DESIGN OF LOWPASS FILTER WITH LOW TOTAL HARMONIC DISTORTION

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ELECTRICAL AND ELECTRONIC ENGINEERING
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By

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

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Approved by,

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(Dr Cheab Sovuthy)

UNIVERSITI TEKNOLOGI PETRONAS
BANDAR SERI ISKANDAR, PERAK
January 2017

CERTIFICATION OF ORIGINALITY

This certifies that I take full responsibility on all of my submitted works for this project and the original work is my own except as specified in the references and acknowledgements. The original work contained herein have not been undertaken or done by any unspecified sources or persons.

MUHAMMAD SAFWAN BIN MOHAMED MASARIK

ABSTRACT

This research is conducted to design a lowpass filter with low total harmonic distortion (THD). The research focuses on the suitable design synthesis of lowpass filter with cutoff frequency at 500kHz, -35 dB attenuation at 1000kHz and -100 dB response of total harmonic distortion. Elliptic filter topology is selected after comparing with Maximally flat, Chebyshev and Inverse Chebyshev topologies because Elliptic filter gives steepest attenuation and lowest THD reading. Elliptic filter results in lowest THD at -35.65 dB. Additionally, research was done on the effect of inductor's number and types on the harmonic responses of filters. Comparison of inductors and capacitors were made and the best component with expected lowest THD was selected for fabrication. Therefore Ferrite pot core inductor and Polystrene film capacitor was selected. Stated design hypothesis is the design of lowpass filter with low THD is possible with less inductor section.

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CHAPTER 1

INTRODUCTION

1.1 Background & Motivation

Application of AC current into non-linear devices such as diode propose a threat of harmonics distortion. Only the fundamental frequency are real power into load therefore its component frequency, harmonics, are waste of energy and results in less quality in audio application due to noise. Therefore a solution was proposed to reduce the total harmonic distortion (THD) by designing a lowpass filter with high selectivity. Hypothesis of the project is to design a lowpass filter with high selectivity, which means more LC section in the lumped circuit will results in steeper attenuation of signals and by experimenting some design methods such as Chebyshev, Butterworth and Elliptic, a best design is constructed to produce reduction of the total harmonic distortion of current, delay distortion due to varying input frequency and increase in the sound quality which are better clarity and less noise.

1.2 Problem statement

Daily electronic application nowadays deals with non-linear devices such as diode and amplifiers. This poses the threat of harmonic current distortion which is the addition of different frequency current signals added into the original signal. Only the fundamental frequency signals deliver real power to the load therefore the other harmonic frequencies are power loss and noise in audio application. Lowpass filter is designed to reject the higher order harmonic frequency and select only the fundamental frequency. The problems occur when it comes to designing a very steep attenuation falloff response which requires more inductor and capacitor sections. The more these sections are added, the greater the total harmonics distortion.

1.3 Objective

The objectives of this project are :-

1. To design the lowpass filter with high selectivity

2. To fabricate and measure the prototype.

1.4 Dissertation Organization

This dissertation is composed of 5 chapters. The introduction chapter presents the background of the project, the problem statement and the objectives. Chapter 2 mainly emphasize on the literature review. It contains all relevant theories, hypotheses, and information which are relevant to the objectives of this project.

Chapter 3 discusses the methodology to achieve the objectives of the project. The project methodology covers Gantt chart, tools for research, filter specifications and mathematical modeling of the filters

Chapter 4 contains the simulation result, prototype measurement and discussion. This chapter presents the findings and outcomes of the project work. Waveform response and total harmonic distortion performance are measured and discussed.

In chapter 5, conclusion of this dissertation is summarized and suggestions for future research are provided.

Chapter 2

LITERATURE REVIEW

2.1 Filters

The filter design technology is the heart of wireless communication because filter allow us to differentiate these varying frequency signal that exists around us [1]. In DC power supply application, filters eliminate unwanted high frequency noise which present within AC line voltage. In addition the usage of non-linear system such as rectifier which introduces voltage spike and dip can be flattened out with filters [2]. In radio communications, the application of filters enables desired signals to receiver. This is achieved with the LC resonant circuit which produces passband response signal. Besides that, for radio transmitter, filter makes generating only 1 signal while attenuating other signals which can interfere with different radio transmission possible. This may be achieved with the practice of lowpass and highpass filters [1]. Filters also makes up to very important component in audio electronics. A good sound which may be C chord from a guitar actually contain additions of harmonics and the fundamental signals altogether producing that good quality sound. The filter networks in audio electronics is called crossover networks [1]. Low frequency audio signals are sent to and reproduced in woofers. Mid-range frequency signals are sent to mid-range speakers while high frequency audio signals are sent and reproduced in tweeters.

Fundamentally there are 2 types of filters which are passive filters and active filters. Passive filters are made up of element such as resistors, capacitors and inductors.

It is most responsive to frequency ranged from 100 Hz to 300 MHz. These low frequency limit are due to the fact that at low frequency the capacitance and inductance value becomes very big and the components become very large in size. Similarly the upper frequency limit are due to at high frequency the capacitor and inductor can malfunction badly and wreak havoc. When designing passive filters with very high steep attenuation falloff responses, the principles that apply deep into the design are to increase more inductor and capacitor section [1]. Nevertheless, by increasing number of LC sections we are compensating the signal quality therefore greater chance for signal loss. Passive filters are best suited for radio frequency applications [1].

The other filter is the active filter. This filters are made up of op-amps, resistors and capacitors and strictly without the inductor. Active filter are best in handling low frequency as low as 0 Hz. Besides that, this filter can be constructed to provide voltage gain. In addition, the desired input and output impedance are not frequency dependable. The only constraints of these filter are very limited high frequency range response as above 100 kHz the op-amps malfunctions [1].

2.2 Filter Types

There are 3 widely used filters which are Chebyshev, Butterworth and Bessel filters. The filters are named after the mathematicians who invented the transfer function which models the attenuation responses. As quoted from the "Practical Electronic for Inventors" book in the chapter of filters, the most popular filter is Butterworth. The reasons are it produces very flat frequency response at middle passband region and the filter are easy to construct [1].

Chebyshev filter on the other hand, models a sharper rate and decent attenuation compared to Butterworth filter but have passband voltage ripples. The size of these passband voltage ripples increase as the order of filter increases. Besides, Chebyshev filter poses weakness such that it is sensitive to component tolerance [1].

Both Butterworth and Chebyshev filters do have one problem in common which is delay distortion. Delay distortion is varying amount of delay time on varying different frequency signals. Such an example is radio modulated signals, the output is definitely distorted. The delay distortion increases as the order of filter increases [1].

In the case of overcoming delay distortion, Bessel filter are the best in choice. Bessel filters produce constant delay on passband response but the falloff response are not sharp compared to Butterworth and Chebyshev [1]. In the case where good signal reproduction at the output is the utmost priority then Bessel filters are best suited for the operation.

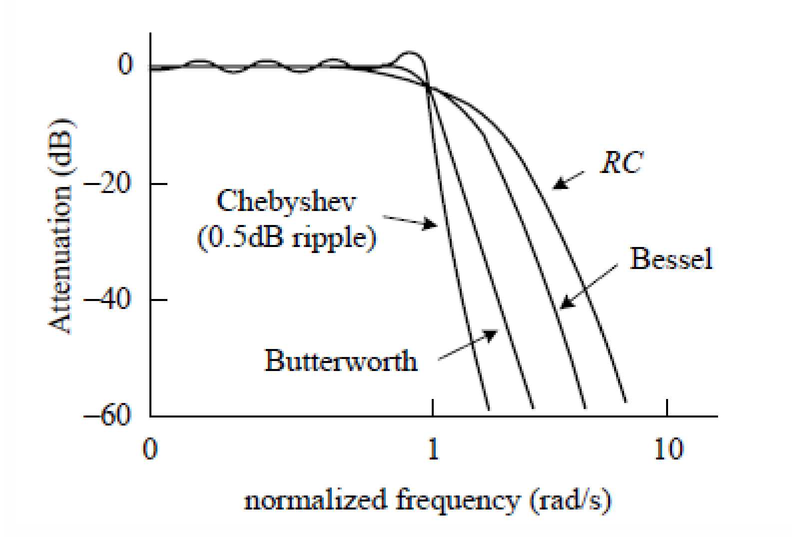

Figure 1 : The various filter design attenuation and fall-off responses

2.3 Ladder Networks

Ladder network is commonly used for filter design in the form of impedance realization. The example of impedance function in partial fraction is formed as below [2]:-

$$Z(p) = 2p + \frac{1}{p} + \frac{2p}{p^2+1}$$

$$= \frac{2p^4+5p^2+1}{p^3+p} \quad (2.40)$$

These equation is further synthesized using continued fraction expansion. As the value Z(p) goes to infinity the only value left will be 2p. Evaluation of the residue left at $p = \infty$ as below :-

$$\lim_{p\to\infty} \frac{Z(p)}{p} = 2 \quad (2.41)$$

Now removing a series of inductor valued at L=2, will leave the remaining impedance at $Z_1(p)$ as below :-

$$Z_1 = Z(p) - 2p$$

$$= \frac{2p^4+5p^2+1}{p^3+p} - 2p$$

$$= \frac{3p^2+1}{p^3+p} \quad (2.42)$$

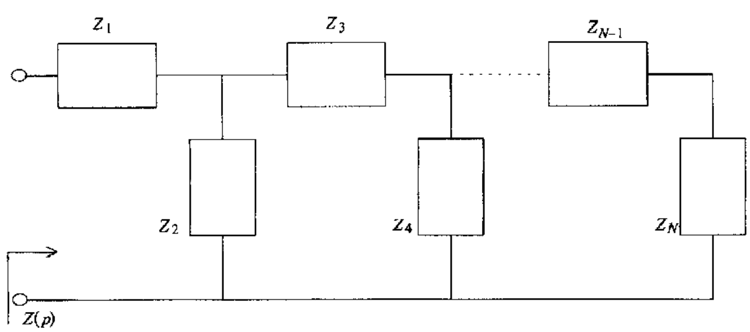

Figure 2 : Ladder Network

2.4 Inductors for LC filter

Inductor plays a major role in the filter design. Inductor is capable to attenuate high frequency electric signals due to its property which produce magnetic field as reactance. In AC application, when inductor conducts current at cutoff frequency and higher, the inductor's reactance become very high due to magnetic flux resisting the flow of current therefore results the inductor to act like an open circuit. This property is definitely useful in the lowpass filter design to remove unwanted frequency signals. There are several important parameters for the inductors design to get best desired response. The electromagnetic theory is the fundamentals to understand inductor's property.

2.4.1 Selecting Inductors for Lowpass Filter Applications

Inductor plays a vital role in the production of harmonic frequency electric signals. Therefore the study and analysis of inductors is very important to select the best desired inductor which meets the criteria as stated below :-

- Capability of operating at 500 kHz cutoff frequency and 1000 kHz passband frequency.
- High Q factor which means higher capability to retain the magnetic field.
- High resistivity to ensure core stability.
- Low core losses as eddy currents or hysteresis.

2.4.2 Inductors comparison

Type	Material	Best Op.Freq	Q factor	Core losses	Stability	Flux leakages
MPP Toroidal Coil 	Molypermalloy powder cores	100 kHz – 999 kHz	High Q with large core	Low	High resistivity Stable with large changes in flux density, freq, temp, DC magnetization	Low
Ferrite Pot Cores 	Ceramic	10 kHz - #MHz	Very high Q	Extremely Low	Very high resistivity, stable with time & temp var.	Very low
Ferrite RM Cores 	Ceramic, rectangular model	10 kHz - #MHz	Very high Q	Extremely Low	Very high resistivity, stable with time & temp var.	High
Powdered Iron Toroids 	Carbonyl iron	1 MHz above (VHF)	Very high Q	Extremely Low	Very stable	Low
Air Core Inductors 	No magnetic material, Ceramic or Phenolic	10 MHz above	Depends on winding as permeability = 1	No core losses		Very high
Surface Mount RF Inductors 	Phenolic or Ceramic (Air Core)	HF but low inductance 1MHz – 50 MHz	permeability = 1	No core losses		
Surface Mount RF Inductors 	Powdered iron	1MHz – 50 MHz	High permeability and very low temperature coefficients			
Surface Mount RF Inductors 	Ferrite	1MHz – 50 MHz	High permeability but highest temperature coefficients			

Table 1 : Inductors comparison

2.5 Capacitors for LC filter

Extensive varieties of capacitors are available to design a filter. In choosing the best capacitor for the filter operation, there are several factors to consider which are stability, size, losses, voltage rating, tolerances, cost and construction [4]. First step in the selection process is to determine the capacitor dielectric which the substance may be air, glass, ceramic, mica, plastic films, aluminum and tantalum.

2.5.1 Selecting Capacitors for Lowpass Filter Applications

i. Film Capacitors

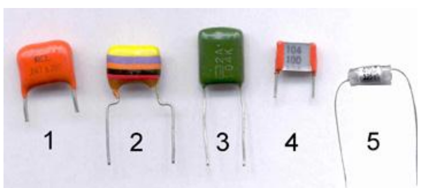

Figure 8 : Polyester capacitors (1, 2, 3), polycarbonate (4), polystyrene (5)

Polyester also known as Mylar or PET are the most economical and smallest film type capacitors. Highest choosing consideration for general purpose filters up to hundred kilohertz range. The feasible temperature goes up to 125° C. Capacitance value range from 1000pF to 10uF [4]. Polyethylene napthalate or PEN film capacitors are similar to PET but are available in higher voltage ratings and tighter tolerances. Other than that is Polyphenylene sulphide or PPS capacitors which have the best qualities compared to the PET and PEN types because it can support higher temperatures during both operation and soldering [4]. Polystrene capacitor is regarded as the best film capacitor because it have the best electric properties. Its temperature coefficient is almost linear. Its losses are extremely small resulting in dissipation factor of 0.01 percent. However the maximum temperature is limited to 85°C. Last in the family is Polypropylene capacitor which has almost similar characteristic as Polystrene except it have a slightly higher dissipation factor and the maximum temperature goes up to 105°C [4].

ii. Ceramic Capacitors

Fig #: Ceramic capacitors, low 'k', 33pF (6), medium 'k', 330pF - 1.5nF (7, 8, 9), high 'k', 100nF (10, 11, 12)

Dielectric constant, *k* as high as 3000 at room temperature is the strong key element of the ceramic capacitor. There are 2 types of ceramic capacitor with the first and most popular class known as EIA Class 1. This class is extremely stable with temperature [4]. The second class is EIA Class 2, it has higher dielectric constant to achieve higher volumetric efficiencies for high capacitance values. This class has piezoelectric characteristic which means any vibration or shock will induce a small generated voltages [4]. Both classes resides ceramic capacitor into values ranging 0.5 pF to 2.2 uF. Ceramic capacitors are most suitable in brute-force filtering applications such as for power supply and IC decoupling. This capacitor is not advisable for precision passive and active filters [14].

iii. Mica Capacitor

Figure 9 : Silver Mica capacitors

The fact that Mica is a rock that is extremely stable and inert, it does cost more than the film and ceramic types capacitor. Mica capacitor has dissipation factor of 0.01 percent as Q = 10,000. It can operate at temperature up to 150°C [4].

Additionally, this capacitor provides excellent performance up to gigahertz region as the dissipation factor remains low and parasitic inductance is small.

iv. Electrolytic Capacitors

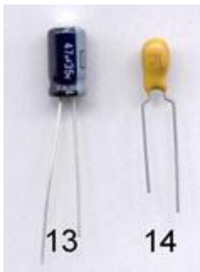

Figure 10 : Aluminium (13) and Tantalum (14) electrolytic capacitor

Majorly suitable for low-frequency bypassing and non-precision timing applications [4]. These aluminium electrolytic capacitor is not suitable for active or passive filters because they have unsymmetrical and huge tolerance gap and requires DC polarization. Reversing polarity can result in devastating explosion. In addition it has poor stability, shelf-life limitation and large parasitic inductance at high frequency [15]. Tantalum capacitor is another form of electrolytic capacitor where the difference is it can operate indefinitely without DC polarization. Nevertheless, tantalum capacitor is not recommended for applications which degree of accuracy is deemed important such as filter design [4].

v. Trimmer Capacitors

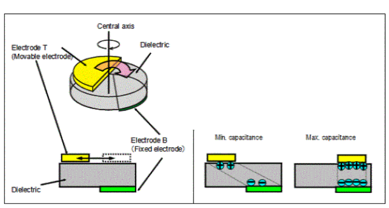

Figure 11 : Basic structure of Trimmer capacitor

Major applications in RF LC filters to resonate a tuned circuit by adjusting capacity rather than inductance [4]. Trimmer's dielectric usually consist of air, ceramic, mica or glass. Trimmer architecture behaves by varying the capacitance by adjusting the opposite area between movable and fixed electrode. Capacitance will be the highest when the opposite area is biggest [15]. Typically, a fixed capacitor having a larger value is placed in parallel to trimmer capacitor to obtain a finer resolution of adjustment.

2.5.2 Capacitors Comparison

Family of Capacitor	Type	Operating Frequency	Capacitance	Temperature	Dissipation factor	Suitability for RF Filter
Film	Polyster (PET)	999kHz	1000pF – 10uF	125°C	1 %	Yes
	Polyphenylene (PPS)	999kHz	1000pF – 10uF	150°C	1%	Yes
	Polystrene	999kHz	1000pF – 10uF	85°C	0.01%	Yes
	Polypropylene	999kHz	1000pF – 10uF	105°C	0.1 %	Yes
Ceramic	EIA Class 1	50 Hz	0.5pF – 2.2 uF	125°C	<0.1%	No
	EIA Class 2	50 Hz	0.5pF – 2.2 uF	85°C	<5%	No
Mica		1GHz	0.1pF-10,000pF	150°C	0.01%	Yes
Electrolytic	Aluminium	125Hz	Any	85°C	1.5-3%	No
	Tantalum	125Hz	Any	85°C	2%	No

Table 2 : Capacitors comparison

2.6 Total Harmonic Distortion (THD)

One method to justify a filter's performance is by measuring its total harmonic distortion at the output of the filter. Harmonic distortion is measured by applying a spectrally pure sine wave to the filter and observing the output spectrum [7]. The amount of distortion present at the output of the filter depends on several parameters such as:-

- Frequency response of the filter.
- Load applied to the output of filter.
- Filter's power supply voltage.
- Internal inductor's impedance and Q factor.
- Number of inductor element presence.
- Circuit board layout.
- Grounding.
- Thermal management.

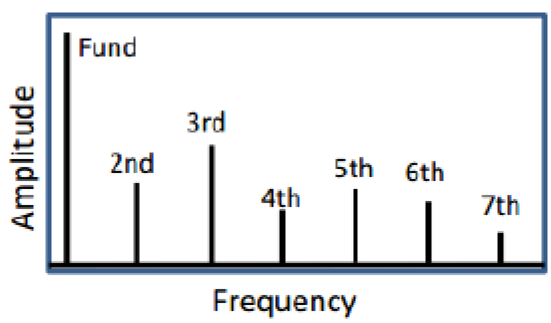

Figure 12 : Typical harmonic content of a filter's output, courtesy of *Microsemi Corporation*.

Equations for THD Calculations.

If the measurement data obtained is in power then,

$$THD(\%) = 100 \, . \sqrt{\frac{P_2+P_3+P_4+\cdots+P_n}{P_1}}$$, where P_n is in watts.

Or if the measurements data obtained is in volt then,

$$THD(\%) = 100 \, . \sqrt{\frac{V_2^2+V_3^2+V_4^2+\cdots+V_n^2}{V_1}}$$, where V_n is in RMS voltage.

2.7 Summary of Literature Review

The study was made on filter types and applications, network realization, inductor and capacitor properties, and total harmonic distortion (THD) definition and calculations. The popular filter topologies are Maximally Flat, Chebyshev, Inverse Chebyshev, Elliptic and Bessel. Lowpass filter circuit can be realized by Ladder network and Darlington synthesize. Inductors quality factor and capacitors dissipation factor are compared with several other parameters such as core loss and operating temperatures. The best components with lowest THD will be selected for fabrication. The literature review made summarize that the design of lowpass filter with lowest THD performance requires less number of inductor and best quality of inductor and capacitor in the lowpass filter circuit.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

To design the lowpass filter with low total harmonic distortion initially requires a lot of study and reading to understand the principle, theories and application of these filters in industry. Understanding the theories and design problems will equip the student with the confident and knowledge to proceed to the 1st design steps which is "Mathematical Modelling". In this step, the student should be able to calculate the actual value of capacitor, inductor and the order of filter which produces the desired output criteria using Maple 2016 software. The output criteria of these project are as below :-

1. Cut-off frequency, f_c = 500 kHz
2. Passband ripple/ insertion loss = $<$ 1dB
3. Attenuation = > -35 dB from f > 1000 kHz
4. Connection = Unbalanced input/output of BNC with 50 ohm
5. THD requirement = $<$ -100 dB

The next step of design is to construct the filter network circuit using Advanced Design System software. In this process ideal filter response will be simulated by applying the calculated values from the Maple software.

3rd is to design the layout of filter topologies in the Eagle software.The placement of components should be precise and compact so as to ensure efficient use of PCB board. The line copper tracing should not be too close or intersect each other as it may cause stray inductance, mutual inductance, and some cases of partial discharge due to shorts.

4th and final design step is to fabricate the designed PCB board by Eagle in the prototype lab. After fabrication of the copper line tracing, soldering of the right value components must be done in careful manner. The inductor legs must be as short as possible as long legs tend to cause stray inductance. In addition, inductor must be placed far from each other as they will produce mutual inductances when magnetic field collide with each other. The design and fabrication must take serious and careful consideration of every possible ways to reduce total harmonic distortion.

Lastly, the fabricated prototype will be tested in the lab using Network Analyzer. The test will be conducted and the data of signal power attenuation response with swept frequency and the response total harmonic distortion will be recorded. The design expected value for attenuation response is -35dB and total harmonic distortion is -100dB.

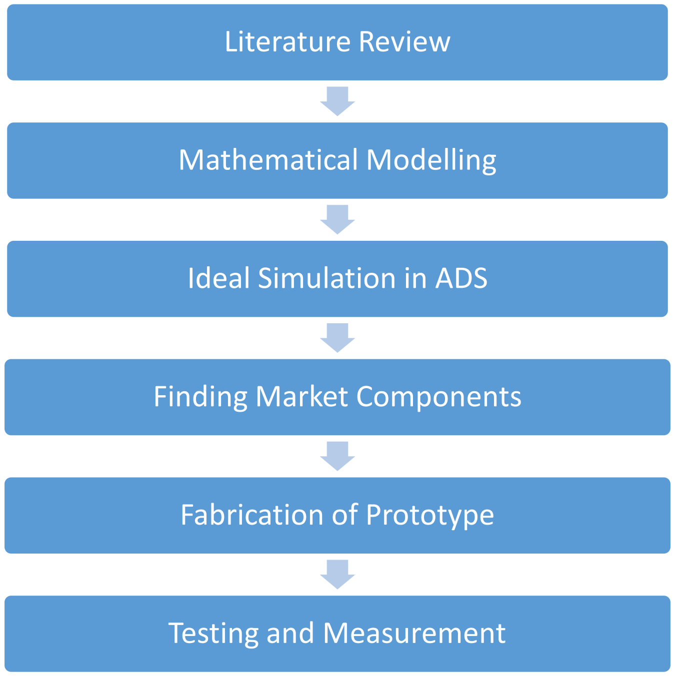

Figure 13 : Process of the project for FYP I and FYP II

3.2 Project Methodology

3.2.1 Gantt chart & Key Milestone

Table 1 and table 2 show the timeline with the details work involved within 14 weeks for FYP I and FYP II respectively.

Table 4: Timeline for FYP I

No.	Details/ Week		FYP 1													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature Review		■	■	■	■										
2	Mathematical modelling						■									
3	Ideal Simulation								■	■		■	■	■	■	
4	Microstrip Simulation											■	■			
5	Momentum Simulation													■	■	
6	Proposal Defense										●					
7	Documentation	Extended proposal						●								
		Interim Report														●

● Key milestone ■ Process

Table 5: Timeline for FYP II

No.	Details/ Week		FYP II														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Improvise filter design																
2	Finalise filter design																
3	Fabrication of Filter prototype																
4	Testing of prototype																
5	Pre-sedex											●					
6	Project Viva														●		
7	Documentation	Progress Report							●								
		Draft Final Report											●				
		Dissertation (soft copy)												●			
		Technical Paper												●			
		Dissertation (hard bound)															●

3.2.1 Tools and Equipment

The tools and equipment used for this project are:

1. **Software**
   - Maple
   - Advanced Design System
   - Eagle
   - Iowa Hills RF Filter Designer

2. **Hardware**
   - Network Analyzer
   - Oscilloscope
   - Function Generator
   - Spectrum Analyzer

3.3 Mathematical Modeling of Filters

Filters are constructed by taking advantage of the inductor and capacitor physical properties at varying low to high frequency. Filter behavior is best displayed in the response curve of V_{out}/V_{in}. This gain equation is called transfer function in terms of circuit impedance. The mathematical modeling of transfer function varies to each corresponding response curve [5]. Mathematical modeling of Maximally Flat, Chebyshev, Inverse Chebyshev and Elliptic lowpass filters are constructed.

3.3.1 Maximally flat lowpass filter

Maximally flat or Butterworth lowpass filter response are such that of 0 dB attenuation, 0 dB ripple in the passband and have an insertion loss $L_{Ar} = 3.01$ dB at the cutoff frequency $\omega_c = 1$. The transfer function of maximally flat filter is as below [5]:-

$$|S_{21}(j\omega)|^2 = \frac{1}{1+\omega^{2n}}$$

n, is the degree of filter which corresponds to the reactive elements in lowpass filter circuit.

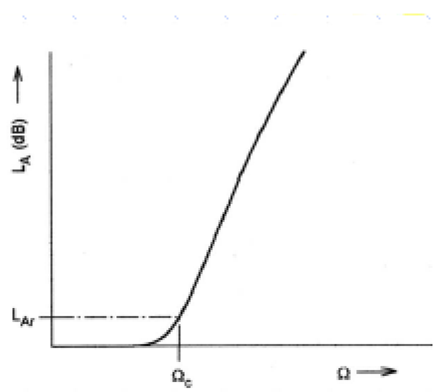

Figure 14 : Maximally flat approximation in the passband is best at ω = 0 but gradually deteriorates as ω approaches the cutoff frequency ω_c. Insertion loss increases as signal approaches cutoff frequency.

The equation below is applied to determine the degree of maximally flat filter, n[5]:-

$$n \geq \frac{\log(10^{0.1L_{As}}-1)}{2log\omega_s}$$

L_{As} , the stopband attenuation of filter, ω_s, stopband frequency of filter.

Calculation for normalized component values of Maximally flat filter:-

$g_0 = 1.0$
$g_i = 2\sin(\frac{(2i-1)\pi}{2n})\ \ for\ \mathrm{i} = 1\ \text{ to n}$
$g_{n+1} = 1.0$

Normalized capacitor and inductor values for Butterworth lowpass prototype filters with g_0=1, ω_c=1, and L_{Ar}= 0.301 dB at ω_c.

TABLE 3.1 Element values for Butterworth lowpass prototype filters (g_0 = 1.0, Ω_c = 1, L_{Ar} = 3.01 dB at Ω_c)

n	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}
1	2.0000	1.0								
2	1.4142	1.4142	1.0							
3	1.0000	2.0000	1.0000	1.0						
4	0.7654	1.8478	1.8478	0.7654	1.0					
5	0.6180	1.6180	2.0000	1.6180	0.6180	1.0				
6	0.5176	1.4142	1.9318	1.9318	1.4142	0.5176	1.0			
7	0.4450	1.2470	1.8019	2.0000	1.8019	1.2470	0.4450	1.0		
8	0.3902	1.1111	1.6629	1.9616	1.9616	1.6629	1.1111	0.3902	1.0	
9	0.3473	1.0000	1.5321	1.8794	2.0000	1.8794	1.5321	1.0000	0.3473	1.0

Table 6 : Element values for Butterworth lowpass filter prototype filters, Coutesy of A. Williams, F. J. Taylor, *Electronic Filter Design Handbook.*

Maximally flat lowpass filter attenuation response curve, frequency vs magnitude:-

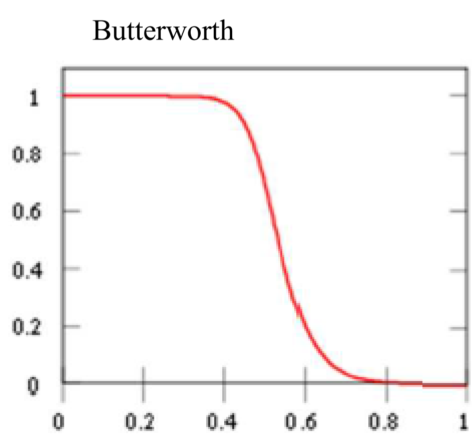

Figure 15 : Maximally flat lowpass filter response, courtesy of W. Tzong-Lin, *Microwave Filter Design.*

3.3.2 Chebyshev lowpass filter

Chebyshev lowpass filter response differs a little from maximally flat response such that it has equal-ripple passband. The amplitude-squared transfer function that describes this type of response is [5]:-

$$|S_{21}(j\omega)|^2 = \frac{1}{1+\varepsilon^2 T_n^2(\frac{\omega_c}{\omega_s})}$$

Where the ripple constant ε is related to passband ripple L_{Ar} in dB by

$$\varepsilon = \sqrt{10^{\frac{L_{Ar}}{10}} - 1}$$

$T_n(\omega)$ is a Chebyshev function of order n, which is defined as:-

$$T_n(\omega) = \begin{cases} \cos(n\cos^{-1}\omega) & |\omega| \le 1 \\ \cosh(n\cosh^{-1}\omega) & |\omega| \ge 1 \end{cases}$$

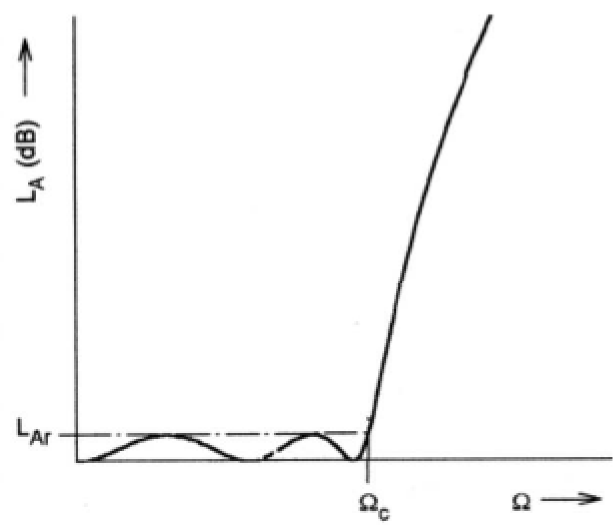

Figure 16 : Chebyshev lowpass approximation produces passband ripple at maximum L_{Ar} . Insertion loss happens at equal-ripples in the passband and increases as signal approaches cutoff frequency [5].

The equation below is applied to determine the degree of Chebyshev filter, n:-

$$n \geq \frac{\cosh^{-1}\sqrt{(10^{0.1L_{As}}-1)/(10^{0.1L_{Ar}}-1)}}{\cosh^{-1}\omega_s}$$

L_{As}, the stopband attenuation,
L_{Ar}, passband ripple,
ω_s, stopband frequency of filter.

Calculation for normalized component values of Chebyshev filter:-

$$\beta = \ln[\coth\left(\frac{L_{Ar}}{17.37}\right)]$$

$$\gamma = \sinh\left(\frac{\beta}{2n}\right)$$

$$g_0 = 1.0$$

$$g_1 = \frac{2}{\gamma}\sin(\frac{\pi}{2n})$$

$$g_i = \frac{1}{g_{i-1}}.4\sin\left[\frac{(2i-1)\pi}{2n}\right].\sin[\frac{(2i-3)\pi}{2n}] \qquad for\ i = 2,3,\ldots n$$

$$g_{n+1} = \begin{cases} 1.0 & for\ n\ odd \\ \coth^2\left(\frac{\beta}{4}\right) & for\ n\ even \end{cases}$$

Normalized capacitor and inductor values for Chebyshev lowpass prototype filters with g_0=1, ω_c=1, and passband ripple L_{Ar}= 0.1 dB.

n	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}
1	0.3052	1.0								
2	0.8431	0.6220	1.3554							
3	1.0316	1.1474	1.0316	1.0						
4	1.1088	1.3062	1.7704	0.8181	1.3554					
5	1.1468	1.3712	1.9750	1.3712	1.1468	1.0				
6	1.1681	1.4040	2.0562	1.5171	1.9029	0.8618	1.3554			
7	1.1812	1.4228	2.0967	1.5734	2.0967	1.4228	1.1812	1.0		
8	1.1898	1.4346	2.1199	1.6010	2.1700	1.5641	1.9445	0.8778	1.3554	
9	1.1957	1.4426	2.1346	1.6167	2.2054	1.6167	2.1346	1.4426	1.1957	1.0

Table 7 : Normalized capacitor and inductor values for Chebyshev lowpass prototype filters, Coutesy of A. Williams, F. J. Taylor, *Electronic Filter Design Handbook.*

3.3.3 Inverse Chebyshev lowpass filter

Inverse Chebyshev filter is closely related to Chebyshev filter in a way that the response curve's ripple is inverted. This filter behaves such as to flat passband magnitude response and an equiripple response at the stopband[6].

As stated previously the Chebyshev's magnitude-squared transfer function is formulated as:-

$$|S_{21}(j\omega)|^2 = \frac{1}{1+\varepsilon^2 T_n^2\left(\frac{\omega_c}{\omega_s}\right)}$$

Therefore Inverse Chebyshev transfer function can be obtained as follow:-

$$|S_{21}(j\omega)|^2 = 1 - \frac{1}{1+\varepsilon^2 T_n^2\left(\frac{\omega_c}{\omega_s}\right)}$$

Finally, the magnitude-squared transfer function of Inverse Chebyshev response is obtained by replacing $\frac{\omega_c}{\omega_s}$ by $\frac{\omega_s}{\omega_c}$. The formulated transfer function is as below[6]:-

$$|S_{21}(j\omega)|^2 = \frac{\varepsilon^2 T_n^2\left(\frac{\omega_s}{\omega_c}\right)}{1+\varepsilon^2 T_n^2\left(\frac{\omega_s}{\omega_c}\right)}$$

Where the ripple constant ε is related to stopband attenuation A_s in dB by

$$\varepsilon = \frac{1}{\sqrt{10^{\frac{A_s}{10}}-1}}$$

$T_n(\omega)$ is an Inverse Chebyshev function of order n, which is defined as:-

$$T_n\left(\frac{\omega_s}{\omega_c}\right) = \begin{cases} \cos(n\cos^{-1}\frac{\omega_s}{\omega_c}) & |\omega| \geq \omega_s \\ \cosh(n\cosh^{-1}\frac{\omega_s}{\omega_c}) & |\omega| \leq \omega_s \end{cases}$$

Identical equation as Chebyshev filter can be implemented to determine degree of the Inverse Chebyshev filter:-

$$n \geq \frac{\cosh^{-1}\sqrt{(10^{0.1L_{As}}-1)/(10^{0.1L_{Ar}}-1)}}{\cosh^{-1}\omega_s}$$

L_{As}, the stopband attenuation,
L_{Ar}, passband ripple,
ω_s, stopband frequency of filter.

3.3.4 Elliptic lowpass filter

Elliptic lowpass filter exhibits both equiripple passband magnitude such like Chebyshev filter and equiripple stopband magnitude such as Inverse Chebyshev filter[5]. The transfer function of Elliptic lowpass filter is as below:-

$$|S_{21}(j\omega)|^2 = \frac{1}{1+\varepsilon^2 F_n^2(\omega)}$$

$F_n(\omega)$ response are calculated for even and odd number of order:-

$$F_n(\omega) = \begin{cases} M.[\prod_{i=1}^{\frac{n}{2}} \frac{\omega_i^2-\omega^2}{} \prod_{i=1}^{\frac{n}{2}} \left(\frac{\omega_s^2}{\omega_i^2} - \omega^2\right)] & for\ n, even \\ N.[\omega \prod_{i=1}^{\frac{n-1}{2}} (\omega_i^2 - \omega^2)/ \prod_{i=1}^{\frac{n-1}{2}} (\frac{\omega_s^2}{\omega_i^2} - \omega^2)] & for\ n \geq 3\ , odd \end{cases}$$

In the equation above ω_i ($0< \omega_i<1$) and $\omega_s>1$ represent some critical frequencies and M and N values are constants to be defined. Elliptic response behave such as $F_n(\omega)$will oscillate between ± 1 for $|\omega| \leq 1$ and $|F_n(\omega = \pm 1)|=1$.

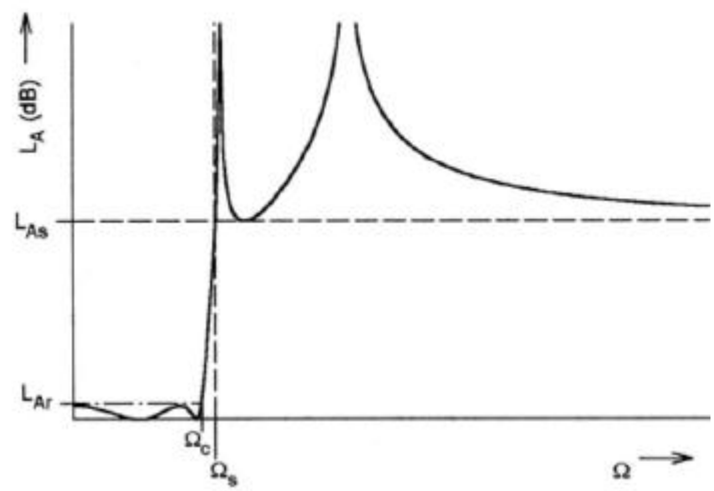

Figure 19 : Elliptic lowpass approximation produces passband ripple at maximum L_{Ar} and stopband ripple at minimumL_{As}. Insertion loss happens at equal-ripples in the passband and increases as signal approaches cutoff frequency but are limited (not approaching inifinity) due to equiripple insertion loss at stopband.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Filter Topologies Design Simulations

The design of the lowpass filters are conducted in the Advanced Design System (ADS) software. The swept frequencies of operation are at 1 Hz to 1000 kHz therefore the frequency range is at radio frequency (RF) range. Lumped circuits work well for lowpass filter design in RF range which is the ladder networks of inductors and capacitors.

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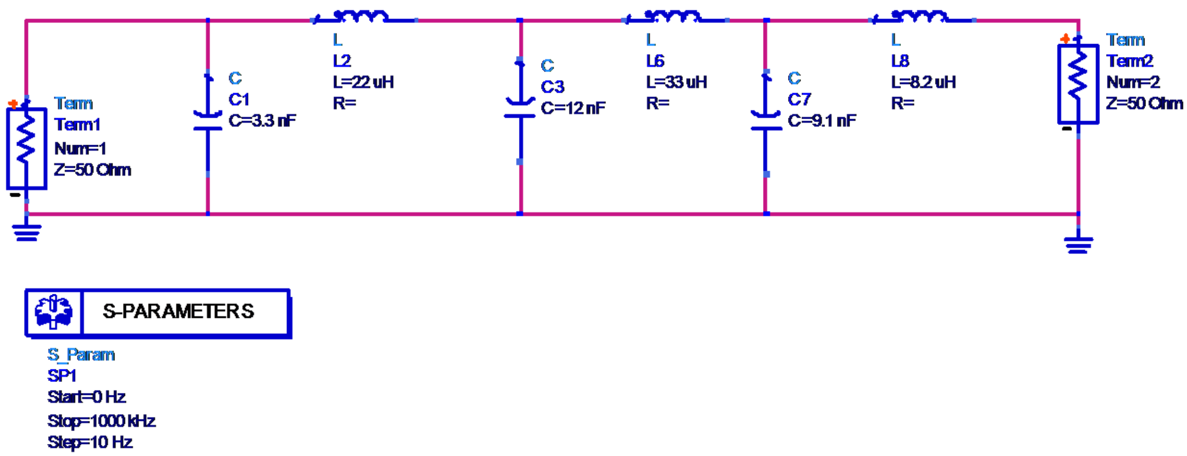
4.2 Design Criteria for Lowpass filter with Low THD

Cutoff Frequency, f_c	500 kHz
Waveform Response Attenuation	-35 dB at 1000 kHz
Total Harmonic Distortion performance, *THD*	< 100 dB
Source & Load Impedance, Ω	50 Ω

4.3 Maximally Flat Lowpass Filter

4.3.1 Simulation of Maximally Flat 6th order LP filter



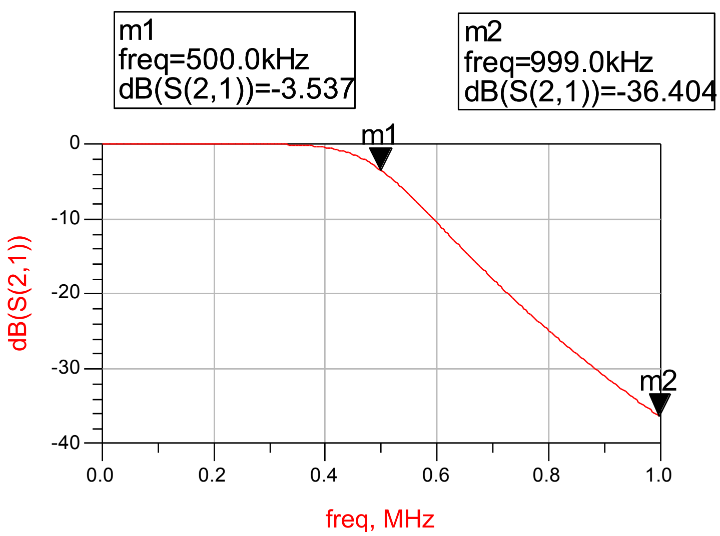


Figure 22.1 : Simulated circuit and waveform response for Maximally Flat 6th order LP filter

4.3.2 Measurement of fabricated Maximally Flat filter

Setup of measuring tools

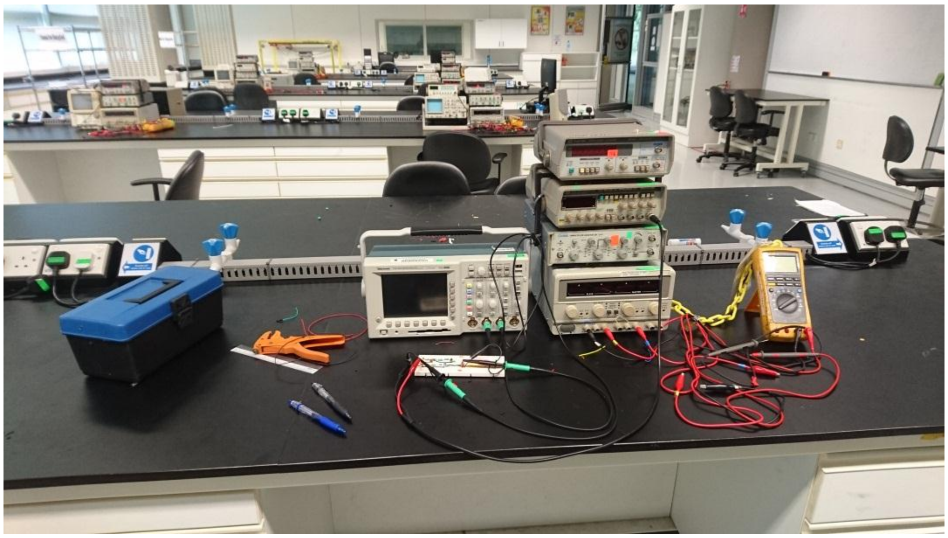


Figure 23 : Measuring tools which consist of a Function Generator, Oscilloscope and Multimeter.

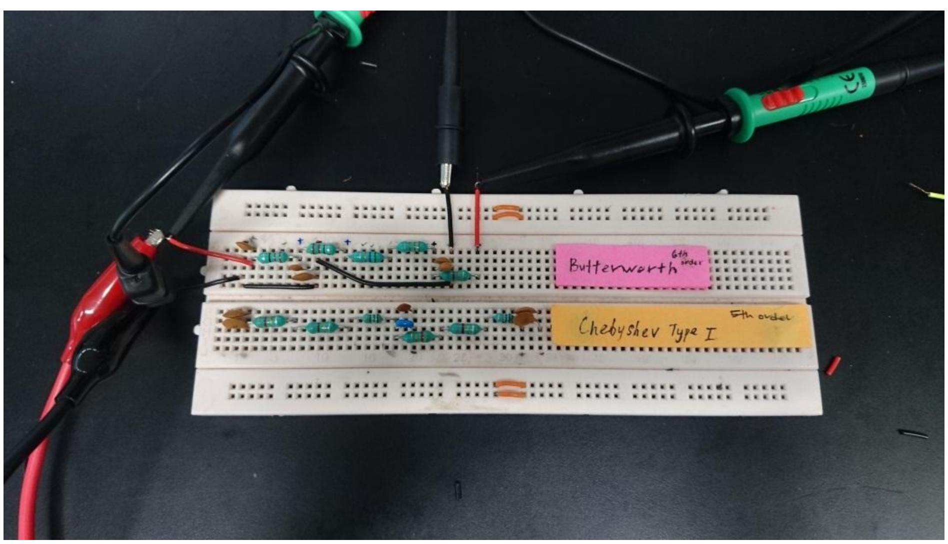


Figure 24 : The setup of connection for Butterworth filter measurement.

Function Generator are connected to positive and negative input terminal of the Butterworth filter. Oscilloscope channel 1 connector are connected to positive and negative terminal of input filter to measure the controlled input frequency produced by

Function Generator. Oscilloscope channel 2 connector is connected to positive and negative terminal of output filter to measure the output signal from the filter.

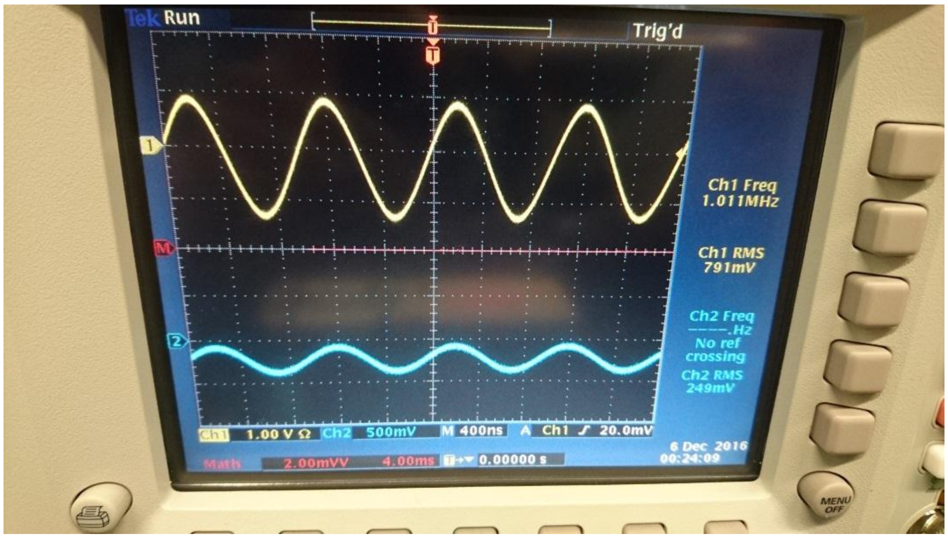


Figure 25 : Voltage peak-peak are measured in the oscilloscope for input frequency of 1MHz to the filter at channel 1 and output peak-peak voltage at channel 2.

The output signal has been drastically attenuated as the lowpass filtering starts at 500kHz and has been attenuated for at least -20dB (100x) reaching stopband frequency which is 1MHz.

4.3.3 Attenuation response measurement of Maximally Flat 6th Order Low pass Filter

Date & Time of Experiment	24/02/2017	11 am
$\boldsymbol{Frequency, f}$	$\boldsymbol{Gain = \frac{Vpp(out)}{Vpp(in)}}$	$\boldsymbol{Attenuation\ in\ dB}$
10	0.943396226	-0.51
200	0.943396226	-0.51
800	0.943396226	-0.51
1,000	0.917431193	-0.75
4,000	0.917431193	-0.75
10,000	0.925925926	-0.67
50,000	0.976887669	-0.20
100,000	0.987987896	-0.10
300,000	0.967908098	-0.28
500,000	0.987655555	-0.11
600,000	0.219780220	-13.16
700,000	0.085616438	-21.35
800,000	0.042918455	-27.35
900,000	0.022727273	-32.87
1,000,000	0.019047619	-34.40
1,500,000	0.005159959	-45.75
2,000,000	0.002419550	-52.33

Table 8 : Table above shows the experimented data on maximally flat lowpass filter.

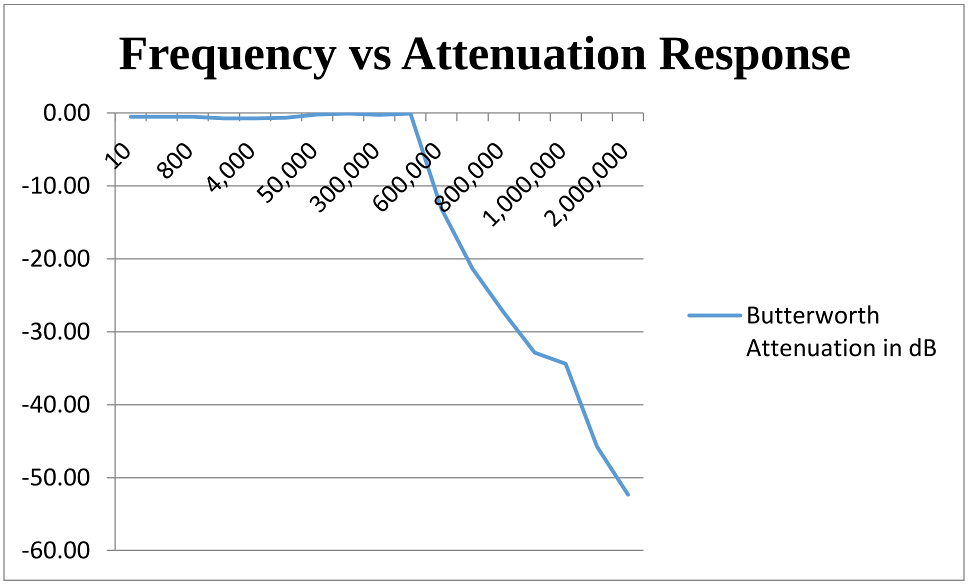


Figure 26 : Frequency vs Attenuation response is plotted using data obtained from experiment.

4.3.4 Total Harmonic Distortion (THD) measurement of Maximally Flat 6th Order Low pass Filter

<u>Setting up of measuring equipments</u>

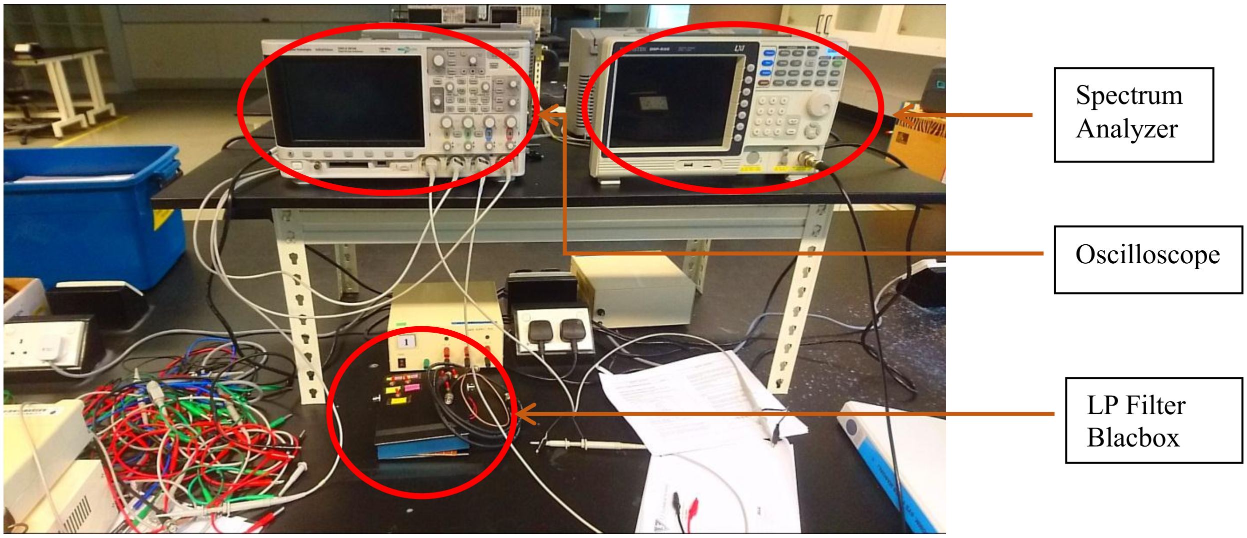


Figure 27 : Equipment required for Butterworth's THD measurements.

Four lowpass filters which can be actively selected by toggle switch are contained in one black box for ease of measurement. The equipment required for measurement are Oscilloscope to generate signal frequency and observe input waveform, Spectrum Analyzer to observe Fast Fourier Transform (FFT) and BNC male connectors.

<u>Measuring of THD with FFT Math function in Oscilloscope</u>

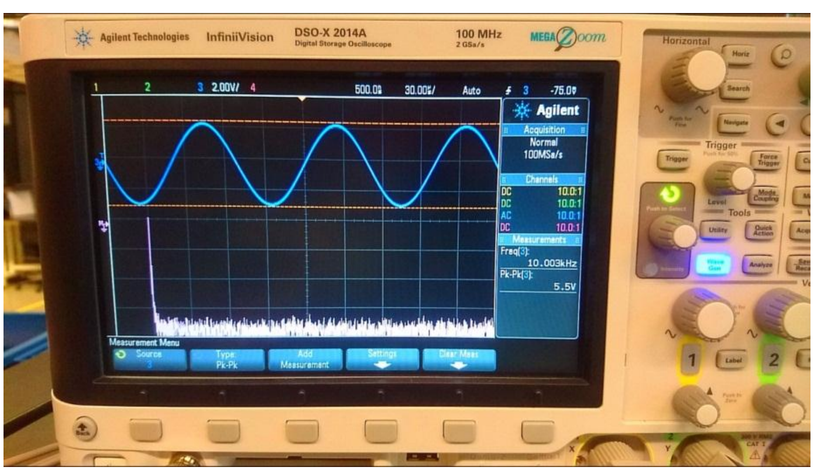


Figure 28 : Input frequency waveform at 10 kHz and FFT measurement at the output of Butterworth filter.

It can be observed that, for Butterworth filter at 10 kHz the fundamental frequency dominates as there are no observable harmonic rises until 2 MHz.

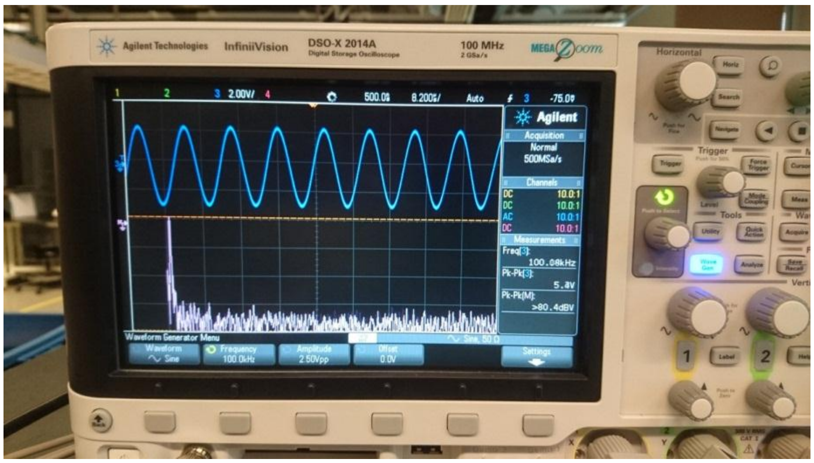


Figure 29 : Input frequency waveform at 100 kHz and FFT measurement at the output of Butterworth filter.

There were some observable spikes of harmonic component at each 1500 kHz per divison. The peak to peak reading of fundamental frequency is at 80.4 dBV.

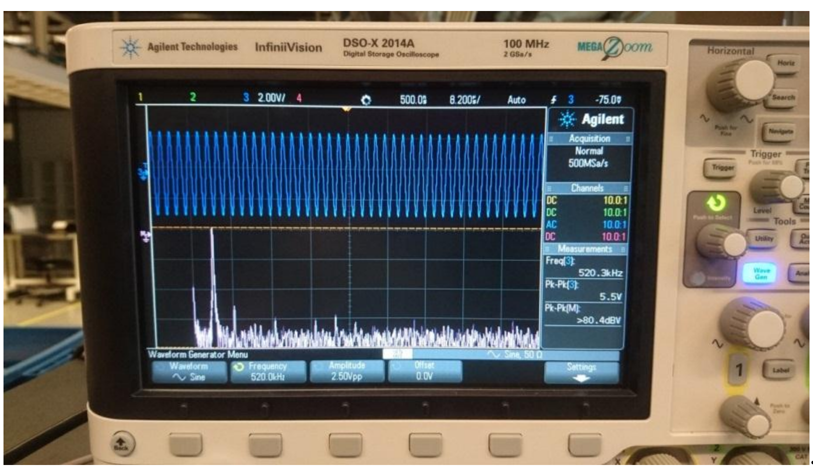


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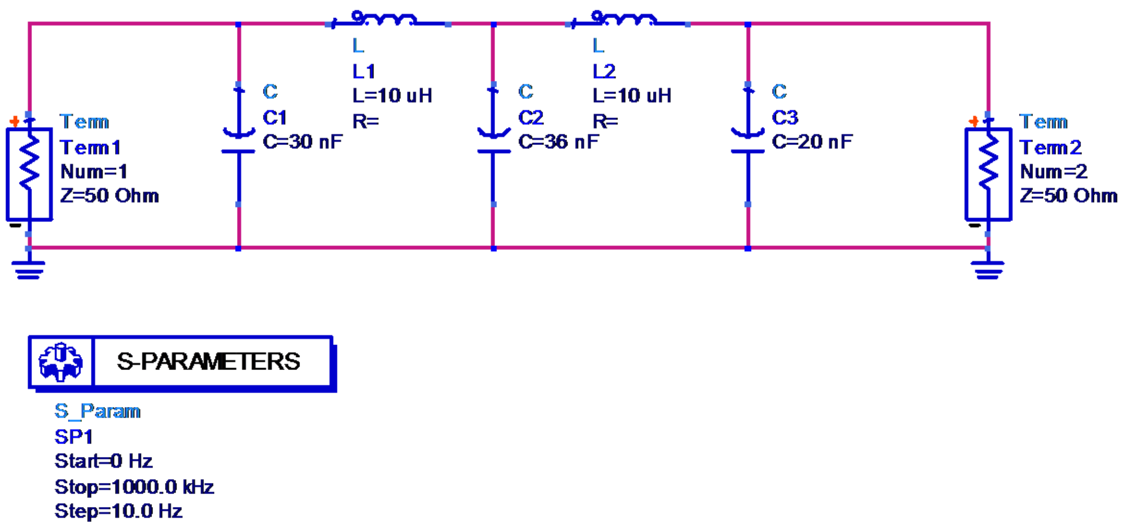
Figure 30 : Input frequency waveform at 500 kHz and FFT measurement at the output of Butterworth filter.

Figure 34 : THD performance are measured using Spectrum Analyzer for Butterworth filter.

Total harmonic distortions are measured using math functions in spectrum analyzer. It performs harmonic component's amplitude iteration up to 9th order. These harmonic components are compared with the fundamental frequency to obtain the percentage of signal distortion. The THD measurement was observed to be 2.26% and -32.89 dB.

4.4 Chebyshev Lowpass Filter

4.4.1 Simulation of Chebyshev filter with 0.5-dB ripple band at 5th order LP filter



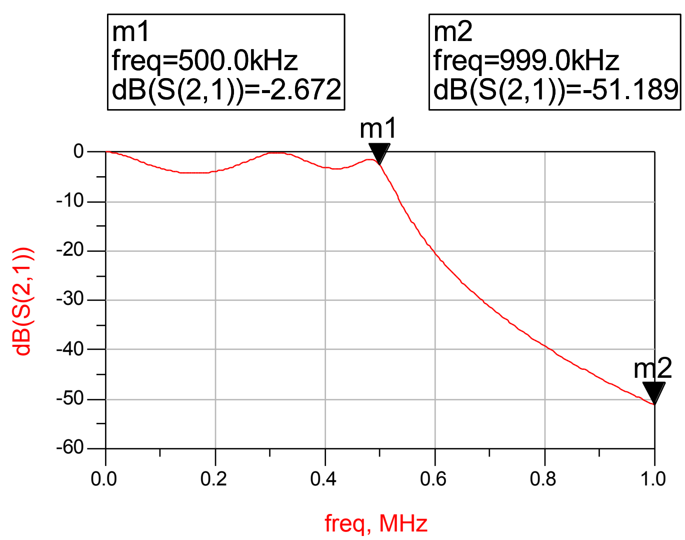


Figure 34.1 : Simulated circuit and waveform response for Chebyshev filter 5th order LP filter

4.4.2 Measurement of fabricated Chebyshev filter

Setup of measuring tools

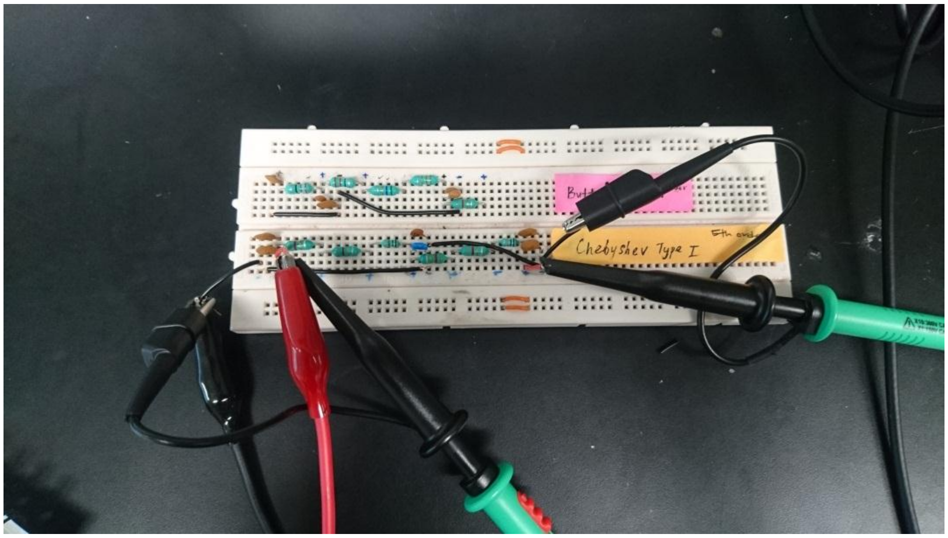


Figure 35 : The setup of connection for Chebyshev filter measurement.

Function Generator is connected to positive and negative input terminal of the Chebyshev filter. Oscilloscope channel 2 connector is connected to positive and negative terminal of input filter to measure the controlled input frequency produced by Function Generator. Oscilloscope channel 3 connector is connected to positive and negative terminal of output filter to measure the output signal from the filter.

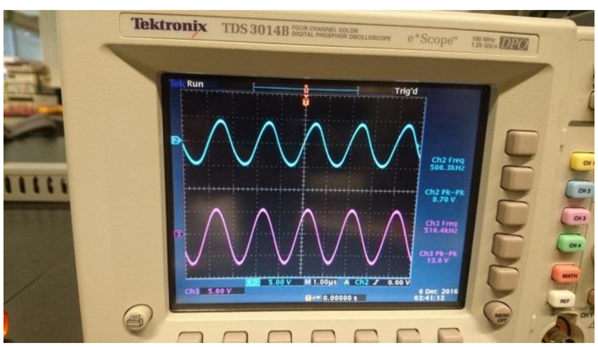


Figure 36 : Oscilloscope reading at 500 kHz input frequency and the output amplitude is observed.

Voltage peak-peak are measured for both input and output of filter at the supplied frequency of 500kHz. Input voltage is 9.7 volt and output voltage is 13.0 volt indicating a last ripple in the passband before attenuation occurs.

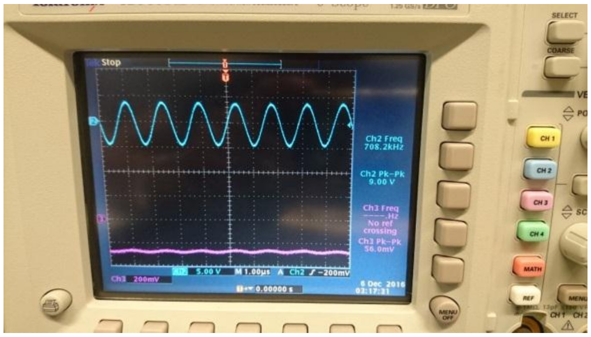


Figure 37 : : Oscilloscope reading at 700 kHz input frequency and the output amplitude is observed.

Voltage peak-peak are measured for both input and output of filter at the supplied frequency of 700kHz. Input voltage is 9.0 volt and output voltage is 56.0 milivolt indicating a great attenuation of signal occured at the output.

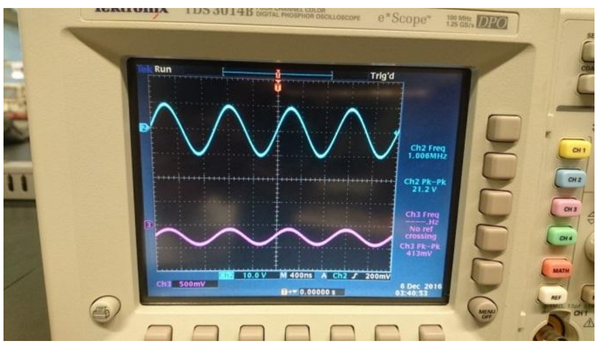


Figure 38 : : Oscilloscope reading at 1,000 kHz input frequency and the output amplitude is observed.

Voltage peak-peak are measured for both input and output of filter at the supplied frequency of 1,000kHz. Input voltage is 21.2 volt and output voltage is 413.0 milivolt indicating a great attenuation of signal occurred at the output as the supplied frequency is at stopband with -45dB attenuation approximation.

4.4.3 Attenuation response measurement of Chebyshev 5th Order Low pass Filter

Date & Time of Experiment	24/02/2017	12 pm
$\boldsymbol{Frequency, f}$	$\boldsymbol{Gain = \frac{Vpp(out)}{Vpp(in)}}$	$\boldsymbol{Attenuation\ in\ dB}$
10	0.943396226	-0.51
200	0.943396226	-0.51
800	0.982342343	-0.15
1,000	0.917431193	-0.75
4,000	0.812345670	-1.81
10,000	0.925925926	-0.67
50,000	0.982342343	-0.15
100,000	0.998877776	-0.01
300,000	0.812345670	-1.81
500,000	0.8976553	-0.94
600,000	0.219780220	-13.16
700,000	0.085616438	-21.35
800,000	0.042918455	-27.35
900,000	0.022727273	-32.87
1,000,000	0.019047619	-34.40
1,500,000	0.005159959	-45.75
2,000,000	0.002419550	-52.33

Table 9 : Table above shows the experimented data on Chebyshev lowpass filter.

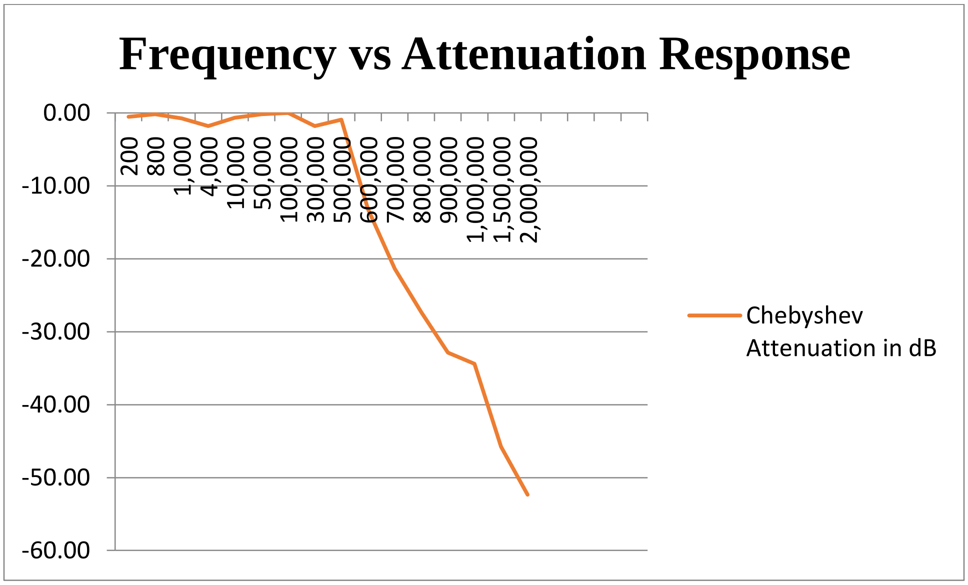


Figure 39 : Frequency vs Attenuation response is plotted using data obtained from the Chebyshev experiment.

4.4.4 Total Harmonic Distortion (THD) measurement for Chebyshev 5th Order Low pass Filter

<u>Setting up of measuring equipment</u>

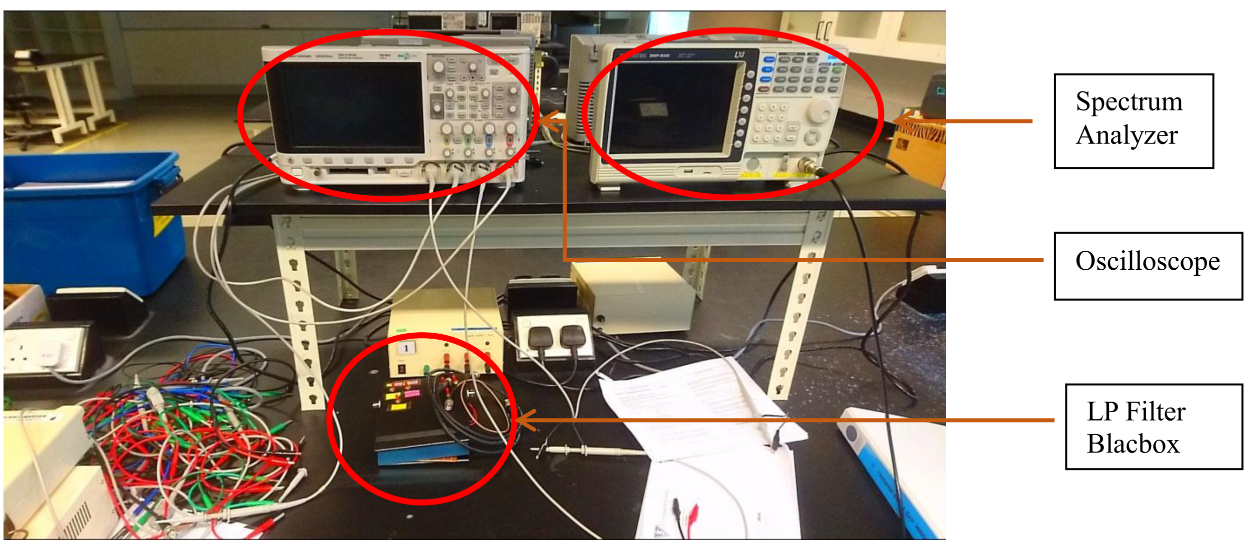


Figure 40 : Equipment required for Chebyshev's THD measurements.

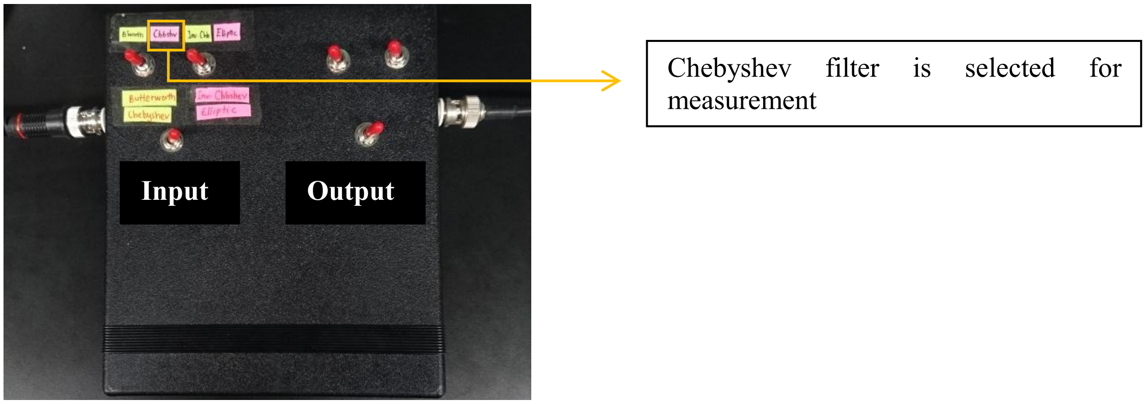


Figure 41 : Input and Output is toggled to Chebyshev. Input BNC connector is connected to frequency generator and Output BNC connector is connected to spectrum analyzer and oscilloscope.

Figure 42 : FFT waveform measured at the output of Chebyshev filter

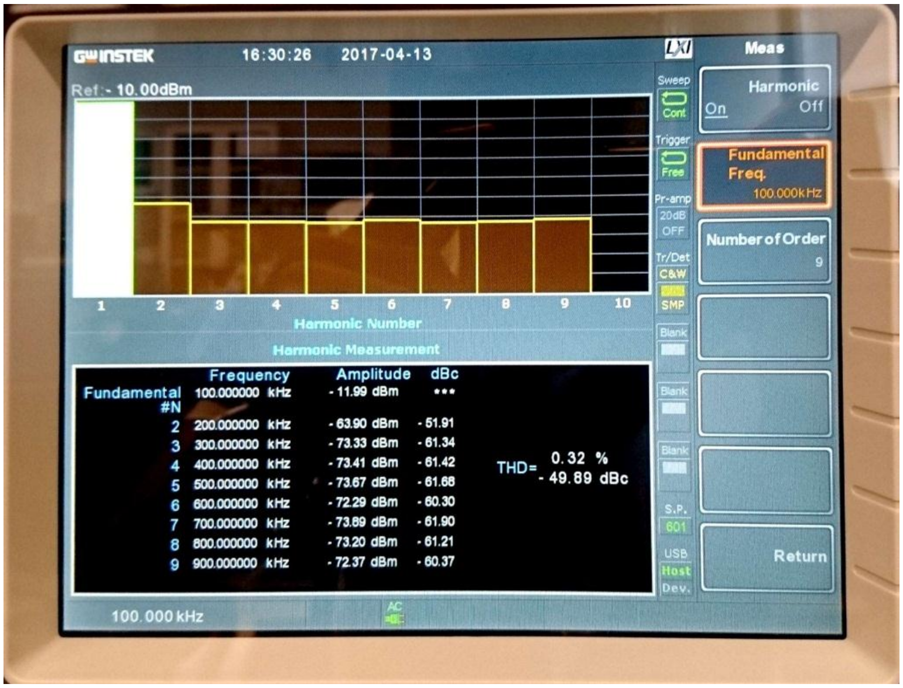


Figure 43 : THD performance are measured using Spectrum Analyzer for Chebyshev filter.

Total harmonic distortions are measured using math functions in spectrum analyzer. It performs harmonic component's amplitude iteration up to 9th order. These harmonic components are compared with the fundamental frequency to obtain the percentage of signal distortion. The THD measurement was observed to be 0.32% and -49.89 dB.

4.5 Inverse Chebyshev Lowpass Filter

4.5.1 Simulation of Inverse Chebyshev filter at 5th order LP filter

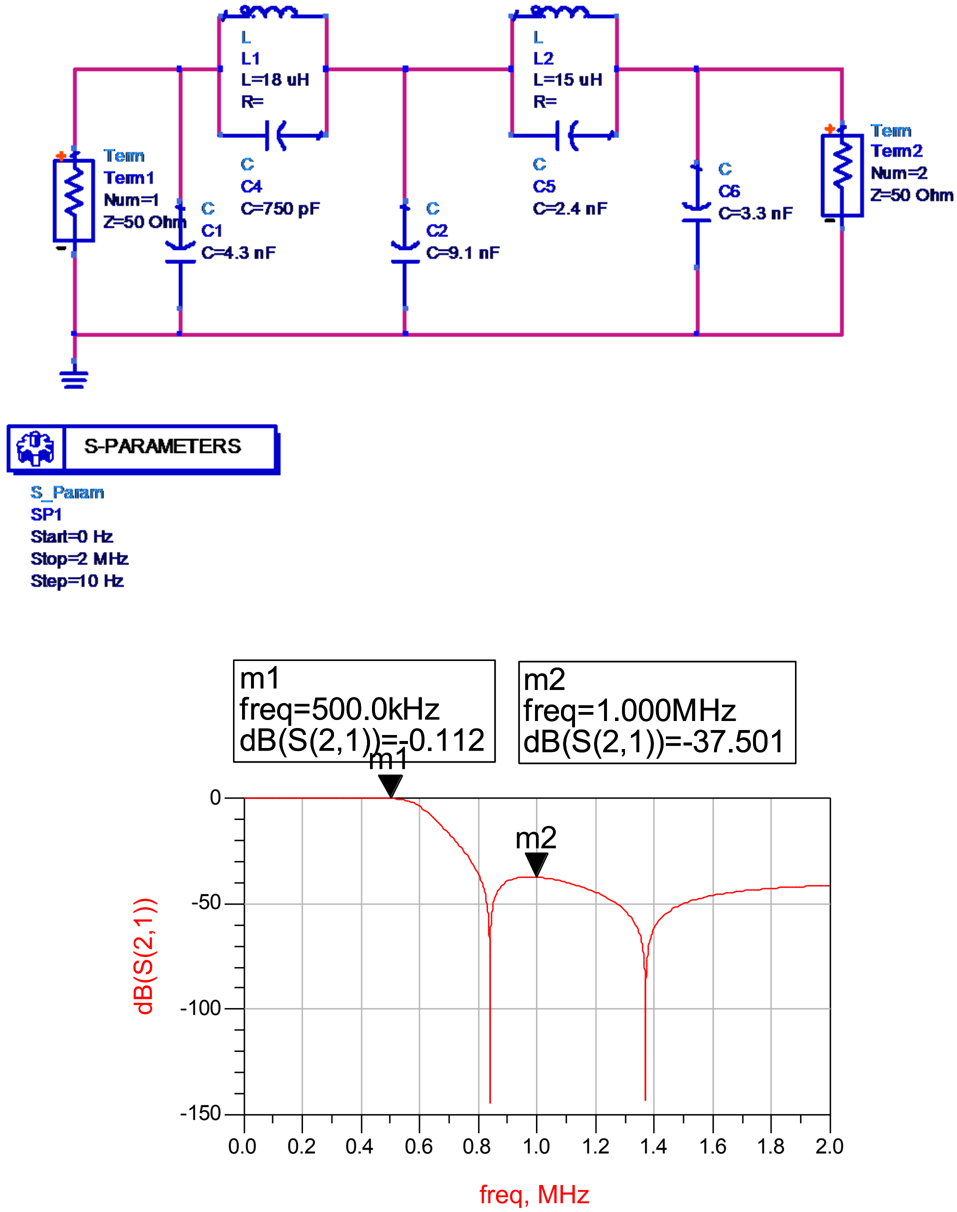


Figure 43.1: Simulated circuit and waveform response for Inverse Chebyshev filter 5th order LP filter

4.5.2 Measurement of fabricated Inverse Chebyshev filter

Setup of measuring tools

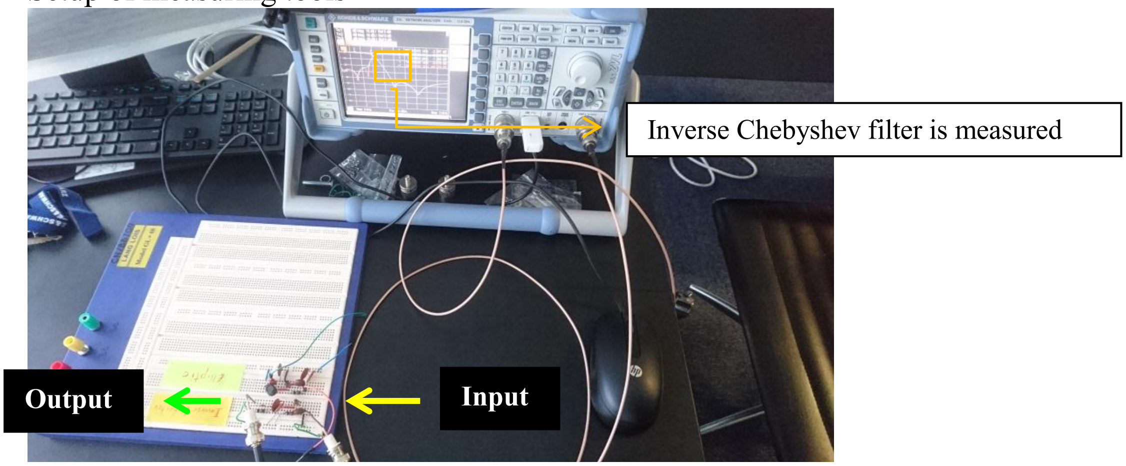


Figure 44 : Input and Output is hooked to Inverse Chebyshev.

Input and output BNC connector are connected Rohde & Schwarz Network Analyzer. The yellow coloured marker indicates the input frequency signal while the green coloured marker indicates the output frequency signal.

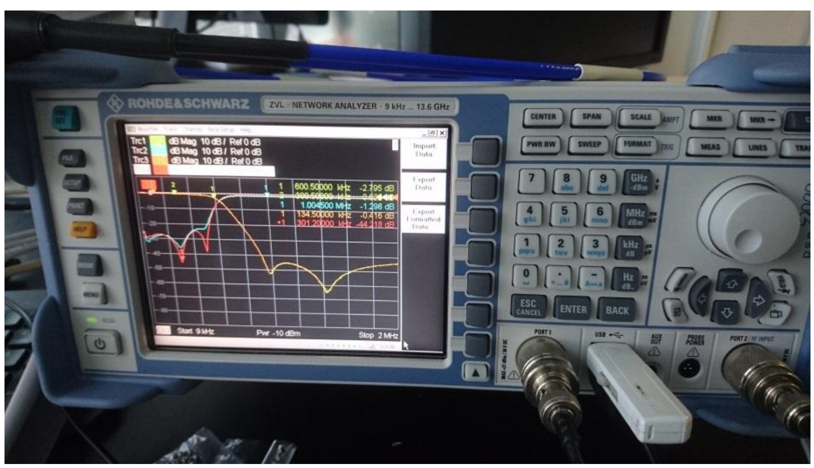


Figure 45 : Network analyzer reading of S_{21} (gain) and S_{11} (reflection).

Orange marker indicates the gain of the filter. Frequency sweep operation is made from 0 Hz – 2 MHz . The response shows flat passband and some ripples at stopband indicating transmission zeros. The falloff response occurs at 500 kHz and the waveform satisfies the Inverse Chebyshev simulation made.

4.5.3 Attenuation response measurement of Inverse Chebyshev 5th Order Low pass Filter

Date & Time of Experiment	13/04/2017	10 am
$Frequency, f$	$Gain = \frac{Vpp(out)}{Vpp(in)}$	$Attenuation\ in\ dB$
10	0.943396226	-0.51
300	0.943396226	-0.51
800	0.943396226	-0.51
1,500	0.917431193	-0.75
2,400	0.917431193	-0.75
4,000	0.943396226	-0.51
6,000	0.943396226	-0.51
8,000	0.943396226	-0.51
10,000	0.917431193	-0.75
50,000	0.917431193	-0.75
100,000	0.925925926	-0.67
200,000	0.917431193	-0.75
300,000	0.917431193	-0.75
400,000	0.943396226	-0.51
500,000	0.953396226	-0.41
600,000	0.025151515	-31.99
700,000	0.037151515	-28.60
800,000	0.004761905	-46.44
900,000	0.005000000	-46.02
1,000,000	0.007352941	-42.67
2,000,000	0.014285714	-36.90

Table 10 : Table above shows the experimented data on Chebyshev lowpass filter.

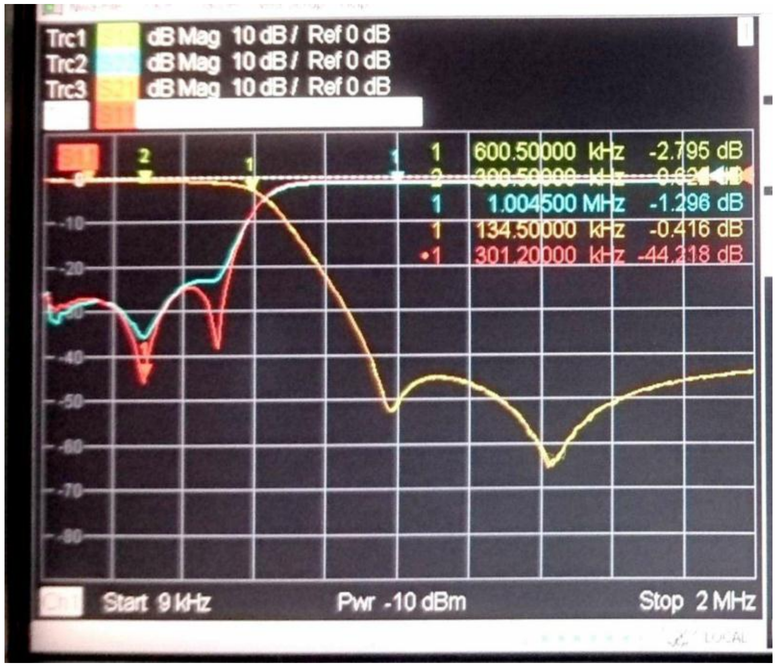


Figure 47 : Frequency vs Attenuation response recorded using data obtained from the Inverse Chebyshev experiment.

4.5.4 Total Harmonic Distortion (THD) measurement for Inverse Chebyshev 5th Order Low pass Filter

Setting up of measuring equipment

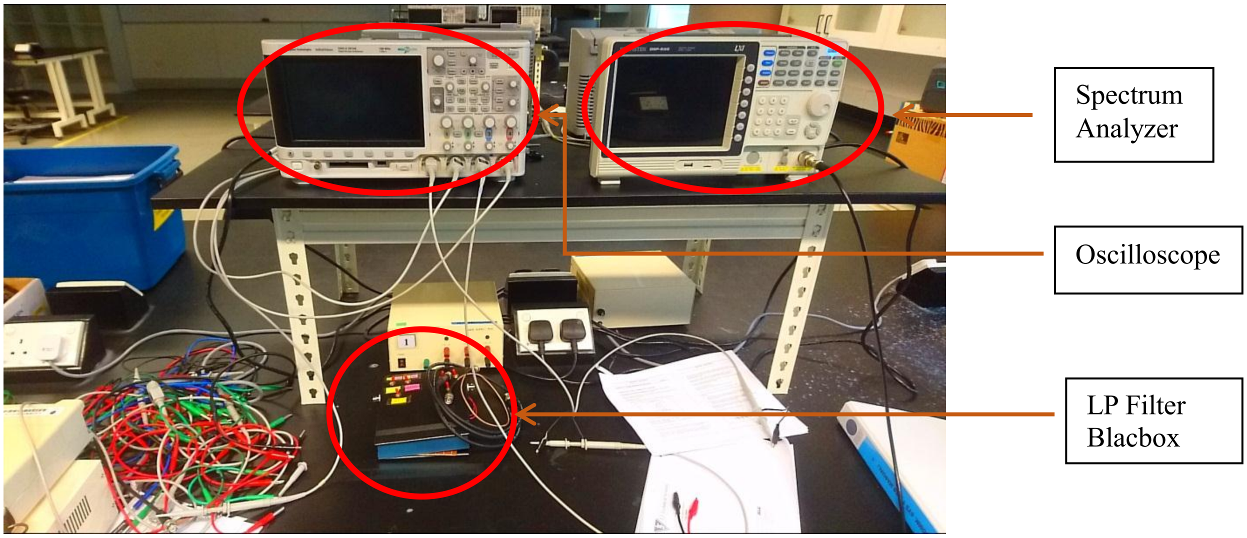


Figure 48 : Equipment required for Inverse Chebyshev's THD measurements.

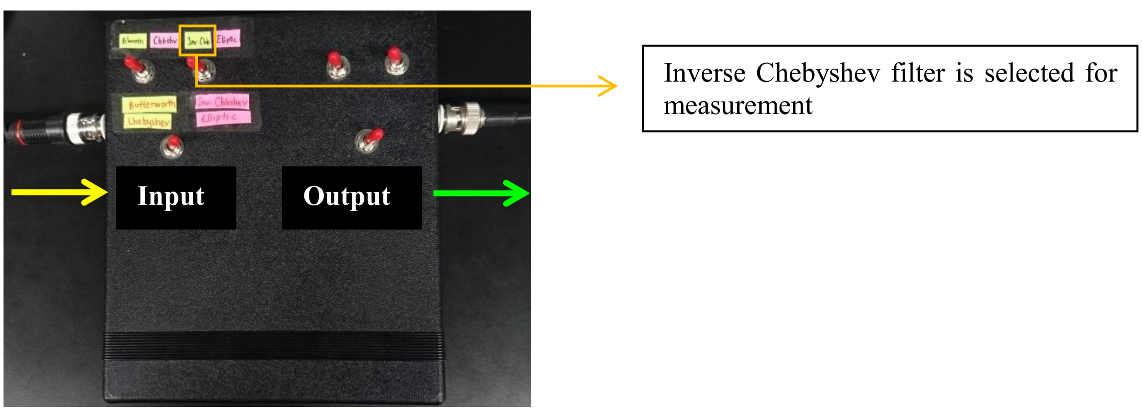


Figure 49 : Input and Output is toggled to Inverse Chebyshev. Input BNC connector is connected to frequency generator and Output BNC connector is connected to spectrum analyzer.

Figure 50 : FFT waveform measured at the output of Inverse Chebyshev filter

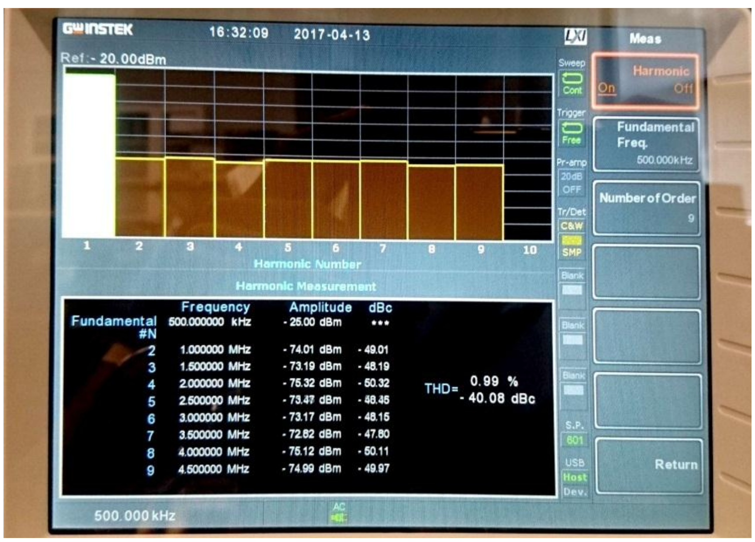
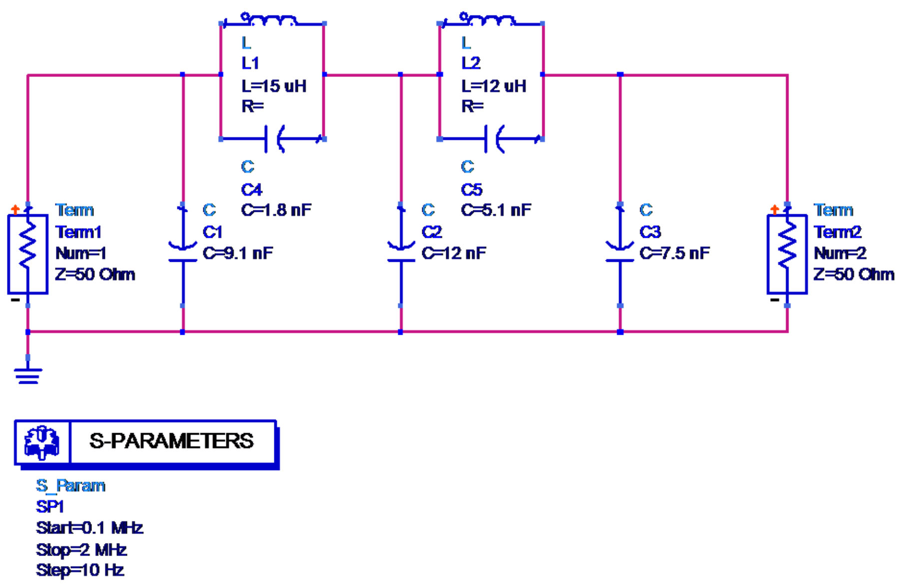


Figure 51 : THD performance are measured using Spectrum Analyzer for Inverse Chebyshev filter.

Total harmonic distortions are measured using math functions in spectrum analyzer. It performs harmonic component's amplitude iteration up to 9th order. These harmonic components are compared with the fundamental frequency of the Inverse Chebyshev to obtain the percentage of signal distortion. The THD measurement was observed to be 0.99% and -40.08 dB.

4.6 Elliptic Lowpass Filter

4.6.1 Simulation of Elliptic filter with 0.5-dB ripple passband and -40dB Elliptic attenuation at 5th order LP filter



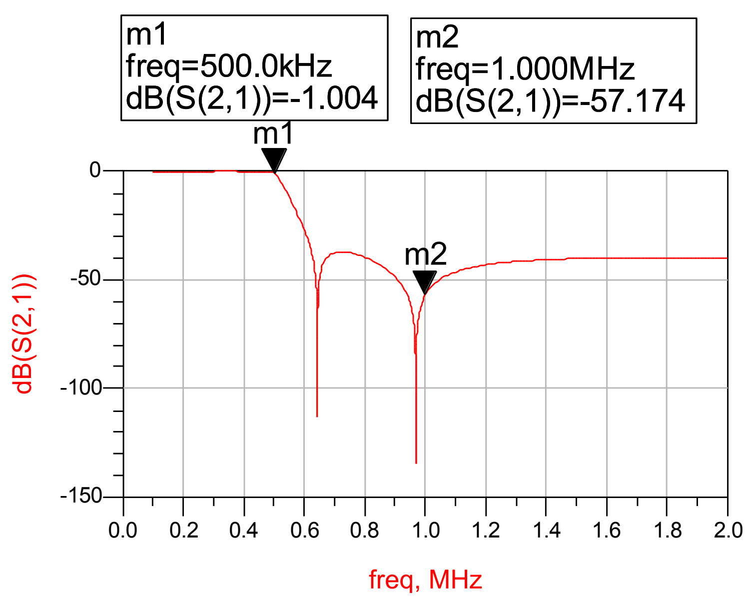


Figure 51.1: Simulated circuit and waveform response for Elliptic filter 5th order LP filter

4.6.2 Measurement of fabricated Elliptic filter

Setup of measuring tools

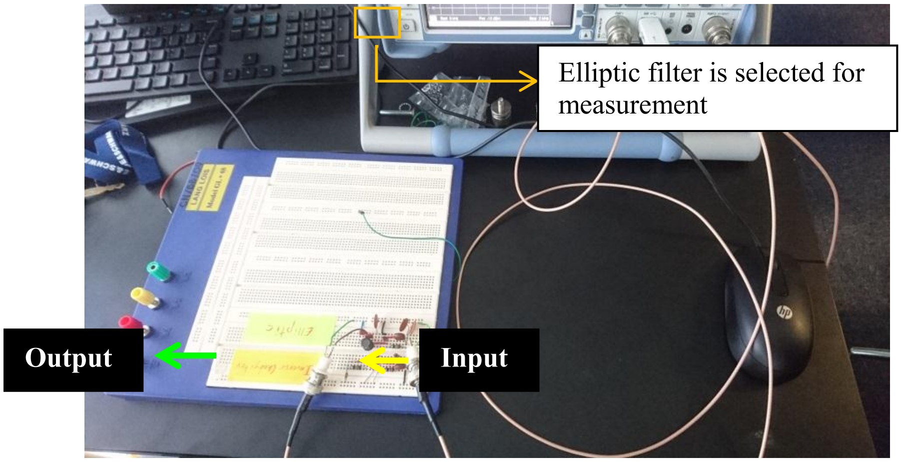


Figure 52 : Input and Output is hooked to Elliptic.

Input and output BNC connector are connected Rohde & Schwarz Network Analyzer. The yellow coloured marker indicates the input frequency signal while the green coloured marker indicates the output frequency signal.

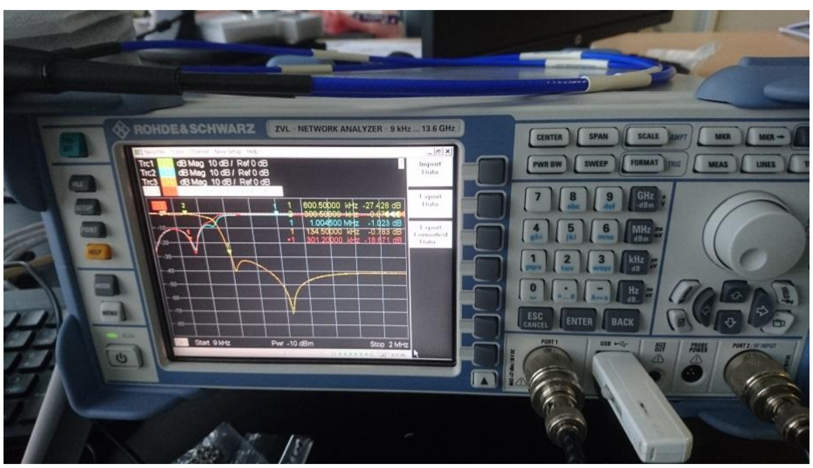


Figure 53 : Network analyzer reading of S_{21} (gain) and S_{11} (reflection).

Orange marker indicates the gain of the filter. Frequency sweep operation is made from 0 Hz – 2 MHz . The response shows ripples in both passband and stopband indicating transmission zeros in both poles and zeros. The falloff response occurs at 500 kHz and the waveform satisfies the Elliptic simulation made.

4.6.3 Attenuation response measurement of Elliptic 5th Order Low pass Filter

Date & Time of Experiment	13/04/2017	12 pm
$\boldsymbol{Frequency, f}$	$\boldsymbol{Gain = \frac{Vpp(out)}{Vpp(in)}}$	$\boldsymbol{Attenuation\ in\ dB}$
10	0.923396226	-0.69
200	0.923396226	-0.69
400	0.989965766	-0.09
800	0.989965766	-0.09
1,000	0.927431193	-0.65
4,000	0.812345670	-1.81
10,000	0.925925926	-0.67
50,000	0.989965766	-0.09
100,000	0.989965766	-0.09
300,000	0.979675766	-0.18
500,000	0.897655300	-0.94
600,000	0.219780220	-13.16
700,000	0.085616438	-21.35
800,000	0.015151515	-36.39
900,000	0.025151515	-31.99
1,000,000	0.037151515	-28.60
2,000,000	0.025151515	-31.99

Table 11 : Table above shows the experimented data on Elliptic lowpass filter.

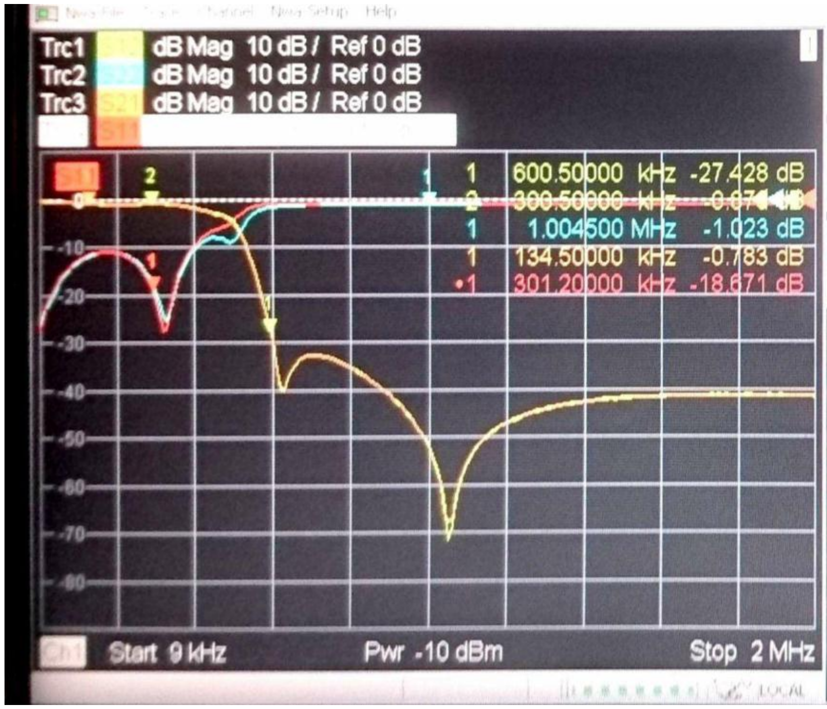


Figure 55 : Frequency vs Attenuation response is recorded using data obtained from the Elliptic experiment.

4.6.4 Total Harmonic Distortion (THD) measurement for Elliptic 5th Order Low pass Filter

Setting up of measuring equipment

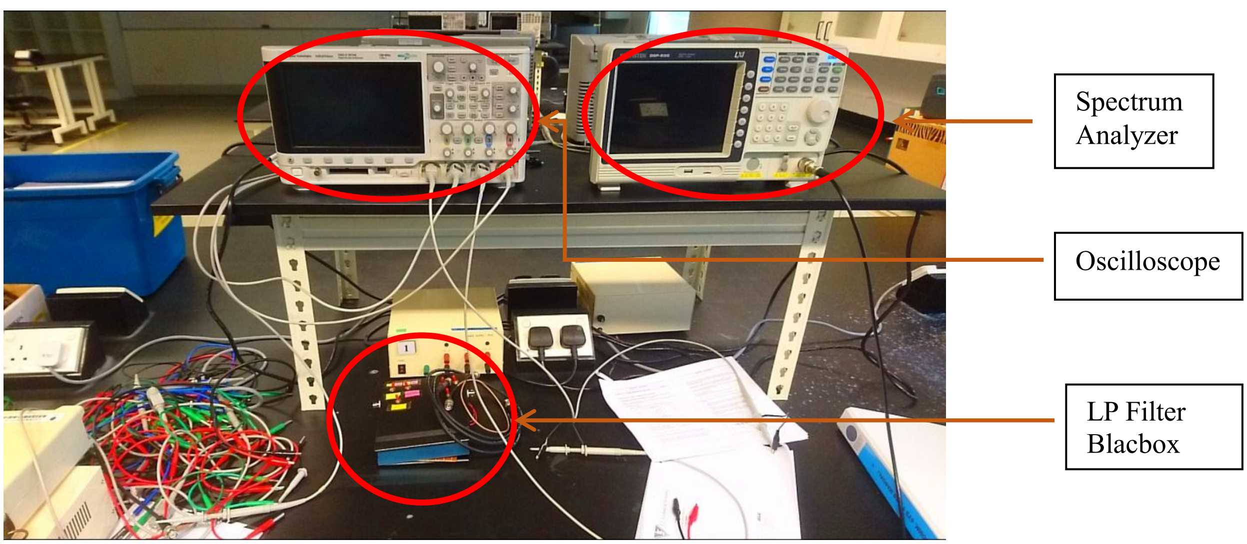


Figure 56 : Equipment required for Elliptic's THD measurements.

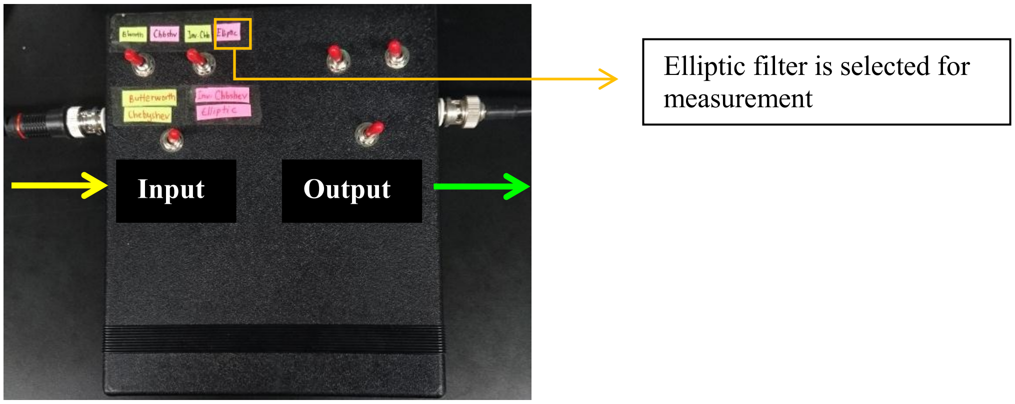


Figure 57 : Input and Output is toggled to Elliptic. Input BNC connector is connected to frequency generator and Output BNC connector is connected to spectrum analyzer.

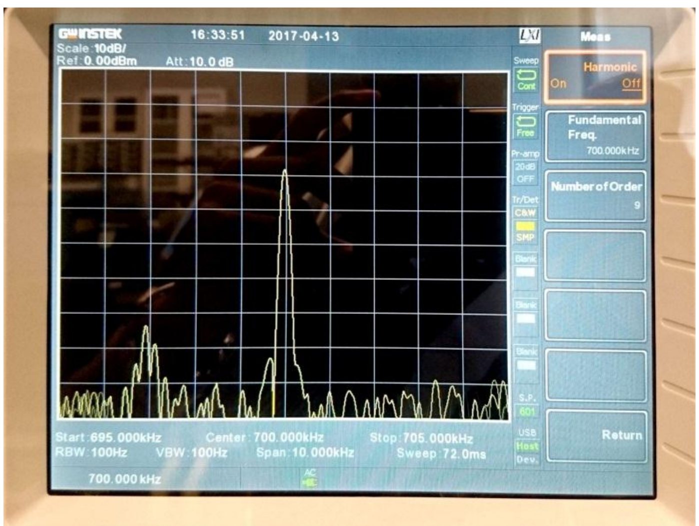


Figure 58 : FFT waveform measured at the output of Elliptic filter

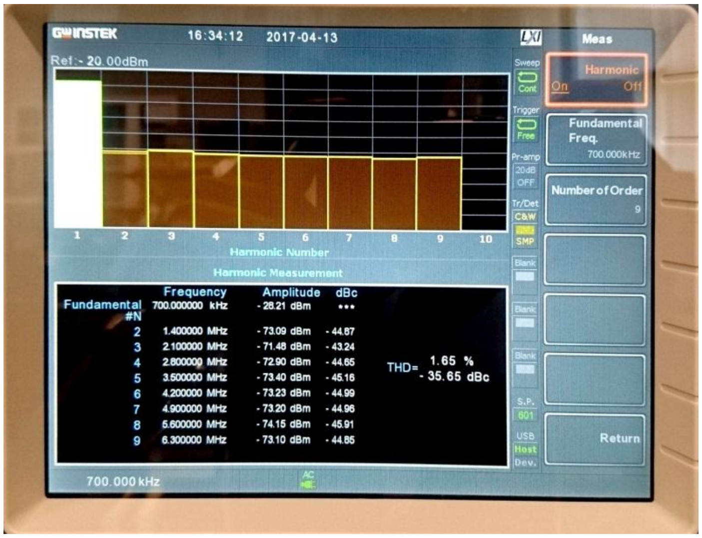


Figure 59 : THD performance are measured using Spectrum Analyzer for Elliptic filter.

Total harmonic distortions are measured using math functions in spectrum analyzer. It performs harmonic component's amplitude iteration up to 9th order. These harmonic components are compared with the fundamental frequency of the Elliptic to obtain the percentage of signal distortion. The THD measurement was observed to be 1.65% and -35.65 dB.

4.7 Inductor's Optimum Performance

Selection of the best inductor will result in good desired attenuation frequency response and low total harmonic distortions. The analysis of good inductors is further described as maximum Q frequency is inversely proportional to core size, core permeability, and the square root of core loss. Major factors in selecting an RF inductor are Q (quality factor), self-resonant frequency (SRF), and inductance tolerance. Q will greatly affect the performance of filter, so highest possible Q over the operating frequency range should be chosen. Solenoid inductors, have lines of magnetic flux that extend to infinity while toroidal construction results in closed magnetic path. Therefore solenoid inductor gives threat of more magnetic coupling to other inductors. Self-resonant frequency (SRF) is frequency where the distributed capacitance of the inductor forms a resonant circuit with actual inductance. When operating frequency reaches SRF, Q will dramatically decrease. Distributed capacitance results to very lossy dielectric material. SRF can be avoided by selecting an inductor with higher inductance, so called effective inductance as it appears higher than true inductance.

4.7.1 Selected Inductor for Optimum Performance

Type	Material	Best Op.Freq	Q factor	Core losses	Stability	Flux leakages
MPP Toroidal Coil	Molypermalloy powder cores	100 kHz – 999 kHz	High Q with large core	Low	High resistivity Stable with large changes in flux density, frequency, temperature, DC magnetization	Low
Ferrite Pot Cores	Ceramic	10 kHz - #MHz	Very high Q	Extremely Low	Very high resistivity, stable with time & temp var.	Very low

Table 12 : Selected optimum performance inductors

Ferrite pot cores is chosen due to its capability of handling 500kHz , very high Q which means bigger charge containing capacity hence less core loss. Besides that, Ferrite pot core has extremely low core losses and higher resistivity and stability compared to MPP Toroidal coil.

4.8 Capacitor's Optimum Performance

Selection of the best capacitor will provide the designer ease of component soldering due to high temperature durability and stable waveform responses due to low dissipation factor. Besides that there are several factors to consider in choosing the optimal capacitor for filter operation such as:-

- Rugged hermetic construction
- Optimized electrode patterns
- Low resistivity electrode and termination materials
- High dielectric strength
- Protective barrier layer between electrodes and termination
- Ultra stable with temperature and humidity
- Extremely high Q

4.8.1 Selected Capacitors for Optimum Performance

Family of Capacitor	Type	Operating Frequency	Capacitance	Temperature	Dissipation factor	Suitability for RF Filter
Film	Polyster (PET)	999kHz	1000pF – 10uF	125°C	1 %	Yes
	Polyphenylene (PPS)	999kHz	1000pF – 10uF	150°C	1%	Yes
	Polystrene	999kHz	1000pF – 10uF	85°C	0.01%	Yes
	Polypropylene	999kHz	1000pF – 10uF	105°C	0.1 %	Yes
Mica		1GHz	0.1pF-10,000pF	150°C	0.01%	Yes

Table 13 : Selected optimum performance capacitors

Based on the comparison made, the best capacitor for 500kHz cutoff frequency lowpass filter is Polystrene Film capacitor as it suits the right optimum operating frequency and within the designed capacitance value of the filter. In addition, polystyrene capacitor works at linear temperature of 85°C which have moderate advantage during soldering process. The major advantage of polystyrene film capacitor is its lowest dissipation factor at 0.01% compared to other types of Film capacitors.

Chapter 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Lowpass filter is an essential system in audio application and is located at the output of amplifier. This paper successfully explained the design of lowpass filter with low total harmonic distortion (THD). The research manages to synthesis a lowpass filter with cutoff frequency at 500kHz, -35 dB attenuation at 1000kHz and -100 dB response of total harmonic distortion. Elliptic filter topology is selected after comparing with Maximally Flat, Chebyshev and Inverse Chebyshev topologies because Elliptic filter gives steepest attenuation at the cost of lesser inductor. This paper researches on the effect of inductor's number and types on the harmonic responses of filters. Comparison of inductors and capacitors are made and the best component with expected lowest THD is selected for fabrication. Therefore Ferrite pot core inductor and Polystrene film capacitor is selected. The designed lowpass filters are tested in the lab and Elliptic filter results in lowest THD at -35.65 dB hence producing better clarity of tones for audio application.

5.2 Recommendation

This project could be further synthesized for 1000 kHz cutoff frequency range as some output of amplifiers is designed in that frequency range. Besides the inductors size could be further reduced by implementing Graphine technology. This technology will enable higher Q factor of inductors and low core losses which will result in very low total harmonic distortion.

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