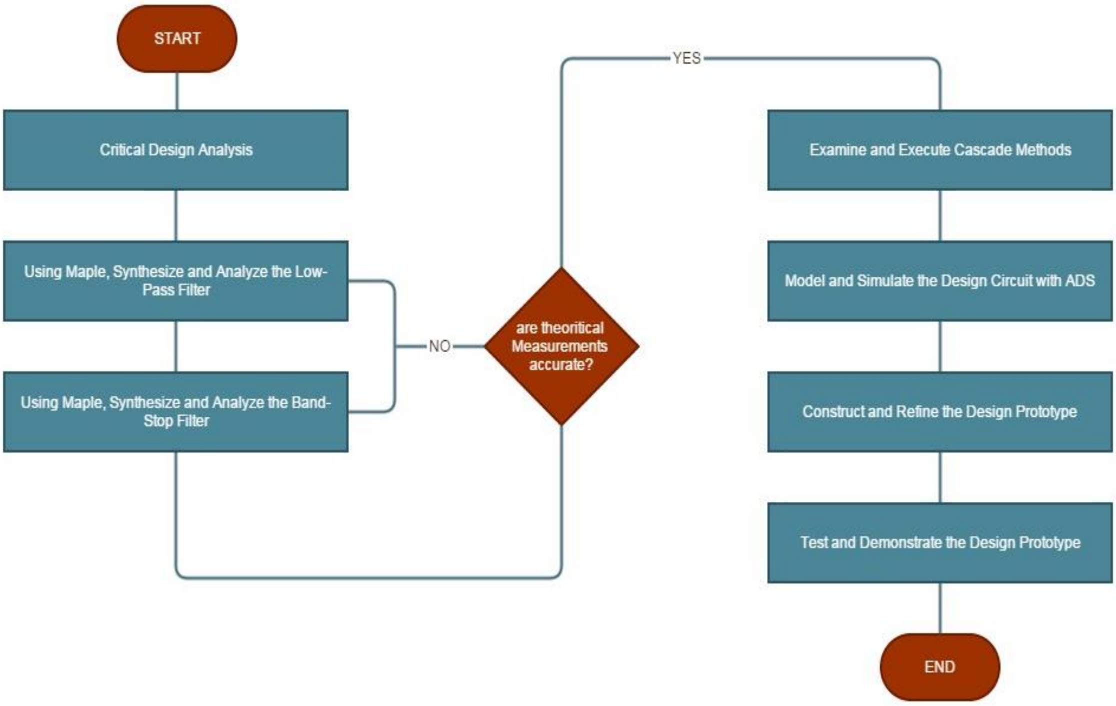
The lumped element filters are widely used for ideal response at low frequencies can control frequency and bandwidth by using variables components. Crucially, for power handling enhancement, tunable bandstop filters can be perfectly synthesized and designed using Advanced Digital System (ADS) simulations and cascade methods. For better cascaded filter structure with less loss, it is considerable to avoid spacing between the various filters used and also utilize higher quality factor (Q) components. [10]. Surprisingly, [11] has proven that lower quality factor (Q) can also lead to larger attenuation in bandstop filter with smaller sized lumped-element circuit.

As for the design of a novel generalized Low Pass Filter cascaded with Band-Stop project, it is intended to work on solving the limitations associated with the current individual response filters by providing a prototype of Lumped element capacitors and inductors cascaded filter that will produce notch at the passband. Although this type of filter is being introduced for the first time, previously studied and proposed methods can be used for individually designing the two filters. The outstanding advantage of this design is the capability of producing complex frequency response and meeting special requirements for Magnetic Resonance Imaging applications.

CHAPTER 3

METHODOLOGY

1. PROJECT METHOLOGY



1.1. Critical Design Analysis

The critical design analysis is based on theoretical studies of the filter design. In fact, in order to do a proper simulation, a concise understanding of the filter topology is the preliminary to the synthesis and analysis of the design measurement via Maple.

The low pass prototype network is mainly used as reference for designing any other filter type. In fact, the angular frequency (ω) of a low pass prototype network is 1 with operation starting from 1 Ω resistor at source into 1 Ω resistor at the load through the filter network. Such low pass network is shown in Figure 1. The considered example of the low-pass prototype is of order n = 4. And it can be clearly observed that the network of low-pass consists of series inductors and shunt capacitors.

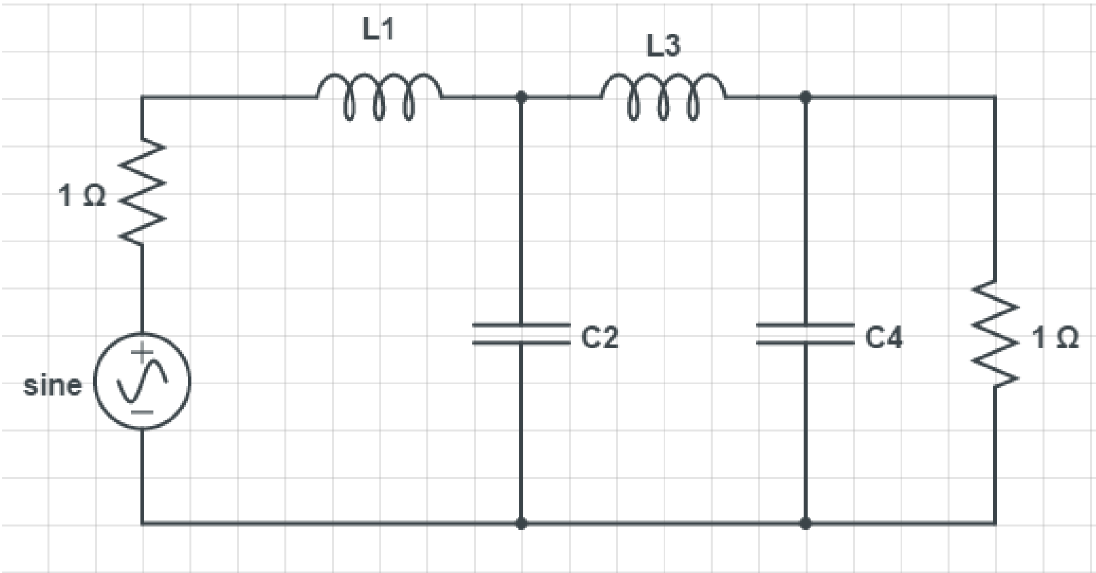


Figure 1 Typical network of low-pass prototype

The low-pass prototype shown in *Figure 1* has the frequency response shown in *Figure 2* and a transmission characteristic of:

$$|S_{12}(j\omega)|^2 = \frac{1}{1 + F_N^2(\omega)} \tag{1}$$

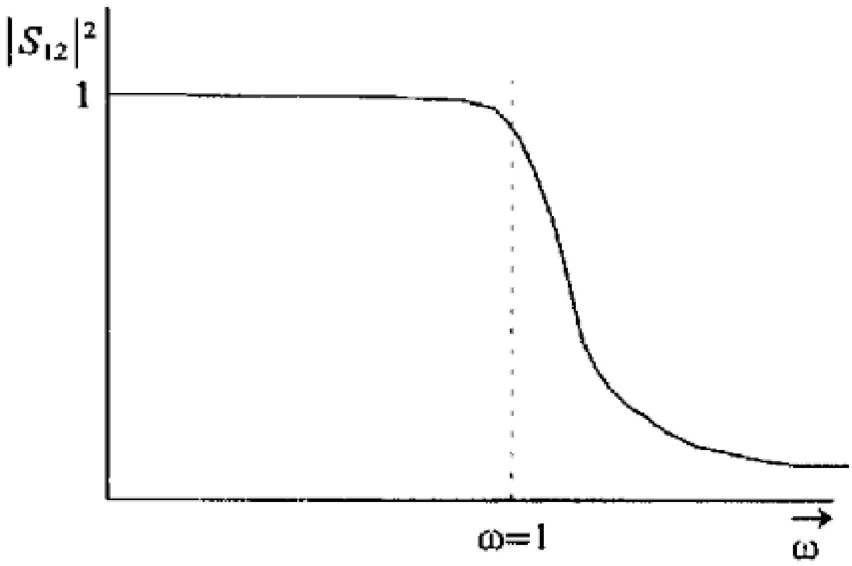


Figure 2 Frequency response of low-pass prototype

In order to design a low-pass filter with arbitrary specifications starting from the general low-pass network, transformation in components values is made as per the followings.

$$\omega \rightarrow \omega/\omega_c \tag{2}$$

Yielding into,

$$|S_{12}(j\omega)|^2 = \frac{1}{1 + F_N^2(\omega/\omega_c)} \tag{3}$$

Also the inductor and capacitor equations are subjected to the transformation. With the respective inductor and capacitor formulas of the low pass prototype to be.

$$Z(j\omega) = j\omega L \tag{4}$$

$$Z(j\omega) = \frac{-j}{\omega C} \tag{5}$$

The resulting inductor and capacitor expressions are:

$$Z(j\omega) = \frac{j\omega L}{\omega_c} \tag{6}$$

$$Z(j\omega) = \frac{-j}{(\omega/\omega_c)C} \tag{7}$$

However, the filter's frequency response at cut-off frequency of $\omega = \omega_c$ will be the same as at band-edge of $\omega = 1$ in *Figure 2*.

As for the design of the band-stop filter, the filter network can be obtained by either connecting a low-pass filter and a high-pass filter in parallel or by transforming the low-pass prototype parameters.

The design from parallel connection of low-pass and high-pass filters requires deeper process as it consists of transforming the low-pass prototype into low-pass filter at first and high-pass filter successively, then connect the two circuits' ports in parallel basis. On the other hand, the direct conversion of low-pass prototype into band stop network is more accurate and less time consuming.

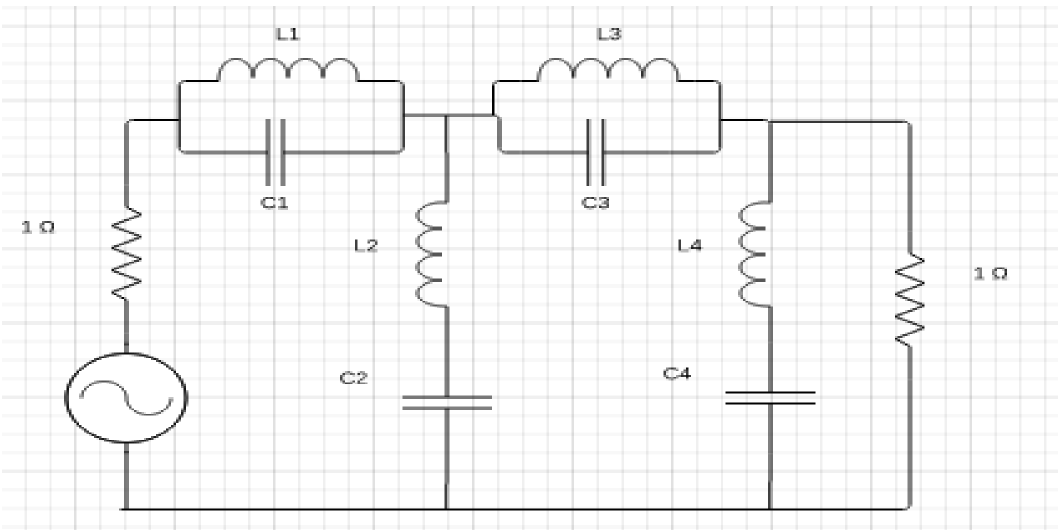


Figure 3 Typical network of band-stop filter

Thus, the low-pass filter network in *Figure 3.1* can be changed into band-stop network by converting the series inductor into shunt resonator and the shunt capacitor into a series resonator as in *Figure 3.3* with the following modifications in components' values:

$$\omega \;\rightarrow\; \frac{-1}{\alpha\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right)} \tag{8}$$

With,

$$\omega_0 = \sqrt{(\omega_1\omega_2)} \tag{9}$$

$$\alpha = \frac{\omega_0}{\omega_2 - \omega_1} = \frac{\omega_0}{\Delta\omega} \tag{10}$$

Hence,

$$|S_{12}(j\omega)|^2 = \frac{1}{1 + F_N^2\left(\frac{-1}{\alpha\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right)}\right)} \tag{11}$$

The frequency response of the band-stop resulting from the transformation of low-pass prototype is as shown in *Figure 4.*

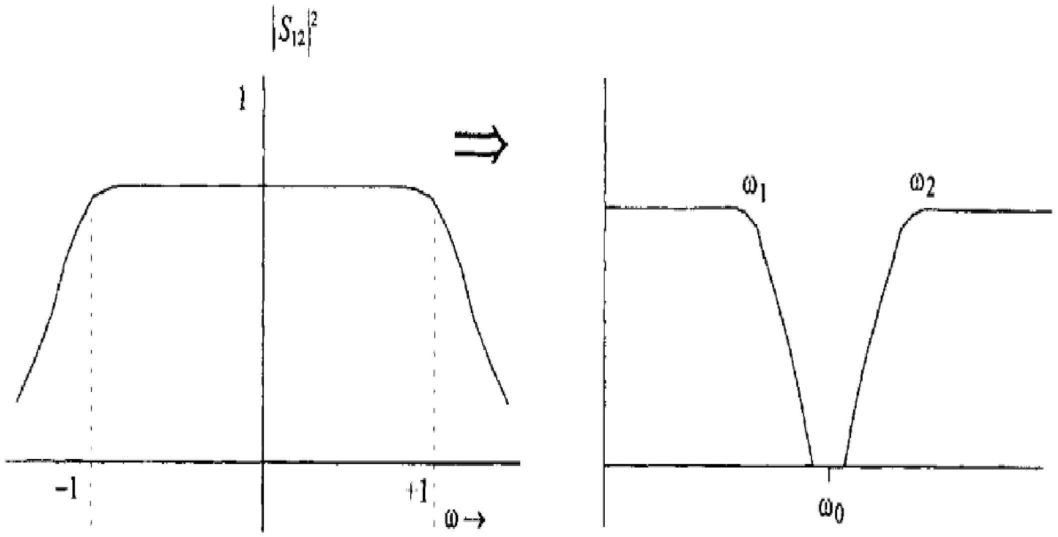


Figure 4 Transformation of low-pass into band-stop filter

1.2. Synthesis and Design

The synthesis of the two filters to be cascaded requires a deep computational analysis of design parameters' values. In order to get accurate data that can approximate the design specifications, a two-port networks is an object of consideration. The network to be synthesis in this project is not consisting of resistors; this is to make the filter possibly lossless. Nevertheless, we will be using input and output system impedances of 50 Ohm for the limitation of losses and power handling capacity.

Moreover, it is hoped to get a frequency response with precise specifications such as in *Figure 5*. For instance, the cut-off frequency, the insertion and rejection losses, the maximum ripple and the filter approximation (N) are the key elements in determining the inductors and capacitors values. Basically, there are several methods of synthesis for designing microwaves filters but the most efficient is the insertion loss method. It is generally used in preference for cases in which the synthesis is to be carried out based on completely specified frequency response as in this project.

The insertion loss method for designing a Chebyshev low pass filter consist of determining the filter element values by carrying out computations using insertion loss, passband and stopband frequencies and find return loss, the filter order, selectivity.

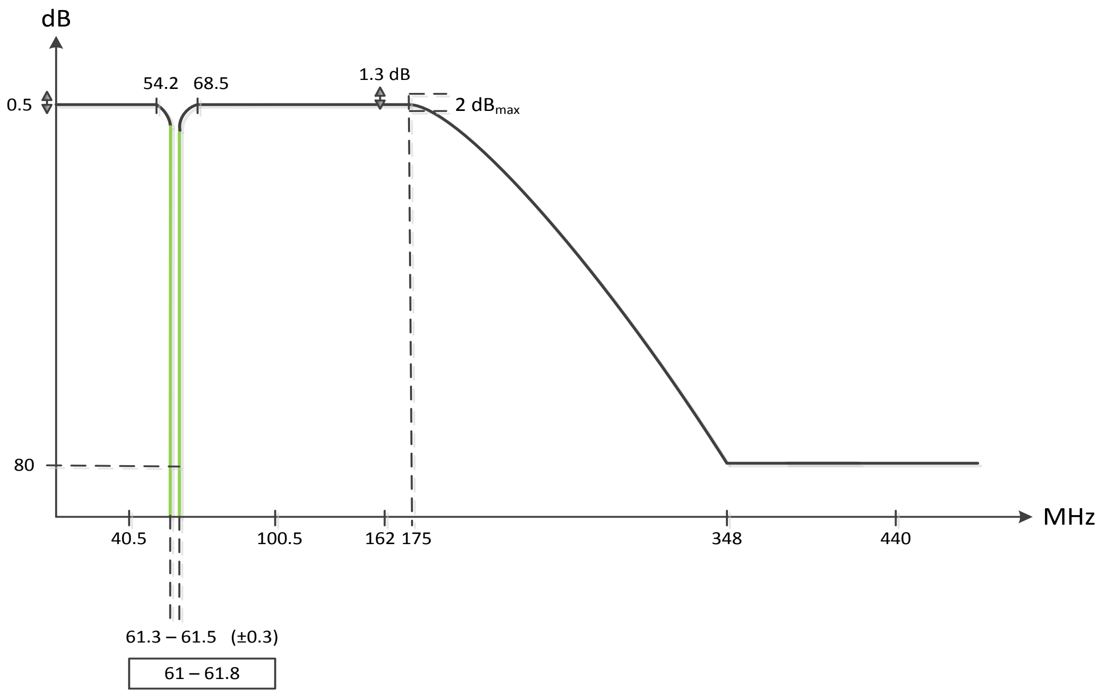
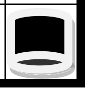


Figure 5 Required frequency response of the cascaded filter

After the determination of the filter element values through insertion loss method, the design simulation of the project is to be carried out using Agilent's Advanced Digital System (ADS). After a comparison between the simulation results and the theoretical specifications, changes and improvement might be done based on the performance of the filter. In the case that the findings are satisfyingly acceptable, the resulting circuit schematic will be printed and sent for fabrication of the complex filter prototype.

2. GANTT CHART

2.1.Final Year Project 1

Task \ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of Project Topic	■	■												
Background knowledge		■	■											
Preliminary Research Work		■	■	■	■									
Literature of Extended Proposal					■	■								
Extended Proposal Submission														
Critical Analysis for Project Design							■	■	■					
Project Proposal Defense								■	■					
Project work continues										■	■	■		
Submission of Interim Draft Report														
Submission of Interim Report														

2.2.Final Year Project 2

Week / Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	…	19
Project work continues																	
Submission of Progress Report																	
Project work continues																	
Pre-SEDEX																	
Submission of Draft Final Report																	
Submission of Dissertation (Soft Bound)																	
Submission of Technical Paper																	
Viva																	
Submission of Project Dissertation (Hard Bound)																	

3. TOOLS REQUIRED

The software types that will be used in this project are Maple and Advanced Design System (ADS). Maple is software for mathematics, modeling and simulation and it will be used for the function of filter design tool. Whereas, ADS provides a big number of circuit simulation methods and models specially oriented to microwave domain.

As for the hardware, an innovative Low Pass Filter with Lumped components cascaded with a Band-Stop Filter consists of a pair of terminals impedances and a combination of inductors and shunt capacitors connected on Printed Circuit Board. The number of the components will be determined by the order of the filter.

CHAPTER 4

RESULT AND DISCUSSION

1. NORMALIZED CHEBYSHEV LOW PASS FILTER

For designing the project filter, it is highly accountable to design first a normalized low pass filter from which we can perform network transformation in order to obtain the desired filter. As discussed in part 1.2 of the methodology chapter, the method used in the fulfillment of this project's objectives is the insertion loss method. Considering Figure 5, we have the insertion loss of 0.5 dB which is used for computing the filter selectivity and order as per the followings:

$$Insertion\ Loss = I_l = 20\ log\sqrt{1+\varepsilon^2} = 10\log(1+\varepsilon^2) = 10\log(\frac{1}{|S_{12}|^2}) \quad (12)$$

$$Return\ Loss = R_l = 10\log(\frac{1}{|S_{11}|^2}) \quad (13)$$

From equation (12), the level of ripple control in the passband is obtained as:

$$\varepsilon = \sqrt{(10^{\frac{0.5}{10}}) - 1} \quad \rightarrow \quad \varepsilon = 0.35$$

And $|S_{12}|^2 = \frac{1}{1+(0.35)^2} \quad \rightarrow \quad |S_{12}|^2 = 0.89$

While $|S_{12}|^2 + |S_{11}|^2 = 1 \quad \rightarrow \quad |S_{11}|^2 = 1 - |S_{12}|^2 \quad (14)$

We obtain from equation (14):

$$|S_{11}|^2 = 1 - 0.89 \quad \rightarrow \quad |S_{11}|^2 = 0.11$$

Hence, solving equation (13) leads to:

$$Return\ Loss = R_l = 10\log(\frac{1}{0.11}) \quad \rightarrow \quad Return\ Loss = R_l = 9.59dB$$

The formula for getting the filter order is given by:

$$N \geq \frac{I_l + R_l + 6}{20\,log\left[S + (S^2 - 1)^{1/2}\right]} \tag{15}$$

Where, S stands for the filter selectivity which is the ratio of the stopband frequency by the passband frequency. Considering that the stopband attenuation of Figure 5 occurs at 348 MHz and the passband is limited at 175 MHz, we have:

$$S = \frac{stopband\ frequency}{passband\ frequency} \quad \rightarrow \quad S = \frac{348}{175} \quad \rightarrow \quad S = 2$$

So, equation (15) becomes:

$$N \geq \frac{0.5 + 9.59 + 6}{20\,log\left[2 + (2^2 - 1)^{1/2}\right]} \quad \rightarrow \quad N \geq 1.41$$

Now, the filter order can be at any value above 1.41. However, the higher the order, the sharper the frequency response rolls off above the passband. Nevertheless, the fabrication will present difficulties for high order. Therefore, we can choose the N order of the filter to be 5 and then simulate to analyze the frequency response whether it is accurate enough in comparison to the required response.

For Chebyshev low pass filter prototypes, the element values at the input impedance of $R_i = 1\ \Omega$, cutoff frequency of 1, insertion loss of 0.5dB and Nth order from 1 to 10, are respectively given in Figure 6.

	0.5 dB Ripple										
N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}
1	0.6986	1.0000									
2	1.4029	0.7071	1.9841								
3	1.5963	1.0967	1.5963	1.0000							
4	1.6703	1.1926	2.3661	0.8419	1.9841						
5	1.7058	1.2296	2.5408	1.2296	1.7058	1.0000					
6	1.7254	1.2479	2.6064	1.3137	2.4758	0.8696	1.9841				
7	1.7372	1.2583	2.6381	1.3444	2.6381	1.2583	1.7372	1.0000			
8	1.7451	1.2647	2.6564	1.3590	2.6964	1.3389	2.5093	0.8796	1.9841		
9	1.7504	1.2690	2.6678	1.3673	2.7239	1.3673	2.6678	1.2690	1.7504	1.0000	
10	1.7543	1.2721	2.6754	1.3725	2.7392	1.3806	2.7231	1.3485	2.5239	0.8842	1.9841

Figure 6 Element Values of Normalized Chebyshev Low Pass Filter

For N = 5, we can observe that:

$L_1 = 1.7058$

$C_2 = 1.2296$

$L_3 = 2.5408$

$C_4 = 1.2296$

$L_5 = 1.7058$

$R_o = 1$

2. FILTER TRANSFORMATION

2.1 Low Pass Filter

In order to transform the normalized low pass filter into the low pass filter with cutoff frequency of 175 MHz, we need to perform scale in term of frequency and also impedance as the terminal impedances are to 50 Ω in instead of 1 Ω. As discussed in part 1.1 of the methodology chapter, in order to carry out scale in term of frequency, we need to divide the original values of inductors and capacitors by ω_c.

Whereas, the network transformation requires multiplication of the inductor and impedance by 50 Ω and division of the capacitor by 50 Ω in term of impedance scale.

Hence, the formulas to be used are:

$$R' = 50R \tag{16}$$

$$L' = \frac{50L}{\omega_c} \tag{17}$$

$$C' = \frac{C}{50\omega_c} \tag{18}$$

So, we get respectively:

$$R_i' = R_o' = 50\ \Omega$$

$$L_1' = \frac{50*1.7058}{2\pi*175\ MHz} \quad \rightarrow \quad L_1' = 77.6\ nH$$

$$C_2' = \frac{1.2296}{50*2\pi*175\ MHz} \quad \rightarrow \quad C_2' = 22.4\ pF$$

$$L_3' = \frac{50*2.5408}{2\pi*175\ MHz} \quad \rightarrow \quad L_3' = 115.5\ nH$$

$$C_4' = \frac{1.2296}{50*2\pi*175\ MHz} \quad \rightarrow \quad C_4' = 22.4\ pF$$

$$L_5' = \frac{50*1.7058}{2\pi*175\ MHz} \quad \rightarrow \quad L_5' = 77.6\ nH$$

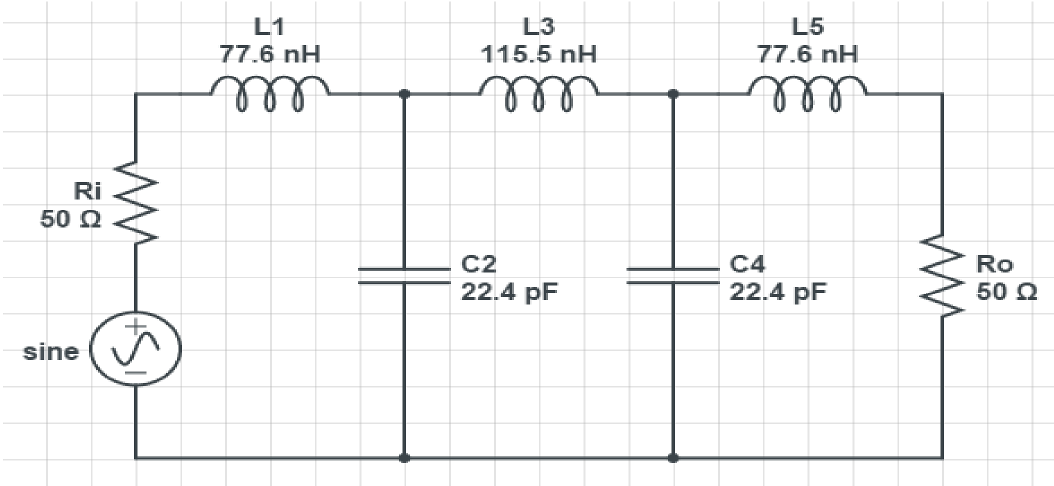


Figure 7 Low Pass Filter

2.2 Bandstop Filter

Similarly to the low pass filter, a transformation of the normalized low pass filter is needed in order to access the design specifications of the bandstop filter. For scaling in term of impedance, we will be use the same concept as for the case of low pass filter. However, the frequency scale needs different computational pattern which transforms each inductor into a pair of shunt resonator and the capacitor into a pair of series resonator. The formulas to be used are:

Inductor transformation:

$$L' = \frac{50 * L * \Delta}{\omega_o} \tag{19}$$

$$C' = \frac{1}{50 * L * \Delta * \omega_o} \tag{20}$$

Capacitor transformation:

$$L' = \frac{50}{\omega_o * C * \Delta} \tag{21}$$

$$C' = \frac{C * \Delta}{50 * \omega_o} \tag{22}$$

Where: $\Delta = \frac{\omega_2 - \omega_1}{\omega_o} \rightarrow \Delta = \frac{68.5\ MHz - 54.2\ MHz}{61.4\ MHz} \rightarrow \Delta = 0.23$

So, the new element values are found as:

- Shunt elements for $L_1 = 1.7058$

$$L_1' = \frac{50*1.7058*0.23}{2\pi*61.4\ MHz} \quad \rightarrow \quad L_1' = 50.85\ nH$$

$$C_1' = \frac{1}{50*1.7058*0.23*2\pi*61.4\ MHz} \quad \rightarrow \quad C_1' = 132.14\ pF$$

- Series elements for $C_2 = 1.2296$

$$L_2' = \frac{50}{2\pi*61.4\ MHz*1.2296*0.23} \quad \rightarrow \quad L_2' = 458.3\ nH$$

$$C_2' = \frac{1.2296*0.23}{50*2\pi*61.4\ MHz} \quad \rightarrow \quad C_2' = 14.66\ pF$$

- Shunt elements for $L_3 = 2.5408$

$$L_3' = \frac{50*2.5408*0.23}{2\pi*61.4\ MHz} \quad \rightarrow \quad L_3' = 75.75\ nH$$

$$C_3' = \frac{1}{50*2.5408*0.23*2\pi*61.4\ MHz} \quad \rightarrow \quad C_3' = 88.71\ pF$$

- Series elements for $C_4 = 1.2296$

$$L_4' = \frac{50}{2\pi*61.4\ MHz*1.2296*0.23} \quad \rightarrow \quad L_4' = 458.3\ nH$$

$$C_4' = \frac{1.2296*0.23}{50*2\pi*61.4\ MHz} \quad \rightarrow \quad C_4' = 14.66\ pF$$

- Shunt elements for $L_5 = 1.7058$

$$L_5' = \frac{50*1.7058*0.23}{2\pi*61.4\ MHz} \quad \rightarrow \quad L_5' = 50.85\ nH$$

$$C_5' = \frac{1}{50*1.7058*0.23*2\pi*61.4\ MHz} \quad \rightarrow \quad C_5' = 132.14\ pF$$

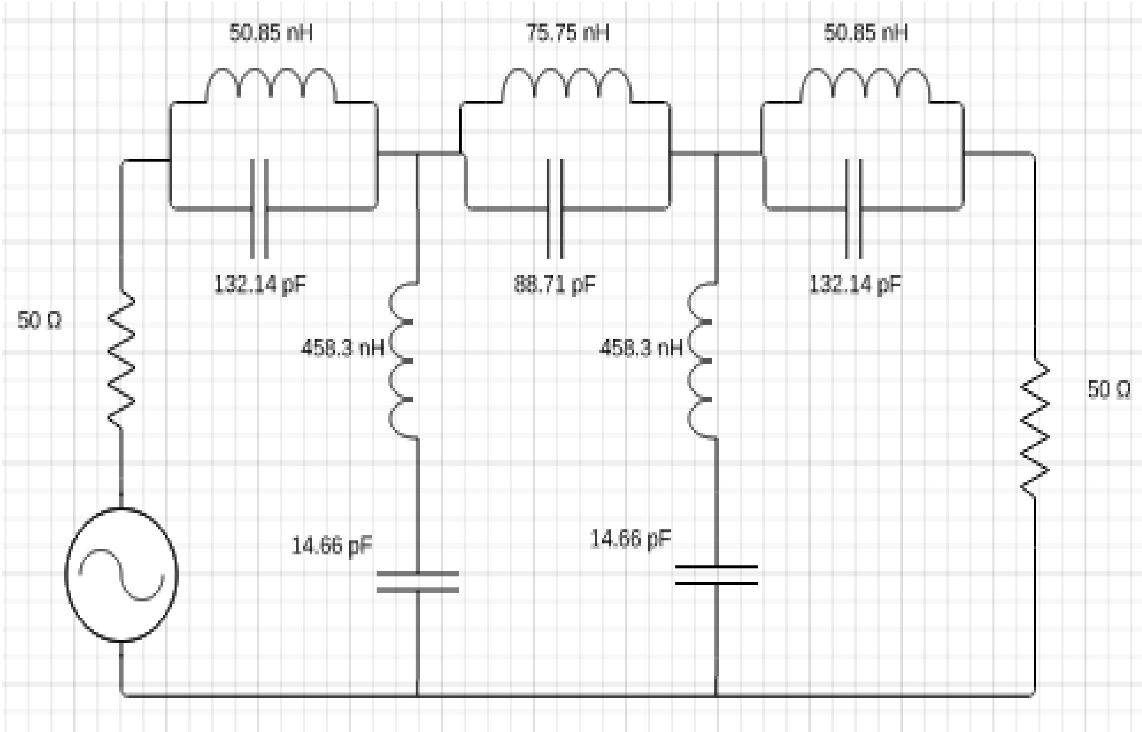


Figure 8 Bandstop Filter of N=5

The cascade of the circuits in Figure 7 and Figure 8 is accomplished as shown in Figure 9 and it is simulated using Agilent's Advance Design Systems. The resulting response is approximately similar to the given response in the passband. However, the roll off above the passband seemed to be less sharp as shown in Figure 10. The reason behind this behavior is the choice of the filter order as a lower filter order displays less selective response. For instance, we need to increase the low pass filter order and maintain the bandstop filter order as the notch in Figure 10 is satisfying.

In order to avoid higher power loss and high cost, we need to keep the filter order to be around 15 in total. In addition, further than this order number, we might face difficulties when it comes to prototype fabrication as the assembly of the elements would be more gigantic than it is desired to be for the MRI equipment. Basically, it's required to consider a normalized filter of order 9 based on the computations carried in part 4.1 and perform network transformation in term of frequency and impedance.

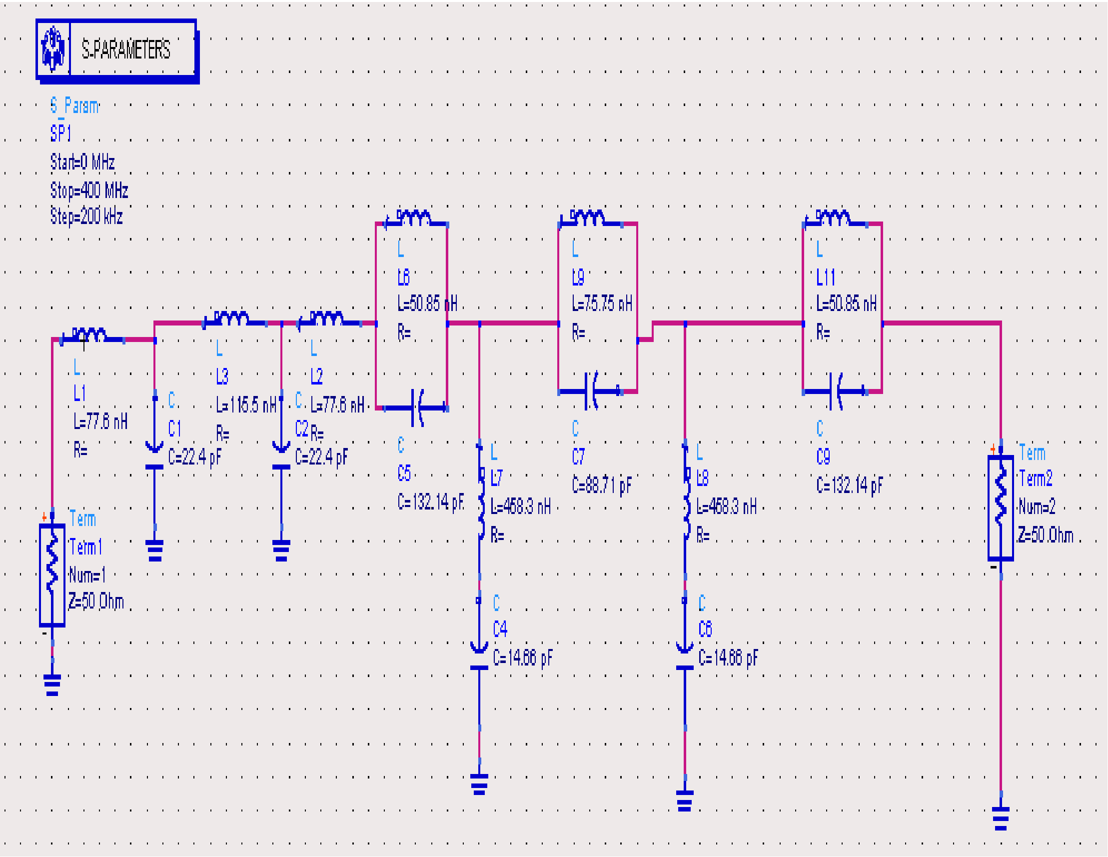


Figure 9 10th Order Cascaded Low Pass Filter with Band-Stop Filter

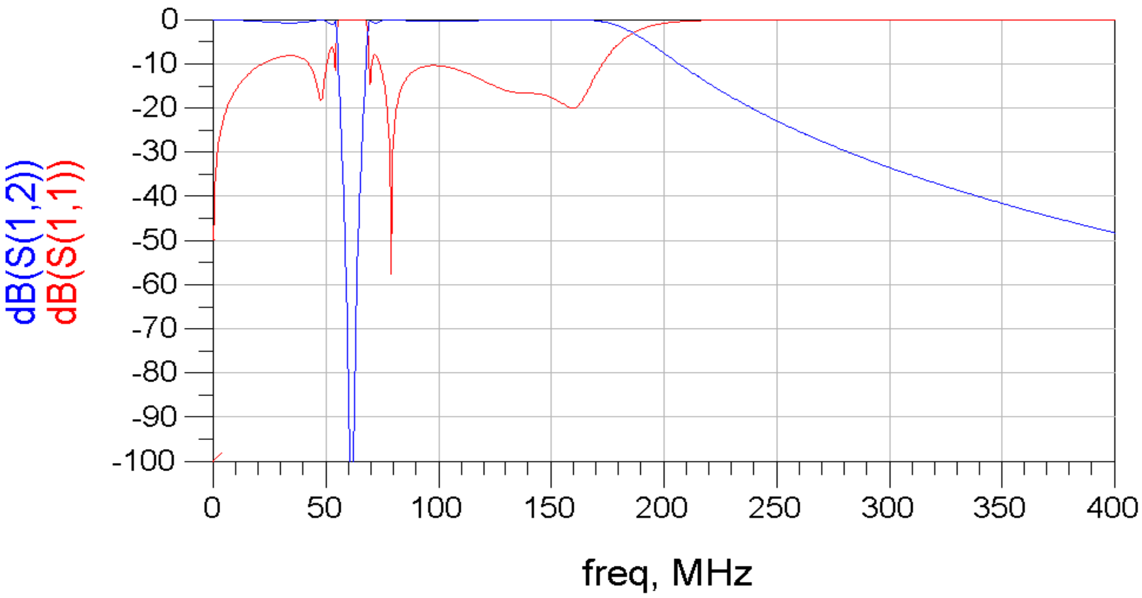


Figure 10 Frequency Response of The Low Pass Filter Cascaded with Band-Stop Filter

According to the data in Figure 6, the normalized low pass filter of order 9 has the element-values of :

L_1 = 1.7504

C_2 = 1.2690

L_3 = 2.6678

C_4 = 1.3673

L_5 = 2.7239

C_6 = 1.3673

L_7 = 2.6678

C_8 = 1.2690

L_9 = 1.7504

R_0 = 1

In order to perform scaling of the above values in term of frequency and impedance, we need to take equations (16), (17) and (18) into consideration. Implementing the elements values in thoses equations leads to the following computations :

$$R_i' = R_o' = 50\ \Omega$$

$$L_1' = \frac{50*1.7504}{2\pi*175\ MHz} \quad \rightarrow \quad L_1' = 79.60\ nH$$

$$C_2' = \frac{1.2690}{50*2\pi*175\ MHz} \quad \rightarrow \quad C_2' = 23.08\ pF$$

$$L_3' = \frac{50*2.6678}{2\pi*175\ MHz} \quad \rightarrow \quad L_3' = 121.31\ nH$$

$$C_4' = \frac{1.3673}{50*2\pi*175\ MHz} \quad \rightarrow \quad C_4' = 24.87\ pF$$

$$L_5' = \frac{50*2.7239}{2\pi*175\ MHz} \quad \rightarrow \quad L_5' = 123.86\ nH$$

$$C_6' = \frac{1.3673}{50*2\pi*175\ MHz} \quad \rightarrow \quad C_6' = 24.87\ pF$$

$$L'_7 = \frac{50*2.6678}{2\pi*175\ MHz} \quad \rightarrow \quad L'_7 = 121.31\ nH$$

$$C'_8 = \frac{1.2690}{50*2\pi*175\ MHz} \quad \rightarrow \quad C'_8 = 23.08\ pF$$

$$L'_9 = \frac{50*1.7504}{2\pi*175\ MHz} \quad \rightarrow \quad L'_9 = 79.60\ nH$$

Therefore, the circuits to be cascaded for the improvement of the response selectivity are as described in Figure 11 and Figure 12 :

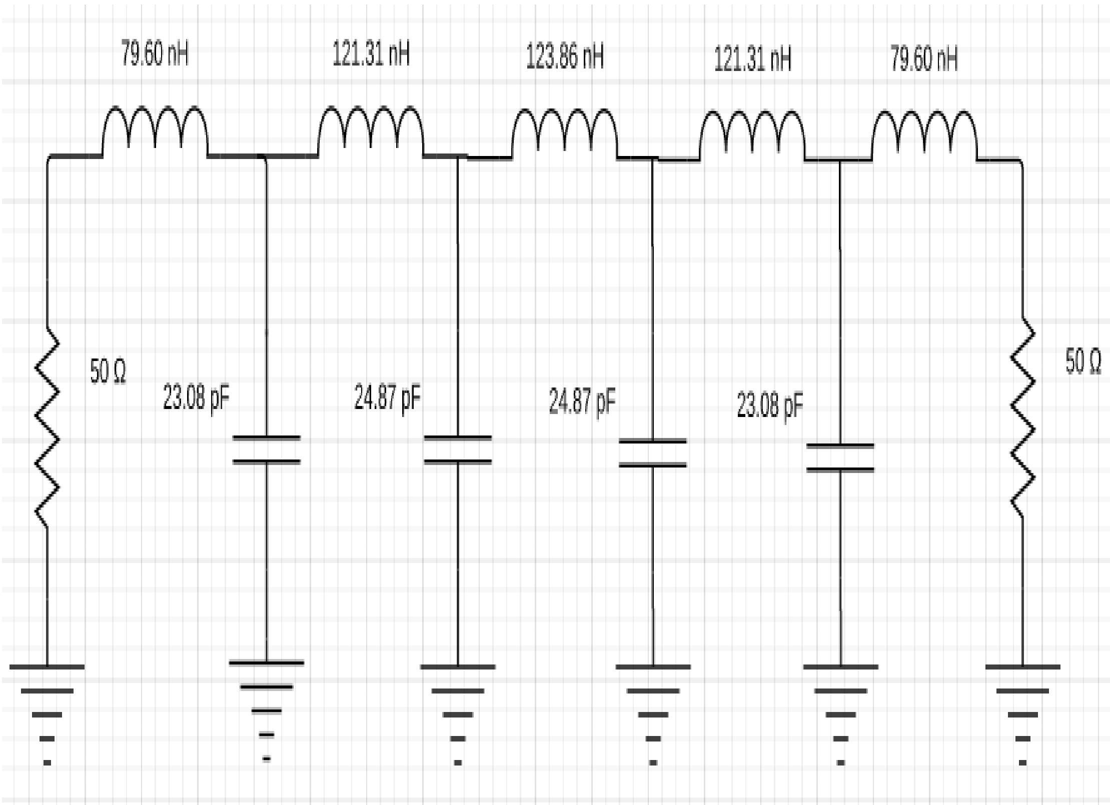


Figure 11 9th Order Low Pass Filter with Lumped Elements

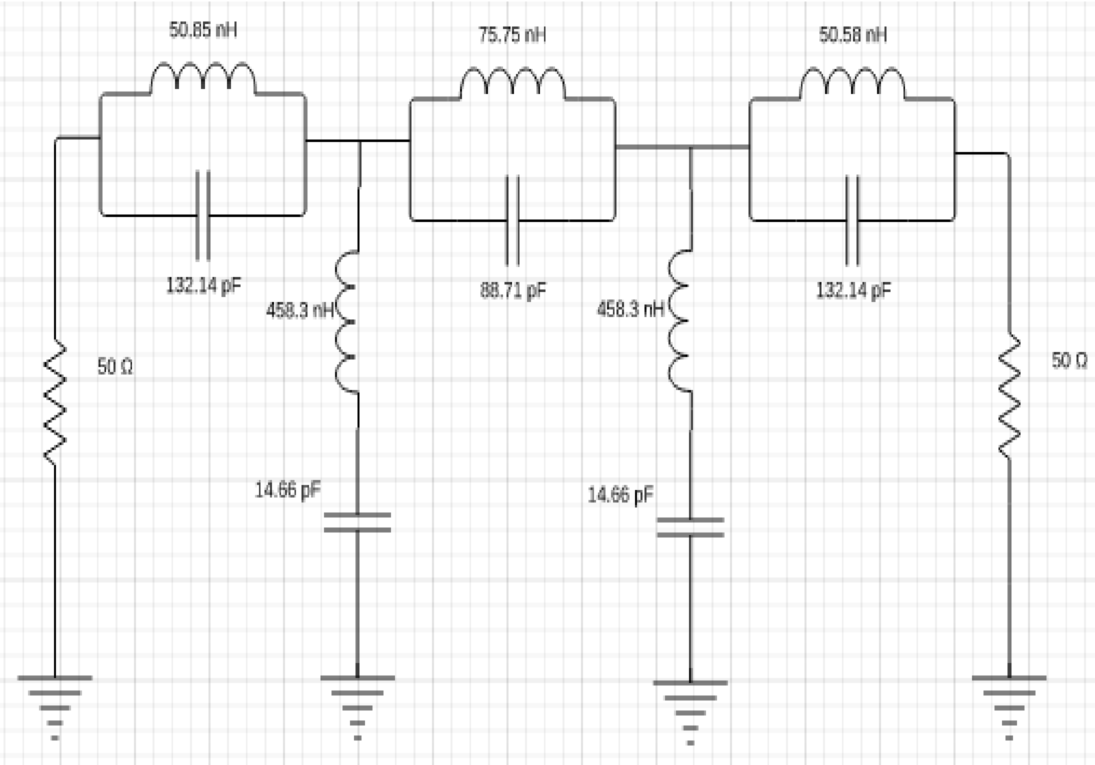


Figure 12 5th Order Lumped-Elements Band-Stop Filter

The improved low pass filter order is chosen to be 9 for the reasons that we need to avoid a total order of the design exceeding 15 and also the Chebyshev approximation provides better performance for odd filter order considering that both terminal resistors are set to identical values. This allows an accurate adjustment of the signal transmission within the filter's transmission lines.

Following the concept of cascade used in Figure 9, the circuit in Figure 13 is the result of cascade of Figure 11 and Figure 12 circuits respectively. The design is then simulated using Advanced Design Systems and we obtained an impeccable frequency response as shown in Figure 13. It can be clearly noticed that the new response has better selectivity and the cut-off frequency below the pointer m1 in Figure 13 is approximated to 175 MHz which is the required value for the fulfillment of the design.

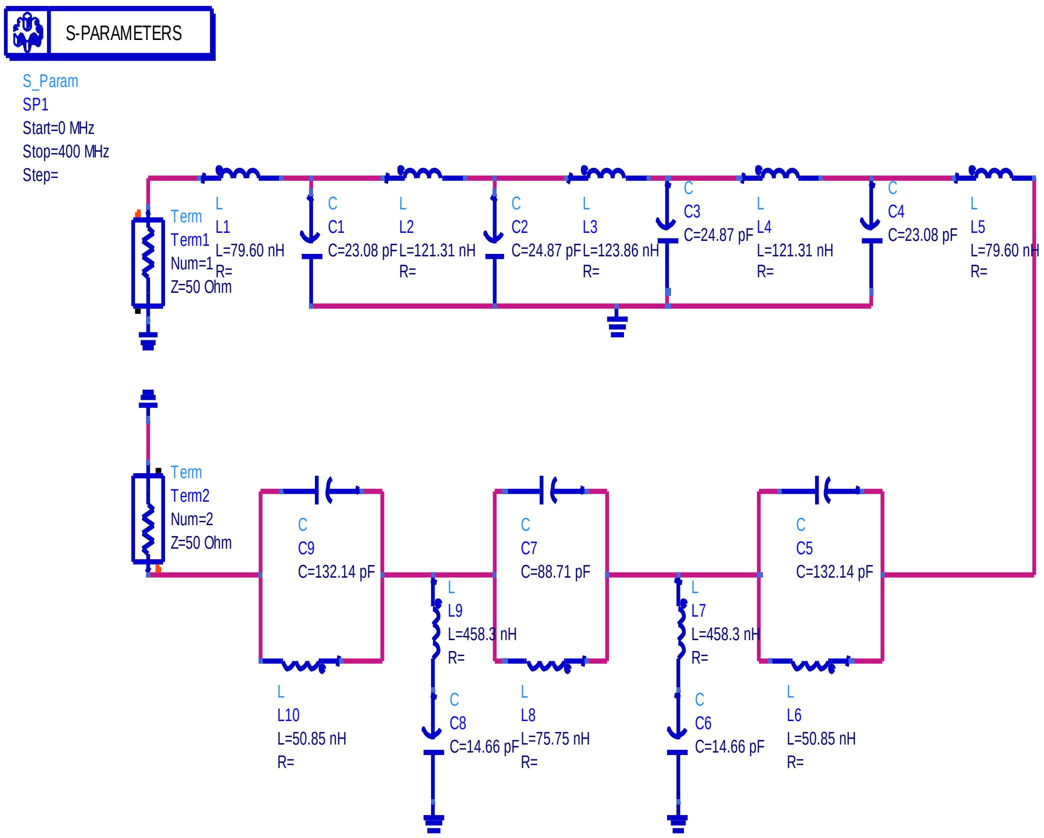


Figure 13 15th Order Cascaded Low Pass Filter with Passband Notch

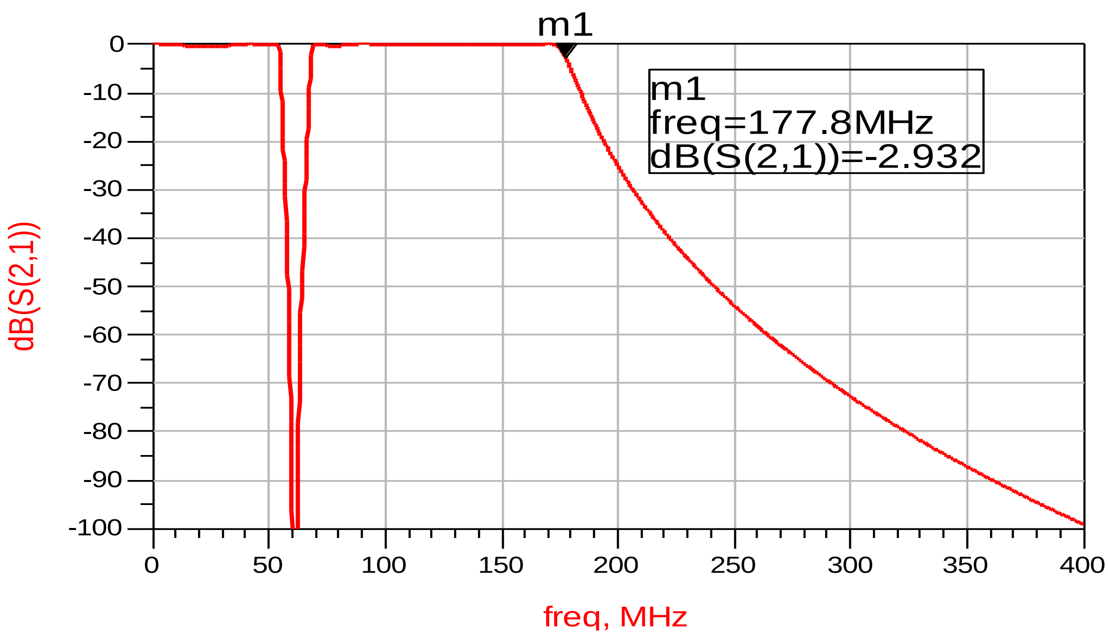


Figure 14 Frequency Response of the Improved Design

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

A novel generalized low pass filter cascaded with passband notch for Magnetic Resonance Imaging (MRI) is to be designed in this project. The project work consisted of separate design of a low pass filter and a bandstop filter using Chebyshev approximation with lumped elements and then cascading them accordingly to obtain an accurate frequency response as per client specifications. The method used in this project is the insertion loss method for filter design because it is highly preferred as it takes into account the synthesis of the filters based on completely specified frequency response.

For instance, a normalized chebyshev low pass filter is synthesized and designed via insertion loss method and the components values are determined for nth order of 5. Nevertheless, the displayed frequency response showed a less selective roll off above the passband with the chosen order. Subsequently, the low pass filter order is improved to 9 due to the limitation of the total design order for reasons of providing an impeccable filter with ability to reduce the noise signal in the modern MRI machines at acceptable power loss, prototype size and cost.

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