

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

IMPLEMENTING ANALOG FILTER APPLICATIONS IN
ELECTRO OPTICAL SENSORS



EMRAH BÖLÜK

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF ELECTRONICS ENGINEERING

ADVISOR: ASSIST. PROF. DR. ATILLA UYGUR

JULY 2025

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**IMPLEMENTING ANALOG FILTER APPLICATIONS
IN ELECTRO OPTICAL SENSORS**

EMRAH BÖLÜK

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF ELECTRONICS ENGINEERING

ADVISOR: ASSIST. PROF. DR. ATILLA UYGUR

JULY 2025

T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

ELEKTRO OPTİK SENSÖRLERDE ANALOG FİLTRE
UYGULAMALARININ GERÇEKLEŞTİRİLMESİ

EMRAH BÖLÜK

YÜKSEK LİSANS TEZİ
ELEKTRONİK MÜHENDİSLİĞİ ANABİLİM DALI

DANIŞMAN: DR. ÖĞR. ÜYESİ ATILLA UYGUR

TEMMUZ 2025

MASTER of SCIENCE JURY APPROVAL FORM

A thesis submitted by Emrah Bölük, defended on 18/07/2025 before the jury formed with the 23/06/2025 date and 2025/33 numbered decision of the GTU Graduate Administration Board, has been accepted as a MASTER of SCIENCE thesis in the Department of Electronics Engineering.

JURY

MEMBER

(THESIS ADVISOR) : Assist. Prof. Dr. Atilla Uygur

MEMBER

: Assoc. Prof. Dr. Doğu Çağdaş Atilla

MEMBER

: Assoc. Prof. Dr. Engin Afacan

APPROVAL

Gebze Technical University Graduate Administration Board
...../...../..... date and/..... numbered decision.

SIGNATURE/SEAL

ABSTRACT

Electro-optical systems are fundamental applications across a wide range of modern technologies. These applications typically include navigation, defense systems, aviation instrumentation, surveillance technologies, and autonomous navigation, all of which require high precision. At the core of such systems are Laser Range Finder modules, which are scientific equipment-based active distance sensors that help measure the distance to an object if the target object is a visible point or gap. These modules find application and performance in many areas such as target detection, motion tracking, and weapon guidance or target detection. Any Laser Range Finder module that helps detect the distances of potential targets and measure them for training/testing ranges is highly dependent on signal processing for measurement performance.

A low-performance signal processing chain has an extremely negative impact on the Signal-to-Noise Ratio of the module. A fully analog, adjustable signal conditioning architecture has been developed to improve and enhance Signal-to-Noise Ratio and frequency tracking. This work uses a new C-gain topology with 4th order adjustable bandpass filters. The fundamental improvement is the development of a 4th-order analog bandpass filter capable of operating at frequency levels ranging from 50 kHz to 4.02 MHz. A multiple-feedback topology is employed within the project to achieve the desired stability and selectivity levels required to obtain the specified adjustable range and frequency. These parameters have been applied in a simulator model to ensure that the behavior of the filter and multiplier circuits closely resembles real-world conditions. The theoretical and simulated responses of the circuits have been thoroughly analyzed to verify the stability, agility, and clarity of the signals.

In this special project, where the use of this technique is likely for military or aviation applications, sufficient tolerance to electromagnetic interference, reliability under harsh atmospheric or other conditions, and high resistance to long-term wear or breakage are some of the basic requirements. The circuit has proven its efficiency across the entire module measurement range by being tested at different frequencies in the range.

Keywords: Laser Range Finder, Tunable Active Bandpass Filter, C Multiplier Circuit, Avalanche Photo Diode, Analog Filtering

ÖZET

Elektro-optik sistemler, çok çeşitli modern teknolojilerde temel uygulamalardır. Bu uygulamalar genellikle navigasyon, savunma sistemleri, havacılık enstrümantasyonu, gözetim teknolojileri ve otonom navigasyon gibi yüksek hassasiyet gerektiren alanları içerir. Bu tür sistemlerin merkezinde, hedef nesne görünür bir nokta veya boşluk ise nesneye olan mesafeyi ölçmeye yardımcı olan bilimsel ekipman tabanlı aktif mesafe sensörleri olan Lazer Mesafe Bulucu modülleri bulunur. Bu modüller, hedef algılama, hareket izleme ve silah güdümü veya hedef algılama gibi birçok alanda uygulama ve performans bulur. Potansiyel hedeflerin mesafelerini algılamaya ve eğitim/test menzilleri için ölçmeye yardımcı olan herhangi bir Lazer Mesafe Bulucu modülü, ölçüm performansı için sinyal işlemeye büyük ölçüde bağımlıdır.

Düşük performanslı bir sinyal işleme zinciri, modülün Sinyal-Gürültü Oranı üzerinde istenilen etkiye sahip değildir. Sinyal-Gürültü Oranı ve frekans izlemeyi iyileştirmek ve geliştirmek için tamamen analog, ayarlanabilir bir sinyal koşullandırma mimarisi geliştirilmiştir. Bu kelime, 4. derece ayarlanabilir bant geçiren filtrelerle sahip yeni bir C-kazanç topolojisi kullanır. Temel iyileştirme, 50 kHz ila 4,02 MHz frekans aralığında çalışabilen 4. derece analog bant geçiren filtrenin geliştirilmesidir. Proje kapsamında, belirtilen ayarlanabilir aralık ve frekansı elde etmek için gereken istikrar ve seçicilik seviyelerini sağlamak üzere çoklu geri besleme topolojisi kullanılmıştır. Bu parametreler, filtre ve çarpan devrelerinin davranışının gerçek dünya koşullarına yakından benzemesini sağlamak için bir simülatör modelinde uygulanmıştır. Devrelerin teorik ve simüle edilmiş tepkileri, sinyallerin istikrarını, çevikliğini ve netliğini doğrulamak için kapsamlı bir şekilde analiz edilmiştir.

Bu özel projede, bu tekniğin askeri veya havacılık uygulamalarında kullanılması muhtemel olduğundan, elektromanyetik parazite karşı yeterli tolerans, zorlu atmosferik veya diğer koşullar altında güvenilirlik ve uzun süreli aşınma veya kırılmaya karşı yüksek direnç temel gereksinimler arasındadır. Devre, tüm frekanslarda test edilerek ölçüm aralığında verimliliğini kanıtlamıştır.

Anahtar Kelimeler: Lazer Mesafe Bulucu, Ayarlanabilir Aktif Bant Geçiren Süzgeç, Kapasitans Çarpıcı Devre, Çığ Foto Diyot, Analog Süzgeç

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my advisor, Associate Professor Atilla Uygur. Sharing his academic and technical knowledge with me and guiding me throughout my master's program has been invaluable to me. I would also like to thank all my professors, mentors, and advisors who have helped me reach this point in my professional and academic career.

One of the greatest acknowledgments goes to my father Engin, my mother Fatma, and my brothers Nurettin and Umut, who have been by my side throughout my academic career. Their support has been one of the greatest sources of motivation that has enabled me to reach this point. I dedicate this work to my entire family.



TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	v
ÖZET	vi
ACKNOWLEDGEMENTS	vii
TABLE OF CONTENTS	viii
LIST OF SYMBOLS AND ABBREVIATIONS	ix
LIST OF FIGURES	x
LIST OF TABLES	xiii
1. INTRODUCTION	1
1.1. Thesis Topic and Purpose	1
1.1. Thesis Questions	2
2. ELECTRO-OPTICAL SYSTEM BACKGROUND	4
2.1. Early Developments in Electro-Optical Systems	4
2.1.1. Applications of Electro-Optical Systems in Defense Industry	5
2.2. Electro-Optical System Overview	7
2.2.1. Lasers in Electro-Optical Systems	9
2.3. Laser Range Finder System Architecture	17
3. ANALOG FILTER APPROACH	26
3.1. Analog Filter Types	26
3.1.1. Low Pass Filter	26
3.1.2. High Pass Filter	29
3.1.3. Bandpass Filter	30
3.1.4. Bandstop Filter	32
3.2. Filter Approximations	33
3.2.1. Butterworth Approximation	34
3.2.2. Chebyshev Approximation	35
3.2.3. Inverse Chebyshev Approximation	36
3.2.4. Cauer Approximation	37
4. TUNABLE ANALOG FILTER DESIGN	39
4.1. Preliminary Designs	41
4.1.1. 4th Order Sallen-Key Bandpass Filter	41
4.1.2. 4th Order MFB Bandpass Filter with Sallen-Key Topology	48
4.1.3. 4th Order MFB Bandpass Filter with Butterworth Topology	51
4.2. Final Filter Circuit Design	52
4.3. Capacitance Multiplier Circuit Design	55
5. RESULTS	58
5.1. Filter Frequency Analysis	58
5.2. Capacitance Multiplier Analysis	84
5.3. Practical Realizations	86
6. CONCLUSION AND FUTURE WORK	93
REFERENCES	97
BIOGRAPHY	101
PUBLICATIONS AND PRESENTATIONS FROM THE THESIS	102

LIST OF SYMBOLS AND ABBREVIATIONS

ADC	: Analog to Digital Converter
APD	: Avalanche Photo Diode
BPF	: Band Pass Filter
CCD	: Charge Coupled Devices
CLDP	: Convertible Laser Designation Pod
CMOS	: Complementary Metal Oxide Semiconductor
COLIDAR	: Coherent Light Detecting and Ranging
CW	: Continuous Wave
DAC	: Digital to Analog Converter
ECG	: Electrocardiography
FPGA	: Field Programmable Gate Array
HPF	: High Pass Filter
LADAR	: Light Detection and Ranging
LCOM	: Laser Communication
LIDAR	: Laser Imaging Detection and Ranging
LPF	: Low Pass Filter
LRF	: Laser Range Finder
LTD	: Laser Target Designator
MEMS	: Micro Electronic Mechanical Systems
MFB	: Multiple Feed Back
MIT	: Massachusetts Institute of Technology
MOSFET	: Metal Oxide Semiconductor Field Effect Transistor
NASA	: National Aeronautics and Space Administration
OTA	: Operational Transconductance Amplifier
SWIR	: Short Wave Infrared
TEC	: Thermo Electric Couplers
TOF	: Time of Flight
TSMC	: Taiwan Semiconductor Manufacturing Company
UAV	: Unmanned Aerial Vehicle

LIST OF FIGURES

	<u>Page</u>
Figure 2.1: Herschel IR activity [3].	5
Figure 2.2: Infrared applications in Italy [9].	6
Figure 2.3: Structure type vs. wavelength comparison[11].	7
Figure 2.4: Lasers working wavelengths [11].	8
Figure 2.5: Laser schematic [14].	10
Figure 2.6: Laser electromagnetic radiation spectrums [11].	11
Figure 2.7: Laser diode schematic [14].	15
Figure 2.8: XM23 LRF model with cabling [23].	16
Figure 2.9: Tornado Paveway II[19].	17
Figure 2.10: LRF transmitter and receiver scheme [19].	19
Figure 2.11: LRF model diagram.	20
Figure 2.12: LRF target measurement data [25].	21
Figure 2.13: LRF target Processed data [25].	21
Figure 2.14: LRF target received signal [26].	22
Figure 2.15: Received target signal 1.	23
Figure 2.16: Received target signal 2.	24
Figure 2.17: Received target signal 3.	24
Figure 2.18: Received target analog signal.	24
Figure 3.1: RC based 1st order LPF circuits [34].	27
Figure 3.2: Ideal and practical LPF amplitude response [34].	28
Figure 3.3: RC based 1st order HPF circuits [34].	29
Figure 3.4: Ideal and practical HPF amplitude response [34].	30
Figure 3.5: BPF frequency response at different Q values [36].	31
Figure 4.1: 2nd order sallen-key BPF [45] .	43
Figure 4.2: 4th order sallen-key BPF circuit (Q=1).	44
Figure 4.3: 4th order sallen-key BPF output at 40 kHz (Q=1).	45
Figure 4.4: 4th order sallen-key BPF output At 1.25 MHz (Q=1).	45
Figure 4.5: 4th order sallen-key BPF output At 1.25 MHz (Q=10).	46
Figure 4.6: 4th order sallen-key BPF circuit (Q=10).	46
Figure 4.7: 4th order sallen-key BPF output at 40 kHz (Q=10).	47
Figure 4.8: 4th order sallen-key BPF output comparison.	47
Figure 4.9: 2nd order MFB BPF [45].	48
Figure 4.10: 4th order MFB Bandpass filter circuit.	49
Figure 4.11: 4th order MFB Bandpass filter output at 270 kHz.	49
Figure 4.12: 4th order MFB Bandpass filter output at 45 kHz.	50
Figure 4.13: Final filter circuit design.	52
Figure 4.14: Capacitance multiplier circuit.	57
Figure 5.1: Filter output at 50 kHz.	58
Figure 5.2: Filter output at 50 kHz close view.	59
Figure 5.3: Filter output at 50 kHz logarithmic view.	59
Figure 5.4: Measured vs theoretical output comparison at 50 kHz.	60
Figure 5.5: Filter output at 65 kHz.	60
Figure 5.6: Filter output at 65 kHz close view.	61
Figure 5.7: Filter output at 80 kHz.	61
Figure 5.8: Filter output at 80 kHz close view.	62
Figure 5.9: Filter output comparison at mid-frequency 65 kHz.	62

Figure 5.10: Filter output comparison at mid-frequency 65 kHz logarithmic view.	63
Figure 5.11: Capacitance vs. frequency curve at 65 kHz.	63
Figure 5.12: Filter output at 105 kHz.	64
Figure 5.13: Filter output at 105 kHz logarithmic View.	64
Figure 5.14: Filter output at 233 kHz.	65
Figure 5.15: Filter output at 233 kHz logarithmic view.	65
Figure 5.16: Filter output at 466 kHz.	66
Figure 5.17: Filter output at 466 kHz logarithmic view.	66
Figure 5.18: Measured vs theoretical output comparison at 466 kHz.	67
Figure 5.19: Filter output comparison at mid-frequency 65 kHz.	67
Figure 5.20: Filter output comparison at mid-frequency 466 kHz logarithmic view.	68
Figure 5.21: Capacitance vs. frequency curve at 466 kHz.	68
Figure 5.22: Filter output at 577 kHz.	69
Figure 5.23: Filter output at 760 kHz.	79
Figure 5.24: Filter output at 760 kHz logarithmic view.	70
Figure 5.25: Measured vs theoretical output comparison at 760 kHz.	70
Figure 5.26: Filter output at 1.13 MHz.	71
Figure 5.27: Filter output comparison at mid-frequency 1.13 MHz.	71
Figure 5.28: Capacitance vs. frequency curve at 1.13 MHz.	72
Figure 5.29: Filter output at 2.18 MHz.	72
Figure 5.30: Filter output at 2.13 MHz logarithmic view.	73
Figure 5.31: Measured vs theoretical output comparison at 2.13 MHz.	73
Figure 5.32: Filter output comparison at mid-frequency 2.13 MHz.	74
Figure 5.33: Capacitance vs. frequency curve at 2.13 MHz.	74
Figure 5.34: Filter output at 3.2 MHz.	75
Figure 5.35: Measured vs theoretical output comparison at 3.2 MHz.	75
Figure 5.36: Filter output at 3.95 MHz.	76
Figure 5.37: Filter output at 4.02 MHz.	76
Figure 5.38: Filter output at 4.02 MHz logarithmic view.	77
Figure 5.39: Filter output comparison at mid-frequency 2.18 MHz logarithmic view.	77
Figure 5.40: Filter output comparison at mid-frequency 3.95 MHz.	78
Figure 5.41: Transient analysis at 50 kHz.	78
Figure 5.42: FFT result at 50 kHz.	79
Figure 5.43: Step response at 50 kHz.	80
Figure 5.44: Spectral noise density at 50 kHz.	80
Figure 5.45: Transient analysis at 1.13 MHz	81
Figure 5.46: FFT result at 1.13 MHz.	82
Figure 5.47: Step response at 1.13 MHz.	83
Figure 5.48: Spectral noise density at 1.13 MHz.	83
Figure 5.49: Capacitance vs. frequency curve.	85
Figure 5.50: Capacitance vs. multiplication factor curve.	85
Figure 5.51: Filter circuit view 1.	87
Figure 5.52: Filter circuit view 2.	87
Figure 5.53: Filter circuit view 3.	88
Figure 5.54: Filter input - circuit and output all view 1.	88
Figure 5.55: Filter input - circuit and output all view 2.	89
Figure 5.56: Filter output view.	89

Figure 5.57: Signal comparison at 100m.	90
Figure 5.58: Signal comparison at 500m.	91
Figure 5.59: Signal comparison at 1000m.	91
Figure 5.60: Signal comparison at 2500m.	92



LIST OF TABLES

	<u>Page</u>
Table 4.1: Capacitance - frequency equation.	54
Table 6.1: Comparison of different studies	93



1. INTRODUCTION

The recent revolution, initiated by the emergence of the laser, has resulted from vast parallel and often symbiotic advancements in resources, materials, and microelectronics. The integration of these technologies has facilitated the development of numerous small gadgets exhibiting unprecedented intelligence and performance. This has facilitated extensive alterations in optical materials, enhancing the utility of optical fiber. The engineering initiatives for the application of diverse optical circuits and sensors have also intensified. The rapid advancement of electro-optics has facilitated numerous areas of research. Research on prospective issues and enhancements has become essential for the advancement of existing systems. Moreover, the increasing complexity of aviation standards has resulted in heightened system requirements and the ongoing advancement of electronic systems. In the defense sector, particularly smart munitions and armed unmanned aerial vehicles, Laser Range Finder (LRF) modules are utilized[1]. Most laser systems are active devices functioning in a manner analogous to microwave radars, albeit at significantly higher frequencies. Conversely, LRF modules exhibit high sensitivity to atmospheric factors due to their reliance on laser signals. This thesis examines the creation of analog electronic circuits for existing electro-optical systems.

1.1. Thesis Topic and Purpose

Laser Range Finder devices are widely used to measure precise distances in electro-optical systems. The working mechanism is mostly based on the runtime, the LRF module sends a laser beam directly to the target object. The signal sent to the target object is generated and transmitted on an electronic circuit based on Avalanche Photo Diode (APD). Electro-optical systems function within the optical and infrared segments of the electromagnetic spectrum. These systems are utilized in imaging, target detection, motion and orientation, and detection applications. Electro-optical systems are favored in aviation, aerospace, military, security, and healthcare sectors[2]. In this thesis, for the specified LRF module was integrated with an analog tunable bandpass filter was applied within a dynamic frequency range to reduce the signal-to-noise ratio. This approach enabled the use of analog signals for highly accurate position detection. The proposed work offers an innovative approach in the

fields of analog signal analysis, capacitance multiplier circuit design, and, most notably, tunable analog filter design, adhering to military standards and providing advancements in sector-specific applications. A tunable analog bandpass filter operating in the frequency range of 50 kHz - 4.02 MHz is worked in thesis for Laser Range Finder modules in the field of electro-optical sensors. To filter the noised signal seen in the APD sensor in modules and to make more accurate measurements, the 4th-order bandpass filter is used which is designed with multiple feedback implementation. The pass band center frequency of the filter is tuned according to the frequency of the input signal by a secondary controller. Thus, the peak frequency of the signal to be filtered is defined and then the required capacitance value is transmitted to the filter circuit after creating a related capacitance value in the C-multiplier circuit. The APD sensor data were generated at a 300-mV amplitude level within the frequency range determined based on real measurement data from the literature. The model was conducted by accounting for all environmental and hardware noise, as well as deviations observed in previous studies. The data were subsequently optimized for testing within the 50 kHz to 4.02 MHz frequency range. Simulation results of the C-multiplier circuit and the filter circuit exhibit close theoretical and simulated responses.

1.2. Thesis Questions

A number of research questions had to be answered in order to present the thesis. The first research question deals with the role of analog circuit design in improving the performance of electro-optical systems and especially Laser Range Finder modules. This is to infer in what ways the analog electronic circuits can indeed improve the system's performance. The accuracy and the constancy of LRF modules that are primarily used in defense, aerospace, precision imaging are of great interest from the technical as well as practical point of view. The second research question What are main difficulties in the design of tunable analog bandpass filters for LRF modules? looks at the problematic action while designing these filters. One of the problems is that these filters need to operate in a wider range of frequency for the incoming signal to pass. Also, the incoming signal varies as well and so the filter needs to change its parameters spontaneously to prevent signal distortion. Hence, the research question is included. Another research question probes into the role of capacitance multiplier circuits, i.e. What is the effect of these circuits on the accuracy of signal processing in

these LRF modules. By dynamically changing the capacitance, the capacitance multiplier circuits can modify the signal in a way that the signal integrity improves and so detection becomes effortless in most environments. There are military-grade standards that need to be followed strictly to consider the real-world applications of these solutions autoimmune. The research question includes the statement That is, do the proposed analog solutions meet military standard if they are durable, accurate, and perform consistently? To determine this, the results from the simulation have been compared to the accepted values which were done for most of the cases regarding the defense-grade solutions. For the study to be covered and to show the differences, the last research question deals with the role of tunable 4th-order analog bandpass filter especially over digital filtering techniques. Thus, the research question asks What is the performance advantage of a tunable fourth-order analog bandpass filter as compared with digital filtering techniques when processing signals from APD? Here, especially in situations where timing and signal clarity are crucial, the aim is to find whether analog filtering offers lower latency and improved responsiveness.

2. ELECTRO-OPTICAL SYSTEM BACKGROUND

2.1. Early Developments in Electro-Optical Systems

The initial research in electro-optical systems commenced in the 1800s with the discovery of infrared radiation by William Herschel [3]. This laid the foundations for electro-optic systems. The theoretical framework of the experiment is based on the idea that electromagnetic radiation exists beyond visible light and that different wavelengths carry different energies. Herschel separated sunlight through a prism and placed thermometers in different parts of the spectrum. He noticed that the highest observed temperature rise occurred in an invisible region, just beyond the red end of the spectrum. This showed that, beyond visible light, there were electromagnetic waves carrying energy that the human eye could not detect.

Herschel's experiment laid the foundations for the modern theory of infrared radiation. Based on electromagnetic wave theory, light waves are divided into different regions according to their frequency or wavelength [4]. Infrared light is also categorized as a form of energy with longer wavelengths beyond the red end of the visible spectrum. Herschel's discovery paved the way for the development of many modern technologies such as heat transfer, astronomy, optical sensors and thermal imaging, and introduced the idea that light is not limited to the visible spectrum [5].

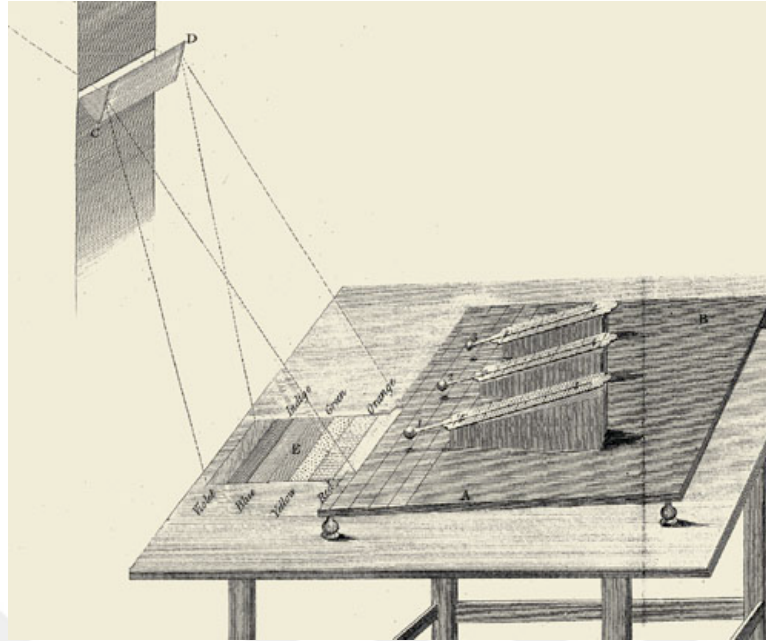


Figure 2.1: Herschel IR activity [3].

Herschel conducted measurements as shown **Figure 2.1**, without the notion of wavelength, delineating five parallel lines and orienting the board such that the red edge aligned with the initial line. His temperature data peaked and diminished approximately half an inch around the red line. The experiment demonstrated that radiant heat possesses identical optical characteristics to light [6]. These studies were the first reference works in the field of electro optics, followed by Willoughby Smith's discovery of photoconductivity in the 1870s, which contributed to the development of the use of optical detectors[7].

Willoughby Smith's experiment aimed to test the phenomenon of photoconductivity in submarine cables. Photoconductivity is defined as the increase in electrical conductivity of a material when exposed to light and is related to electron band theory [7]. This theory evolved a critical role in the development of photodetectors, optosensors and semiconductor technologies and laid the foundation for modern light sensing process.

2.1.1. Applications of Electro-Optical Systems in Defense Industry

The application of electro-optical investigations for military reasons escalated during World War I especially optical sights and periscopes were initially utilized [8]. In

addition, during World War II, activities in the fields of radar thermal imaging technologies accelerated and infrared night vision systems were used by the German and American armies [9].



Figure 2.2: Infrared applications in Italy [9].

During World War II, the most advanced and sensitive infrared idea was developed by the Italian Defense Forces. The system created as a result of the studies is shown in **Figure 2.2**.

In the 1950s, electro-optical systems began to be used in air defense and guided missile systems. In the 1960s, electro-optical systems made a breakthrough with the development of laser technology. The foundations of LIDAR and fiber optic systems were laid.

Following these developments, the studies gained a little more speed and accelerated. In the 1970s, one of the most important studies in this field was carried out by NASA. Charge Coupled Device (CCD) and infrared sensors began to be used in space exploration [10].

With these developments, studies on technological developments such as laser rangefinders, electro-optical targeting systems, laser range finders, thermal imaging devices have gained momentum. In the 2000s, interest in artificial intelligence-supported scanning and imaging activities gained momentum and studies were carried out in this field. Electro-optical systems have started to be used in autonomous vehicles and smart ammunition systems.

In the future, the use of electro-optical technologies in the field of quantum optics and high-resolution LIDAR systems will again come to the fore. Along with advanced communication technologies, smart cities and augmented reality applications are also one of the fields of electro-optical systems. Electro-optical systems have developed considerably throughout history and continue to do so. It has provided revolutionary

innovations in many disciplines and sectors. It is expected to continue this development in the future.

2.2. Electro-Optical System Overview

Electro-optical systems consist of various basic components. In this section, the basic components will be discussed respectively.

Light Sources: Light sources appear as the active component of electro-optical systems. It enables the generation of electromagnetic radiation at the targeted wavelength and material type.

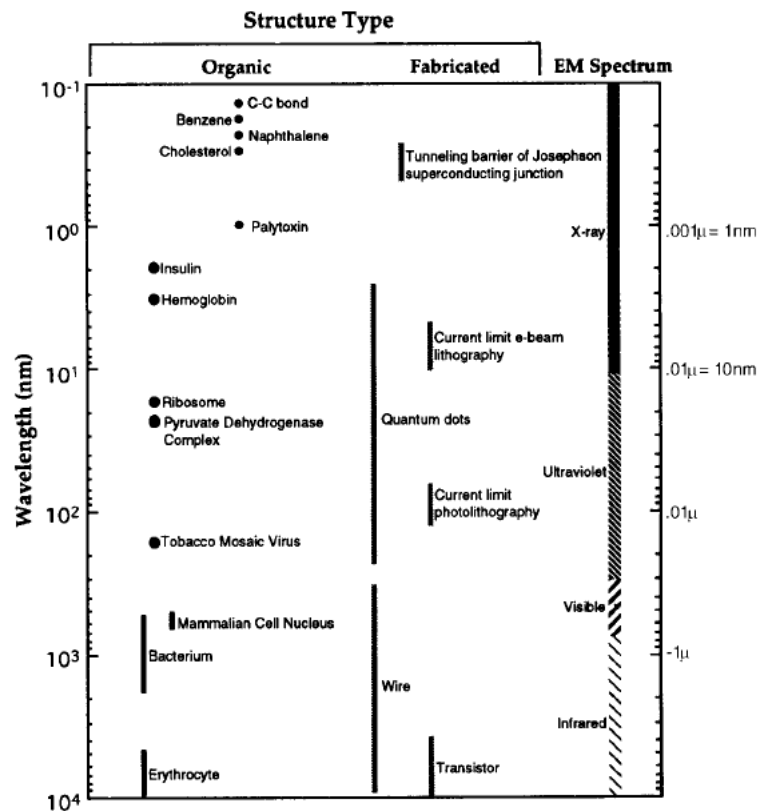


Figure 2.3: Structure type vs. wavelength comparison [11].

Figure 2.3 illustrates the correlation between structural type and analyzing wavelength. All light sources typically utilized in electro-optical systems are depicted.

Lasers are among the most utilized light sources in electro-optical systems. Lasers offer the benefits of monochromatic light production, excellent directivity, and coherence. Lasers are extensively utilized in distance measurement instruments,

LIDAR systems, and various military applications. The long-range light emission capacity of lasers offers a very advantageous performance compared to other methods[11]. In addition, since the accuracy factor is a very important criterion in measurements, lasers are preferred in most applications requiring high precision. Lasers are widely used in precision optics systems.

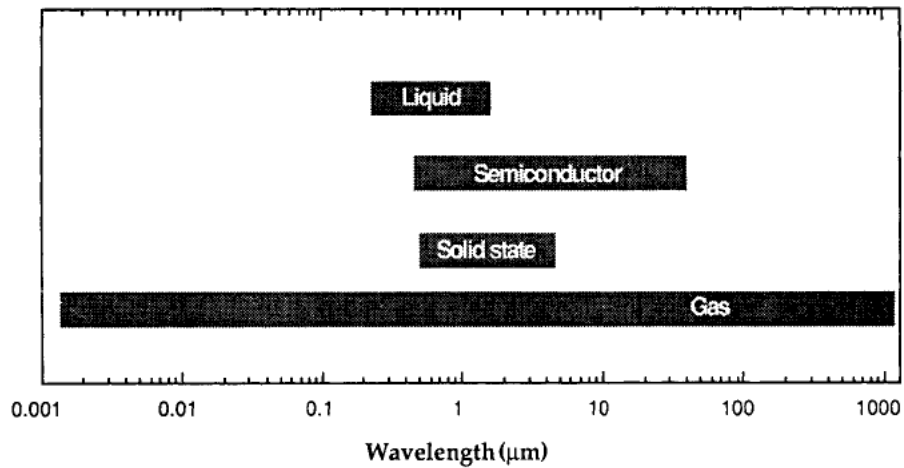


Figure 2.4: Lasers working wavelengths [11].

The wavelengths and spectral regions at which laser types operate are shown in **Figure 2.4**. Analyzing the wavelength ranges correctly and selecting the laser source according to the system requirements is an important factor in terms of system efficiency.

Optoelectronic Detectors: In electro-optical systems, optoelectronic detectors are needed to convert the light energy received from the light source into an electrical signal and analyze it. The working principle of optoelectronic sensors is based on the interaction of photons with a semiconductor or photoconductive material to form electron-hole pairs, resulting in an electric current [12].

They are generally classified according to their application areas, detection spectra, operating speeds and sensitivity. They are divided into photodiodes, photoconductive detectors, thermal detectors and photomultiplier tubes.

The most widely used are photodiodes. Photodiodes aim to convert incoming light directly into an electrical signal. In the working principle, they are made photosensitive by p-n connection and reverse polarization. Incoming photons excite the electrons in

the semiconductor material and create free electron-hole pairs. In this way, current is generated by providing movement with the effect of electric field.

Photodiodes are used in 2 basic types as Pin and APD. Pin photodiodes allow more photons to be absorbed and high quantum efficiency. It achieves this due to its high resistance structure. In APD photodiodes, although the structure is like pin photodiodes, the electrons obtained by working under high voltage are accelerated and then secondary electron avalanches are produced. In this way, sensitivity is increased to higher levels and high signal output is achieved even if the light level is not at the desired level [13].

Electronic Circuits and Control Units: The data received from light sources and converted into electronic signals in optoelectronic detectors are processed and optimized in electronic circuits and control units. These units may include sub-units such as various signal amplifiers, control circuits, analogue-digital converters, image processing units. It is customizable according to the requirements of the designed system and does not have a specific form. It is responsible for system optimization and communication between all units. These units complete the main processing load.

Power Sources and Cooling Systems: It covers all internal and external energy sources for stable and safe operation of the system. Cooling is a critical factor in high voltage and high current laser systems and thermoelectric coolers (TEC) are widely used. The selection and integration of each unit and component is critical for optimal system stabilization and performance.

2.2.1. Lasers in Electro-Optical Systems

A laser is a device that amplifies light and produces a highly directional, high-intensity beam that often has a very pure frequency or wavelength [14]. The basic principles of laser technology are based on the generation of light as a directed, high-intensity beam. To better understand this principle, it is useful to consider the natural propagation of light. For example, the light from a lit candle is scattered in all directions and illuminates objects at a given distance evenly. In contrast, laser systems use a special mechanism that prevents this random distribution of light and concentrates all the energy in a specific direction.

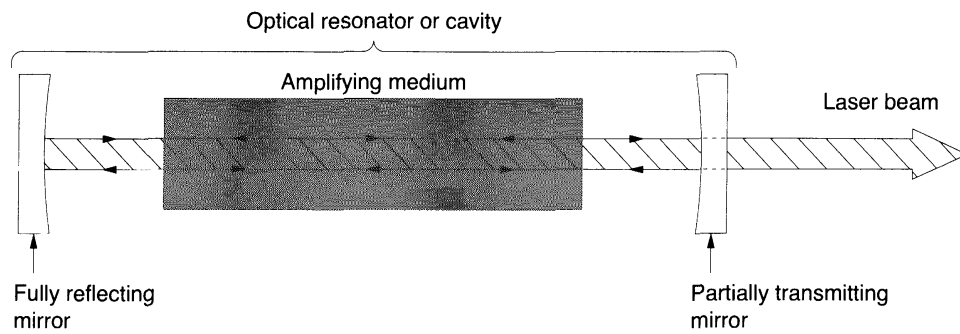


Figure 2.5: Laser schematic [14].

Figure 2.5 shows a schematic representation of a basic laser. The laser system starts with an optical resonator located between 2 mirrors. One of these mirrors is fully reflective and the other is partially reflective. Inside the resonator, as shown in the figure, the amplifying medium is excited by the energy coming from the outside and allows the photons to be reproduced by emission. The fully reflective mirror reflects the light continuously and becomes coherent as the intensity increases as it passes through the amplifying medium. At the last stage, the high intensity directed light beam coming out of the partially transparent part is obtained as a laser beam. Thus, the laser is obtained as a phase-coherent, high-energy light source. To illustrate this with an example; if all the light emitted from a candle were focused on an area of about 3 mm in diameter of the human pupil and you were 1 meter away from this light source, the perceived light intensity would be 1,000,000 times brighter than the candlelight you normally see. This is precisely the principle that lasers use to produce light as a high-intensity, unidirectional beam. However, an ordinary light source such as a candle does not have the stimulated emission mechanism required for laser production. Therefore, natural light sources cannot directly generate lasers [15].

Lasers are one of the most critical components of electro-optical systems, greatly improving the performance of optoelectronic systems by providing high precision and energy efficiency in areas such as communications, medical imaging, military targeting, industrial automation and scientific research. In particular, the development of laser diodes, solid-state lasers and fiber lasers has enabled electro-optical systems to become more compact, reliable and efficient [16].

Lasers require certain physical and optical conditions to operate. In these systems, special mechanisms such as optical pumping, stimulated propagation and optical resonators are used to propagate light in a single direction. Light waves, which are normally scattered in random directions, are concentrated in the same phase, at a specific wavelength and at an acute angle in the laser environment. In this way, laser systems can produce much brighter, coherent and directed light compared to conventional light sources.

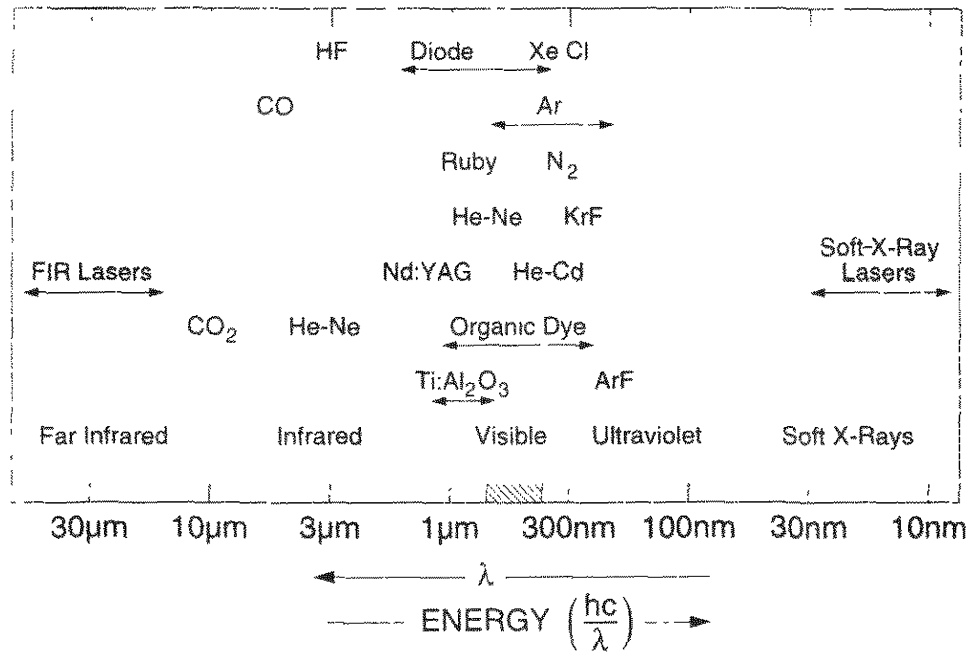


Figure 2.6: Laser electromagnetic radiation spectrums [11].

The light beam produced by lasers has many unique characteristics. Compared to conventional light sources, there are sharp differences in certain parameters. Factors such as high directivity, spectral distribution width, scattering intensity are among the important evaluation criteria. Laser beams generally have a narrower frequency range, a shorter pulse duration, a higher light intensity and a greater degree of collimation. For this reason, they are more preferred in special applications beyond general use.

Figure 2.6 shows the spectrum of electromagnetic radiation covered by existing lasers. To define laser wavelengths;

- 1 Angstrom = 10^{-10} m

- $1 \text{ nm} = 10^{-9} \text{ m}$
- $1 \text{ } \mu\text{m} = 10^{-6} \text{ m}$

It is stated as. While nanometer and angstrom units are used towards the Soft-X-Ray region; as we move towards the Infrared region, laser wavelength is defined using the μm unit.

Laser radar systems come from LADAR (Laser Detection and Ranging). It refers to the technique of monitoring radio-based electromagnetic waves reflected to detect objects on the target. The main differentiations here are;

- The type of measurement performed,
- Detector type,
- Target size,
- To the wavelength being studied,
- Type of laser,
- To the modulation method,
- The type of interferometer used,
- Detection technique,
- The type of data collected,

It can be categorized accordingly. These basic classifications are one of the main reasons for the function and versatility of the system. Considering the technological limitations and system requirements, laser radar systems with different performance levels and operating conditions can be developed. However, since each system is customized in its own way, the system requirements should be considered accordingly when comparing performance. One of the most important factors affecting the performance of laser radar systems is the characteristics of the source used. In this section, the types of sources that can be used in laser radar systems will be discussed.

Pulse Lasers:

Pulse Lasers are light pulses in which the laser beam is pulsed for a certain wave duration rather than continuously. They are especially preferred in systems developed for use in activities such as LIDAR activities, distance measurements, high precision scanning operations [11].

The working principle follows the same structure as the basic laser systems. Firstly, energy is stored from the power supply, then electrons are raised to high energy levels with the help of a resonator. After the process of increasing and accumulating the energy to the desired level is completed, this energy is released in a very short time and short-term light pulses with maximum high intensity are obtained. Pulse durations generally vary between 10^{-9} s and 10^{-15} s [11].

The most widely used pulse generation technique is Q-Switching. It is aimed to discharge the energy accumulated in the laser environment in a very short time. The loss factor of the laser cavity is kept quite high at the beginning, and after the sufficient energy level is reached, the Q-switching process is completed by switching to the low-loss mode suddenly.

Gain-Switching technique is a technique in which the pumping energy is changed in the laser environment. Pulse generation is performed by adjusting the desired energy level to be used. Its cost and sensitivity are lower than other systems.

Mode-Locking technique is another method that can be used. It works with a similar architecture to the Q-Switching technique, but short duration (femtosecond) pulses are generated at a much higher frequency.

Pulse lasers have a wide range of applications in electro-optical systems.

- Military and Industrial Applications: Map-based military marking systems, autonomous vehicle sensor systems, high frequency and resolution distance measurement applications can be developed.
- Material and Industrial Applications: Applications that require high energy transfer such as surface treatment, cutting and welding can be performed with minimum loss.
- Scientific and Medical Studies: It can be used in laser, spectroscopy and dermatology activities in the field of human health.

Relatively high peak power, precisely controllable pulse timing and wide range of applications, especially those mentioned above, are among the advantages of pulse lasers.

Fiber Lasers:

Fiber laser systems consist of active fiber, pumping source, fiber bragg gratings (FBG) and cooling system [14]. Doped optical fibers are used as the active medium. These are usually composed of rare earth elements. This enables the laser beam to be formed and guided. One of the biggest advantages of fiber lasers is that the light is regularly controlled along the fiber to minimize losses, thus maximizing efficiency. Other advantages are respectively:

- Optimum Beam Quality,
- Low Periodic Maintenance Requirement,
- Modular Design,
- Low Heat Losses.

In addition, fiber laser systems have some limitations. The optical fiber ends used have a certain level of resistance to optical density, so they can store a relatively certain level of energy and the damage limit is limited. In addition, the small core diameter of the fiber limits the power that can be obtained at the output. System designs should be made by considering these limitations.

Continuous Wave Lasers:

Continuous Wave (CW) lasers are systems that generate and emit the laser beam continuously and steadily. This is the most obvious difference compared to other systems. In this way, it can provide high stability in application areas that require continuous energy. [17]

CW lasers rely on continuous pumping to maintain the energy level at the same level as the laser medium. Stimulated emission is a regular process. The regular circulation of photons in the optical resonator ensures a constant amplitude beam output. The energy input and losses in the system are to be balanced and the system is to be stabilized. CW lasers are characterized by their low power consumption and long lifetime. The operation of semiconductor lasers in CW mode provides a great advantage here. CW lasers;

- Pumping Source,
- Laser Environment,
- Optical Resonator,
- Heat Management System,

consists of its basic components. The most prominent features can be expressed as efficiency, beam quality, minimum modulation requirement, and constant output power, respectively. CW lasers are widely used in next generation electro-optical systems due to their stable and regular beam power [18]. They also have wide applications in measurement, fiber optic communication and medical applications.

Laser Diodes:

The laser diode is a semiconductor optical amplifier, Semiconductor lasers are commonly referred to as laser diodes. As the name implies, semiconductor material is used in laser light production to create compact, efficient, low-cost laser systems. In addition, low power consumption and easy adaptability are among its other prominent features [19].

The basic operating principle is based on a p-n junction semiconductor diode structure. When a forward voltage is applied in the active region of the diode, the junction is realized. This results in photon emission due to the difference in energy levels. The stimulated emission process is then triggered and the laser beam is generated.

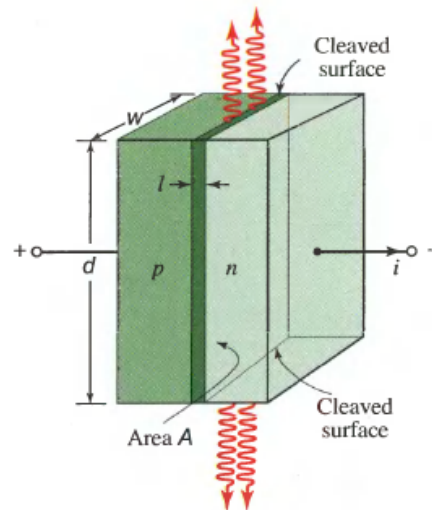


Figure 2.7: Laser diode schematic [14].

Figure 2.7 shows a schematic illustration of the basic working structure and principle of the laser diode. A forward polarized p-n diode is in the center. The active region is located at the junction line and is seen as two parallel cleaved surfaces. The laser beam is formed in this region. Photons in the optical resonator support photon generation by

providing a gain. The excited photons combine with the mechanism to form a coherent laser beam and are transmitted to the outside. Since the early days with the increasing use of laser technology, military studies on laser systems have been categorized under four main areas. These are;

- Laser Range Finders (LRF) and Laser Target Designators (LTD)
- Laser Radars
- Laser Communication Systems (LCOM)
- Direct Energy Weapons

Classified as. In this thesis, an innovative analog electronic filter system has been developed by working specifically with Laser Range Finders. Range finding is one of the first studies in laser technology in the military field. In 1960, with the invention of the laser by Theodore Maiman, laser range finder system models for military purposes began to be developed in 1965 [20]. In 1961, Maiman and his working group developed the “Coherent Light Detection and Ranging” (Colidar) System This system uses the distance calculation method based on the return time of the laser-focused signal, which is still widely used today [21]. The first commercial laser range finder was brought into military use in 1965 as the Barr Stroud LF1 model in cooperation with Hughes Aircraft. In line with the subsequent developments and needs, the LF2 model was developed in 1969 and integrated into the sight of the Chieftain tank and started to be used [22]. During this period, the XM23 LRF model which is shown in the **Figure 2.8** was developed at the Pitman-Dunn Laboratory. What makes this model different from the others is the use of ruby laser and being the first artillery laser.

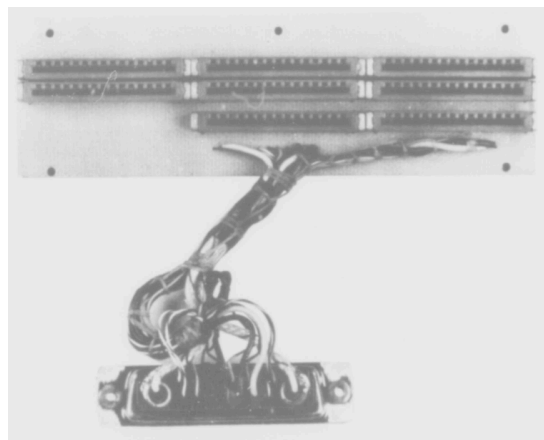


Figure 2.8: XM23 LRF model with cabling [23].

All these studies carried out in the past have been a reference for the systems currently used. Laser range finders make it possible to find the distance with high accuracy thanks to their high brightness and narrow beam width. Today, data and markings obtained by LRFs are used in Fire Control Systems in all armed and unarmed unmanned aerial vehicles. Studies on LRF have continued in the fields of both system development and integration of the developed system into military platforms.

In the 1990s, the Italian Air Force Flight Test Centre continued its activities related to the integration of laser systems into TORNADO- IDS aircraft. In this study, they focused on the Convertible Laser Designation Pod (CLDP). The CLDP unit is positioned on the left shoulder pylon in the mechanical scheme of the aircraft and has become a mandatory unit that cannot be removed from the aircraft [19]. Then, they continued their work on more modular aircraft and the positioning of smart ammunition. **Figure 2.9** shows the Tornado Paveway II flight moment. It is the first smart ammunition system with LRF.



Figure 2.9: Tornado paveway II [19].

2.3. Laser Range Finder System Architecture

LRFs that can work at long range without eye damage operate in the SWIR light spectrum, typically with a wavelength of 1500-1575nm [24]. The sun emits a wide spectrum of light, including SWIR, so the receiver also reads millions of photons directly or indirectly from the sun during the day. This reading may result in an

inaccurate reading of the target distance. If the sun's reflection is stronger than the LRF beam, it will provide an inaccurate or no reading at all because the intense light overwhelms and confuses the LRF's signal. This component is extremely sensitive and the signal sensitivity increases considerably with a longer range. This means that sunny days can result in reduced performance, reduced accuracy and false or no readings. This effect is particularly common in urban environments with many reflective surfaces. Cloud cover can help performance, such as ranging from one shadow to one shadow, but only marginally. The longest-range distance can be achieved in cloudy weather, at dusk or at night. These conditions ensure that the LRF cannot reach its full-rated performance for targets such as vehicles. Another factor to consider when ranging near the water table is that bodies of water can reflect, absorb and scatter both the sun and the LRF's laser. Relative humidity levels above 55 percent can greatly affect performance at long ranges, because ranging in a high-humidity atmosphere reacts much like trying to range in water [19].

Another critical issue is that laser light scattered by air molecules and suspended aerosol particles are detected by the receivers so that backscattering coefficient profiles can be determined. These aerosols are indicators of atmospheric pollution. In summary, there are many obstacles that the LRF beam encounters and if these obstacles are serious enough, these can either render the LRF completely useless or significantly reduce its range and accuracy. Additionally, for the experimental activities of aircraft equipped with LRF modules, it is important to optimize the test missions by considering the tactics of using the systems in different operational scenarios and verifying the performance of the systems in realistic environments at ranges.

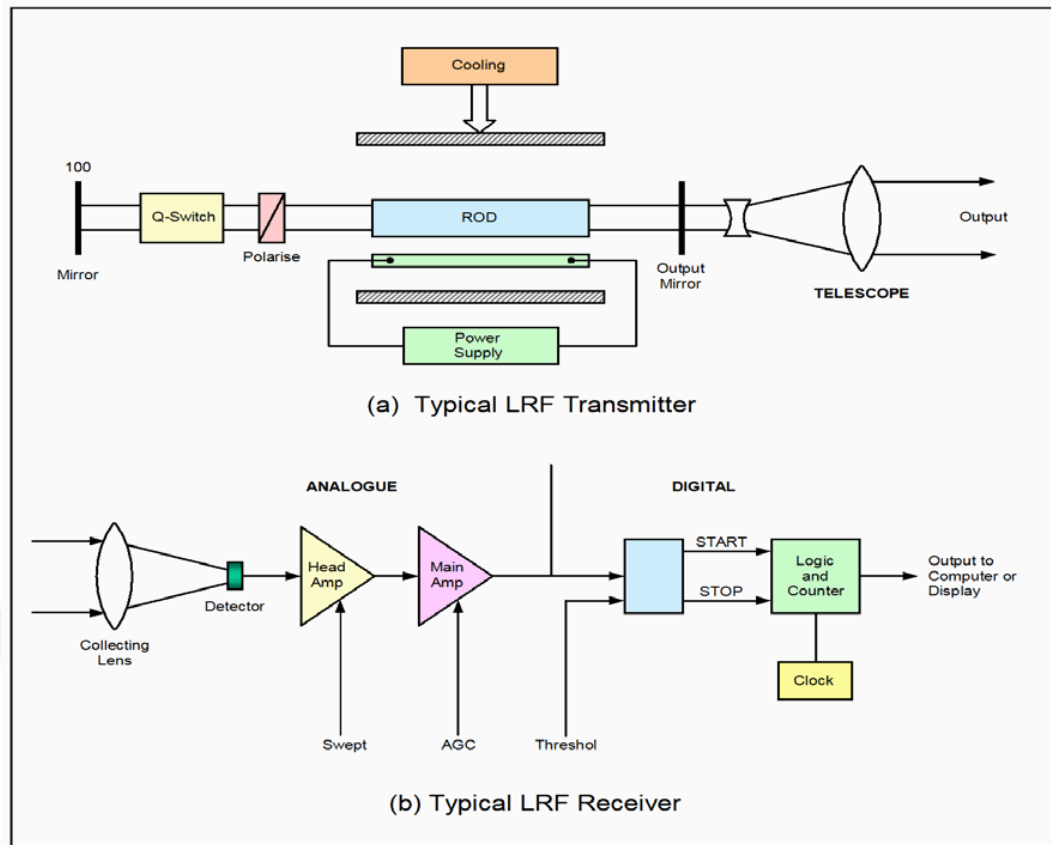


Figure 2.10: LRF transmitter and receiver scheme [19].

Figure 2.10 shows the LRF transceiver system architecture from the past. The transmitter structure shown in part A in **Figure 2.10** represents the scheme of generation and transmission of the laser pulse to the target. In this diagram, the Q switch allows the laser pulse to be controlled at the desired time and the laser ROD represents the part where the laser beam is actively generated. The schematic is completed by adding the required power supply, mirror system and polarizer. In part B, the circuit diagram required for distance calculation based on the back reflection of the laser pulse is given. In this scheme, the laser beam obtained on a collector lens is focused and transferred to the detector. After being transferred to the detector, transmission to the analog circuits is provided. Head amplifier and main amplifier circuits and analog filter circuits can be added in this section. After the filtering and amplification process is completed, the signal is digitized according to the specified algorithm and transferred to the main command computer and the distance measurement is completed in this way.

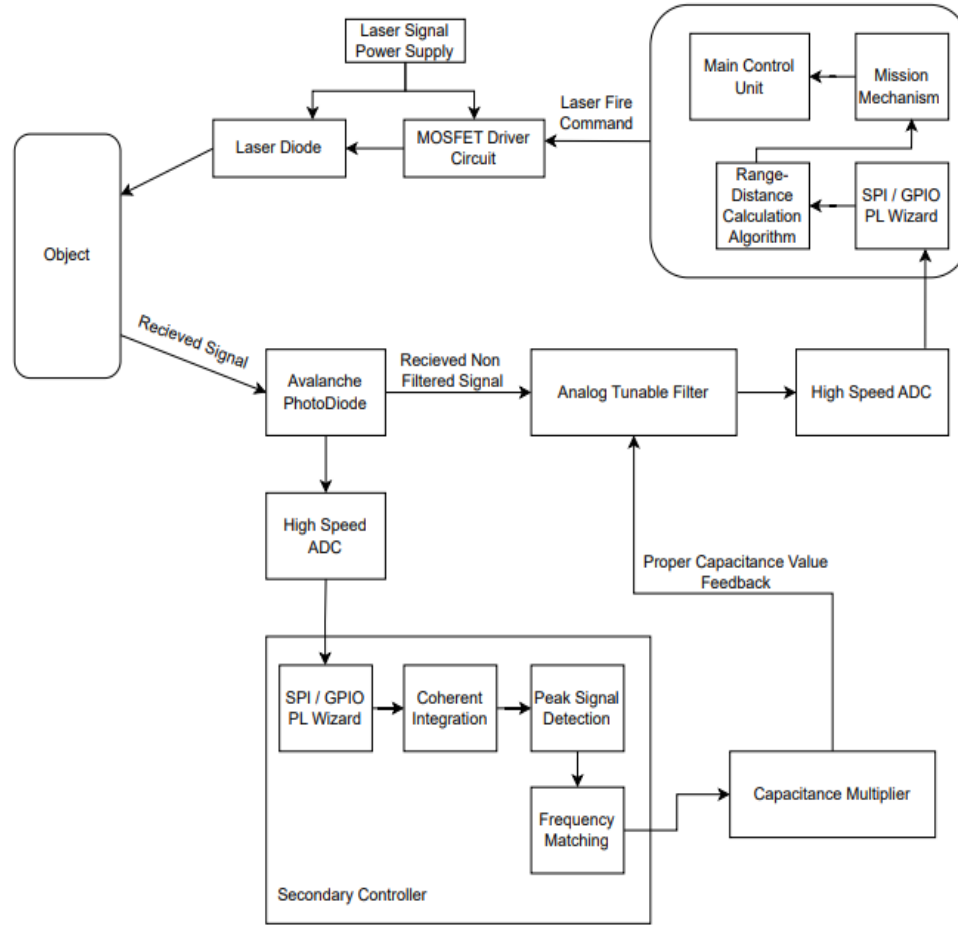


Figure 2.11: LRF model diagram.

The LRF system is controlled by the main control computer. The laser firing command is given in line with the commands from the unmanned aerial vehicle and the decisions taken by the mission mechanism. Subsequently, the power supplies are activated, the MOSFET driver and the laser diode are transmitted, and the laser is fired toward the object. The signal reflected from the object is obtained on the APD. Due to atmospheric conditions and laser scattering, the obtained signal is noisy compared to expected. Therefore, the signal needs to be filtered from noise. The analog signal is digitalized using a high-speed ADC module. Then, the frequency range with the highest amplitude is determined by the algorithms listed by the secondary control processor. This frequency range is equated to being directly proportional to the voltage. The capacitance multiplier circuit is expected to move depending on the voltage. Capacitance multiplication is provided according to the frequency data

obtained from the noisy signal. The capacitance values in the tunable bandpass filter are adjusted. Then the noise in the circuit is reduced by the bandpass filter. The filtered signal is transmitted to the main control computer using a high-speed ADC module. The distance of the target object is determined by processing this data in the main control computer. This task is completed by transferring this detected distance to the necessary main mechanisms. **Figure 2.11** shows the block diagram of the system in its entirety.

In the LRF System, the accuracy and processability of the received signals returning from the object are very important for accurate distance measurement. At this point, the noise factor is critical. To develop noise analyses and related solutions, it is first necessary to obtain the received signal. In this context, the studies in the literature have been analyzed in detail.

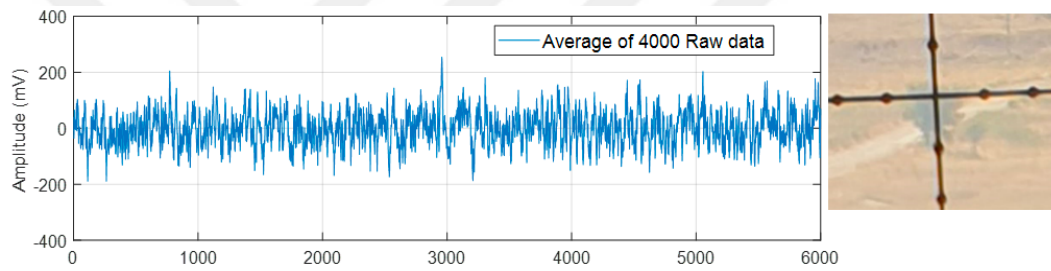


Figure 2.12: LRF target measurement data [25].

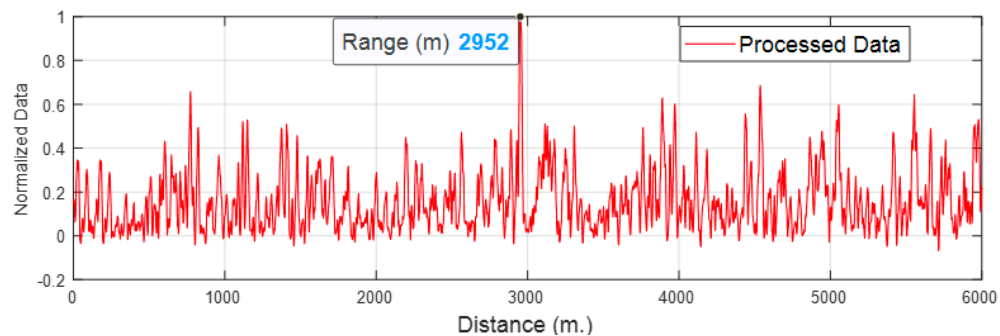


Figure 2.13: LRF target processed data [25].

Figure 2.12 shows the noisy LRF measurement data reflected from the target. It is very difficult to distinguish between noise and target. **Figure 2.13** shows the filtered

and processed version of the noisy LRF measurement data reflected from the same target. The difference between the two signals is clearly visible.

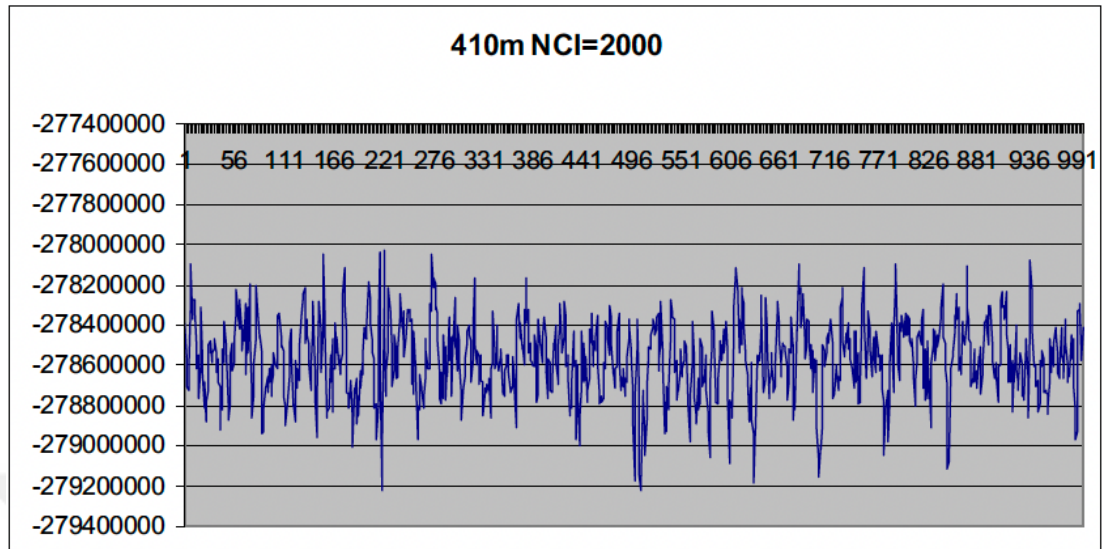


Figure 2.14: LRF target received signal [26].

Figure 2.14 shows a signal reflected from the target. In this data, the signal and noise are completely mixed and it has become more difficult to determine the peak value, in other words the correct distance.

Three types of signals can be distinguished from the received signals: composite signals, noise signals, and attenuated signals. To guarantee measurement accuracy, each type poses different difficulties and calls for specialized processing techniques.

In an effort to recover useful information from weak signals which are often reduced by surface dispersion or ambient influences amplification and filtering are required. Sophisticated filtering and noise reduction techniques, such as matched filtering and coherent integration, reduce noise signals caused by electronic interference or ambient light. Moreover, composite signals a combination of noise and attenuated signals can occasionally be present in real-world occurrences. Another point for target signal, to distinguish between genuine reflections and noise while preserving important information, the combined signals require robust filtering methods. Also, to achieve high-precision measurements in LRF systems, it is essential to comprehend and analyze these signal forms, including composite signals.

Numerous techniques have been employed in electro-optical laser systems to minimize noise and measurement errors. In the study described [27], a band-pass filter was used to suppress 9th order harmonic distortion, and a low-pass filter was used to effectively reduce ambient noise in the signal derived from the photodetection module. The time-of-flight (TOF) method was then used to determine the absolute distance. A laser with a repetition rate of 1 kHz and a pulse width of 100 ns was employed in a different study conducted in accordance with military standards [25]. FPGA-based noise extraction methods were used to process the laser's output signals. Several techniques for signal extraction and noise reduction have been reported in the literature. One of the most popular methods for noise reduction is the signal accumulation technique [28], which assumes that there is zero mean random noise. The Wiener-Hopf filter, a well-known statistical adaptive filtering technique, and coherent averaging stand out for their ability to effectively reduce noise [29]. Although laser rangefinder sensors are frequently employed in defense applications, most research in the literature focuses on digital signal processing, with little attention paid to enhancing accuracy through the analysis of analog signals. In [30], an OTA-C-based low-pass filter for ECG sensor data was introduced, and in [31], a CMOS-based filter for biomedical applications was detailed. In order to reduce subthreshold noise and enhance the incoming signal's readability, both studies employed filtering strategies with a narrow cut-off frequency range. Environmental factors such as, electronic interference, ambient light or noise from devices are the sources of noise signals. These signals are unpredictable, often interfering with the main signals and reducing the accuracy of the measurements. The system uses noise reduction strategies like filtering and thresholding to lessen this effect. The waveform's irregular oscillation highlights how crucial improved signal filtering is for separating real signals from noise.

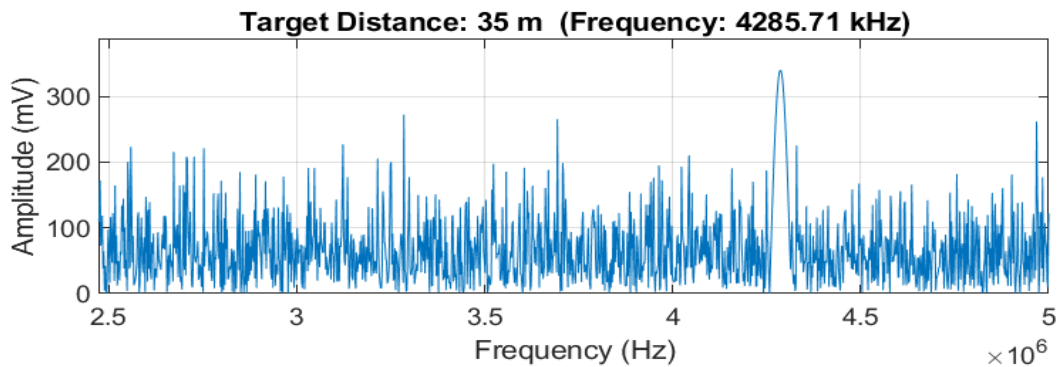


Figure 2.15: Received target signal 1.

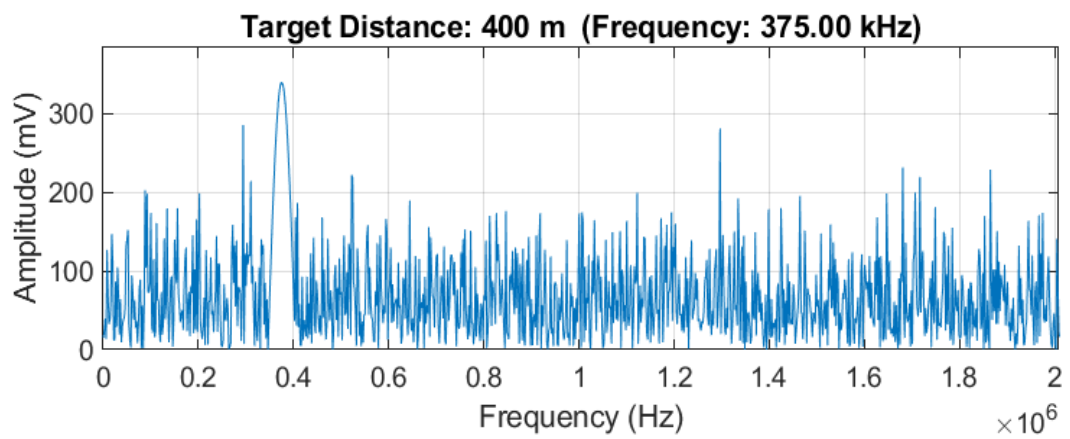


Figure 2.16: Received target signal 2.

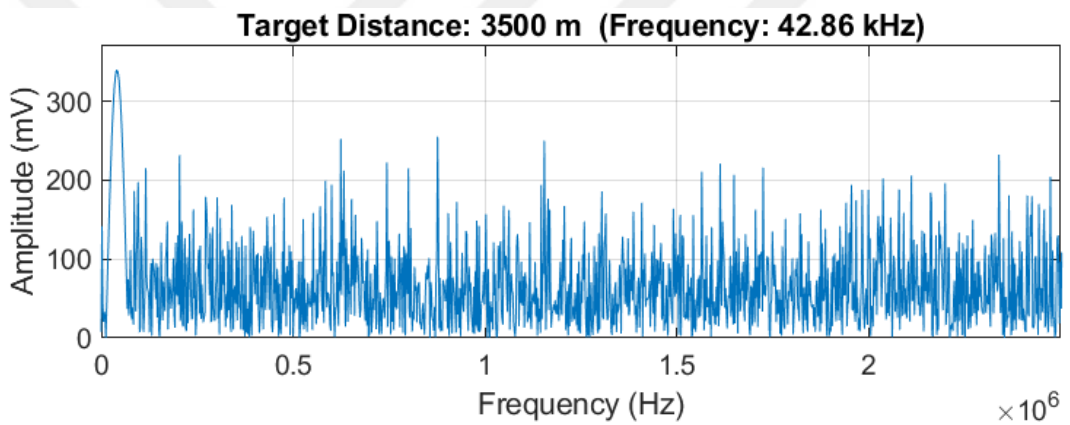


Figure 2.17: Received target signal 3.

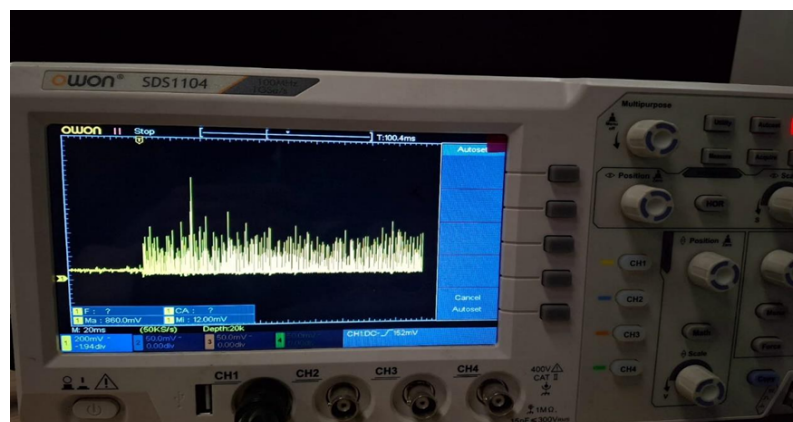


Figure 2.18: Received target analog signal.

Data signal which is necessary to use in this thesis was artificially generated in a certain pattern using studies in the literature [25][26][32][33]. It covers all distances within the operating range of the filter and allows the state analyses to be performed by modulating the noise factor. With the aim of model different environmental and atmospheric conditions, it was aimed to increase the testability of the system to a higher level by producing artificial signals.

The data from the literature was thoroughly analyzed and MATLAB Simulink was used to visualize the data. The analog signal was created using the Data Acquisition Toolbox for Analog Device 2.

Figure 2.15, Figure 2.16 and Figure 2.17 show the signals reflected from targets located at different distances. The distances of the targets are 35 meters, 400 meters and 3500 meters respectively. In addition, **Figure 2.18** shows the oscilloscope output of the analog signal generated using the generated data set.

3. ANALOG FILTER APPROACH

Analog electronic filters are primarily used to confine an electrical signal to a specific frequency band or attenuate unwanted noise and interference while selectively transmitting specific frequency components of the signal. These filters are crucial for maintaining signal integrity, especially in optoelectronic, control, and communication applications. In signal processing circuits, analog filters can be built as passive (RC, RL) or active (based on operational amplifiers) configurations. They are mainly divided into low-pass, high-pass, band-pass, and band-stop types.

Analog filters used in signal processing in LRF and LIDAR systems reduce high-frequency electrical interference from the environment, making it easier to distinguish the real signal. As a result, measurement systems achieve improved stability and precision. In this sense, analog filtering is a crucial step in the signal processing process for high-precision electro-optical systems.

3.1. Analog Filter Types

The clearest feature used in the classification of analog filters is the effect of the filter on the frequency spectrum. Accordingly, filter types are;

- Low pass
- High pass
- Band pass
- Band stop

3.1.1. Low Pass Filter

Filtering is a fundamental method used in electronic engineering and signal processing to reduce undesired frequencies and allow the transmission of the intended frequency components of a given signal. Low-pass filters (LPF) in this context are either analog or digital circuit components allowing frequencies below a given cut-off frequency to pass while attenuating frequencies across that threshold. Among the several uses for low-pass filters are power electronics, audio engineering, electro-optical sensing systems, and communication systems. A low-pass filter (LPF) attenuates components

over a given frequency threshold (cut-off frequency), so allowing the transmission of signal components within that threshold. Maintaining the integrity of the lower frequency components of the signal, the main goal is to separate noise, extraneous signals, or high-frequency interference. Both in the temporal and frequency domains, low-pass filters are used to smooth or filter signals. They are thus very much used, especially in analog and electro-optical systems.

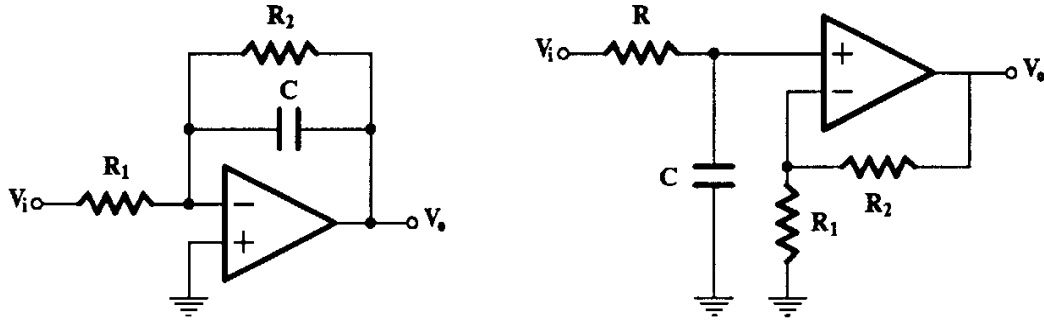


Figure 3.1: RC based 1st order LPF circuits [34].

Figure 3.1 shows two different LPF circuits. The circuit on the left is a commonly used classical approach. In this circuit, the input signal passes through a resistor and is applied to the inverting input of the Op-Amp. The resistor in the feedback path allows both gain adjustment and low pass filtering to be achieved through the capacitance present. The circuit on the right shows a different circuit that performs the same function.

Usually, the LPF is presented using simple RC (resistor-capacitor) circuits both physically and mathematically. An RC low-pass filter circuit has a ground-based capacitor in parallel and a resistor in series. The capacitor diverts high-frequency components to ground as the input signal passes the resistor, so enabling just low frequencies to reach the output. There are usually three methods that can be used for low pass filtering; [35]

- The Chebyshev low-pass filter (LPF) allows ripples to exist in the passband by providing a more gradual transition in the output characteristic.
- The Butterworth low-pass filter achieves the maximum flatness in the passband with minimal ripple.

- The elliptic LPF provides the most abrupt transition and causes a significant amount of ripple in both the passband and the stopband.

$$H(s) = \frac{1}{sRC + 1} \quad (3.1)$$

$$f_c = \frac{1}{2\pi RC} \quad (3.2)$$

The transfer function of the first-order RC LPF is given in Equation 3.1. In addition, the cutoff frequency formula of the filter is given in Equation 3.2 is provided.

$$|H(j\omega)| = \frac{1}{\sqrt{1 + \left(\frac{\omega}{\omega_c}\right)^{2n}}} \quad (3.3)$$

In Equation 3.3, the amplitude response equation for an LPF of n th order using the Butterworth approach is given. ω_c is the cutoff angular frequency of the filter. When designing a filter, certain criteria must be considered based on the signal to be filtered. First, it must be decided whether the filter will be active or passive. Then, the filter approach should be selected by considering the passband slope and phase behavior criteria. Finally, the design should be completed by paying attention to component tolerances. Low pass filters have a wide range of applications. Examples of LPF usage include filtering ripple voltage from power sources, removing high frequencies from audio systems, and filtering high frequencies from components before ADC.

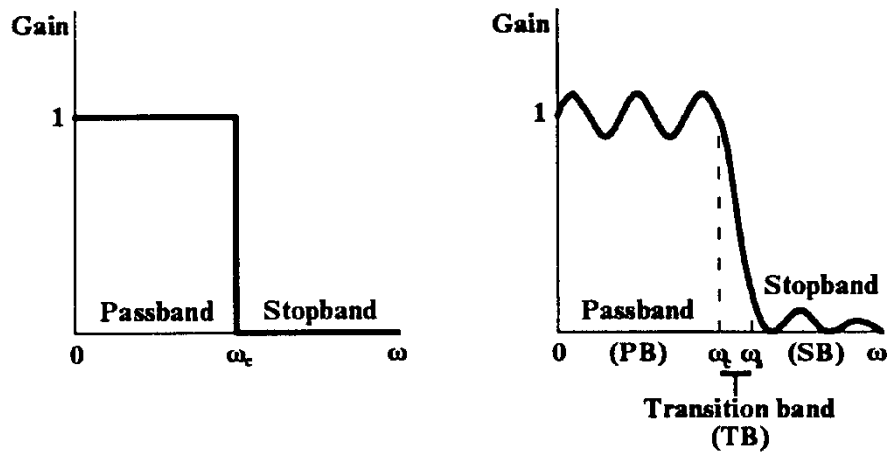


Figure 3.2: Ideal and practical LPF amplitude response [34].

Figure 3.2 shows the ideal and practical LPF amplitude response. In practice, fluctuations occur in the passband and stopband, and there is a transition band between the passband and stopband.

3.1.2. High Pass Filter

High-pass filters are designed to filter out low frequency signals and allow only signals over a particular frequency to pass through. An ideal high-pass filter blocks all frequencies below the cut-off frequency, while allows those above the cut-off frequency to pass through without any loss of output in it. They are used for removing DC components or to filter out low frequency.

$$H(s) = \frac{sRC}{sRC + 1} \quad (3.4)$$

The transfer function of the first-order RC HPF is given in Equation 3.4. Furthermore, the cutoff frequency formula of the filter is the same as that of the LPF and is given in Equation 3.2.

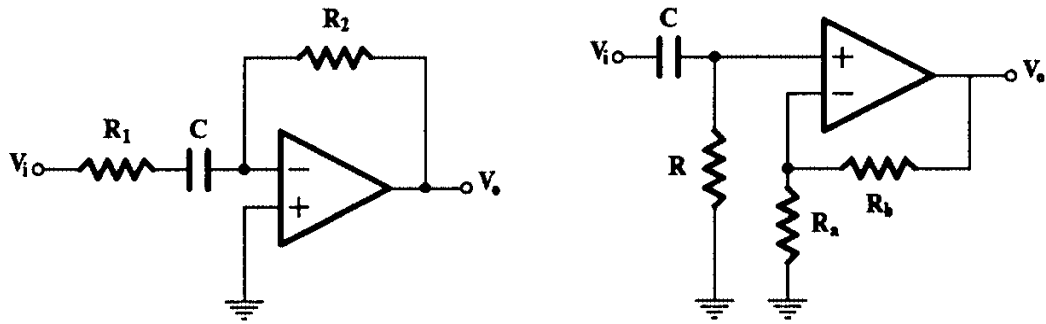


Figure 3.3: RC based 1st order HPF circuits [34].

Two model circuits for RC-based first-order high pass filters are shown in **Figure 3.3**. In both circuits, a capacitance connected in series to the input is used to suppress low frequencies and allow high-frequency signals to pass through. The designed active filter blocks allow signals above the cutoff frequency to pass through while providing the desired signal gain.

While using HPF, the filter approach should be selected by considering the phase criterion and transition characteristics specific to the application area, as in LPF. In addition, the design should be completed by paying attention to the Op-Amp band width and other specific features in the active filter design.

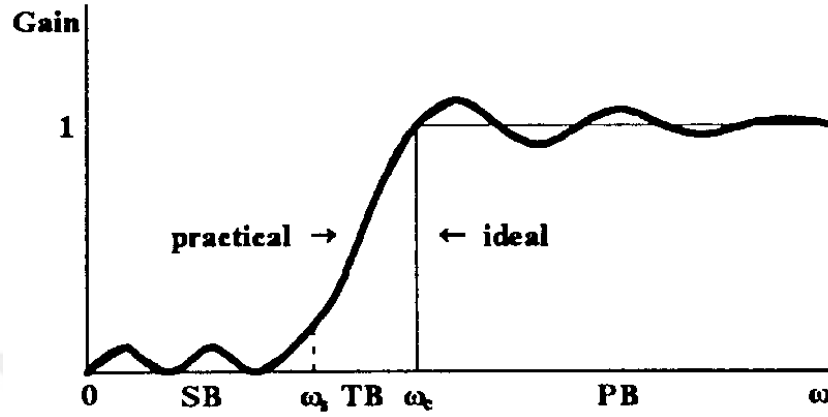


Figure 3.4: Ideal and practical HPF amplitude response [34].

Figure 3.4 shows the amplitude response of the HPF. As in the LPF, the difference between practical and theoretical values can be observed here as well.

3.1.3. Bandpass Filter

Bandpass filters (BPF) are analog circuits that allow signals within a specific frequency range to pass through and block frequencies that are below or above the required band. Bandpass filters are significantly essential for processing of analog and digital signals. Bandpass filters are used for multiple applications such as communication systems, audio processing applications, biomedical device applications, radar technology and much more. The essential function of the bandpass filter is that it is used to choose the desired frequency range and eliminate unwanted signals or noise. There are two main parameters that determine the characteristics of bandpass filters, and they are lower cut-off frequency (f_L) and upper cut-off frequency (f_H). The band between these two frequencies is called the passband of the filter.

$$f_0 = \sqrt{f_L \times f_H} \quad (3.5)$$

$$\text{Bandwidth (BW)} = f_H - f_L \quad (3.6)$$

$$\text{Quality Factor } (Q) = \frac{f_0}{BW} \quad (3.7)$$

The ratio of the lower to upper cutoff frequencies is described by the center frequency in the Equation 3.5. The given value states the frequency at which the filter has its peak response or minimal response. This value serves as a symmetrical reference point on a logarithmic frequency scale.

The difference between the upper and lower cutoff frequencies according to the Equation 3.6 is the bandwidth. The filter determines the frequencies that are blocked and the ones passing through. The bandwidth is less if the filter selects only a narrow-edged frequency range, and it will be more if the wider frequency range is processed.

The filter's selectivity or sharpness of the response with respect to the center frequency is measured using the quality factor (Q)- a unitless quantity listed in the Equation 3.7. In the resonant circuits, a high Q factor means narrow bandwidth and high accurate frequency discrimination. The low Q factor means wider and less focused frequency response. Since they define the fundamental performance aspects in the frequency domain, both analog and digital filters depend on their analysis and design on the parameters above.

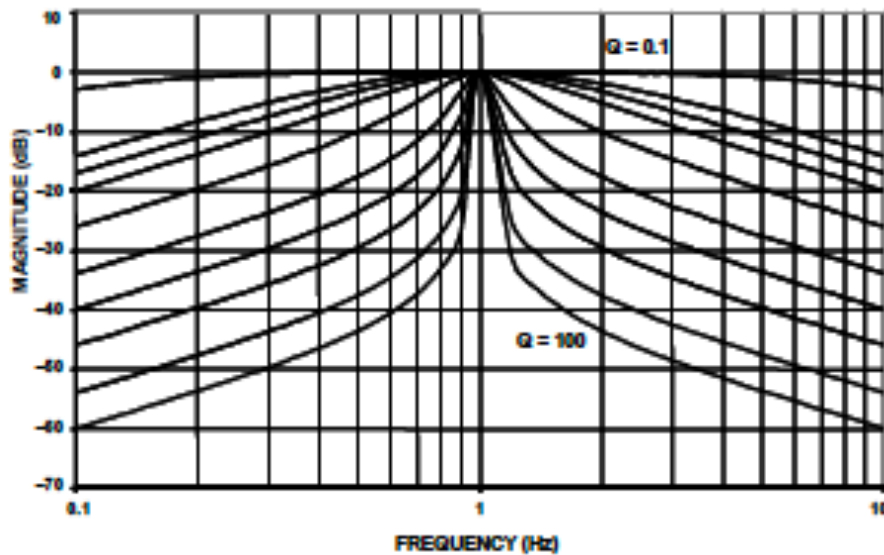


Figure 3.5: BPF frequency response at different Q values [36].

In bandpass filters, the Q factor determines the band width of the filter. It is also the most important criterion in determining filter performance. The Q value should be determined according to the desired design, and the design should be started from there. Equation 3.7. shows the relationship between the Q factor, center frequency, and band width. In addition, **Figure 3.5** shows the filter frequency response at different Q values.

3.1.4. Bandstop Filter

Bandstop filters are a type of filter used to suppress a specific frequency range and block all other frequencies. They are typically used to filter out specific noises and interference.

A band-stop filter, also known as a notch filter, is a circuit that is designed to allow a specific range of frequencies to pass through and block the frequency signal that falls within the set range. While all notch filters are band-stop filters, a notch filter typically refers to a narrow band rejection filter for a very specific frequency. The band-stop filter is also represented as a combination of a low-pass and high-pass filter together if the low-pass filter, comprising of the bandpass range frequency, is below the stopband; and the high-pass circuit component comprising of the high pass range frequencies are above the stopband. The circuits are widely used for processing an analog and digital signal in telecommunication, audio engineering, power electronics, and also in biomedical systems. They are used for numerous applications, such as eliminating a signal source that produces a constant signal like the 60 or 50 Hz power line noise, isolating a specific radio frequency interference component [37].

The notch filter or the band-stop filter's performance mainly depends on the particular set of features including the center frequency, the quality factor or the bandwidth (A high-quality factor would imply that the stopband (the band having a 0 gain) would be narrow and is required for most applications that require a rejection of a particular frequency, as mentioned earlier. Thus, a lower Q would mean a wider rejection band will be produced. These types of filters are realized by either using passive elements including the regular resistors, capacitors, and inductors, or by active elements, by using operational amplifier or other type integrated circuits and transistors. The passive circuits are easier in design but less tunable, while the active filters can be tuned to

give the designed performance. Each of these band-pass implementations can produce an ideal band-pass filter only for one transfer function. Furthermore, this transfer spillover function can then be altered mathematically to give a transfer function that portrays a classic band-stop filter. In conclusion, the main goal for a signal processed in a band-pass filter is to remove all the unwanted frequency content from the signal and allow all the other signals with a different frequency.

$$H(s) = \frac{s^2 + \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \quad (3.8)$$

This is a standard form of band-stop (notch) filter which is a second-order transfer function also given in Equation 3.8.

ω_0 is the value of the frequency in angular terms which is to be suppressed (notch). Q is defined to be the quality factor, i.e., the ratio of the bandwidth with respect to the center frequency. In this equation, there is a capacity for passage at all frequencies. On the other hand, gain is to be reduced around a specific frequency. The formation of the structure is that instead of the numerator in the expression letting all frequency pass in all the terms in the denominator let the gain reduced. This guarantee of the decline of gain is achieved by bringing the systems gain to close to zero when $\omega_0 = \omega$.

$$f_0 = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} \quad (3.9)$$

The circuit elements that affect the center frequency in the filter structure are R_1 , R_2 , C_1 , and C_2 it can be seen in Equation 3.9. Thus, the frequency at which the circuit will stop can be adjusted. If the symmetry in the RC product is broken, the center frequency will shift according to the desired level. To avoid such problems, attention should be paid to element tolerances and design parameters.

3.2. Filter Approximations

In this section, filter design approaches found in the literature will be examined, and a decision will be made on which approach should be used in the thesis.

3.2.1. Butterworth Approximation

Butterworth filter was first introduced by Scientist Stephen Butterworth in 1930. Butterworth filters are considered to be the most easily constructed filters because it has a flat response in the passband (namely no ripples) making this filter perfect for the application where precise values of all signal frequency are significantly needed.

The cut off frequency occurs at -3dB from the maximum value in the passband, and beyond that the reduction is quite smooth and predictable. However, the reduction post cutoff frequency is much slower when compared to Chebyshev or Elliptic filters for the same order of the filter. Further, the Butterworth filter will give rise to a disturbed output wave if the input wave was disturbed, given that there is no distortion in the amplitude of the waves. So, in general when distortion less frequency chosen, the resulting curve is said as Flat Magnitude Response with zero dB in the passband, to indicate that the pass-band magnitude is constant[38].

One of the most common features of the Butterworth filter which makes this a preferred choice is the gradual roll off associated with the stopband, however, the roll off rate of the Butterworth filter is limited to $20n$ dB per decade beyond the cut-off point. If in general, the filter has a higher order, it functions more effectively[39].

From a design point of view, the Butterworth filter is easier to generate when compared to most other types of filters since the realization of filter profile can be simplified as well. The most common types of circuits can be easily designed via both passive and active networks. The component values are much easier to handle, tuning and maintaining designs which closely resemble the prototype Butterworth filter. However, when we use more complex filters, the prototype network comes much harder to resemble and hence hard to achieve. Common uses of an in design or selection process are the following:

- Anti-Aliasing filters in Analog to Digital Converter (ADC)
- Reconstruction filters in Digital to Analog Converter (DAC)
- Low noise front ends in biomedical
- Crossover network in audio systems
- Smoothing filters in data loggers and sensor circuits

While Butterworth filter may not be the optimal choice for every specification, especially where aggressive stopband attenuation is required, it remains the gold standard for synthesis tasks requiring high linearity, flat gain, and minimal phase distortion in the passband. Finally, from the results above, we can conclude that Butterworth approximation provides a simplistic, mathematically elegant while being Practically effective output. Its unique flat response characteristic is the main reason why it is more commonly used in numerous Analog and Mixed-Signal systems, especially where good signal integrity with high noise suppression is required [34].

3.2.2. Chebyshev Approximation

Chebyshev approximation, one of the classical methods, used in designing analog filter, are named after a Russian mathematician Pafnuty Chebyshev. He used Chebyshev polynomial to get the results. In comparison with Butterworth filters, these filters have steep frequency responses. The Chebyshev filter is named because as it introduces ripple in its frequency response than that of Butterworth filter [40].

Butterworth filters have maximally flat magnitude response in the passband whereas Chebyshev filter can be either type 1 or type 2. The Chebyshev filter can either introduce ripple in the stopband or passband. The passband ripple is constant and is called as ϵ and stopband ripple is uniform and is called as δ .

The passband ripple is sometimes referred to Type I or direct and stopband ripple as Type II or inverse filter. The passband of a Type I filter shows ripple while that of a Type II filter of a Chebyshev filter. In a Type I filter, the magnitude response of the filter shows equi-ripple behavior in the stopband. The ripple is generally in terms of amplitude. Its determinant is in terms of the passband ripples. Whereas in a Type II filter, a Chebyshev filter, it is known as an inverse Chebyshev filter. It's the only difference is the magnitude response of the filter shows an equi-ripple behavior in the passband instead of the stop band [41].

The roll-off of the Chebyshev filter, irrespective of the type is sharper than that of Butterworth filter of the same order. In any system in which the signal has to be filtered weak or no-load systems. Such applications can be a low-pass filter; the better result can be obtained with Chebyshev filter as minimum as 3dB. Chebyshev filters are widely used in analog and digital filters. Few of the applications are communication

systems, instrumentation filters, signal acquisition circuits, biomedical signal processing, etc. [42].

The limitation of the passband ripple in Type I and stopband in Type II filter is the Chebyshev filter. If the ripple is too large, the filter is less useful. For example, excessive variations may degrade signal quality in case of high precision applications. It is also a similar case insensitive to the out-of-band interference. So, ripples have both advantages and limitations.

3.2.3. Inverse Chebyshev Approximation

Distinctive equiripple behavior in the stopband and a maximally flat magnitude response in the passband define the well-known approximation in analog filter theory as the Inverse Chebyshev or Chebyshev Type II filter. Whereas the Type I variant of the Chebyshev filter shows ripples in the passband to attain faster roll-off, the Type II variant of the Chebyshev filter moves the ripples to the stopband. When amplitude uniformity in the passband is vital but sharp attenuation is still required above the cutoff frequency, the special design of the Inverse Chebyshev filter makes it perfect[36].

This approximation wise, the Inverse Chebyshev filter provides more stopband attenuation than Butterworth or even Type I Chebyshev filters. Nevertheless, this performance comes at the cost of more challenging design since transmission zeros must be exactly in the stopband. Particularly in sensitive or high frequency uses, this requires exact layout and careful component choice. These filters particularly fit for:

- Anti-aliasing is essential in precision ADC systems to preserve passband integrity and guarantee appropriate attenuation of high-frequency signals.
- Receivers of communication to maintain signal integrity within the operational range by means of interference reduction from surrounding channels.
- Components of physiological signals that, in biomedical signal acquisition systems such as ECG or EEG, must be sent with the least possible distortion.
- Front ends for data acquisition and instrumentation where a clear, undistorted passband is absolutely essential.

Inverse Chebyshev filters can be implemented from common active filter topologies including Sallen-Key, multiple feedback (MFB), or Tow-Thomas biquad configurations. Their high roll-off rate and passband flatness make these filters a sensible choice when low distortion and effective spectral separation are required.

All things considered, the Inverse Chebyshev filter serves as a strong midway ground between flat passband behavior and enhanced stopband rejection. Particularly when balancing signal accuracy and selective attenuation, this dependable and widely used method in analog filter design has particular advantages and solid theoretical underpinnings.

3.2.4. Cauer Approximation

Considered as the most general and best form of classical filter approximations is the Cauer or Elliptic filter. Named for Wilhelm Cauer, who first presented this approach in the 1930s, the elliptic filter uses carefully placed both poles and transmission zeros in the complex frequency domain to attain equiripple characteristics in both the passband and stopband. For a given filter order, this dual-ripple structure minimizes the complexity of the filter by allowing the strongest possible transition between passband and stopband, so preserving performance. Though at the cost of phase linearity and higher sensitivity to component variations, this approximation guarantees ideal selectivity and compact realization[36].

Cauer filters are one of the recommended choices in the following applications.

- Extreme selectivity, as shown in wireless communication systems by adjacent channel rejection.
- Compact implementation in which order and circuit complexity must be minimized.
- Specifically in radar and telemetry systems where spectral separation is essential, precision signal conditioning
- Digital-to- analog and analog-to- digital interfaces requiring strict bandwidth control and rejection of high-frequency noise.

Though theoretically better, Cauer filters are more difficult to apply, particularly in analog fields. Multiple transmission zeros increase component sensitivity and, in

poorly designed cases, might cause possible instability. Modern implementations thus usually depend on computer-aided design (CAD) tools that automatically synthesize the filter transfer function into realizable circuit topologies using active or passive networks.

The following topologies are typically used to apply elliptic filters:

High-order realizations using generalized impedance converters (GICs), Active RC networks using op-amps in biquad configurations, switched-capacitor designs in integrated circuit implementations for tunability and precision.

All things considered, the Cauer filter is the gold standard in uses needing both spectral precision and space economy since it provides an unparalleled performance-to-order ratio. Unquestionably, it is useful in high-performance analog and mixed-signal systems even though its nonlinear phase response makes it unsuitable for phase-sensitive applications. Modern electronics advanced filter design still reflects the mathematical grace and pragmatic force of the Cauer approximation.

4. TUNABLE ANALOG FILTER DESIGN

Tunable analog filters are instrumental in various fields, due to their ability to dynamically control the spectral characteristics of signals. They find significant utility in sectors such as Telecommunications, Sensing and Spectroscopy, Wireless Systems, Medical, Military, and Commercial Applications, Emergency Services. Among these domains, electro-optical sensors emerge as a crucial application. These sensors, pivotal in laser-guided targeting, facilitate precise measurements before target identification and engagement, underscoring their indispensable role in modern-day operations.

Armed Unmanned Aerial Vehicles (UAVs) with electro-optical systems typically can engage targets within a dynamic range of 35 meters to 3.5 kilometers. However, when operating across such a wide dynamic range, certain distortions and margins of error have been observed in sensor outputs. Ensuring maximal accuracy in both target detection and engagement is paramount. To navigate the frequency range of 50 kHz to 4.02 MHz, which fluctuates continuously, the deployment of an analog tunable filter is vital. Unlike their non-tunable counterparts, analog tunable filters facilitate more accurate results, while significantly reducing power consumption, resource allocation, and material usage.

Our initial endeavor in this thesis involved the design of an analog model capable of operating over a wide frequency range of 15 kHz to 600 kHz. Having achieved this, we broadened our goal to address the main challenge for electro-optical systems led to the design of a tunable filter designed to operate over a specific working range. Our new model exhibits remarkable adaptability with a frequency range tunable from 50 kHz to 4.02 MHz. This versatility positions our model as a suitable solution to meet the demands specific to electro-optical systems. There are several studies in the literature on analog filtering at fixed frequencies. For example, [43] presents a third-order low-pass filter designed for biosensor applications, providing filter responses for different resistance values. Another study [31] uses an OTA-based fifth-order Butterworth low-pass filter for ECG applications with a tunable cut-off frequency between 17 Hz and 250 Hz.

In contrast, the study offers a broader cutoff frequency range compared to existing works and introduces an innovative approach by utilizing capacitance variation as the

filtering method rather than resistance changes. Given the wide dynamic range of LRF signals based on their operational mechanism and the lack of a dedicated filter for specific data, this research uniquely applies filtering to synthetic data trained on entirely experimental datasets. This aspect further distinguishes the study and highlights its novel contribution to the field. The presented filter has a tunable structure in the dynamic range and operates in the specified needed frequency range. The application is planned to be used directly in electro-optical systems. The implementation of an analog filter system as described proposal appears to be a significant and innovative contribution to the related field. Here's a breakdown of the key points and the potential impact of the proposed analog filter system:

- High-Frequency Range
- Direct Integration
- Computer-Aided Modeling
- Novelty
- Alternative to FPGA-Based Filters

This part will elucidate the design of the analog tunable bandpass filter, which constitutes the foundation of the thesis work. An analog tunable bandpass filter is applied to the signal read from the APD to reduce the signal's noise. Therefore, the measurement accuracy increases and the system performance and reliability are improved. Tunable bandpass filters are very promising for future communication and defense systems. Piezo-controlled SIW blocks, MEMS capacitors and varactors are used for tuning the filters [44]. Frequency tuning was performed using a varactor. The signal obtained from the LRF module is converted from time domain to the signal domain. Filter simulation is presented according to a model that can operate in the range of 35 m - 3.5 km. Based on the operating range of the device, the tunable range of the filter is selected as 50 kHz - 4.02 MHz range. The band frequency of the circuit will be automatically tuned according to the peak frequency of the signal reflected from the object as stated in the upper section. While selecting the filter topology, the received input signal was analyzed in detail.

It is understood that the narrow bandwidth is pivotal in reaching the correct signal. The 4th order Tunable Bandpass Filter design is completed with Butterworth Approach, Multiple Feedback Implementation.

4.1. Preliminary Designs

This section will present the work carried out prior to the final design and the results obtained. When selecting the filter topology, bandpass filter structures were analyzed in detail and tested. First, a Sallen-Key Band Pass filter design was created.

4.1.1. 4th Order Sallen-Key Bandpass Filter

The Sallen-Key topology is a very popular and robust filter topology used in the design of active analog filters. Initially introduced by R.P. Sallen E. L. Key in the year 1955 in the Lincoln Laboratory of M.I.T. the topology has been in continuous usage till now due to its ease of implementation, simple and high versatile structure[45]. It is also one of the best choices of active filter topology to give a second-order filter using the minimum number of active and passive components (preferably one op-amp, two resistors and two capacitors). One of the greatest advantages is that the tuning of center frequency and Q can be easily adjusted as separate factors without requiring much complexity in the circuit [46].

The circuit is also called an amplifier made up of two resistors and two capacitors. In the low pass filter realization, the network of feedback to determine the positions of poles and zeros in the s-plane of an amplifier built using the Sallen-key structure ($Q=1$). Adjusting the positions of the reactive parts i.e. capacitors we could also build other sorts of topologies of Sallen-Key to obtain a high pass, bandstop or bandpass filters. Therefore Sallen-Key provides an easiest possible realization for different types of filters that can be obtained for any other circuits. This ability to reconfigure the type of filter in a Sallen-Key filter is much useful in dynamic control systems or also when there is a need for different filter types to be available on the same hardware platform[47].

Moreover, the reason that makes the Sallen-Key filter preferred among others is the predictable behavior, low sensitivity with components and less output impedance that

will help in cascading and drive loads strongly without the buffer. Therefore, the low output impedance and less sensitive components to low-frequency filters allow selecting it for different regions in the circuits. The Sallen-key acoustic filter has been in continuous usage for low-capacity sensors in instrumentation amplifiers, audio and telecommunications and is also used at the beginning in analog-to-digital converters in the low-pass filters. Their ability to create smoother transition signals or roll-off characteristics create a feature which suits them to be the best type of filters for anti-aliasing and construction in data acquisition systems. A significant drawback of the Sallen-Key topology is that for high Q designs gain bandwidth product and the slew rate of the op-amp becomes critical. Here, any parasitic effects from the PCB layout must also be considered and also component mismatches which leads to changes in high-Q behavior. Hence, careful design, simulation, and prototyping are required accordingly. Though the design has limitations, Sallen-Key filters are still used for making analog electronics simple to understand and implement. It is simpler and easy to analyze both academically and practically.

The Sallen-Key topology effectively transmits signals inside a specified frequency band while suppressing high and low frequency components outside of it. This topology is commonly used for second-order filter implementation because it offers high-frequency stability and cost-effective implementation using only a single operational amplifier and a small number of passive components (capacitors and resistors). In a bandpass filter design, the Sallen-Key topology gives you direct control over the center frequency and quality factor. This study used the previously mentioned topology to implement a bandpass filter design and analyze the frequency response using circuit parameters in order to detail the system's passband and rejection performance at specific frequencies.

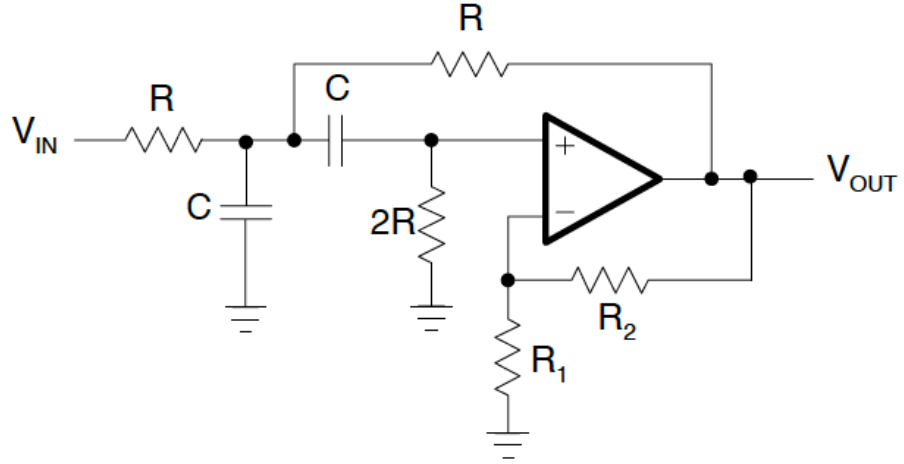


Figure 4.1: 2nd order sallen-key BPF [45].

A 2nd Sallen-Key bandpass filter referenced in **Figure 4.1** is presented. Using this topology, a cascade design was created to obtain a 4th filter, which was then applied to the input signal.

The transfer function of the filter is given by Equation 4.1. The variable G in this equation is defined as Inner Gain and its mathematical equality is seen in Equation 4.3.

$$H(s) = \frac{GRC\omega_m s}{1 + RC\omega_m(3 - G)s + R^2C^2\omega_m^2 s^2} \quad (4.1)$$

Equation 4.2 is used to calculate the passband center frequency of the filter and the $R - C$ values in the design.

$$\text{Mid - Frequency: } f_m = \frac{1}{2\pi RC} \quad (4.2)$$

The Inner Gain (G) value, it can be given in the Equation 4.3, is calculated using the R_1 and R_2 resistors used in the Op-Amp feedback network.

$$\text{Inner Gain: } G = 1 + \frac{R_2}{R_1} \quad (4.3)$$

The A_m value gives equality at the filter passband center frequency and is related to the G value.

$$\text{Gain at } f_m: A_m = \frac{G}{3 - G} \quad (4.4)$$

Finally, the equation used to calculate the Q value used to adjust the filter's bandwidth is presented in Equation 4.5.

$$\text{Filter Quality Factor: } Q = \frac{1}{3 - G} \quad (4.5)$$

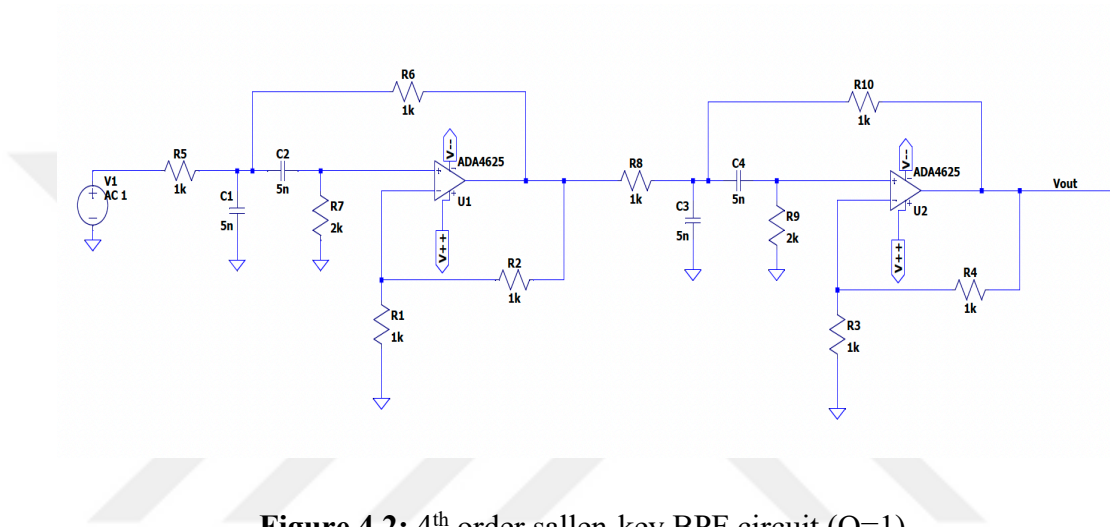


Figure 4.2: 4th order sallen-key BPF circuit (Q=1).

A 4th order Sallen-Key BPF design has been implemented in the base circuit shown in **Figure 4.2**. The design was first tested at relatively lower Q values. The Q value was calculated as 1 using Equation 1. The simulation results also confirm that the mathematical equality is satisfied.

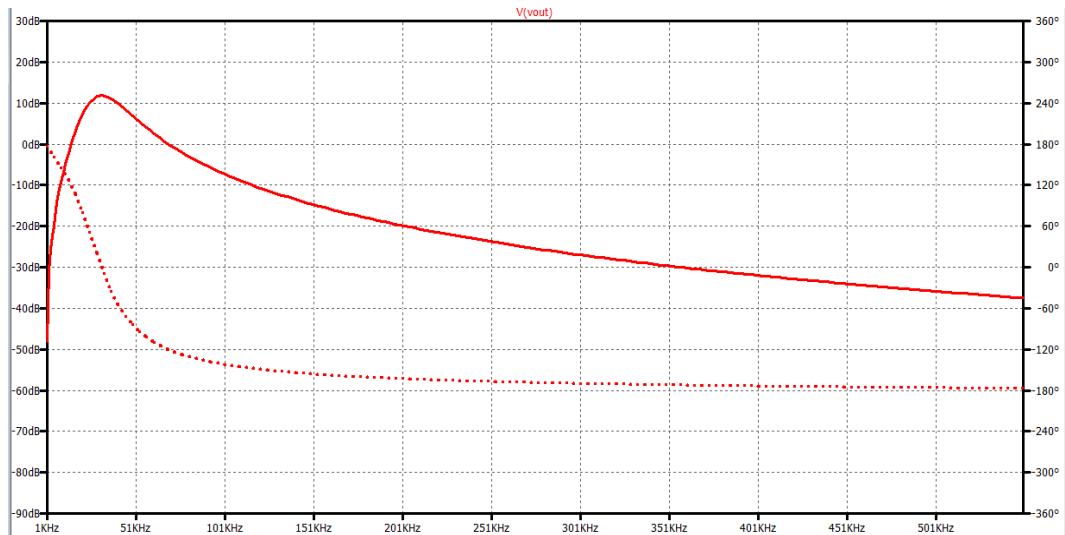


Figure 4.3: 4th order sallen-key BPF output at 40 kHz ($Q=1$).

The analysis resulting from the design shows that the design operates at a passband center frequency of 40 kHz, as shown in **Figure 4.3**. The filter characteristics were found to be suitable as a result of the simulation. Therefore, it was decided to test the design across the entire frequency range.

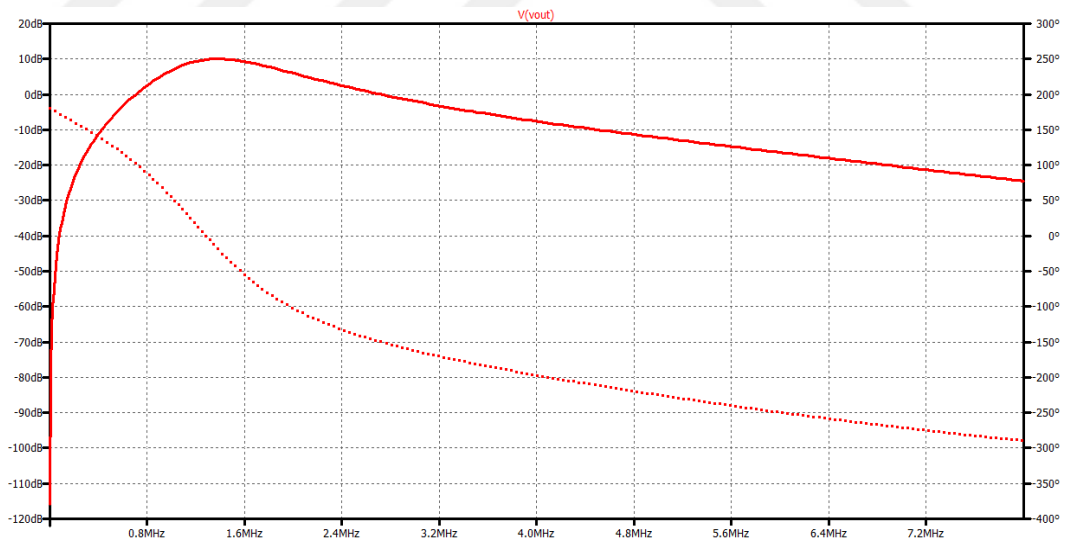


Figure 4.4: 4th order sallen-key BPF output at 1.25 MHz ($Q=1$).

Figure 4.4 shows the filter response at a passband center frequency of 1.25 MHz. The only parameter changed in the filter design was C , which was set to 100 pF. When the filter response was analyzed, it was found to be unreasonable due to its low Q value. At high frequency values, the increase in bandwidth depending on the Q value leads

to incorrect measurement results. Therefore, it was decided to repeat the design with $Q=10$.

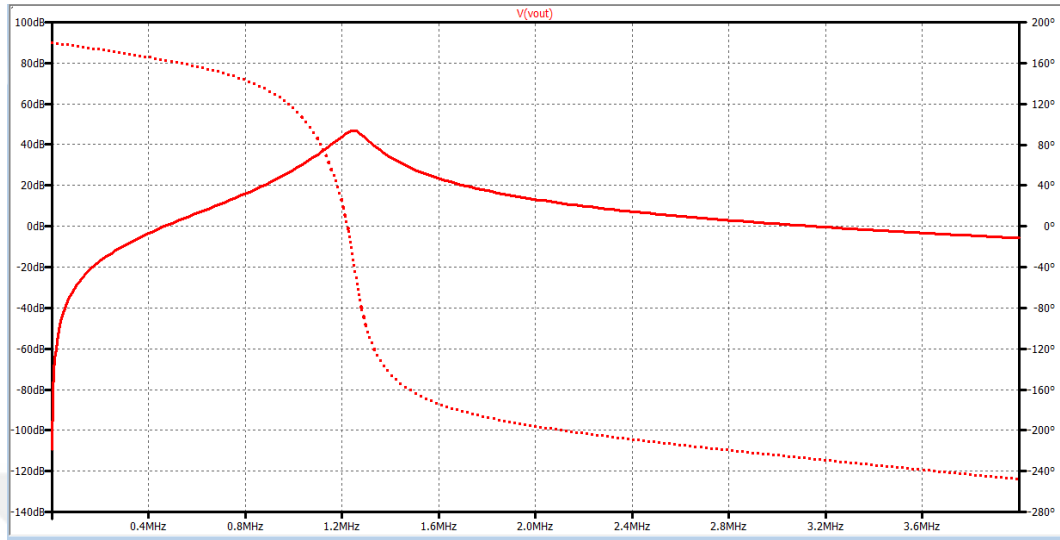


Figure 4.5: 4th order sallen-key BPF output at 1.25 MHz ($Q=10$).

The frequency response obtained in the design with $Q=10$ is shown in **Figure 4.5**. Since the design was found to be acceptable at high frequency values, its applicability across the entire frequency band was analyzed.

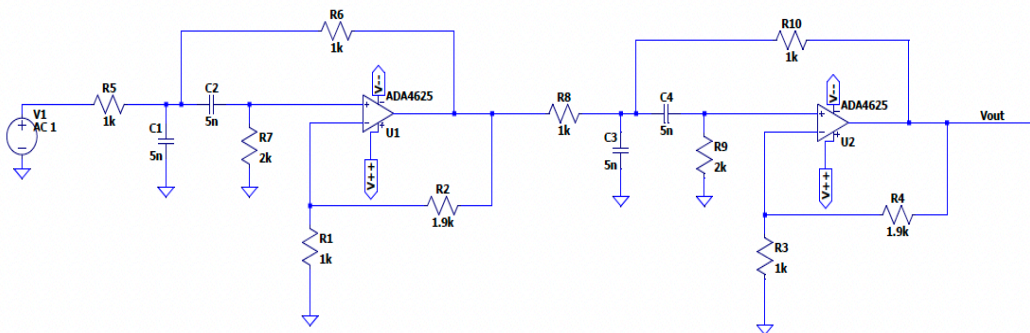


Figure 4.6: 4th order sallen-key BPF circuit ($Q=10$).

The Q value of the filter can be adjusted based on the relationship between resistors R_1 and R_2 . The circuit in which the Q value has been increased to 10 as a result of

mathematical calculations is shown in **Figure 4.6**. For a complete comparison, the passband center frequency was kept unchanged at 40 kHz for analysis.

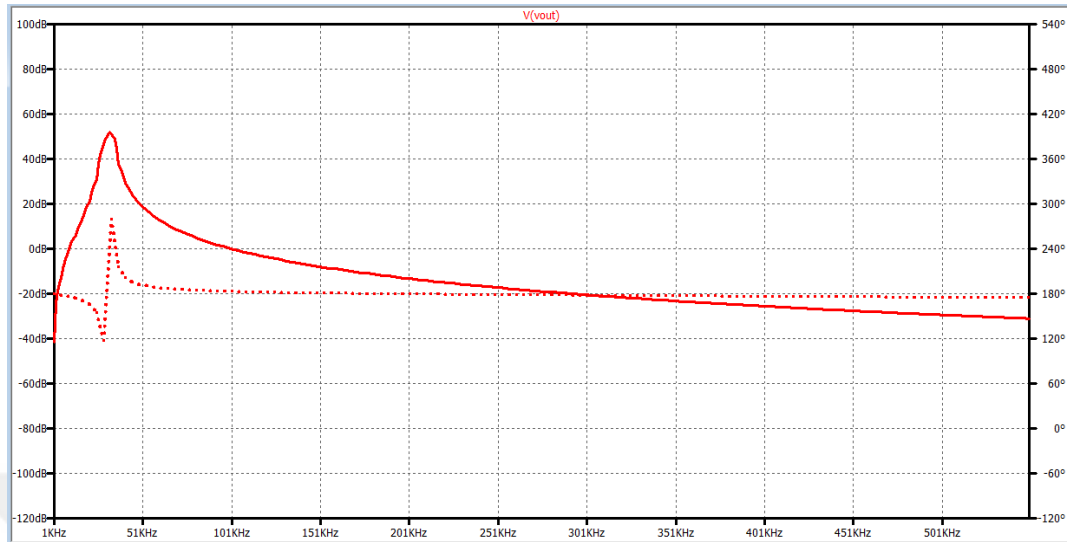


Figure 4.7: 4th order sallen-key BPF output at 40 kHz (Q=10).

When examining the filter response presented in **Figure 4.7**, phase distortions and unexpected fluctuations in the frequency response are observed.

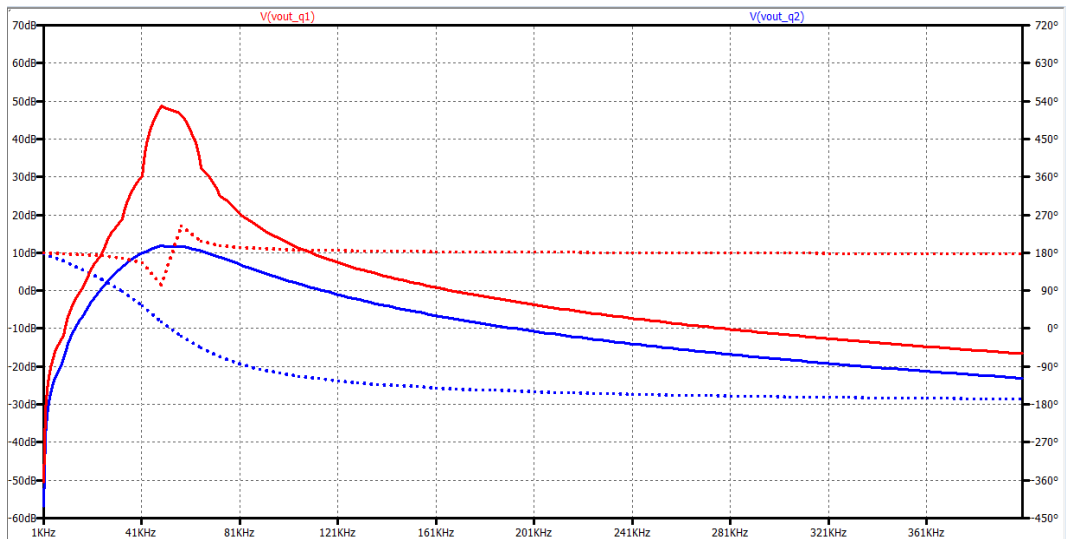


Figure 4.8: 4th order sallen-key BPF output comparison.

Whereas the blue signal indicates the response of the filter built with Q=1, the red signal in **Figure 4.8** shows the response of the filter intended with Q=10. Under close inspection of both signals, it was found that the filter shows a steady and consistent

structure at $Q=1$ but gets unstable and irregular as the Q factor rises. Consequently, it was found that the Sallen-Key method is not appropriate for building a filter with high Q values in the low-frequency range needed in this thesis.

The results obtained in the simulation environment were efficient within the LRF signal operating range, but work continued to improve the system. The initial design was found to have some shortcomings and needed to be improved. The shortcomings were as follows:

- The Q value could not be changed independently of the Inner Gain value
- Too many active circuit elements were used
- Phase and frequency response shift of the filter at high Q values

A detailed literature search revealed that bandpass filters with Multiple Feedback Topology (MFB) can be implemented using fewer active elements. Therefore, filter studies were continued using MFB topology.

4.1.2. 4th Order MFB Bandpass Filter with Sallen-Key Topology

Multiple Feedback Implementation is used in narrowband applications where the Q value may be in the range of 10-20, requiring high frequency selectivity [45].

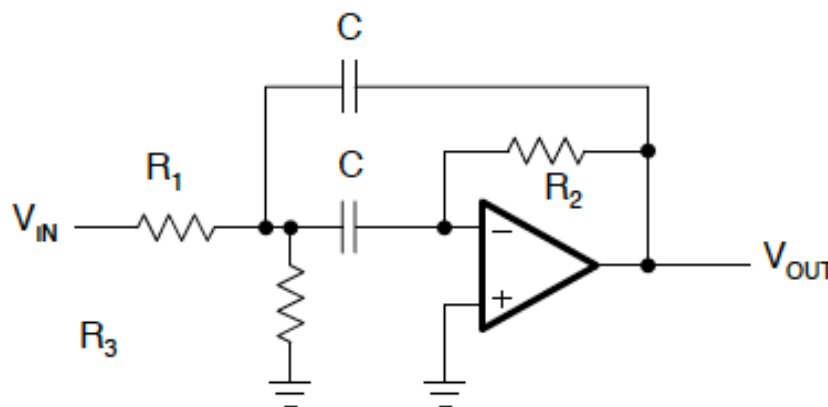


Figure 4.9: 2nd order MFB BPF [45].

Based on the second-order MFB-based bandpass filter circuit shown in **Figure 4.9**, a circuit design consisting of two identical circuits connected in series and an additional

resistor added to the feedback side to adjust the gain, similar to the Sallen-Key circuit, has been developed.

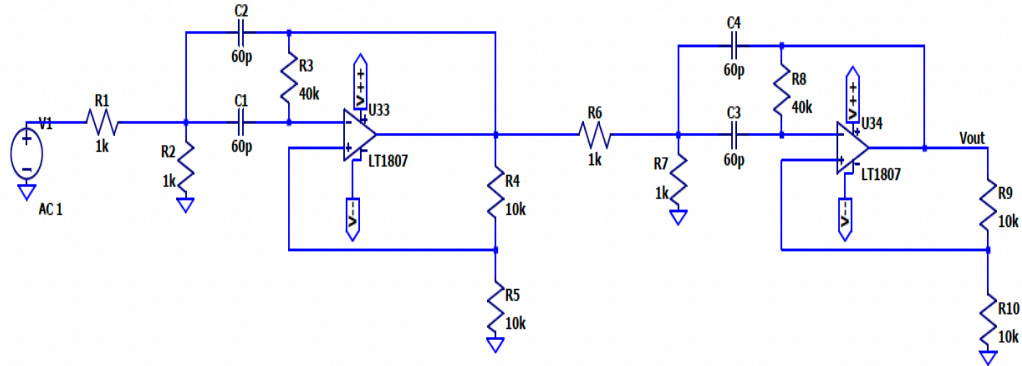


Figure 4.10: 4th order MFB bandpass filter circuit.

A 4th order MFB bandpass filter design has been created using the LT1807 Op-Amp. The ADA4625 Op-Amp model was used in the previous section, but a different model was chosen in this section to achieve the desired performance across a wider frequency band. The completed design and component values are clearly shown in **Figure 4.10**. The filter passband center frequency is set to 270 kHz.

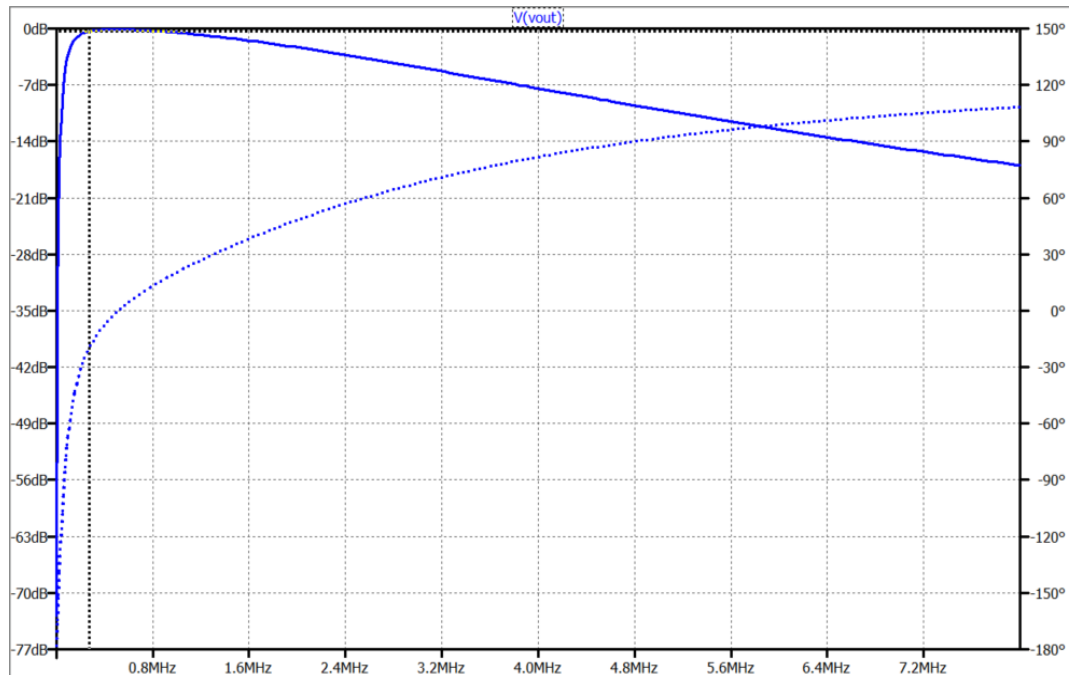


Figure 4.11: 4th order MFB bandpass filter output at 270 kHz.

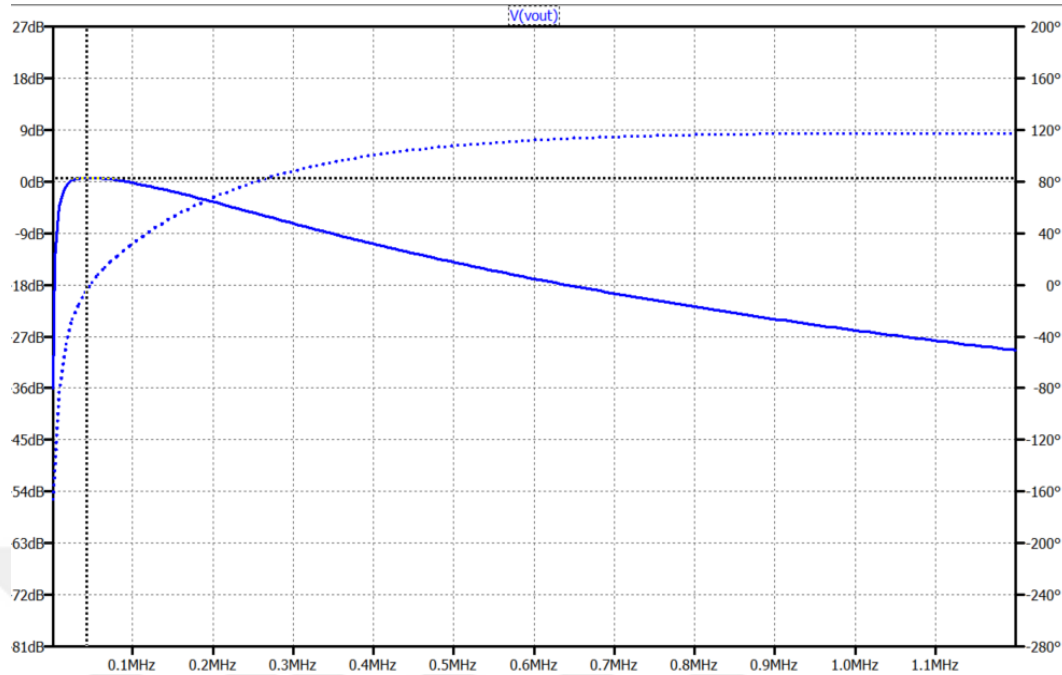


Figure 4.12: 4th order MFB bandpass filter output at 45 kHz.

The outputs generated at 45 kHz and 270 kHz for the designed filter are shown in **Figure 4.11** and **Figure 4.12**, respectively. When the results were analyzed, the bandwidth of the filter was found to be significantly higher than calculated. A discrepancy was detected between the mathematical model and the simulation results. Therefore, it was decided not to use the designed filter.

To support the applied filter design, extensive simulation studies were carried out; the findings revealed that, in terms of gain, phase response, and frequency response, the system generally generated stable results close to the desired performance. Still, the filter behavior proved insufficient in this respect when compared to the target quality factor (Q) value. While theoretically a smaller and more selective passband is expected when the Q value is raised, simulation results reveal that this increase causes undesired distortions in the phase and frequency response of the system. In this sense, it was found that the Sallen-Key topology is restricting in terms of stability and accuracy at high Q values. The model was rebuilt using a Butterworth filter approximation to provide a flat frequency response in the passband, so optimizing performance. This method change was meant to guarantee more steady system dynamics.

4.1.3. 4th Order MFB Bandpass Filter with Butterworth Topology

Butterworth bandpass filters are maximally flat magnitude filters since it is designed in such a way that there will be no ripples in the frequency response. They are preferred in applications that need to produce a uniform gain at both lower and upper cut-off frequencies.

In case of bandpass filters, the Butterworth approach to filter design ensures that the signal components at the center frequency are transmitted accurately, and the component signals away from center frequencies are suppressed effectively. In the case of lower-order Butterworth filters, the width of the passband is broader while, in the case of higher-order filters, the passband width is narrow and hence can suppress unwanted frequencies more effectively.

The design procedure of Butterworth bandpass filters considers the placement of poles on the unit circle such that the poles have equal angles among them so that the characteristics of the filter are predictable and hence stable. The features that make Butterworth bandpass filters most preferred are, these bandpass filters have real poles, and they have equal distances from each other.

ADA4625 Op-Amp model was tested. The model used gave efficient results in the 45 kHz - 400 kHz region of the filter operating frequency, but the expected performance could not be obtained at signals above 400 kHz, so it was not preferred for the final design.

Subsequent to the ADA4625 model, the LT1806/1807 models were tested.

In these models, signal distortion occurred as a result of filtering in the low frequency range (45kHz-400kHz), and it was observed that they did not operate with the same stability across the entire frequency range.

4.2. Final Filter Circuit Design

In the final study, the LT6202/6203 Op-Amp model was used. In these studies, the desired performance level was very close. It was decided to use LT62 series Op-Amp. Then, as a result of the detailed analysis, apart from the filter frequency range, parameters such as output current, noise voltage, offset voltage were evaluated. Essential research was conducted in accordance with the system requirements, leading to the selection of the LT6231 model as the ultimate decision.

The LT6231 is a high-performance operational amplifier that designed for precision applications, offering exceptional signal fidelity and efficiency. It features an ultra-low noise voltage of $1.1\text{nV}/\sqrt{\text{Hz}}$, making it ideal for sensitive signal processing applications. The amplifier operates over a wide supply voltage range of 3V to 12.6V while consuming a low supply current of 3.5mA. With an impressive common mode rejection ratio (CMRR) of 115 dB, the LT6231 minimizes interference and ensures robust signal integrity.

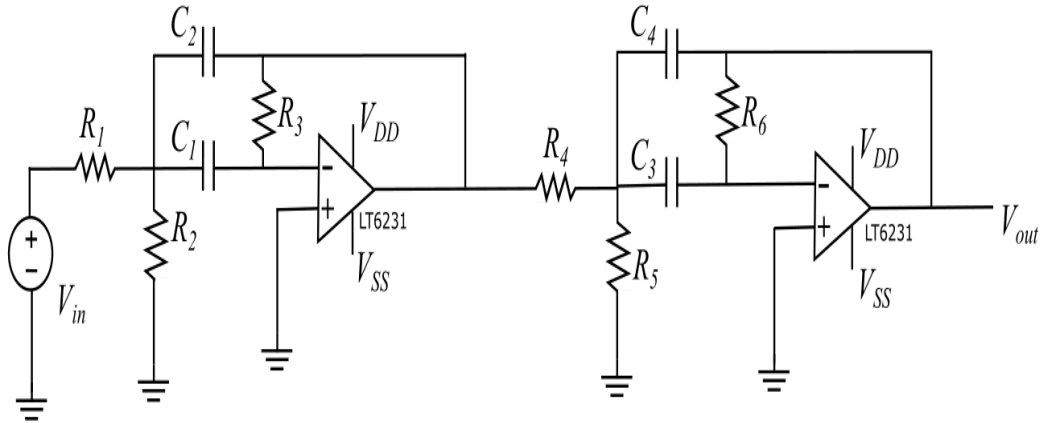


Figure 4.13: Final filter circuit design.

The designed filter model is given in **Figure 4.13** a multiple feedback implementation is disclosed, considered one of the finest ways of producing an all-pole response. The all-pole structure offers desirable features making it effective at processing analog signals. This kind of arrangement also shows various advantages, a most crucial benefit being its phase linearity. A multiple feedback arrangement finds extensive use in those applications where a narrowband filtering is required to be implemented

successfully. One would prefer multiple feedback concerning the LRF system because applying the LRF system, we try to achieve the narrowest possible band filtering.

$$f_0 = \left(\frac{1}{2\pi C} \right) \left(\sqrt{\frac{R_1 + R_2}{R_1 R_2 R_3}} \right) \quad (4.6)$$

In the Equation 4.6, the required relationship for the passband center frequency of the designed filter is given. These values must be adjusted for the filter to be tunable within the specified frequency range. Minimizing the number of variables is very important in tunable filters. Therefore, the R_1, R_2, R_3 variables required for tuning the center frequency have been set so that their values do not change. The goal is to adjust the frequency value in proportion to the capacitance value.

$$Q = \frac{1}{2} \sqrt{\frac{R_3}{R_2}} \sqrt{\frac{R_1}{R_1 + R_2}} \quad (4.7)$$

$$Q = \pi f_0 R_3 C \quad (4.8)$$

The mathematical equation required for calculating the Q value, i.e., adjusting the bandwidth of the circuit, is given in Equation 4.7. When this equation is combined with the equation given for f_0 , a more understandable form with fewer parameters emerges, as shown in Equation 4.8.

$$BW = \frac{1}{(\pi R_3 C)} \quad (4.9)$$

The formula required to calculate the bandwidth valid at the passband center frequency designed for the filter is clearly shown in Equation 4.9. Since the C value is the only variable parameter in the design, BW and C are seen to be related to each other.

$$H(s) = \frac{-\frac{R_2 R_3}{R_1 + R_3} C \omega_0 s}{1 + \frac{2R_1 R_3}{R_1 + R_3} C \omega_0 s + \frac{R_1 R_2 R_3}{R_1 + R_3} + C^2 \omega_0^2 s^2} \quad (4.10)$$

Frequency, bandwidth, and Q values were calculated using the relevant equations. Then, the transfer function expression in Equation 4.10, which determines the characteristics of the filter, the filtering region, the gain, and the phase response, was given. This structure is widely utilized in analog signal processing and is highly effective in applications requiring narrowband filtering. In the context of the LRF system, the multiple feedback implementation is preferred, as achieving the narrowest possible band filtering is a primary objective.

Resistance values in the circuit are respectively; $R_1 = 1\text{k}\Omega$, $R_2 = 50\Omega$, $R_3 = 9.2\text{k}\Omega$, $R_4 = 1\text{k}\Omega$, $R_5 = 50\Omega$, $R_6 = 9.2\text{k}\Omega$. C_1 , C_2 , C_3 , and C_4 capacitors were left as a variable so that they can be tuned depending on the frequency of the signal.

Table 4.1: Capacitance - frequency equation.

Capacitance Value	Frequency
$C_1 = 60\text{ pF}$	$f_0 = 4.2\text{ MHz}$
$C_1 = 205\text{ pF}$	$f_0 = 1.35\text{ MHz}$
$C_1 = 410\text{ pF}$	$f_0 = 680\text{ kHz}$
$C_1 = 1\text{ nF}$	$f_0 = 280\text{ kHz}$
$C_1 = 5\text{ nF}$	$f_0 = 56\text{ kHz}$
$C_1 = 6\text{ nF}$	$f_0 = 45\text{ kHz}$
$C_1 = C_2 = C_3 = C_4$	

As can be seen in **Table 4.1**, the frequency band varies between 50 kHz - 4.2 MHz, while the capacitance values are between 60 pF - 6 nF. The final filter circuit is now complete. Detailed comments and analysis results regarding the filter will be presented and examined in results.

Capacitance elements are used for the circuit to tune itself in range. As explained in the LRF system block diagram shown in **Figure 2.11**, a Capacitance Multiplier Circuit

was designed to adjust the capacitance values. Detailed literature reviews and circuit studies conducted on this subject will be examined in Capacitance Multiplier Circuit part.

4.3. Capacitance Multiplier Circuit Design

The filter design must be tunable within the specified frequency range. The section 4. TUNABLE ANALOG FILTER DESIGN specifies that the necessary variable is the capacitance used in the circuit. It has been decided to design a capacitance multiplier circuit to ensure that the capacitance value varies within a certain range.

This circuit aims to change the capacitance values depending on the signal frequency. According to the specified operating frequency range, the capacitance value range of the circuit was obtained as 60 pF - 6 nF. The model used has been added to the system regarding the studies in the literature [48][49][50] The MOSFET is operated in the subthreshold region. Working in the subthreshold region is important in applications requiring low power consumption and high accuracy. Operating region is based on the control of the I_D current, which depends on the voltage V_{GS} . In addition, since the current is quite low at the mode of operation, even small changes on V_{GS} are effective on the current. So that, precise switching between capacitance values will be possible.

$$V_{GS1} + V_{GS2} = V_{GS3} + V_{GS4} \quad (4.11)$$

The Capacitance Multiplier Circuit is modeled based on four identical MOSFETs. There is a double relationship between the gate-source voltages of the MOSFETs, and the mathematical equation for this is given in Equation 4.11. This ensures that the current is equal in the MOSFETs used in the circuit.

$$I_{D1}I_{D2} = I_{D3}I_{D4} \quad (4.12)$$

Using the gate-source voltage equation given in Equation 4.12, the current equation for each MOSFET is given in Equation 4.13. In the given equation, it can be seen that the product of the two currents is equal to the product of the other two currents.

$$I_D = \frac{W}{L} I_{D0} e^{\left(\frac{V_{GS}-V_{TH}}{nV_T}\right)} \quad (4.13)$$

MOSFETs behave like bipolar transistors in the subthreshold region. The MOSFET equation used in the system, which depends on the W/L parameter, gate-source voltage, and temperature parameter, is presented in Equation 4.14.

$$(i_0 + I_4)I_3 = I_2(I_1 + i_1) \quad (4.14)$$

The relationship between each current in the circuit is shown in Equation 4.15. This equation is very important for mirroring the currents and calculating the required capacitance multiplication.

$$G = \frac{I_2}{I_3} \quad (4.15)$$

The value of G in the equation x represents the current gain. To adjust the gain, these two currents are selected as references while the other two currents are kept constant.

$$Z_{eq} = \frac{V_X}{i_X} = \frac{V_X}{i_1 + Gi_1} \quad (4.16)$$

$$Z_{eq} = \frac{Z}{(G + 1)} \quad (4.17)$$

The relationship between the values of Z_{eq} and Z in the Equation 4.16 and 4.17 is shown. The mathematical expressions are thus complete.

As seen in the equations, the tunable capacitance value is controlled by the G value by using the MOSFET current equations in the circuit. G value is associated with I_2 and I_3 the current values in the circuit. The voltage in the circuit is controlled by the auxiliary controller. Thus, the current values are provided to change. The circuit is implemented on LTspice using the 180nm TSMC MOSFET model.

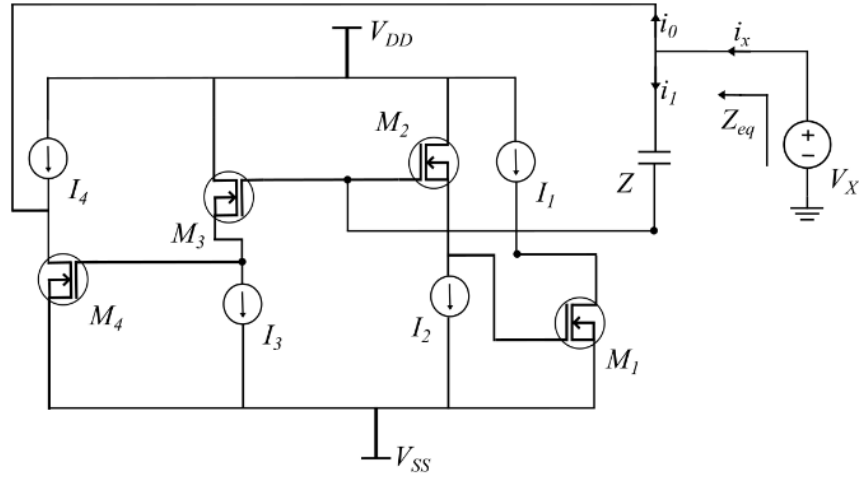


Figure 4.14: Capacitance multiplier circuit.

The circuit, which is shown in the **Figure 4.14**, is supplied with $\pm 0.75\text{V}$. The aspect ratio of all MOSFETs was set to $7/2\ \mu\text{m}$. The I_1 and I_3 currents in the circuit were set to $10\ \text{nA}$. The current I_4 is followed by the equation GI_1 . The I_2 current was chosen as the gain variable. This way, it tries to reduce the complexity by depending on one parameter. Multiplication factor varies between 1-150. The capacitance value is between $50\ \text{pF}$ - $7.5\ \text{nF}$. Due to possible losses and threshold values, the multiplication factor is left wider than the desired range. Assuming $Z \gg$ the impedance at the node of M_1 because it is a regulated cascade then and Equation 4.16 can be written as Equation 4.17, as can be seen, the capacitance relationship is given. It is clear from Equation 4.17 that Z was replaced by a capacitance then a capacitance multiplier completed with multiplication factor $= G+1$. Using LTspice simulation tools the C-multiplier circuit functionality has been confirmed in $0.18\ \mu\text{m}$ CMOS technology. The design is compact and provides a sufficient multiplication factor for capacitance.

5. RESULTS

In this section, simulation and practical application results related to the filter design will be discussed, which was completed in previous section. The designed filter was first tested in the LTspice simulation environment. LTspice software is a widely used program for simulating analog electronic circuit applications. Within the program, parameters such as tolerance, heat, and component flexibility can be customized to create design conditions that are as close to reality as possible. This ensures the consistency and accuracy of mathematical and theoretical calculations. The aim is to complete the study by analyzing the filter results in detail across the entire frequency range.

5.1. Filter Frequency Analysis

In this section, the performance of the completed filter at different frequencies will be examined and commented on.

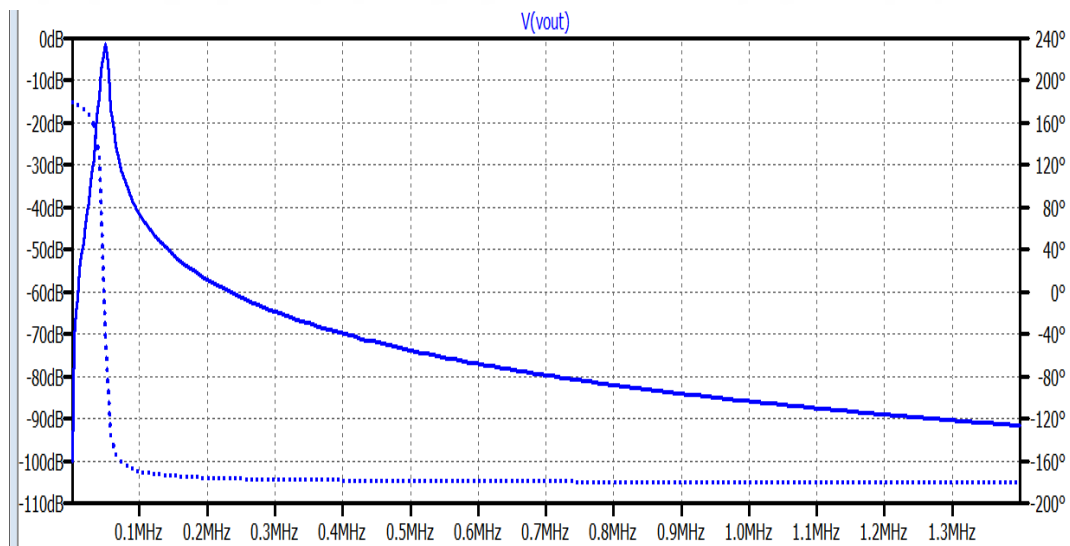


Figure 5.1: Filter output at 50 kHz.

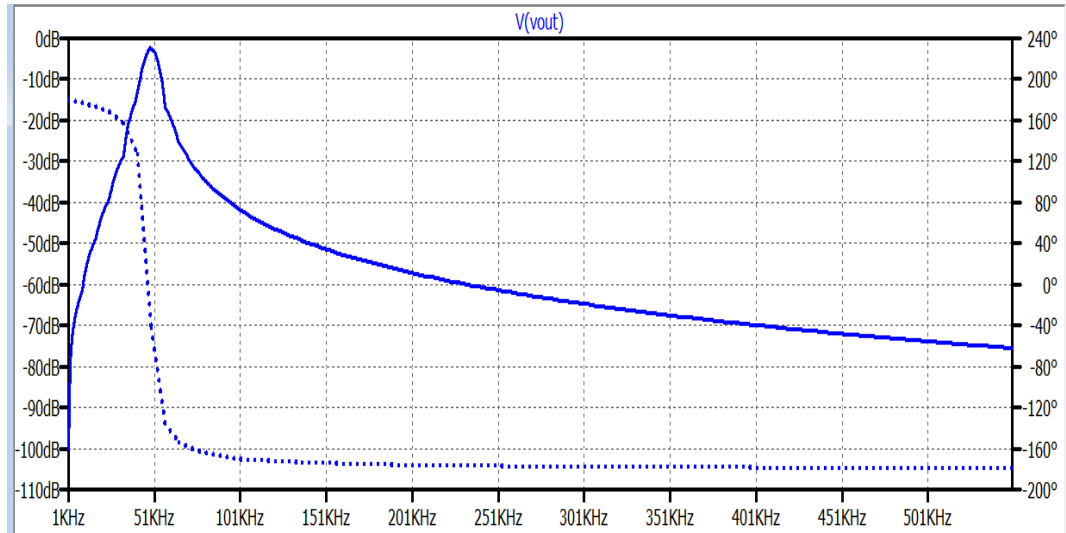


Figure 5.2: Filter output at 50 kHz close view.

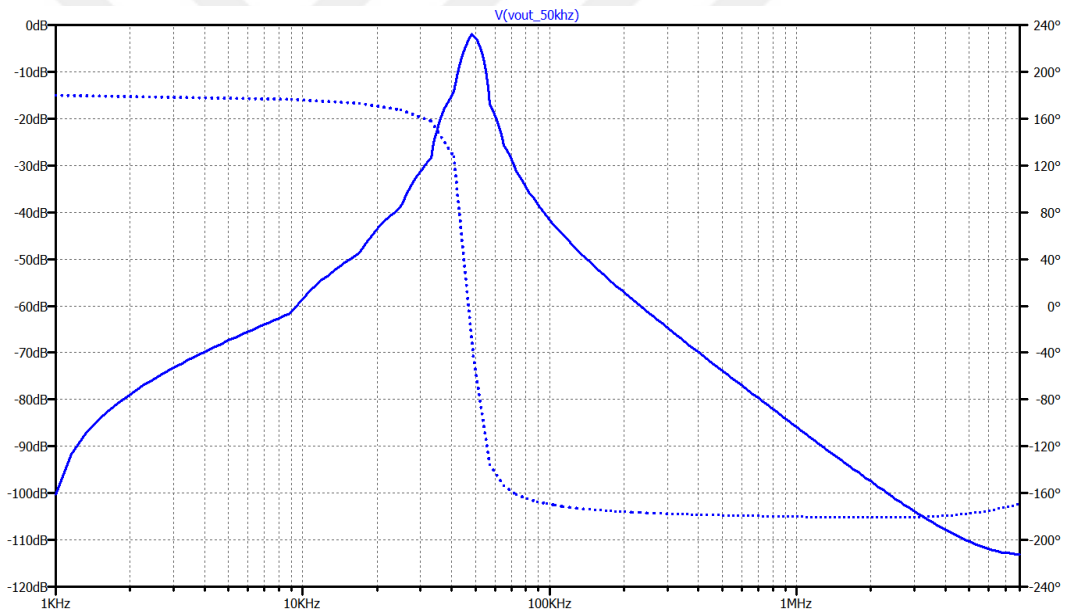


Figure 5.3: Filter output at 50 kHz logarithmic view.

Figure 5.1 and **Figure 5.2** show the frequency and phase response of the filter with a passband center frequency measured as 50 kHz. In addition, **Figure 5.3** shows the frequency and phase response on a logarithmic scale. It has been observed that they are consistent with the theoretical calculations. The lowest frequency at which the filter design developed in the thesis should operate was selected as 50 kHz. Therefore, the design was tested starting from the lowest frequency.

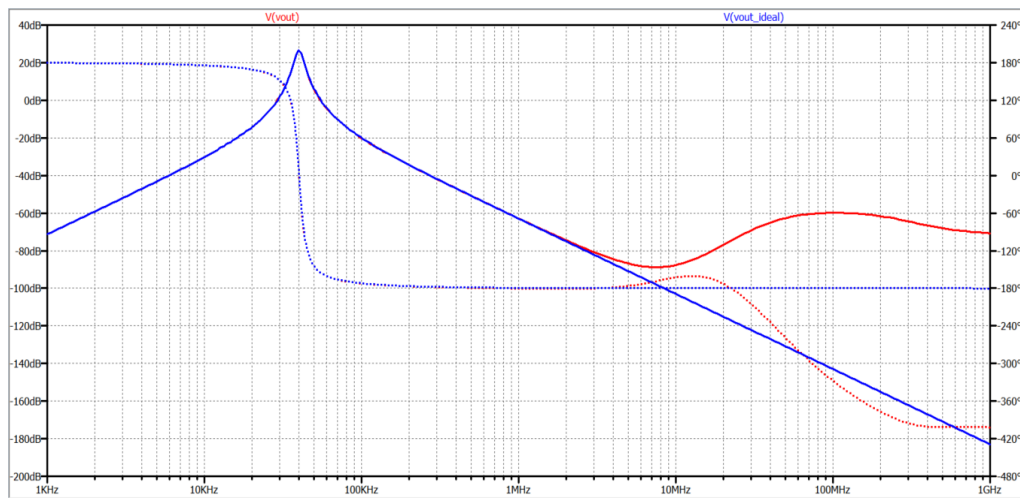


Figure 5.4: Measured vs theoretical output comparison at 50 kHz.

Figure 5.4 compares the filter analyzed with an ideal Butterworth 4th order bandpass filter. The filter center frequency is 50 kHz. The Q factor is ideally 10, measured as 7.25 in the analysis. The phase response appears to be quite close to the ideal. In the frequency response, the Q factor has approached the ideal, but differences are still apparent.

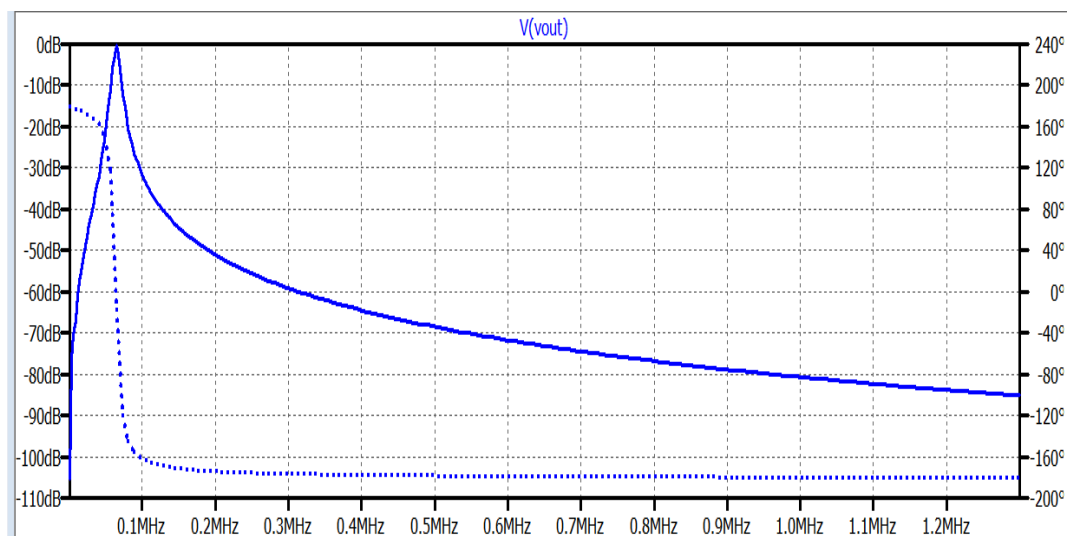


Figure 5.5: Filter output at 65 kHz.

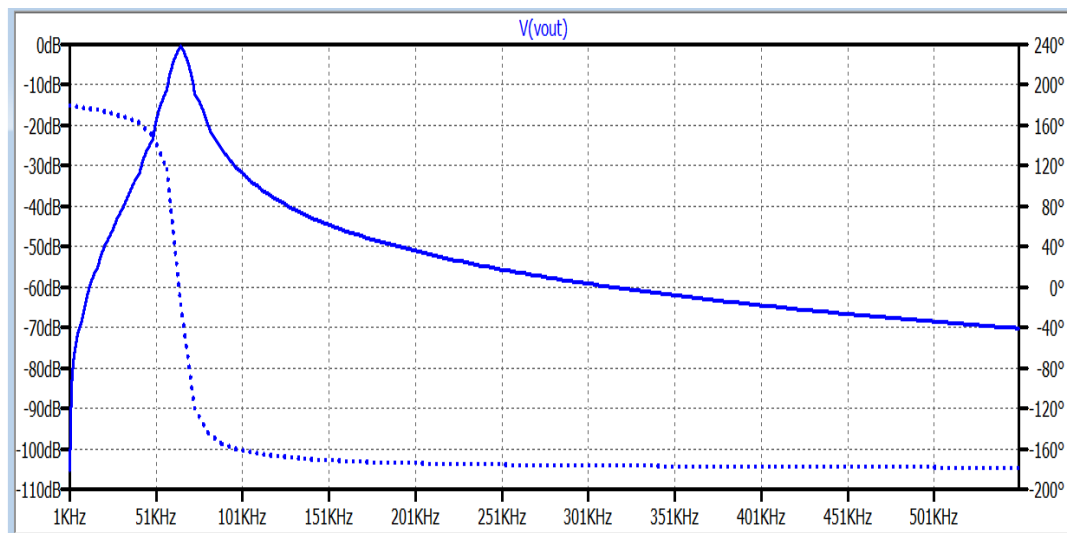


Figure 5.6: Filter output at 65 kHz close view.

Measurements were repeated at close frequency values to see the sensitivity and accuracy of the filter's frequency response in more detail. **Figure 5.5** and **Figure 5.6** show the frequency and phase response of the design with a passband center frequency measured at 65 kHz.

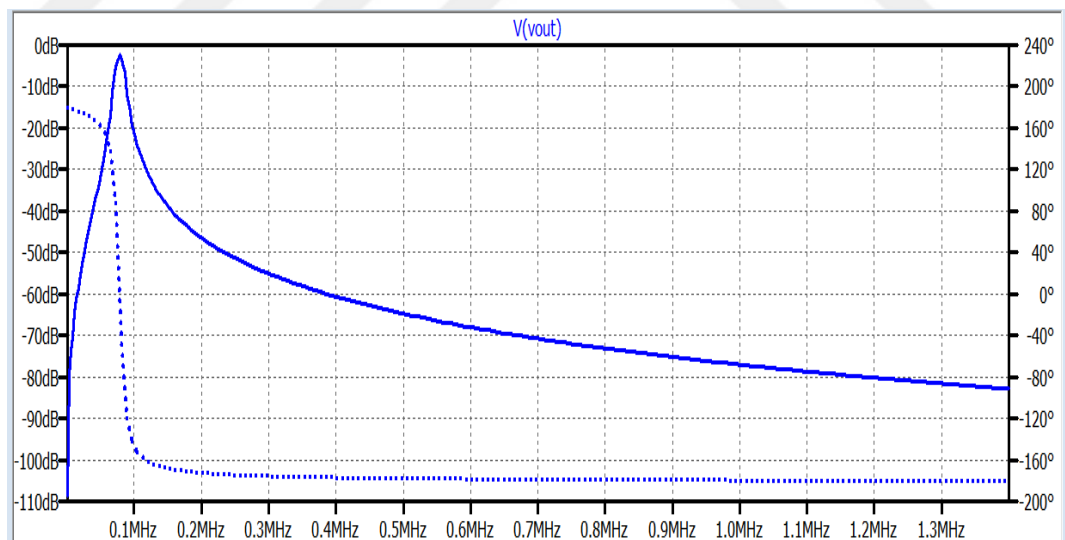


Figure 5.7: Filter output at 80 kHz.

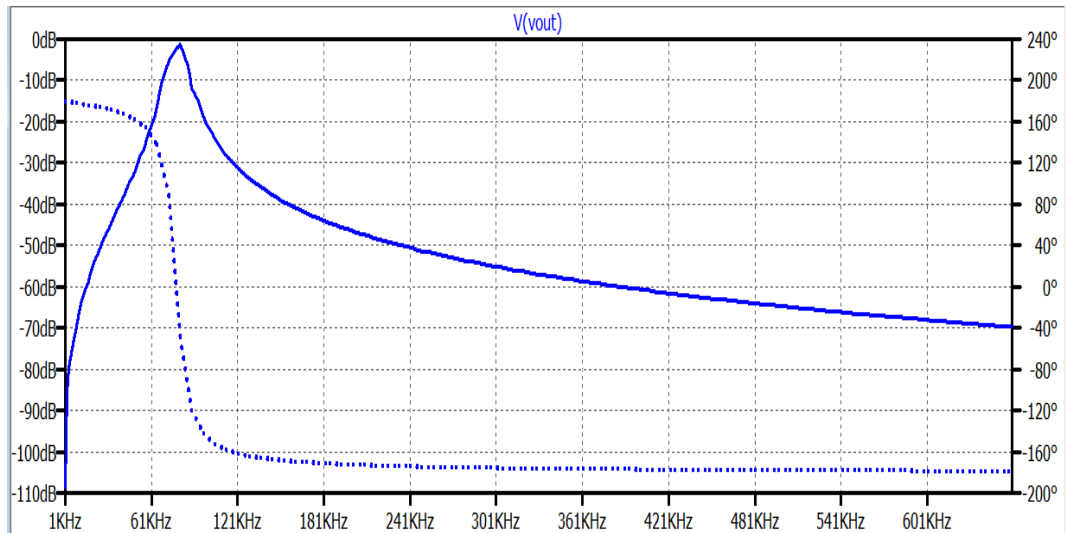


Figure 5.8: Filter output at 80 kHz close view.

The filter circuit measurement was repeated at 80 kHz, and the results obtained are shown in **Figures 5.7** and **5.8** after obtaining this result, a comparison was made at the three closest lower limit frequency values.

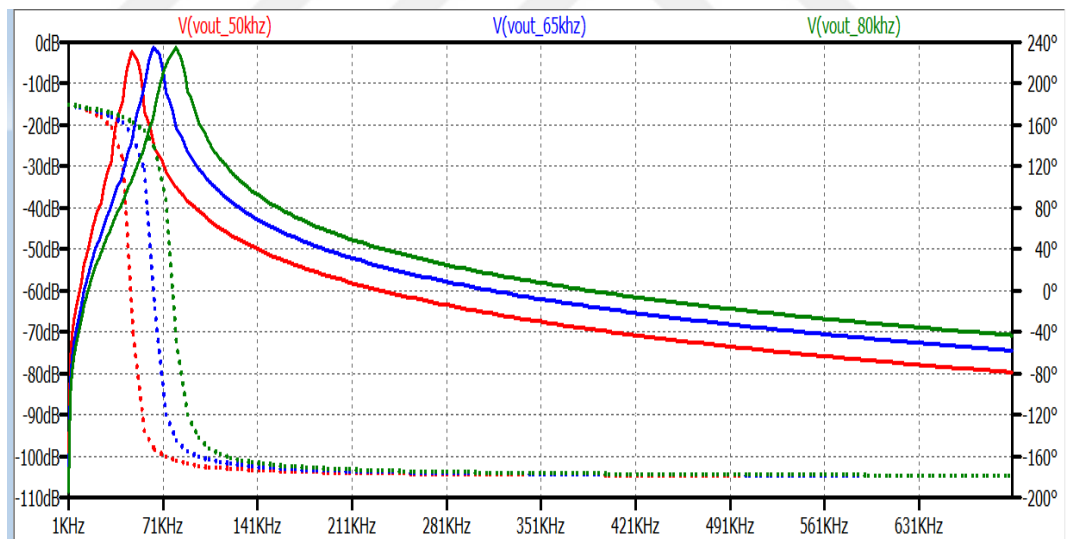


Figure 5.9: Filter output comparison at mid-frequency 65 kHz.

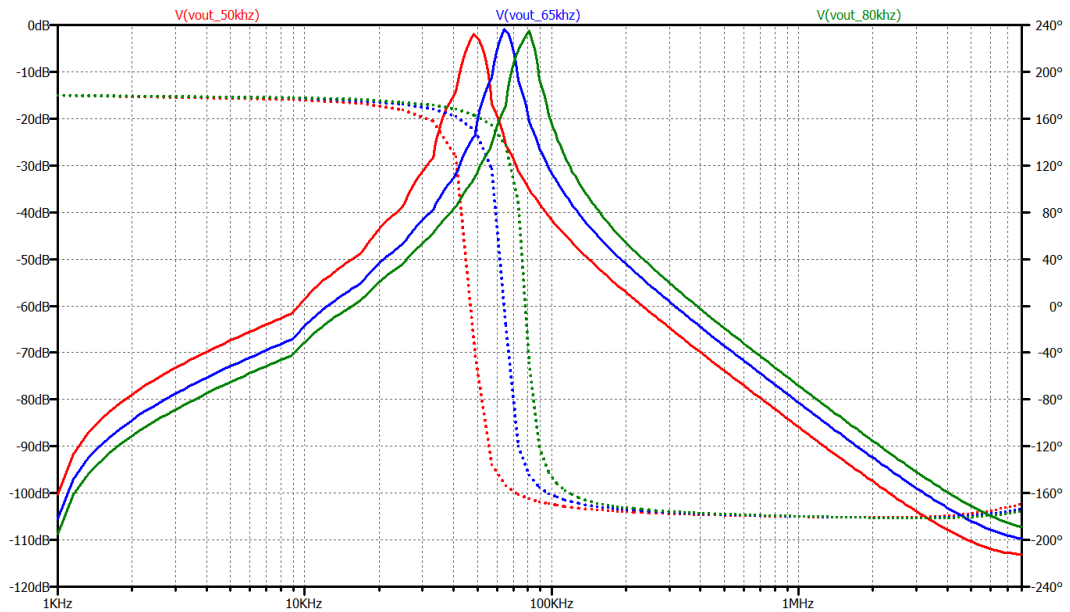


Figure 5.10: Filter output comparison at mid-frequency 65 kHz logarithmic view.

Figure 5.9 shows the filter outputs obtained at 50 kHz, 65 kHz, and 80 kHz, respectively, on the same graph. There is no degradation in the filter characteristics, Q value, or phase response was observed. In addition, **Figure 5.10** shows the frequency and phase response on a logarithmic scale.

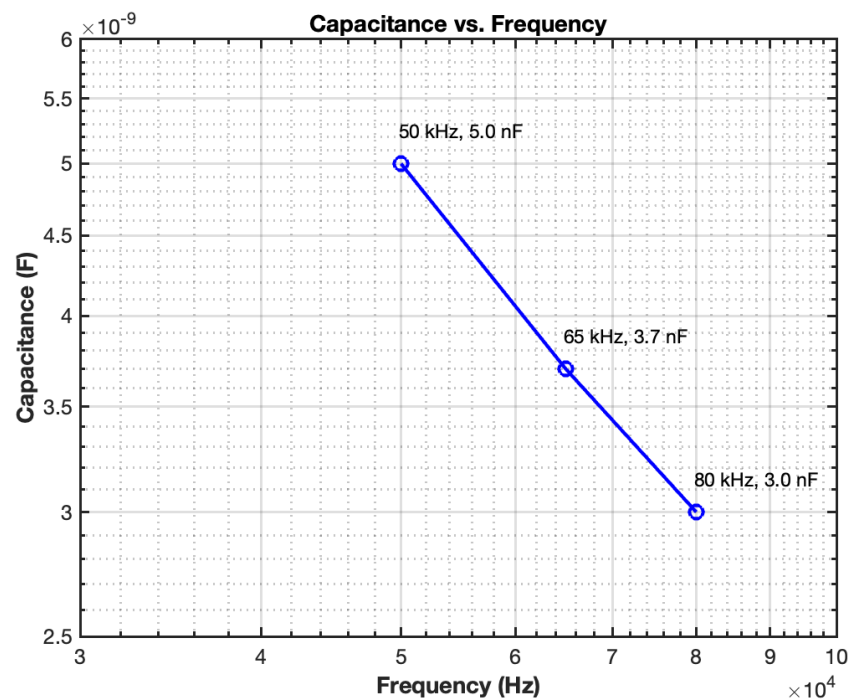


Figure 5.11: Capacitance vs. frequency curve at 65 kHz.

Figure 5.11 shows the measurements taken in the low frequency band and the corresponding capacitance values. When the filter is operating at low frequencies, the change in frequency shows a change that is close to the change in capacitance in percentage terms.

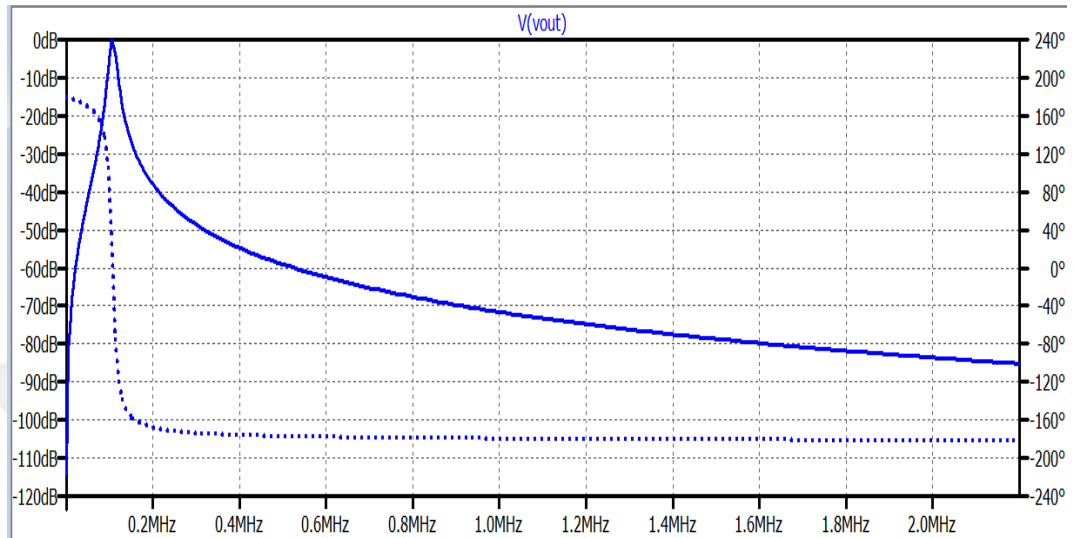


Figure 5.12: Filter output at 105 kHz.

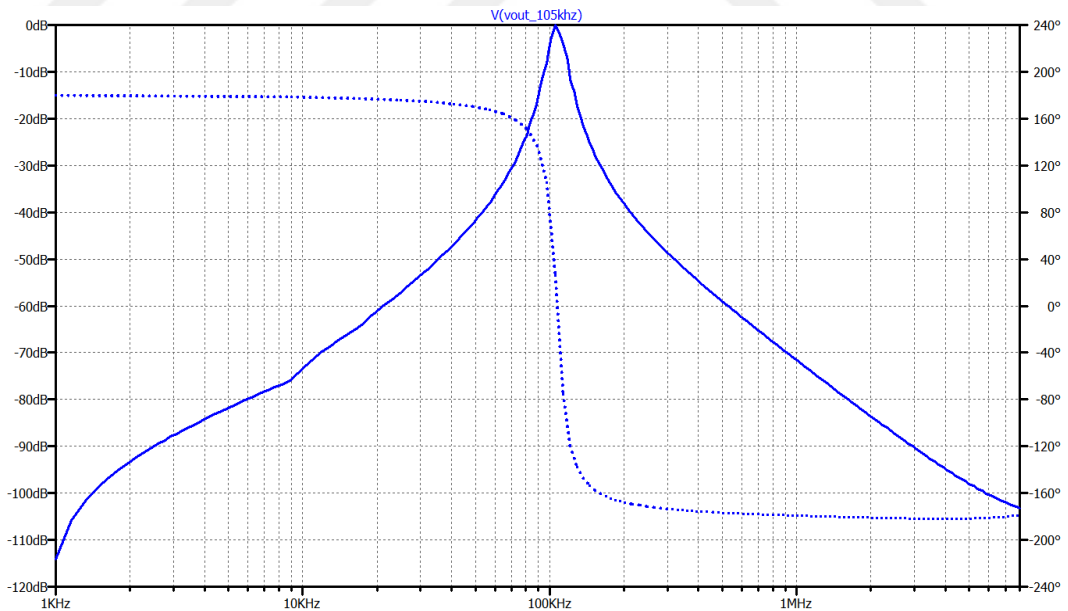


Figure 5.13: Filter output at 105 kHz logarithmic view.

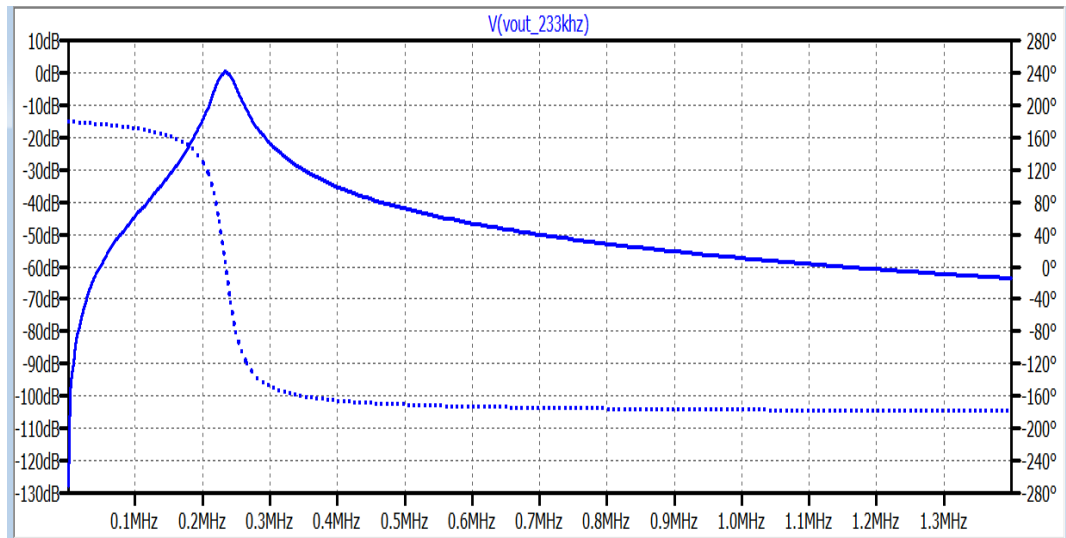


Figure 5.14: Filter output at 233 kHz.

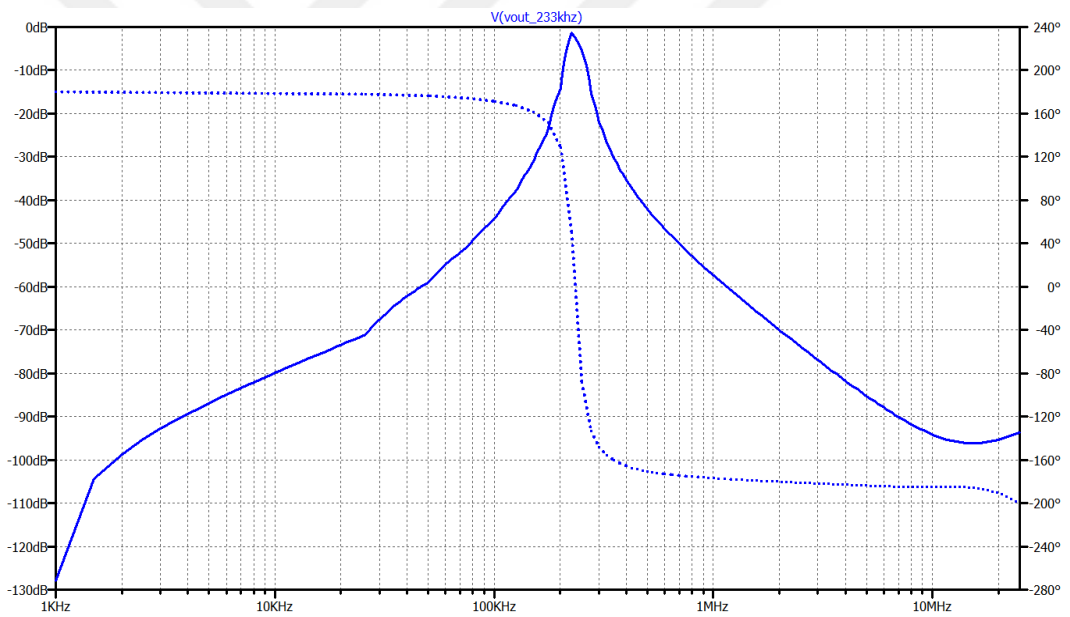


Figure 5.15: Filter output at 233 kHz logarithmic view.

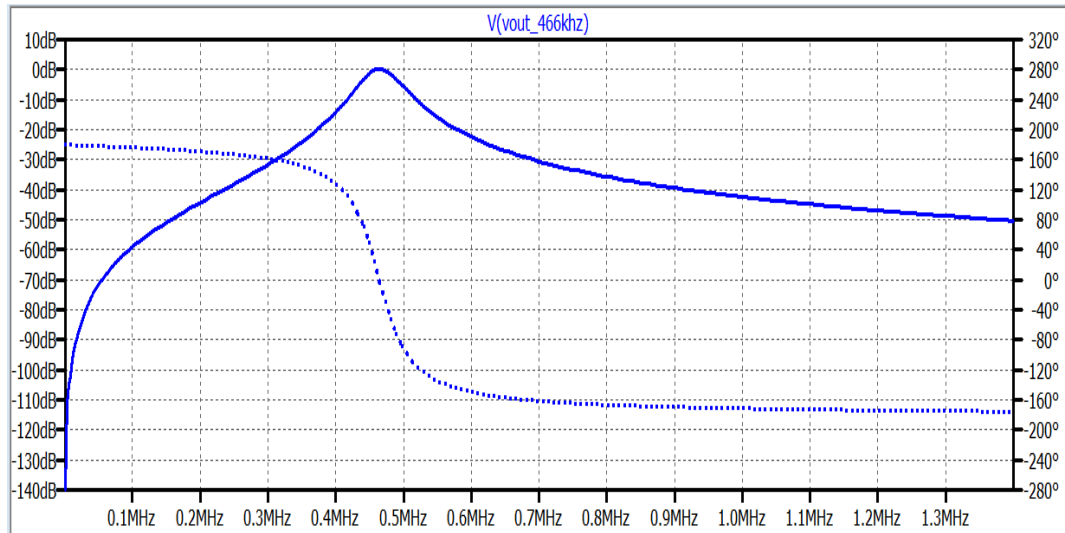


Figure 5.16: Filter output at 466 kHz.

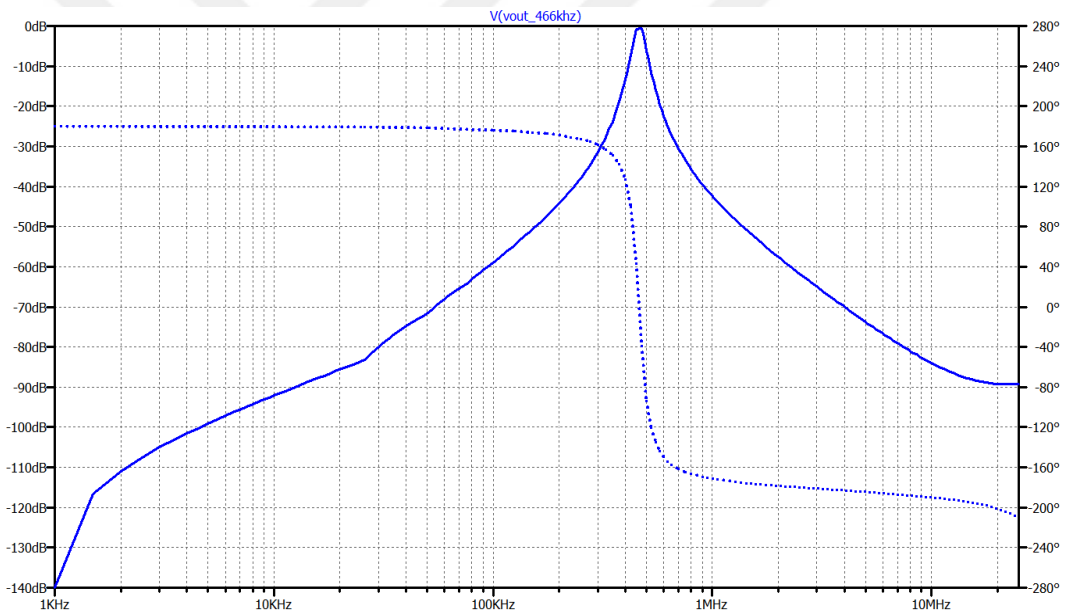


Figure 5.17: Filter output at 466 kHz logarithmic view.

Figures 5.12, 5.14, and 5.16 show the filter frequency and phase responses at 105 kHz, 233 kHz, and 466 kHz, respectively. In addition, Figure 5.13, 5.15 and 5.17 shows the frequency and phase response on a logarithmic scale. The frequency has been increased logarithmically also no changes have been observed in the filter characteristics.

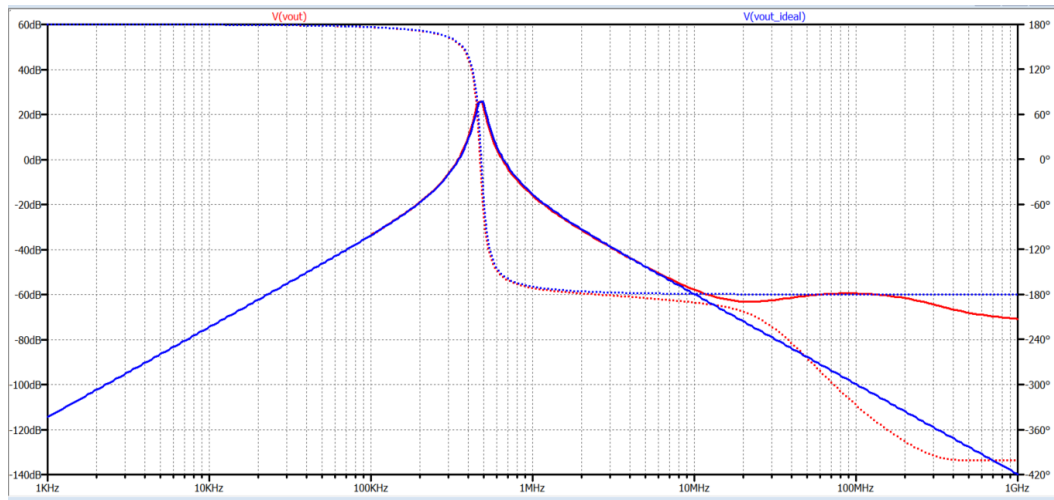


Figure 5.18: Measured vs theoretical output comparison at 466 kHz.

Figure 5.18 compares the filter analyzed with an ideal Butterworth 4th order bandpass filter. The filter center frequency is 466 kHz. The Q factor is ideally 10, measured as 7.25 in the analysis. The phase response appears to be quite close to the ideal. In the frequency response, the Q factor has approached the ideal, but differences are still apparent.

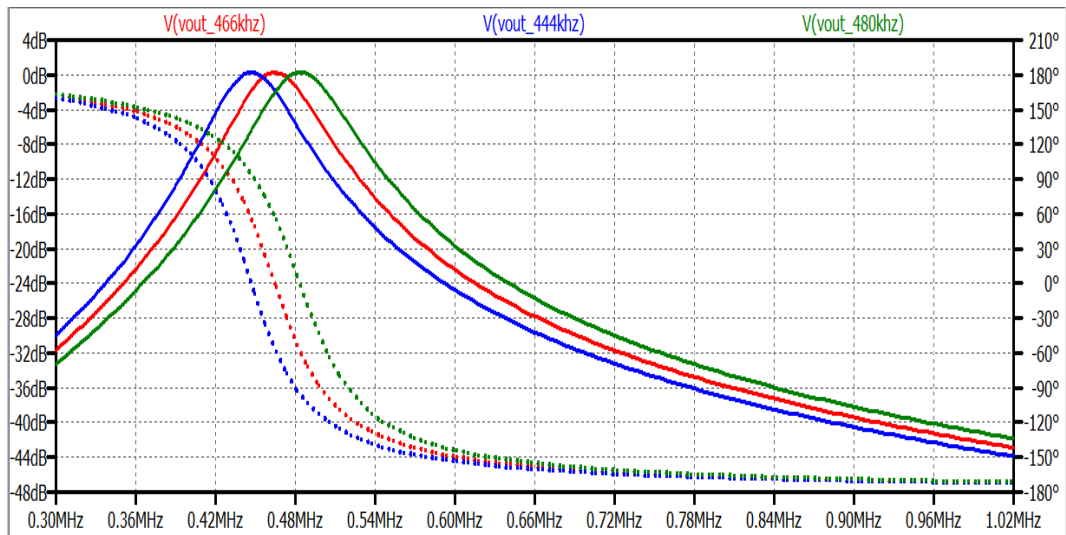


Figure 5.19: Filter output comparison at mid-frequency 466 kHz.

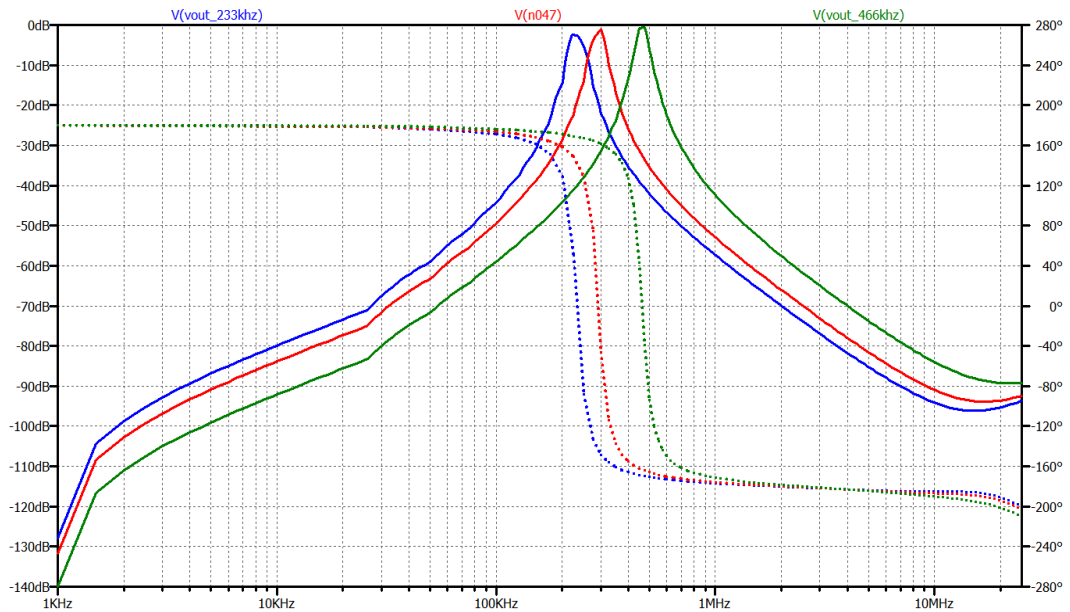


Figure 5.20: Filter output comparison at mid-frequency 466 kHz logarithmic view.

To demonstrate the filter sensitivity, measurements taken at frequencies of 444 kHz and 480 kHz with a center frequency of 466 kHz are presented in the same graph in **Figure 5.19**. This proves the frequency sensitivity and characteristic compatibility of the filter in this region as well. In addition, **Figure 5.20** shows the frequency and phase response on a logarithmic scale.

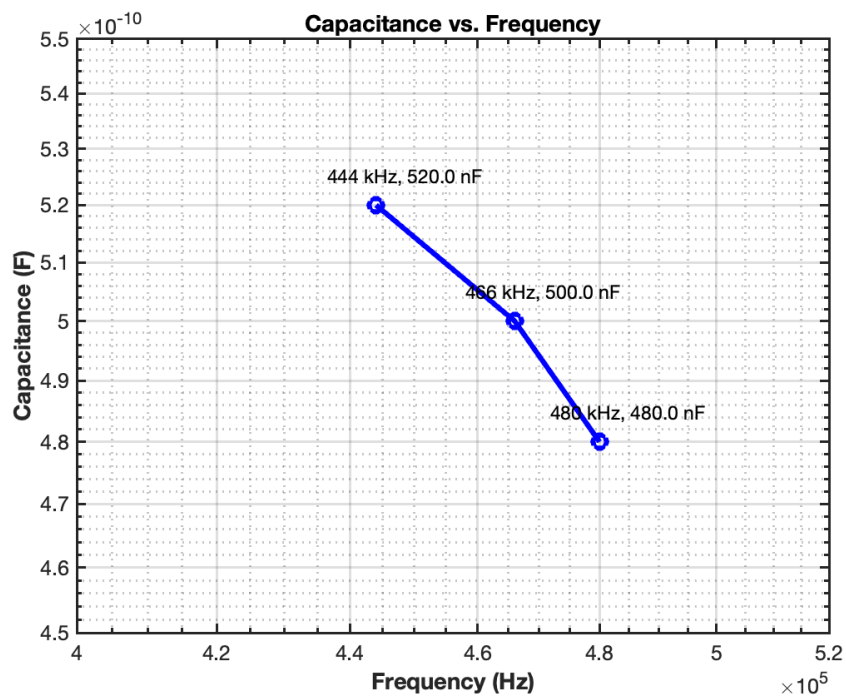


Figure 5.21: Capacitance vs. frequency curve at 466 kHz.

Precise measurements were made using 466 kHz as the center frequency. The results obtained from the precise measurements are presented in **Figure 5.21**. The frequency capacitance curve exhibited the same behavior as the low frequency band.

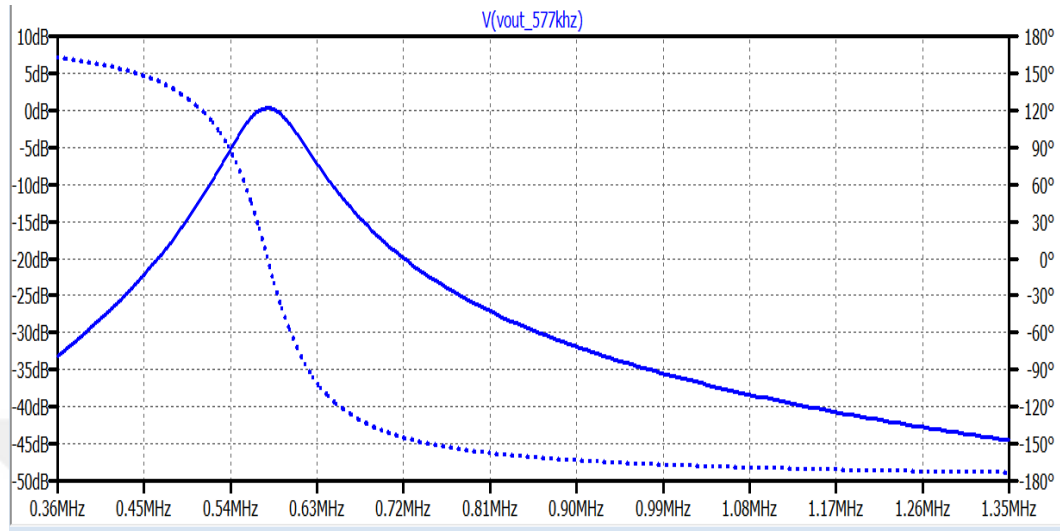


Figure 5.22: Filter output at 577 kHz.

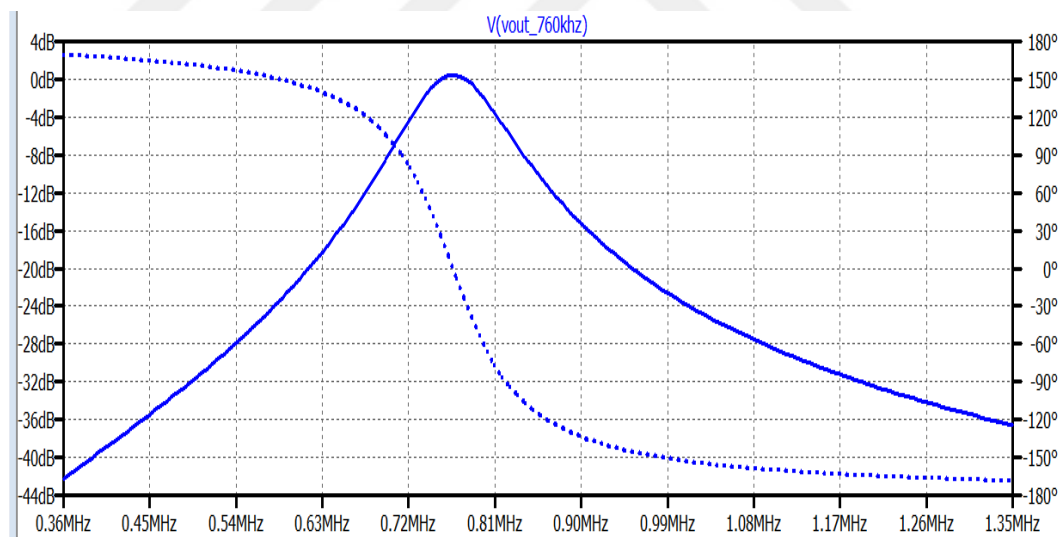


Figure 5.23: Filter output at 760 kHz.

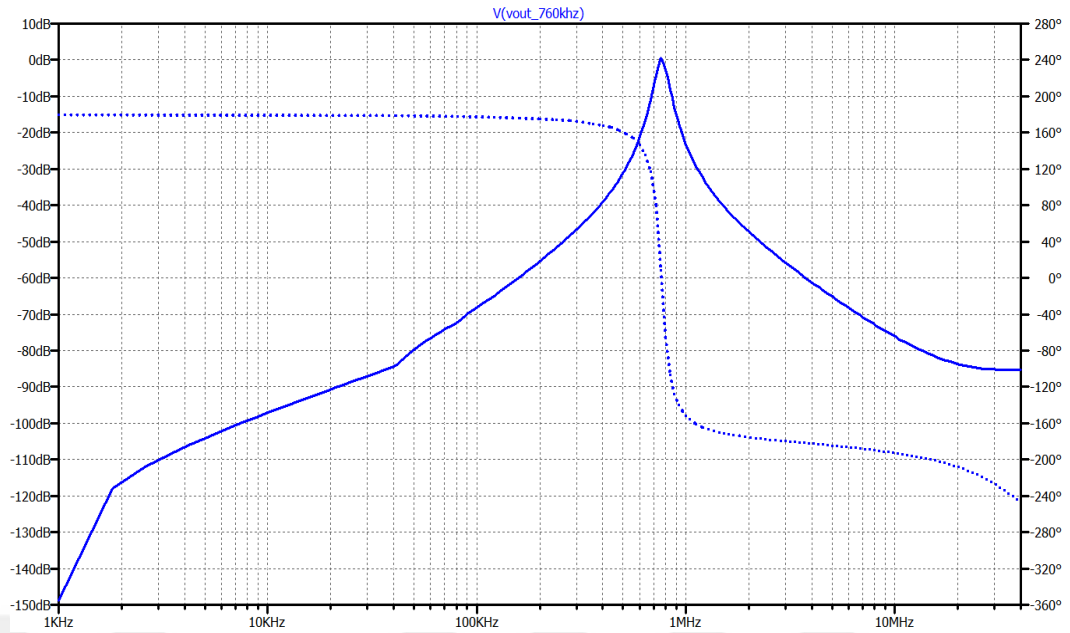


Figure 5.24: Filter output at 760 kHz logarithmic view.

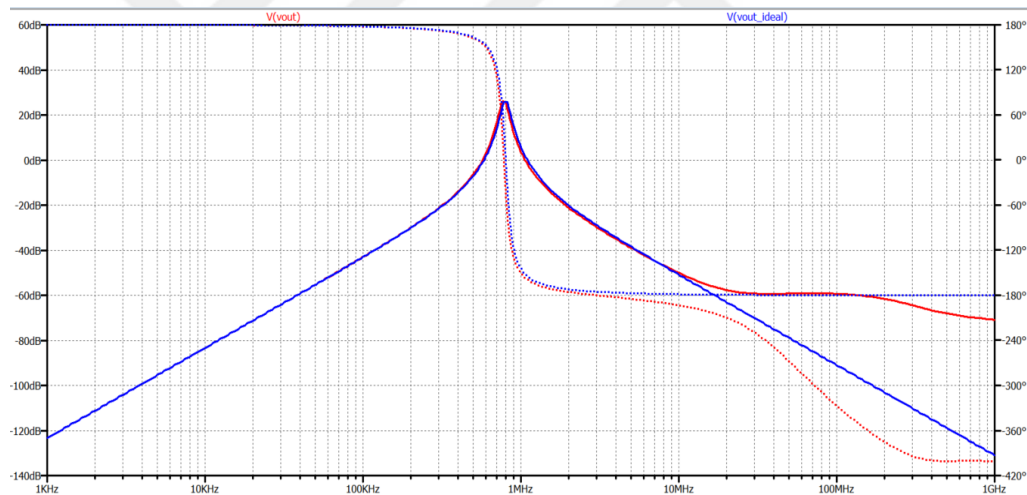


Figure 5.25: Measured vs theoretical output comparison at 760 kHz.

Figure 5.25 compares the filter analyzed with an ideal Butterworth 4th order bandpass filter. The filter center frequency is 760 kHz. The Q factor is ideally 10, measured as 7.25 in the analysis. The phase response appears to be quite close to the ideal. In the frequency response, the Q factor has approached the ideal, but differences are still apparent.

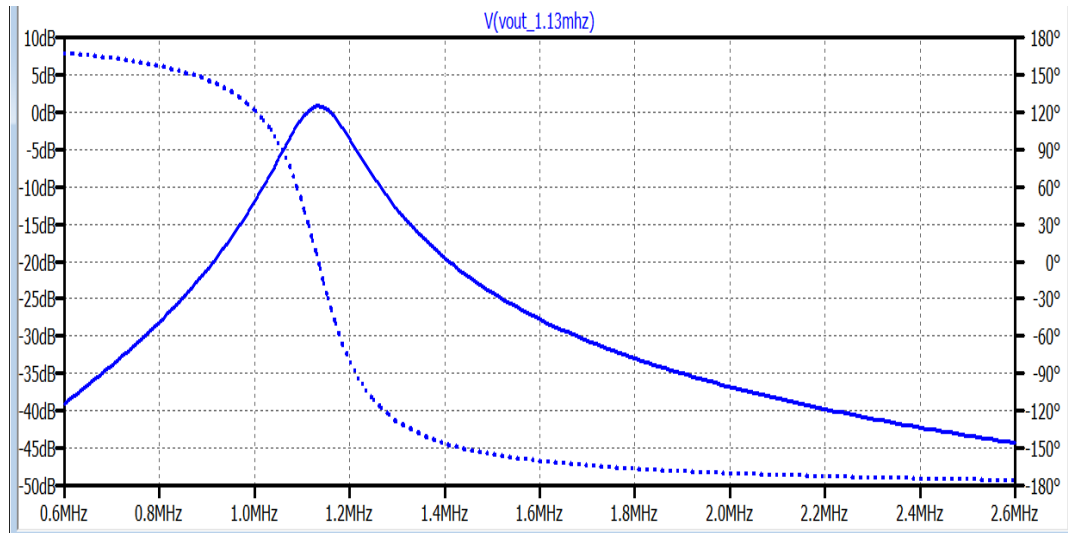


Figure 5.26: Filter output at 1.13 MHz.

The filter's operating frequency was gradually increased and the analysis continued. **Figures 5.22, 5.23, and 5.26** shows the results obtained at 577 kHz, 760 kHz, and 1.13 MHz, respectively. The filter operating band was extended to the middle frequencies. The results obtained were found to be suitable and the analysis continued. In addition, **Figure 5.24** shows the frequency and phase response on a logarithmic scale at 760 kHz frequency.

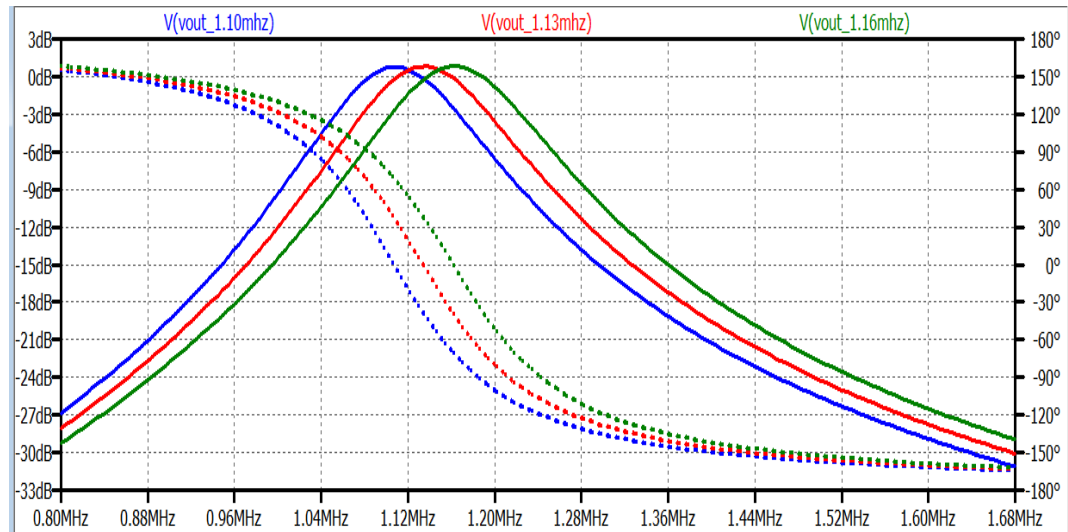


Figure 5.27: Filter output comparison at mid-frequency 1.13 MHz.

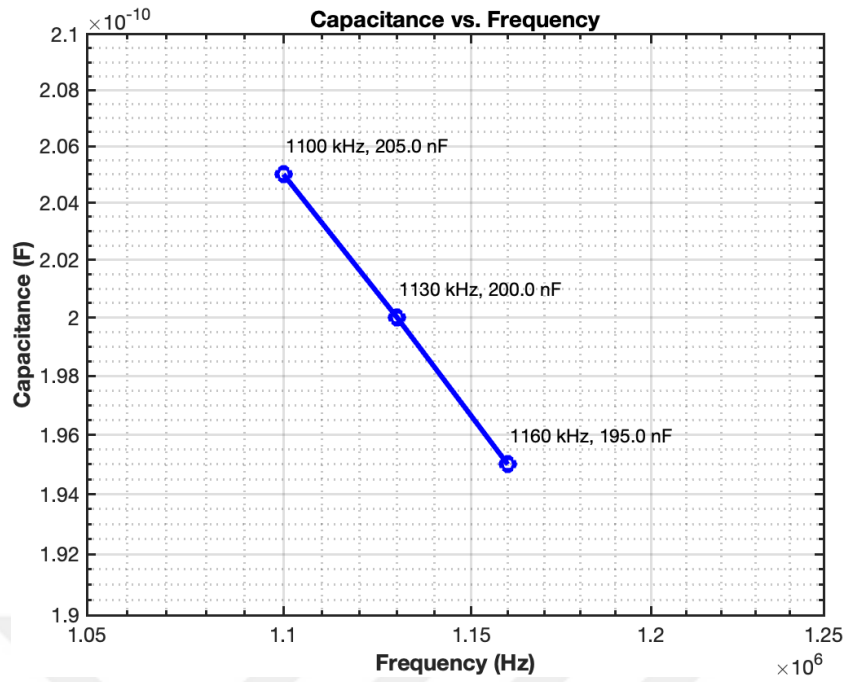


Figure 5.28: Capacitance vs. frequency curve at 1.13 MHz.

One of the center frequencies of the designed filter's operating frequency range has been accepted as 1.13 MHz. Therefore, measurements taken at frequencies of 1.10 MHz, 1.13 MHz, and 1.16 MHz are provided in **Figure 5.27** and **5.28** for sensitivity and detailed analysis. When the data was analyzed, the operating performance and sensitivity were found to be positive.

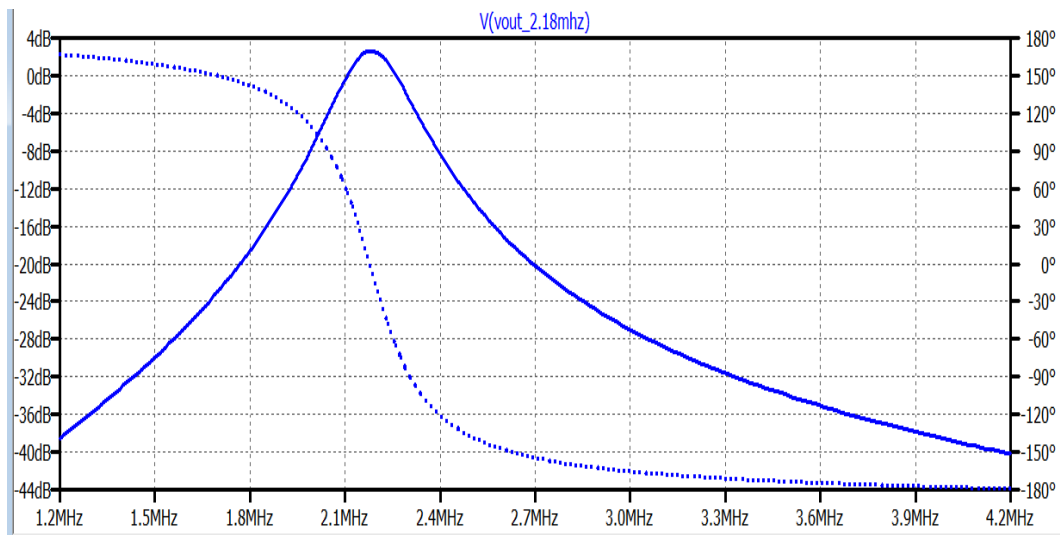


Figure 5.29: Filter output at 2.18 MHz.

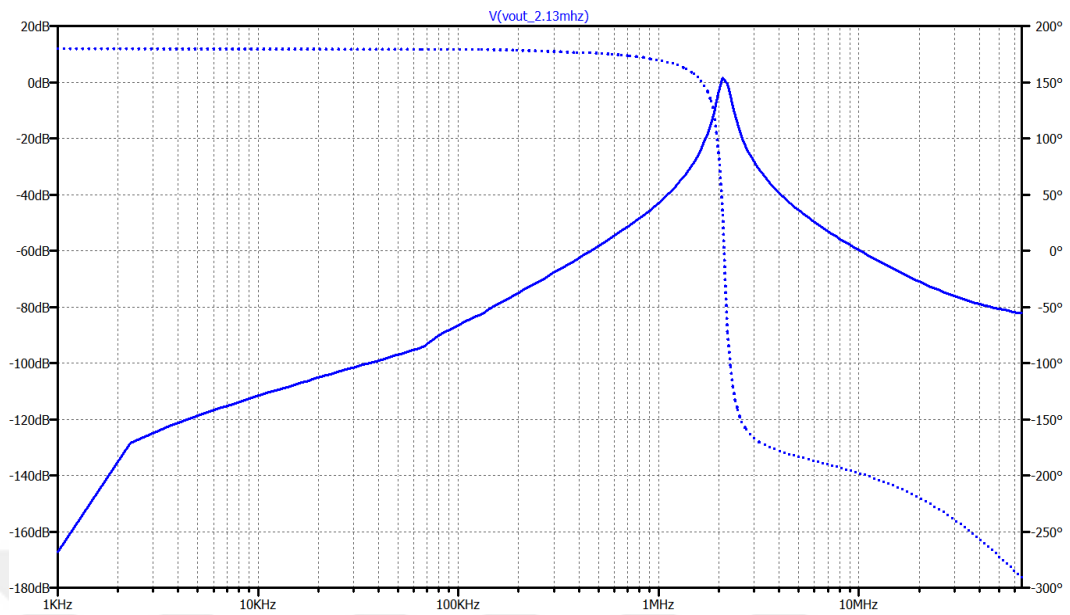


Figure 5.30: Filter output at 2.13 MHz logarithmic view.

The filter was tested at high frequencies. The measurements obtained at 2.18 MHz are shown in **Figure 5.29**. The measurements were found to be acceptable, and the filter performance was observed to be stable. In addition, **Figure 5.30** shows the frequency and phase response on a logarithmic scale.

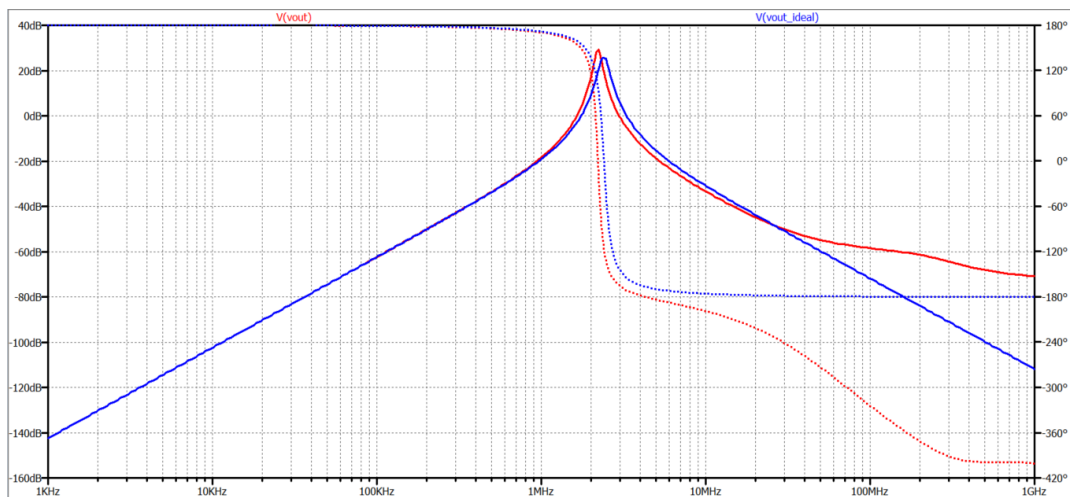


Figure 5.31: Measured vs theoretical output comparison at 2.13 MHz.

Figure 5.31 compares the filter analyzed with an ideal Butterworth 4th order bandpass filter. The filter center frequency is 50 kHz. The Q factor is ideally 10, measured as

7.25 in the analysis. The phase response appears to be quite close to the ideal. In the frequency response, the Q factor has approached the ideal, but differences are still apparent.

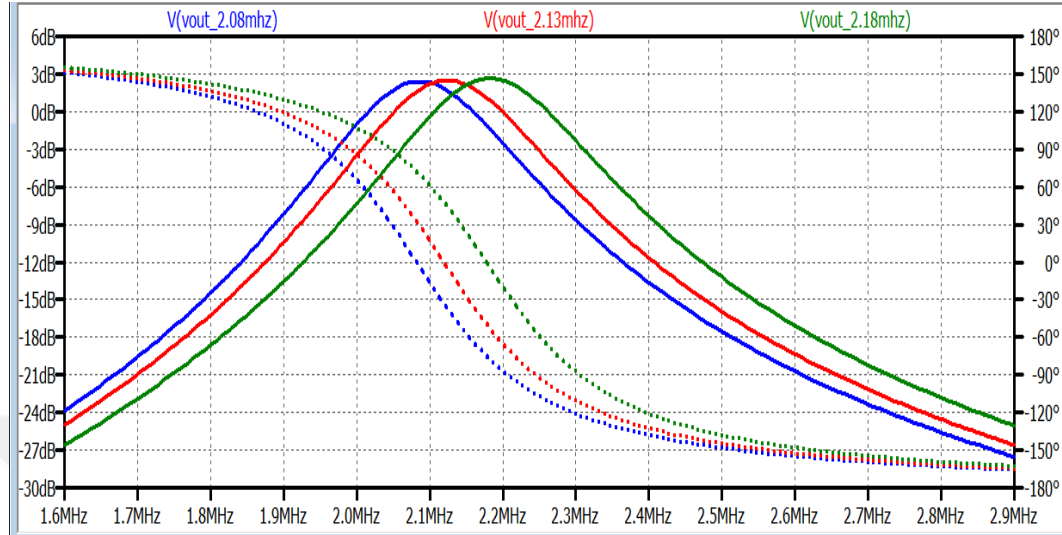


Figure 5.32: Filter output comparison at mid-frequency 2.13 MHz.

Another center frequency within the filter's operating range has been set at 2 MHz to observe the filter sensitivity and measurement accuracy, measurements were repeated at passband center frequencies of 2.08 MHz, 2.13 MHz, and 2.18 MHz and are shown in **Figure 5.32**.

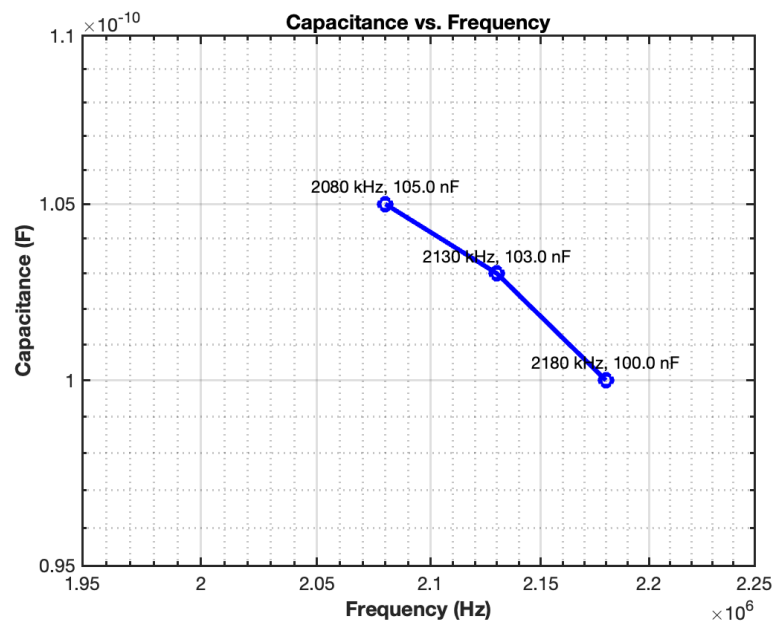


Figure 5.33: Capacitance vs. frequency curve at 2.13 MHz.

Another of the filter operating band's mid-frequencies, around 2 MHz, was accepted as the passband center, and the sensitive measurement was repeated. The sensitive measurement results obtained were found to be stable and consistent regardless of the frequency band and are given in **Figure 5.33**.

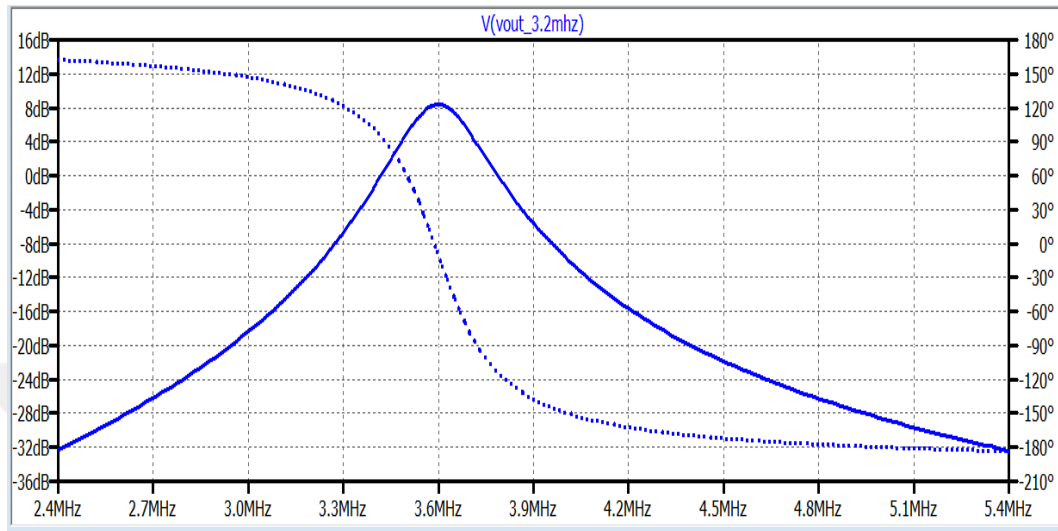


Figure 5.34: Filter output at 3.2 MHz.

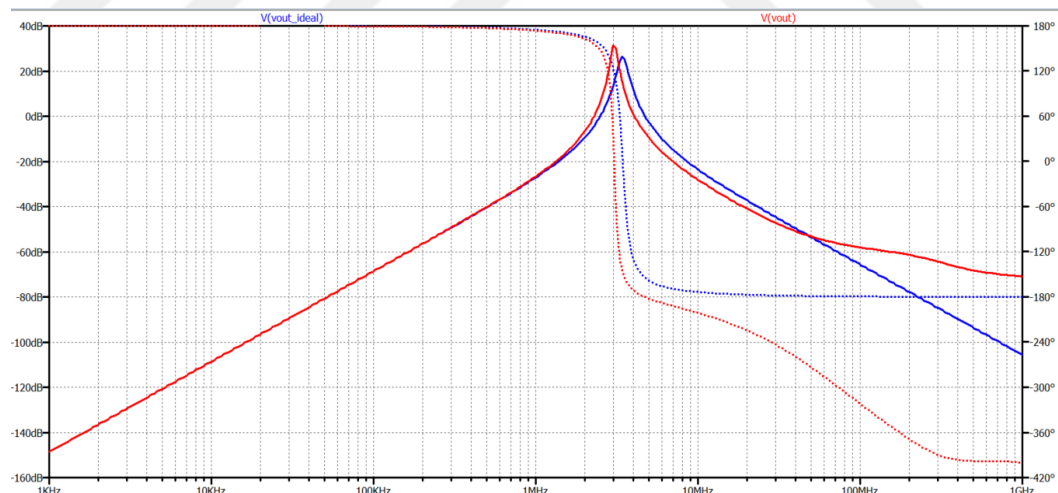


Figure 5.35: Measured vs theoretical output comparison at 3.2 MHz.

Figure 5.35 compares the filter analyzed with an ideal Butterworth 4th order bandpass filter. The filter center frequency is 3.2 MHz. The Q factor is ideally 10, measured as 7.25 in the analysis. The phase response appears to be quite close to the ideal. In the

frequency response, the Q factor has approached the ideal, but differences are still apparent.

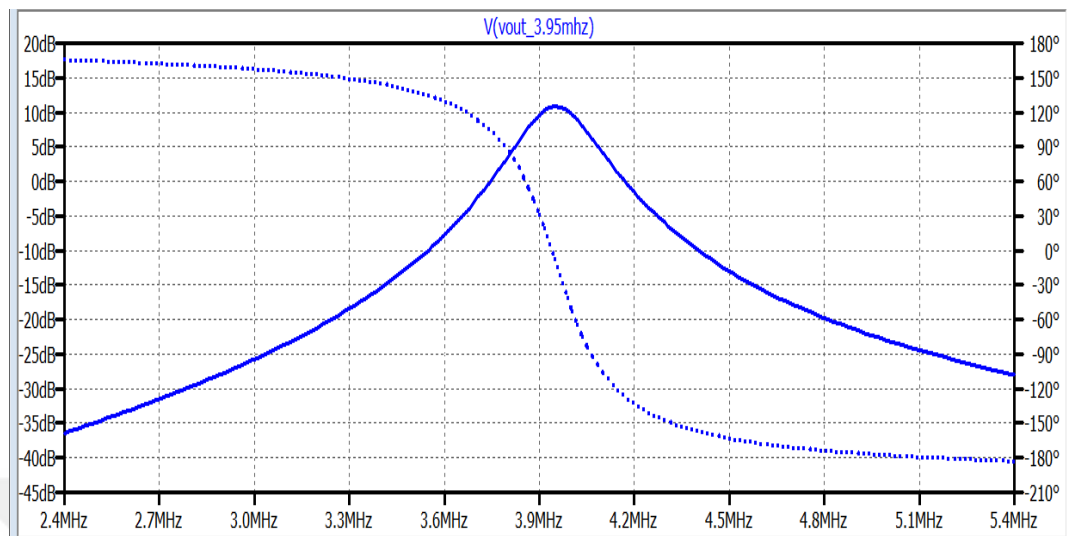


Figure 5.36: Filter output at 3.95 MHz.

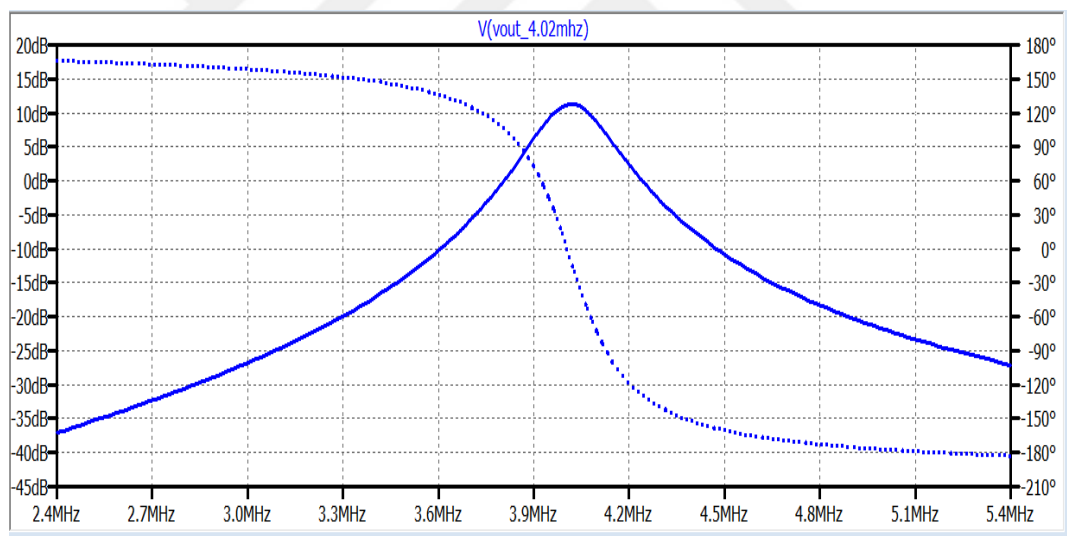


Figure 5.37: Filter output at 4.02 MHz.

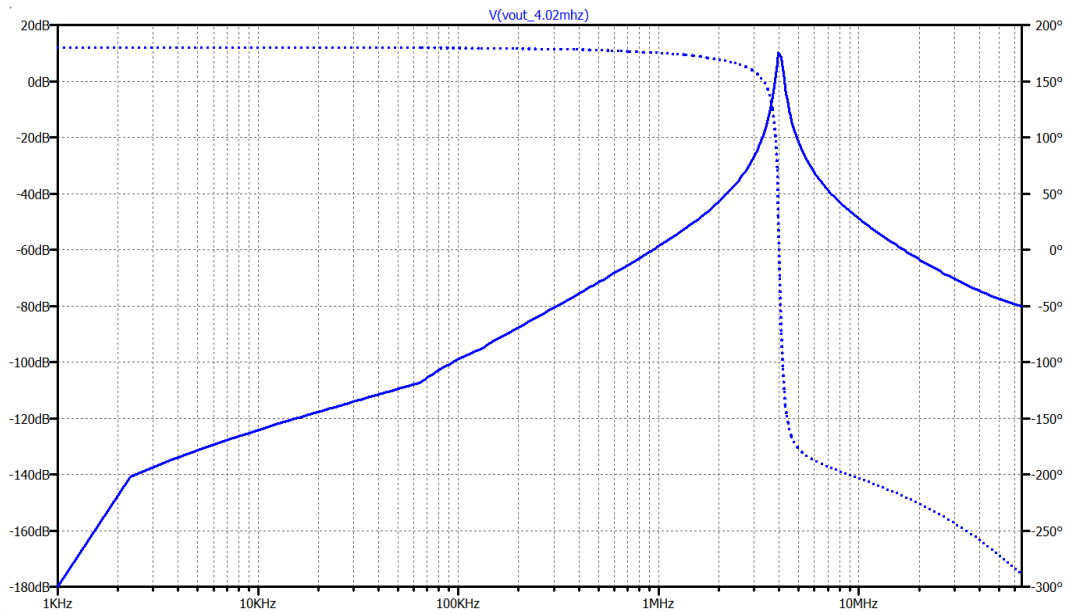


Figure 5.38: Filter output at 4.02 MHz logarithmic view.

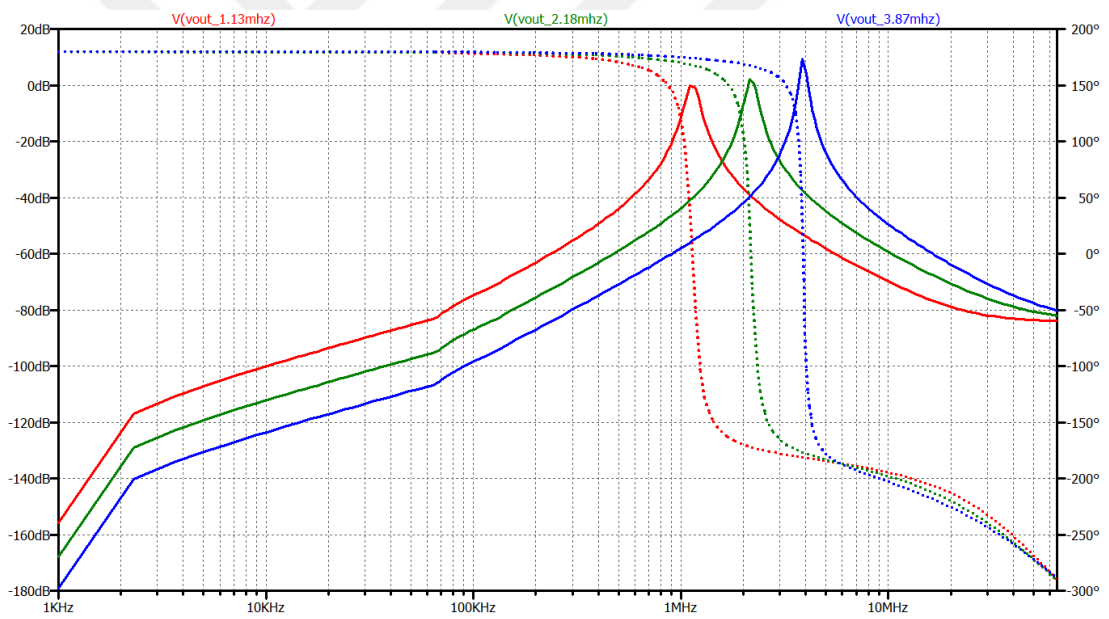


Figure 5.39: Filter output comparison at Mid-frequency 2.18 MHz logarithmic view.

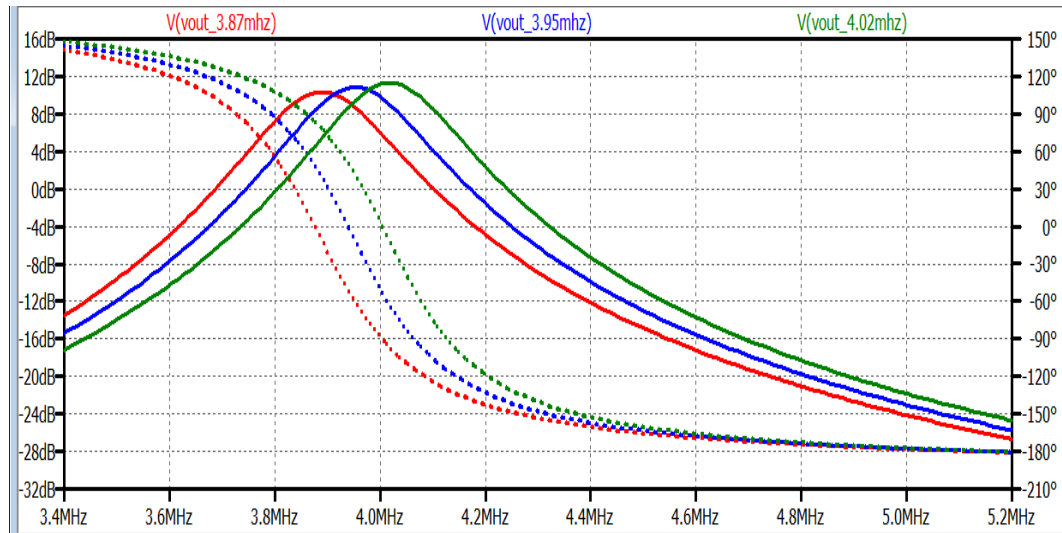


Figure 5.40: Filter output comparison at mid-frequency 3.95 MHz.

Finally, the filter was tested at frequencies of 3.2 MHz, 3.95 MHz, and 4.02 MHz, and the measurements obtained are presented in **Figure 5.34**, **5.36**, **5.37** and **5.40**. Thus, all values in the frequency range of the filter design were analyzed in the simulation environment. In addition, **Figure 5.38** and **5.39** shows the frequency and phase response on a logarithmic scale. The analysis results indicate that the filter exhibits the same characteristic properties across entire operating range and that performance is stable.

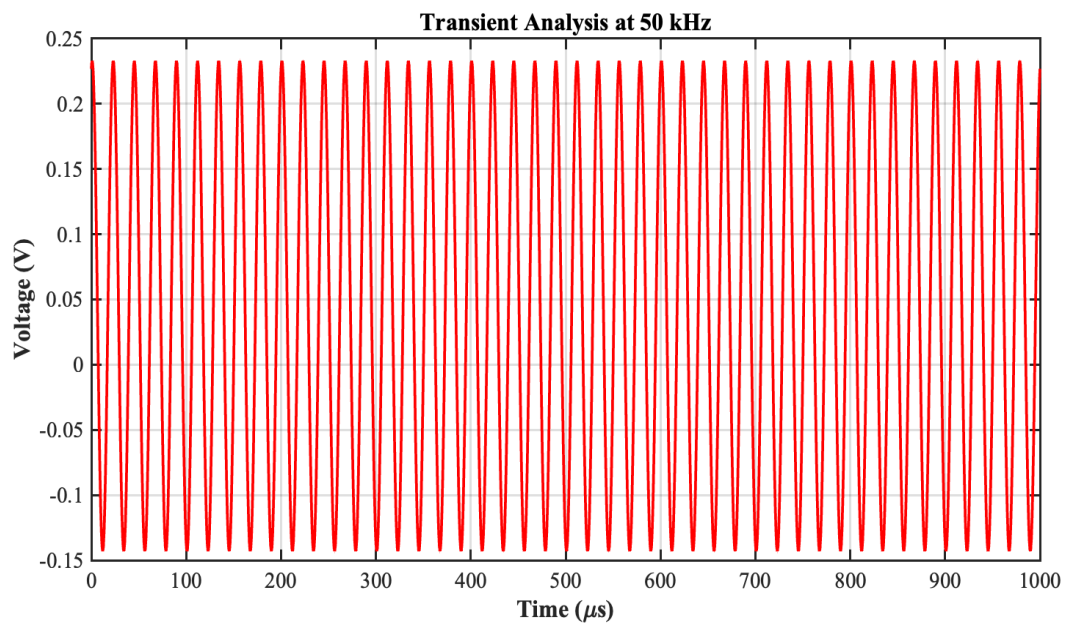


Figure 5.41: Transient analysis at 50 kHz.

The **Figure 5.41** shows the steady-state transient response of the band-pass filter operating at 50 kHz. The output exhibits a stable amplitude with low distortion in response to the input signal. This confirms that the filter operates with high stability and low loss at the designed center frequency.

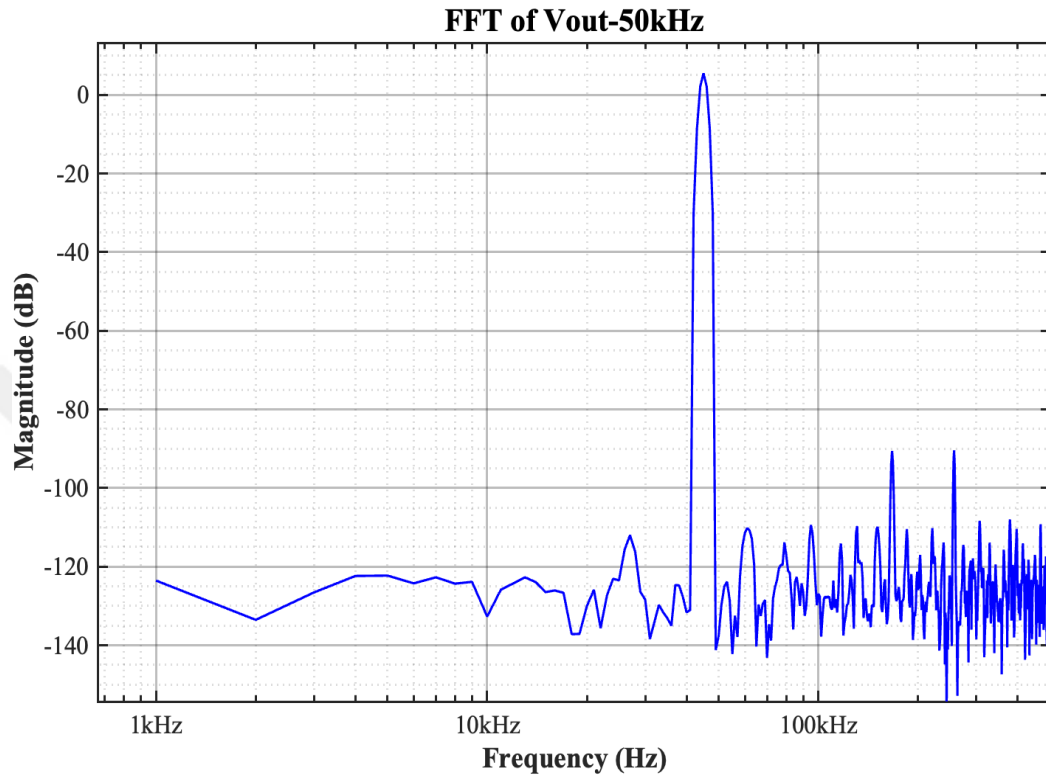


Figure 5.42: FFT result at 50 kHz.

The **Figure 5.42** presents the FFT spectrum of the filter output operating at a center frequency of 50 kHz. A distinct peak at 50 kHz and effective suppression of low-frequency components are observed. This confirms that the filter exhibits high selectivity at the target frequency and effectively attenuates undesired noise components

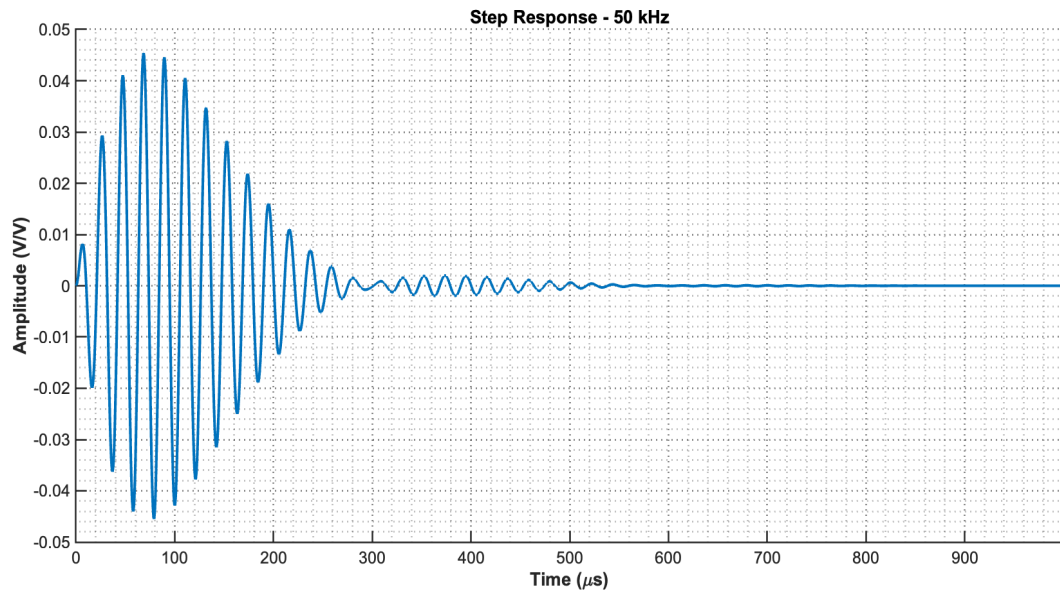


Figure 5.43: Step response at 50 kHz.

The **Figure 5.43** illustrates the step response of the band-pass filter with a center frequency of 50 kHz. The observed damped oscillations in the output waveform indicate the natural resonant behavior of the filter and its moderate-to-high Q factor. This result confirms that the filter operates stably in the transient regime and quickly settles to equilibrium after a step input

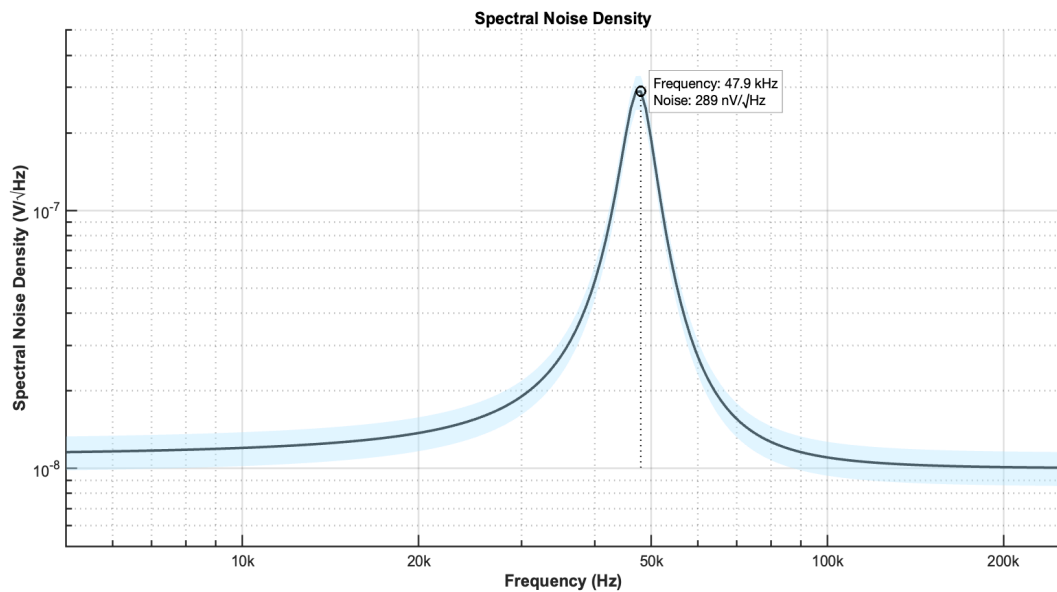


Figure 5.44: Spectral noise density at 50 kHz.

The **Figure 5.44** shows the spectral noise density at the output of the band-pass filter. A distinct noise peak of approximately $289 \text{ nV}/\sqrt{\text{Hz}}$ is observed at 47.9 kHz , indicating the noise amplification at the filter's center frequency. The results confirm that the narrow-band structure of the filter increases the noise level at the target frequency while maintaining low noise characteristics outside the passband.

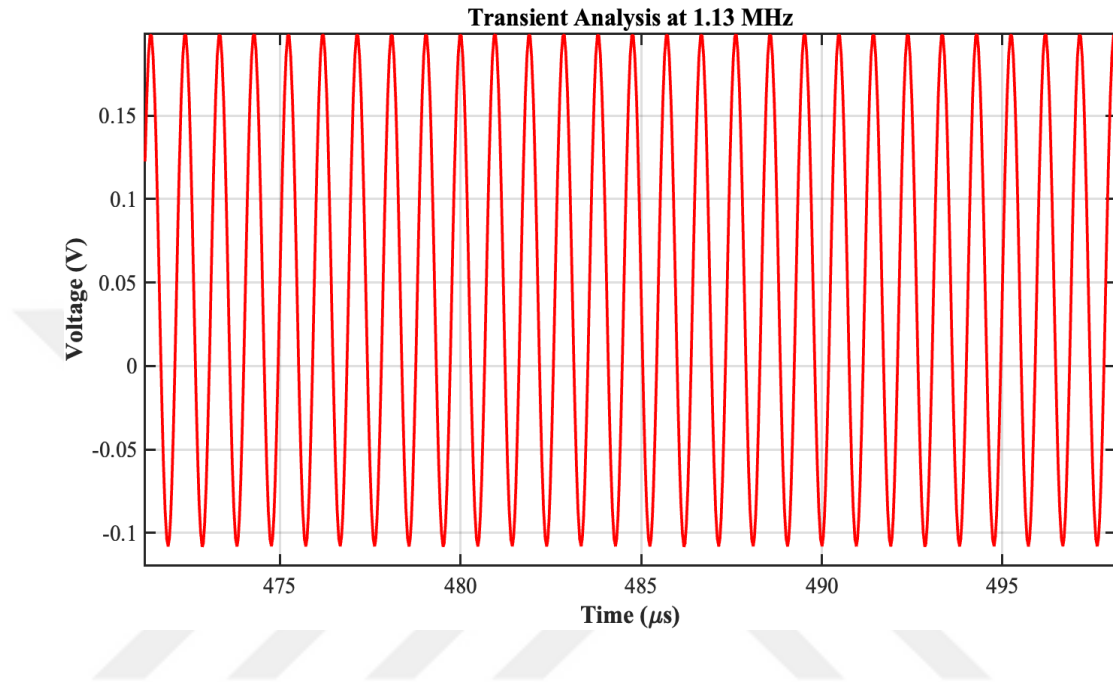


Figure 5.45: Transient analysis at 1.13 MHz.

The **Figure 5.45** illustrates the steady-state transient response of the band-pass filter operating at 1.13 MHz . The output signal maintains a stable amplitude with low distortion, indicating effective operation of the filter at high frequency. This result confirms that the filter exhibits stable and reliable performance at the designed center frequency.

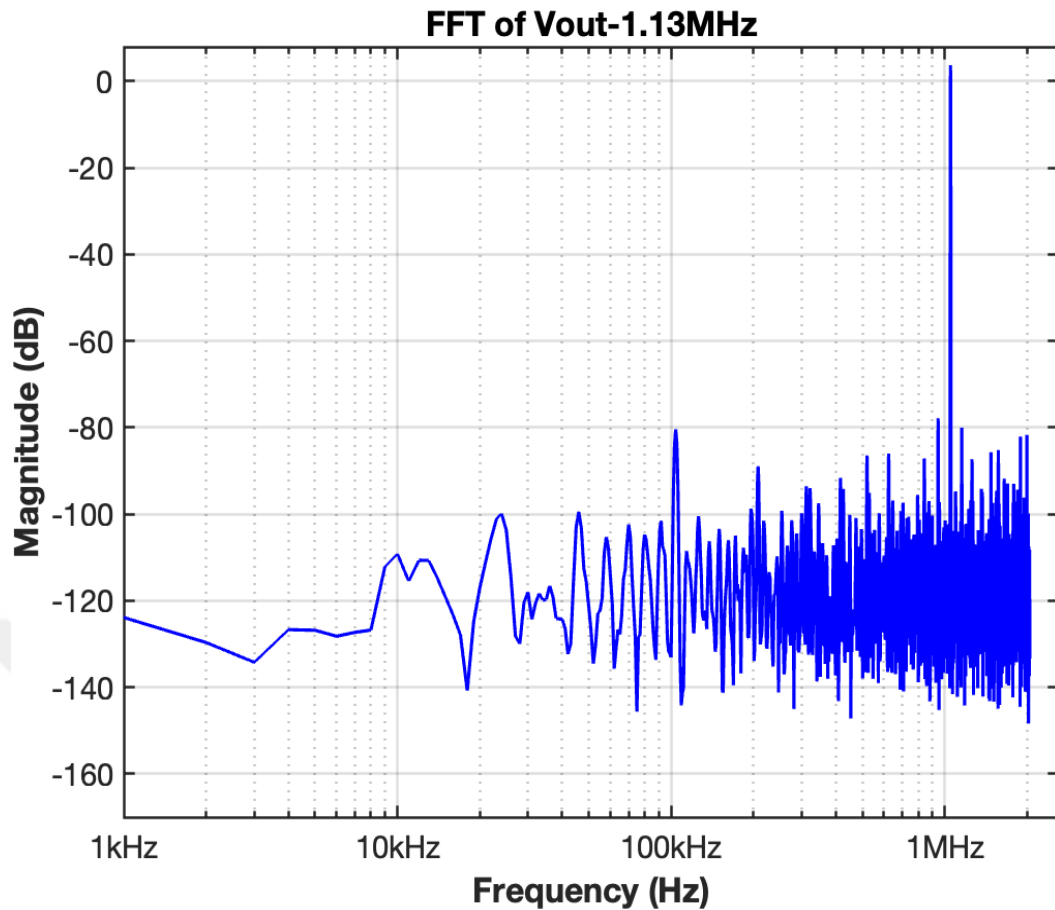


Figure 5.46: FFT result at 1.13 MHz.

The **Figure 5.46** presents the FFT analysis of the output signal of the band-pass filter operating at a center frequency of 1.13 MHz. A strong peak at 1.13 MHz and a significant attenuation of other frequency components are observed in the spectrum. This demonstrates that the filter maintains its narrow-band characteristics at high frequency, ensuring effective signal selectivity.

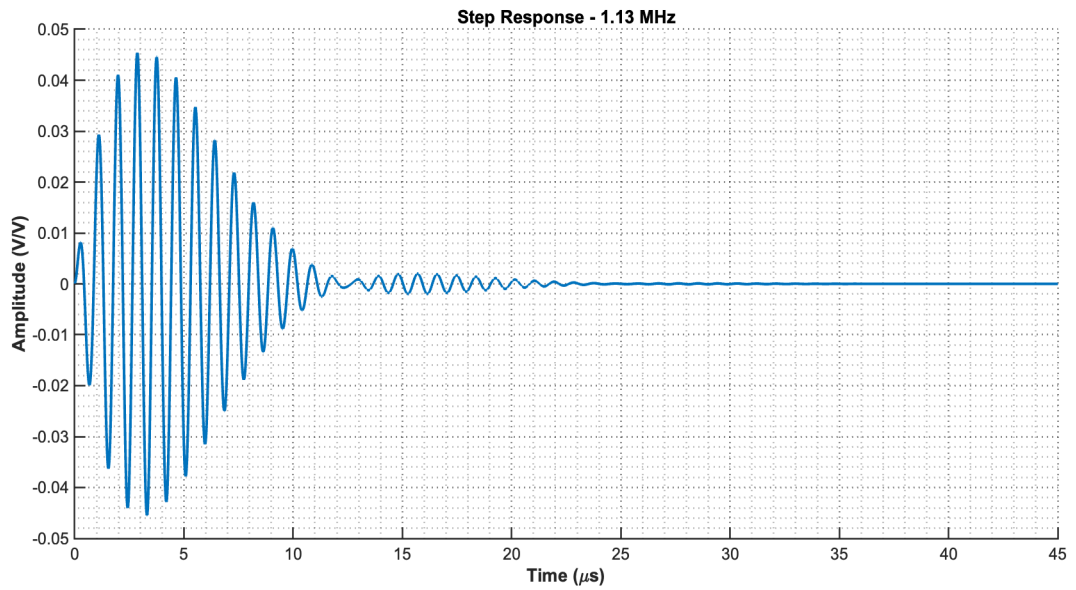


Figure 5.47: Step response at 1.13 MHz.

The **Figure 5.47** illustrates the step response of the band-pass filter with a center frequency of 1.13 MHz. The output exhibits high-frequency oscillations that decay rapidly, indicating a fast transient response and well-controlled resonance behavior of the filter. This result demonstrates the filter's stable and quick settling performance at high frequency.

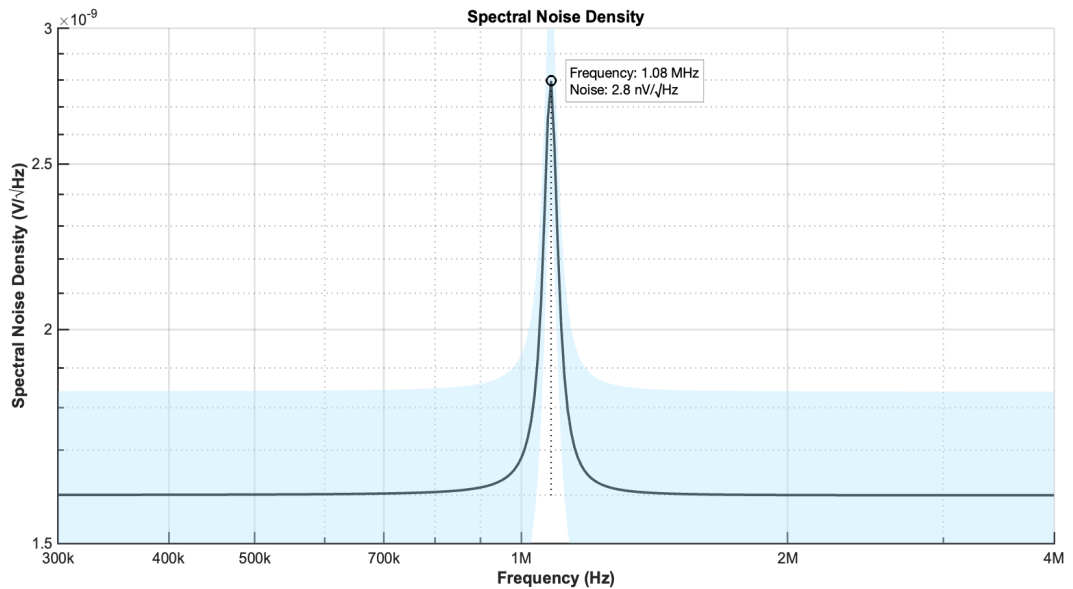


Figure 5.48: Spectral noise density at 1.13 MHz.

The **Figure 5.48** presents the spectral noise density of the band-pass filter operating at a center frequency of 1.13 MHz. A narrow-band noise peak of approximately $2.8 \text{ nV}/\sqrt{\text{Hz}}$ is observed around 1.08 MHz, indicating an increase in noise power density at the filter's center frequency. These results clearly demonstrate the in-band noise characteristics and narrow-band behavior of the filter at high frequencies.

Overall, as expected from the filter design, the passband has a maximum flat response, while the stopband attenuation increases sharply. The circuit parameters determine the center frequency for each configuration, resulting in a bandwidth determined by the Q-factor. From the graphs derived from the filter's output response, the calculated Q-factor value was determined to be approximately 7.25. This value reflects the sharpness and selectivity of the filter, indicating a high-quality resonance. The higher frequency response has a sharper peak and higher gain, indicating a higher quality factor. The designed filter works as expected in all required frequency ranges. Peak frequency and cut-off frequency values are specific to the signal and are as expected.

5.2. Capacitance Multiplier Analysis

This section presents the simulation results of the completed C multiplier circuit design. To allow for tunability, a C multiplier circuit based on MOSFETs was created. The purpose of this circuit is to adjust capacitance values based on the frequency of the signal. Based on the designated operating frequency range, the circuit's capacitance value range was found to be 60 pF to 6 nF. Capacitance must be doubled 100 times. A MOSFET-based design is used to illustrate the C Multiplier circuit. The data used in these analyses were graphed using MATLAB.

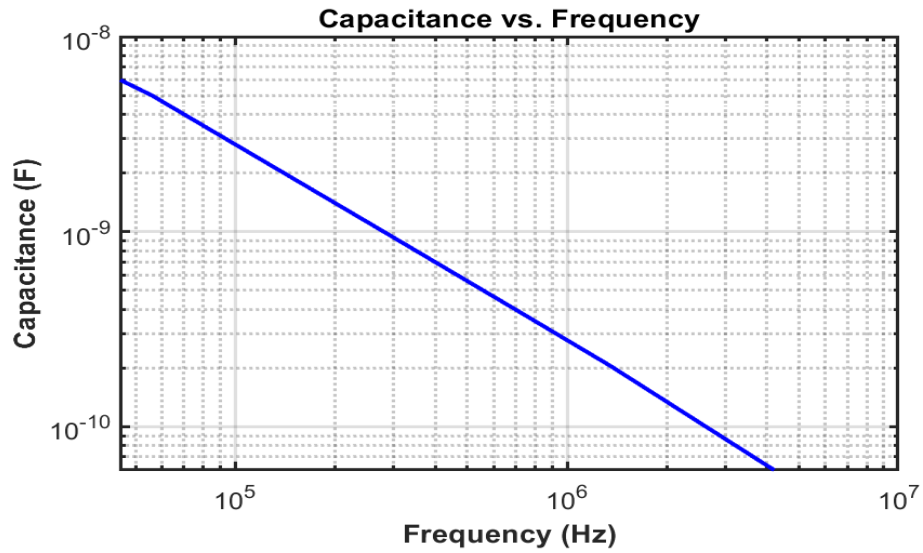


Figure 5.49: Capacitance vs. frequency curve.

The relationship between the peak frequency of the unfiltered input signal and the capacitance values generated by the capacitance multiplier circuit is shown in **Figure 5.49**. The trend shows that capacitance decreases with increasing frequency. This behavior complies with the given filter requirements and is consistent with the data.

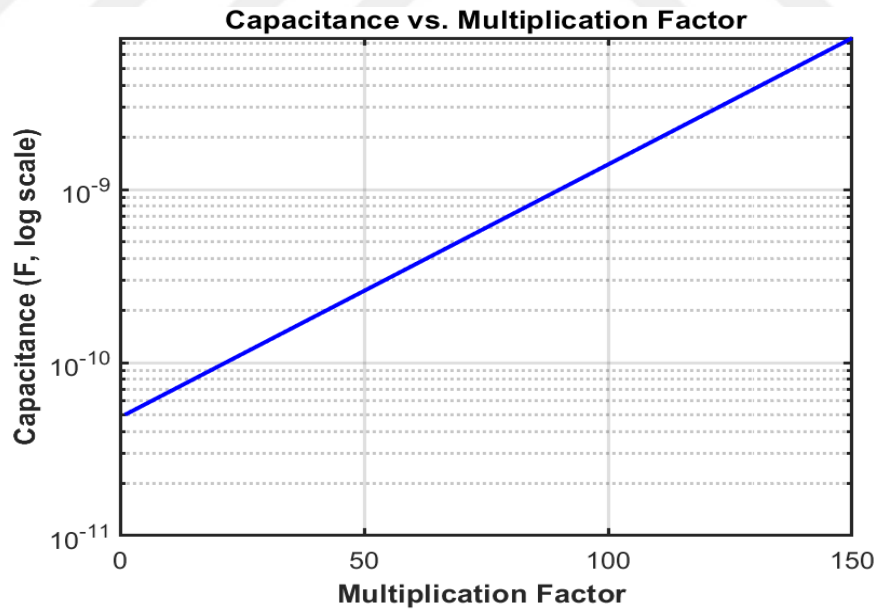


Figure 5.50: Capacitance vs. multiplication factor curve.

Capacitance values have been tuned to cover the filter frequency band. The G parameter (Multiplication Factor) used in mathematical modeling has been compared

with theoretical and simulation results. The results obtained are stable and at the desired level. **Figure 5.50** shows the relationship between Capacitance and Multiplication factor.

5.3. Practical Realizations

This section will present the laboratory tests conducted on the completed filter work. Distinguishing genuine reflections from noise while preserving important information requires robust filtering methods.

First mathematically modeling the desired filter characteristics helped one to obtain the system's transfer function. This transfer function allowed one to ascertain the circuit parameters and also provide an analytical frequency domain behavior of the system description.

The circuit was modeled to validate the theoretical model using LTspice. The computed frequency response was compared with the simulated circuit behavior and theoretical expectations to guarantee consistency.

Following the simulation, the circuit was physically built on a breadboard in order for experimental validation. The Analog Discovery 2 (AD2) test platform was used for signal generation and measurement both. A test signal was produced using the function generator feature of the AD2; the sample count and frequency were chosen to match those used in the LTspice simulations. The response of the circuit was then real-time viewed using the oscilloscope module of the AD2.

Usually found in lab environments, the UA741 was the operational amplifier for the circuit—a generally available general-purpose op-amp. There was dual power supply for the op-amp from $\pm 5\text{V}$. Surface-mount resistors of the 1206 package type were mounted on adapter boards such that they could be placed into the breadboard without soldering. Ceramic capacitors were used since their low parasitic inductance helps to contribute stability at higher frequencies.

Real-time waveform monitoring was made possible by the filter's output's direct connection to the oscilloscope input of the AD2. Measurements were taken to evaluate the practical performance of the circuit, so verifying the accuracy of the design, and then compared with the theoretical and simulation results.

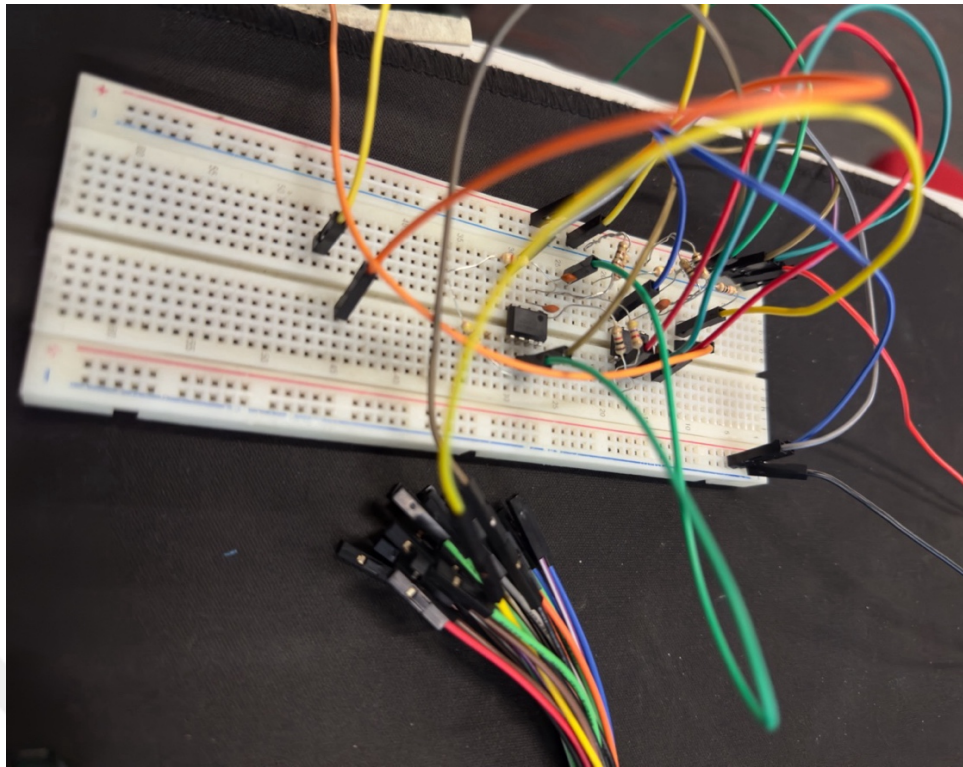


Figure 5.51: Filter circuit view 1.

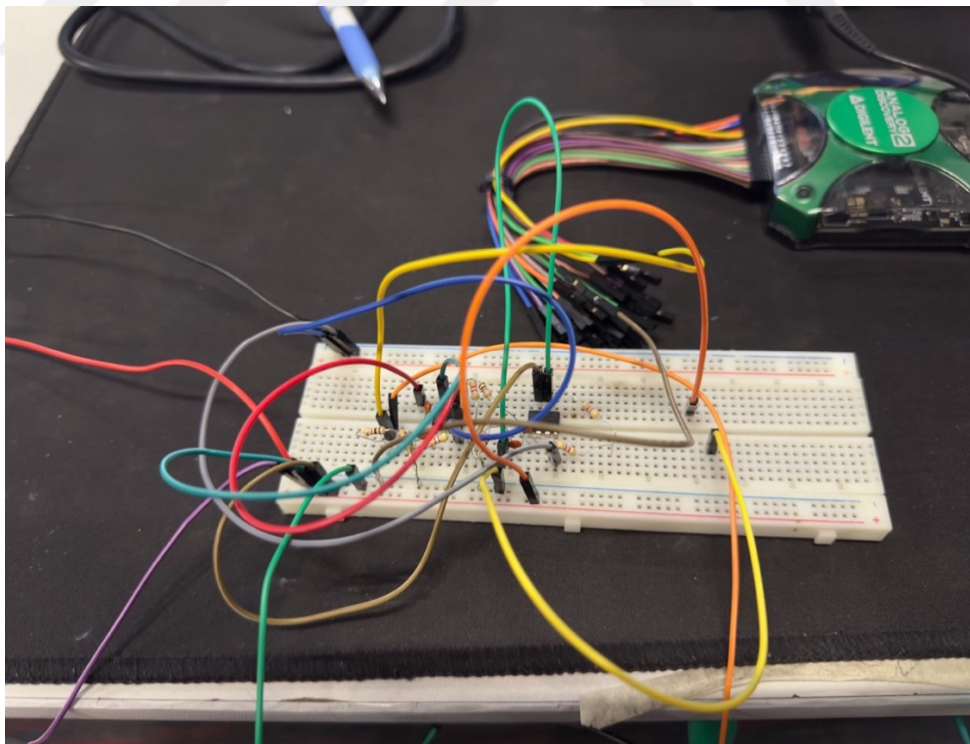


Figure 5.52: Filter circuit view 2.

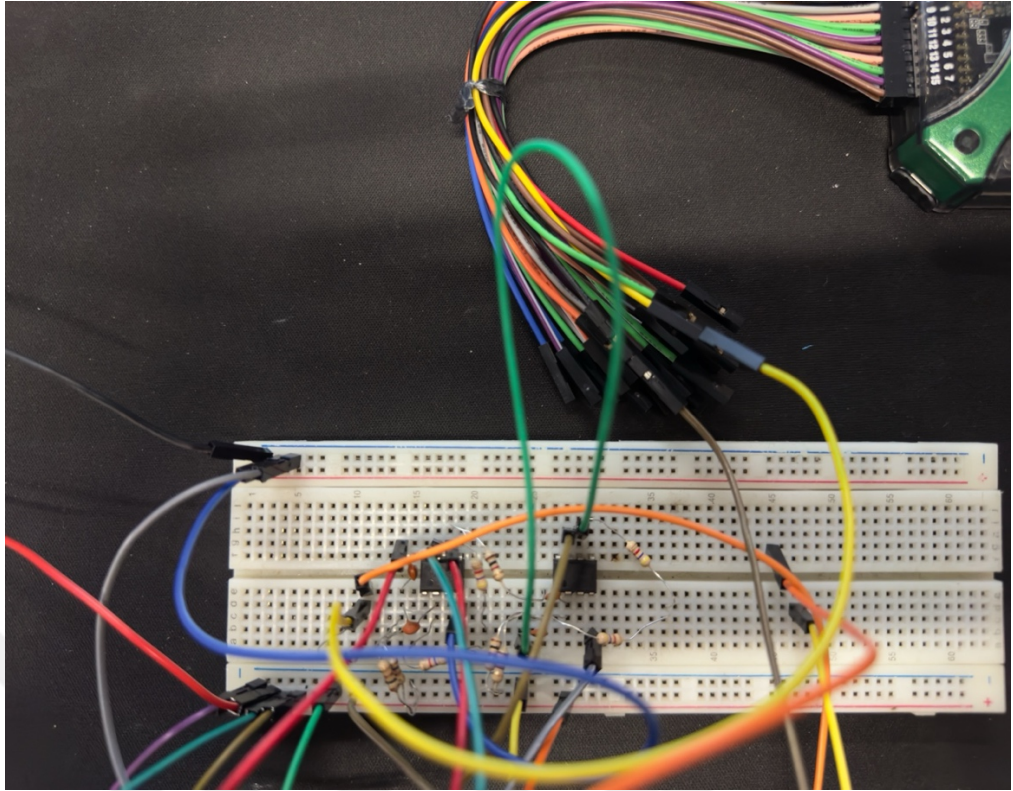


Figure 5.53: Filter circuit view 3.

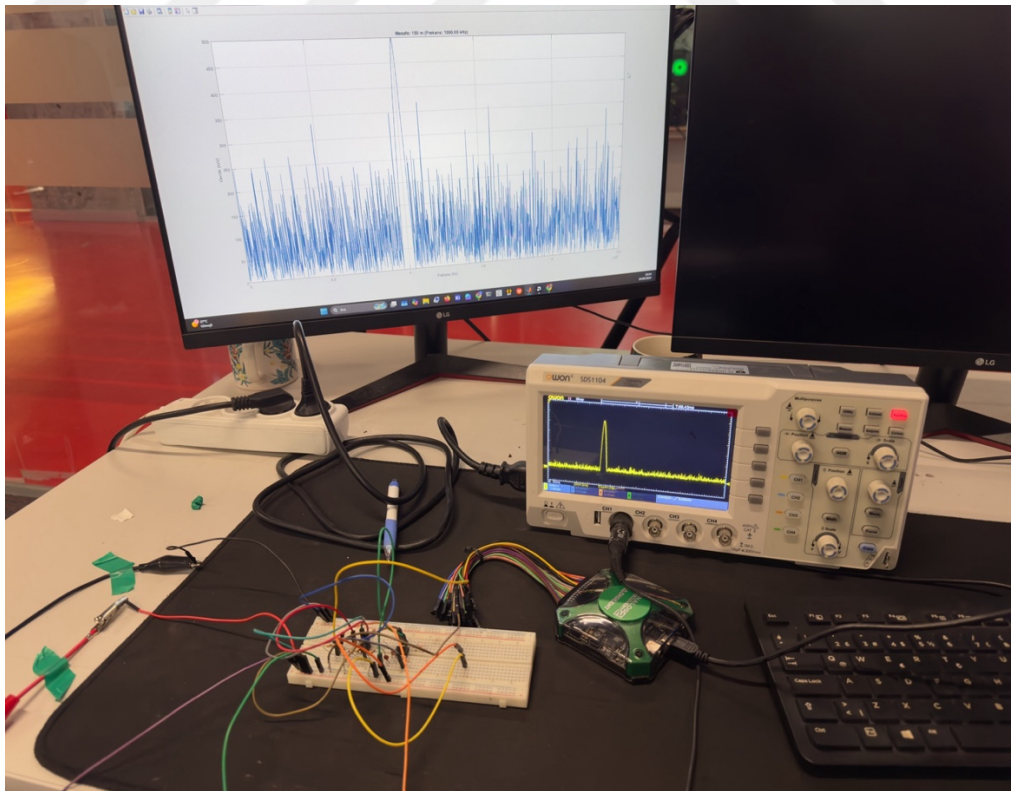


Figure 5.54: Filter input - circuit and output all view 1.

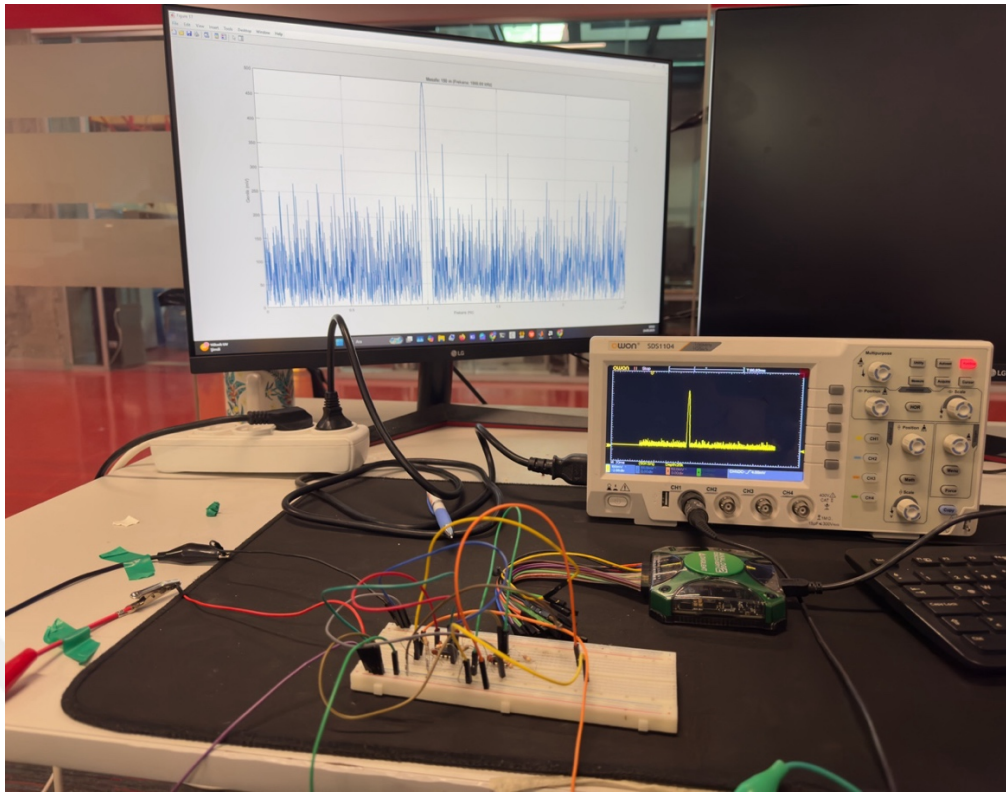


Figure 5.55: Filter input - circuit and output all view 2.

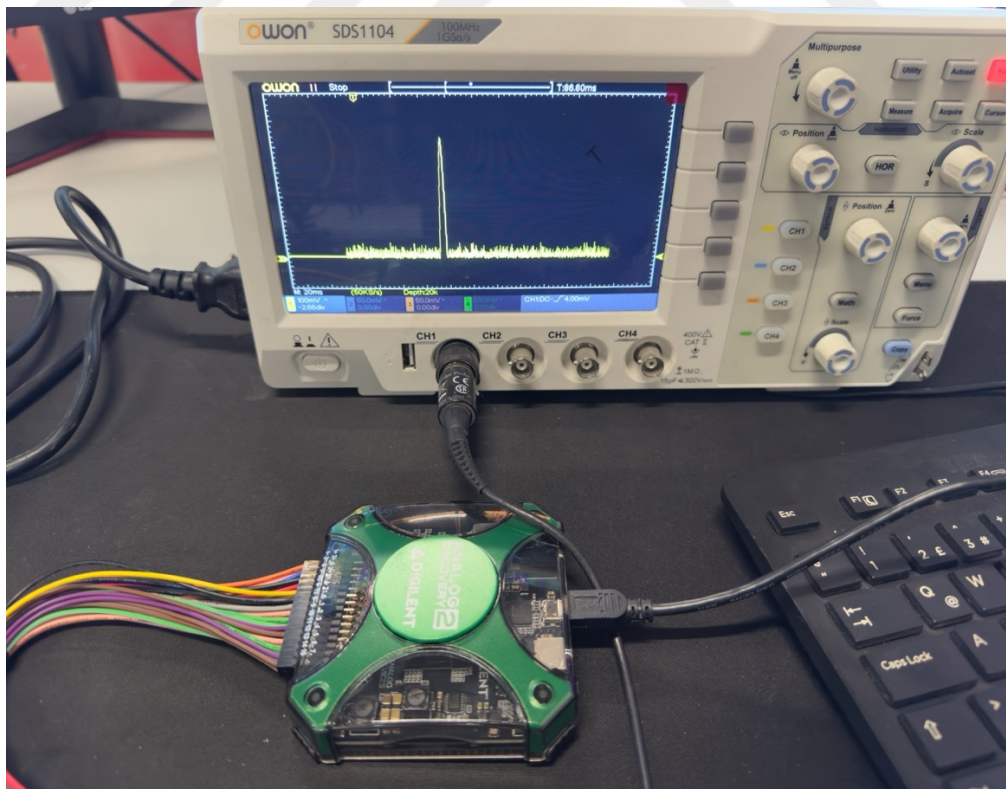


Figure 5.56: Filter output view.

Figure 5.51, 5.52 and 5.53 show the assembled filter circuit on a breadboard from different angles. This completely modifiable circuit has been assembled on a breadboard using jumper cables for testing purposes. This design considers the parasitic effects that will occur within the circuit. The operating frequency has been set to 100 kHz. The input signal represents a target located at an average distance of 1500 meters.

Figure 5.54 and 5.55 provide all details regarding the filter operation simultaneously. The blue signal on the left of the figures represents the input signal received from the LRF. After passing through the filter circuit, the input signal produces an output signal, which can be seen on the oscilloscope on the right-hand side of the figure. The output signal performs close to the expected level of noise suppression. **Figure 5.56** shows the filter output in more detail. As can clearly be seen in this figure, however, noise is still present in the signal. This is believed to be due to the components and wiring used in practice. It is anticipated that such noise will not occur when the filter design criteria are applied and the module is designed on a PCB. For this reason, PCB circuit design for the filter circuit is at the forefront of future work, and drawing work is continuing.

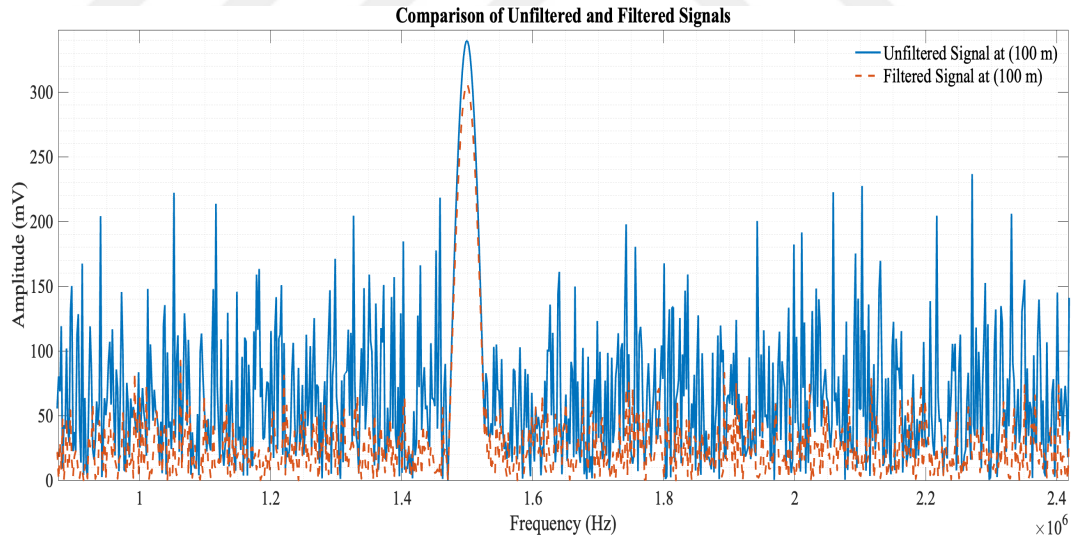


Figure 5.57: Signal comparison at 100m.

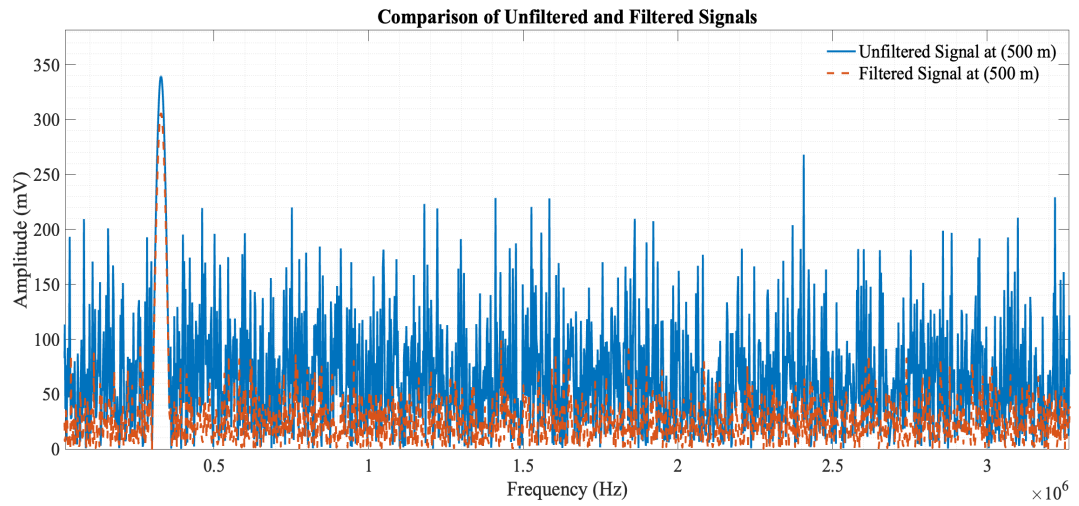


Figure 5.58: Signal comparison at 500m.

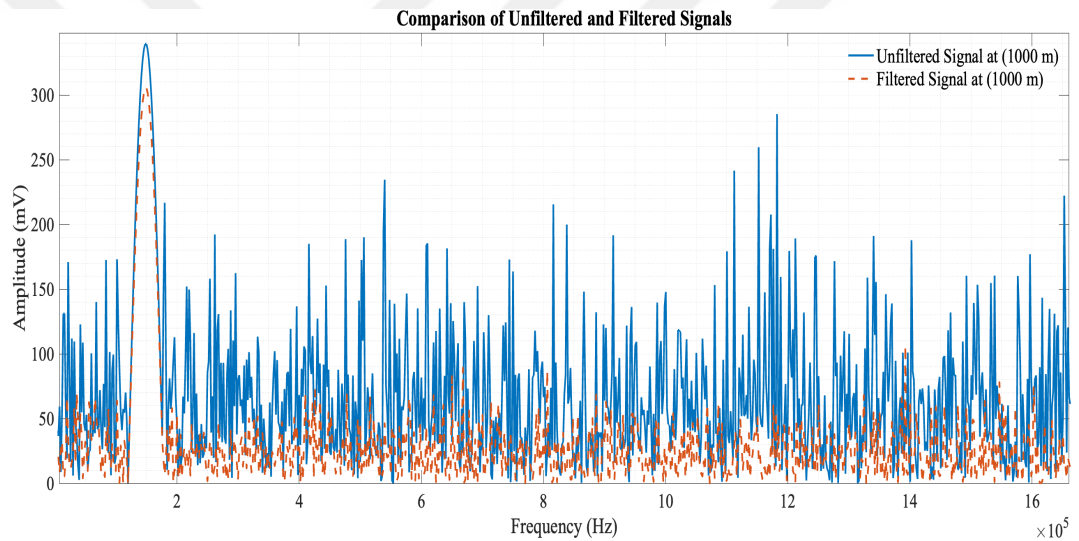


Figure 5.59: Signal comparison at 1000m.

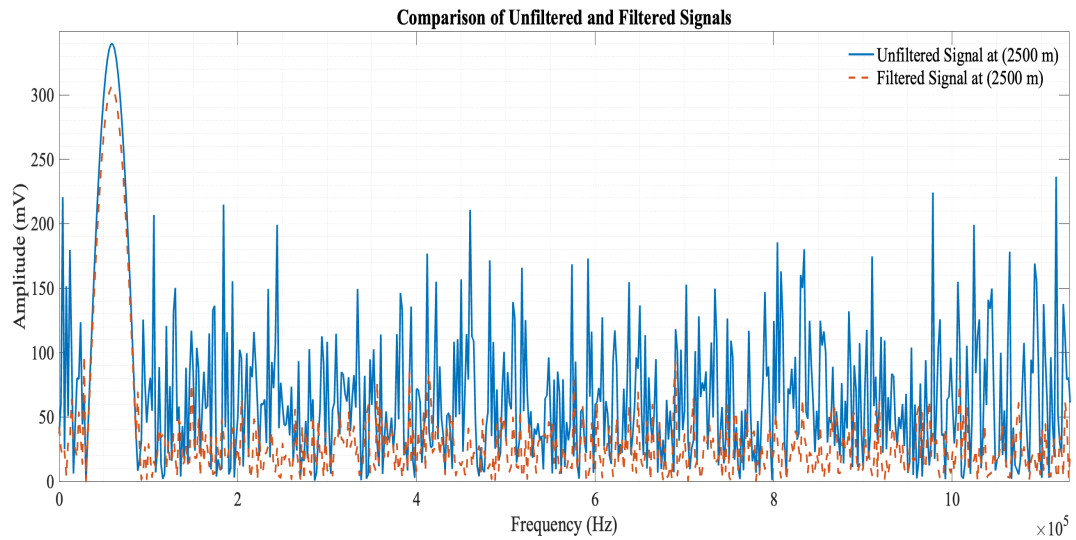


Figure 5.60: Signal comparison at 2500m.

Measurements were taken at different frequencies on the designed circuit. The filtered signal obtained from these measurements was improved and graphed in MATLAB. The signals and their filtered versions at 100 meters, 500 meters, 1000 meters, and 2500 meters are shown in **Figure 5.57**, **5.58**, **5.59** and **5.60**, respectively. The result obtained in **Figure 5.57** represents a 100 meter signal, 1.5 MHz; the result obtained in **Figure 5.58** represents a 500 meter signal; the result obtained in **Figure 5.59** represents a 1000 meter signal, 150 kHz; and the result obtained in **Figure 5.60** represents a 2500 meter signal, 60 kHz. In this way, the extreme frequency ranges at the filter's operating frequency were tested, and it was observed that the filter functioned properly. The filtered and unfiltered signals were presented on the same graph to provide a clearer view of the effect of the filter. Overall, the filter design has been validated and the thesis study has been completed, with the desired level of performance achieved.

6. CONCLUSION AND FUTURE WORK

Specifically, within Laser Range Finder (LRF) modules, this thesis presents the design of a tunable analog band-pass filter suited to meet the complex signal processing requirements of modern electro-optical systems. In order to guarantee high-frequency sensitivity, selectivity, and minimum insertion loss, the proposed architecture combines a filter structure into the analog domain of the electro-optical signal chain. Target identification and distance measurement are among the uses the design fits for defense and aerospace technologies, where dependability and accuracy are absolutely important.

Theoretically, the system was established prior to empirical validation by means of a synthetic input signal created under model based on real-world experimental data spanning the whole frequency range of relevance. This improves practical relevance as well as offers a complete structure for assessing the behavior of the filter under controlled circumstances.

Table 6.1: Comparison of different studies.

Feature	Study [31]	Study [51]	Study [52]	Study [53]	This Thesis
Frequency Range	0.5 Hz – 40 Hz	0.3 GHz- 1.1 GHz	100 kHz – 6 MHz	–	50 kHz – 4.02 MHz
Number of Tunable Elements	2	6	2	–	4
Filter Order	5	3	3	2	4
Technology	CMOS		CMOS		Analog-CMOS
THD	49.9 dB	Not Given	Not Given	Not Given	52 dB
Capacitance Multiplication	–	–	10-30	17	100
Capacitance-Frequency Linearity	–	–	Less stable	–	Improved stability
System-Level Optimization	Fabrication	Fabrication	Fabrication	Fabrication	Real-time dynamic optimization

Existing filtering techniques were evaluated by means of an extensive literature review. Limitations of present structures—especially in terms of controllability and observability—were found, and the suggested approach brings appreciable changes. Using both theoretical and simulation-based methods, engineering parameters engaged in the design process—including center frequency, quality factor (Q), bandwidth, and transition characteristics—were thoroughly examined.

Table 6.1 shows the studies conducted and their specific characteristics. The study will be completed by examining the data in more detail. The number of circuit elements and power consumption used in the existing [31] study in the literature were found to be partially advantageous compared to the study conducted in this thesis; however, the filter frequency range in that study was 0.5 Hz – 40 Hz, while the work completed in this thesis offers a solution for a much wider frequency range of 50 kHz – 4.02 MHz.

Also compared to another existing study [51], the thesis study was conducted as follows: In this study, the structure required for the filter to be tunable was provided with flexible resonance control. In this study, the frequency adjustment of the circuit is performed by controlling six circuit elements; in our thesis study, this number is four. This allows for fewer changes to the circuit elements, resulting in power savings while minimizing the potential for errors and losses. This reduction in the number of tunable elements decreases the overall system complexity, minimizes the potential for tuning errors and parasitic losses, and contributes to overall power savings.

Dynamic filter optimization in response to changing input conditions was made possible by including a MOSFET-based capacitance multiplier (C-multiplier) circuit. This part greatly helps the system to be flexible since it offers exact parameter control with fast response time. By use of the instantaneous properties of the input signal, the C-multiplier not only enhanced filter performance but also enabled real-time system-level optimization.

When comparing the capacitance multiplier circuit used in this study with similar work in the literature [52], it was observed that the capacitance coefficient is quite close to each other. The linearity of the capacitance-frequency curve was found to be more stable in this thesis study.

Additionally, another study [53] used the same CMOS technology, but achieved a capacitance multiplication of 17 times, whereas the thesis study achieved a capacitance multiplication of 100 times, reaching a wider scale. Thus, covering a substantially broader capacitance tuning range. As a result, all required filter specifications were met using a single, compact circuit implementation. As a result, all filter requirements were met using a single circuit.

Smart platform integration was always in mind while developing the whole system. Coupled with the adaptive C-multiplier, the analog band-pass filter proved able to self-adjust in real time depending on input signal dynamics. Applications in guided missiles, autonomous aerial systems, and real-time target recognition modules depend strategically on such capabilities. The modular and scalable architecture of the proposed system makes it quite fit for high-precision electro-optical platforms.

With all supporting data supplied, performance analysis confirmed the filter obtained the intended pass-band characteristics. Increasing the filter order presents a great chance for improvement since it would produce a better Q factor, smaller transition band, and better peak frequency isolation, so raising measurement accuracy. The most effective change to lower error in real-time measurements is clearly improving the Q factor.

Results of experiments and simulations confirmed the effectiveness of the C-multiplier architecture. To support hardware-level validation, nevertheless, more testing under diverse environmental conditions—including temperature fluctuations, electromagnetic interference, and power supply noise—should be done. This guarantees the design's resilience under practical limitations.

Although the frequency-dependent behavior of the capacitance of the C-multiplier was investigated and revealed to be stable, extending the frequency tuning range could increase filter precision and noise resilience. Furthermore, supporting more accurate tuning would be changing the capacitance range to better fit the operational frequency band of the filter.

The present system modulates the working frequency by means of embedded control. Future research could investigate adaptive tuning using machine learning or neural network-based approaches, so allowing the system to independently choose best configurations depending on learned signal patterns.

Although the presented filter design runs with a single passband, future versions could profit from multi-band capability. Given dynamic spectrum management is crucial in advanced applications in cognitive radar and electronic warfare, this would make the filter appropriate.

Eventually, radiation-hardened PCB design can be included to support photodetectors, ignition circuits, and control interfaces in full system integration inside electro-optical modules. This would open the path for more general application of the system over several aerospace and defense platforms, providing a strong and flexible answer to new technological problems.



REFERENCES

- [1] Hui Y. L., O'Sullivan M., (2023), "Characterization of Optical Devices," Fiber-Optic Measurement Techniques, 1st Edition, Elsevier, 297–446.
- [2] Livada B., Peric D., Peric M., (2017), "Challenges of Laser Range Finder Integration in Electro-Optical Surveillance System," 25th Telecommunications Forum (TELFOR), pp. 1–4, Belgrade, Serbia, 21–23 November 2017.
- [3] Cool Cosmos, "Herschel's Experiment," California Institute of Technology. Available: https://coolcosmos.ipac.caltech.edu/page/herschel_experiment (Accessed: April 11, 2025).
- [4] Ford B. J., (2004), "Herschel and the Puzzle of Infrared," American Scientist. Available: <https://www.americanscientist.org/article/herschel-and-the-puzzle-of-infrared> (Accessed: April 10, 2025).
- [5] White J. R., (2002), "Herschel and the Puzzle of Infrared," American Scientist, 90(3), 206–211. Available: <https://www.americanscientist.org/article/herschel-and-the-puzzle-of-infrared> (Accessed: April 10, 2025).
- [6] Caltech - Cool Cosmos, (2025), "Herschel Experiment." Available: https://coolcosmos.ipac.caltech.edu/page/herschel_experiment (Accessed: April 10, 2025).
- [7] Infrared Training Institute, "Willoughby Smith." Available: <https://infraredtraininginstitute.com/infrared-thermographyhistory/willoughby-smith> (Accessed: April 11, 2025).
- [8] Wikipedia Contributors, (2025), "First World War Glass–Rubber Exchange," Wikipedia, The Free Encyclopedia. Available: https://en.wikipedia.org/wiki/First_World_War_glass-rubber_exchange (Accessed: April 17, 2025).
- [9] Corsi C., "Infrared Sensors' History in Italy," Consorzio CREO. Available: <https://www.researchgate.net/publication/309770639> (Accessed: June 10, 2025).
- [10] Rogalski A., (2009), "Infrared Detectors for the Future," Acta Physica Polonica A, 116(3), 389–406.
- [11] Waynant R. W., Ediger M. N., (2000), Electro-Optics Handbook, McGraw-Hill.
- [12] Träger F. (Ed.), (2012), Springer Handbook of Lasers and Optics, 2nd Edition, Springer.
- [13] Saleh B. E. A., Teich M. C., (2019), Fundamentals of Photonics, 3rd Edition, Wiley.

- [14] Cheremisinov P. A., (2013), *Lasers and Optical Engineering*, Springer.
- [15] Milonni P. W., Eberly J. H., (2010), *Laser Physics*, Wiley.
- [16] *High Power Laser Science and Engineering*, Cambridge University Press. Available: <https://www.cambridge.org/core/journals/highpower-laser-science-and-engineering> (Accessed: April 20, 2025).
- [17] Jin P., Lu H., Yin Q., Su J., Peng K., (2018), “Expanding Continuous Tuning Range of a CW Single-Frequency Laser by Combining an Intracavity Etalon with a Nonlinear Loss,” *IEEE Journal of Selected Topics in Quantum Electronics*, 24(5).
- [18] Richardson D. J., Nilsson J., Clarkson W. A., (2010), “High Power Fiber Lasers: Current Status and Future Perspectives [Invited],” *Journal of the Optical Society of America B*, 27(11), B63–B92.
- [19] Sabatini R., Richardson M. A., Gardi A., Ramasamy S., (2015), “Airborne Laser Sensors and Integrated Systems,” *Progress in Aerospace Sciences*, 76, 70–120.
- [20] Maiman T. H., (1960), “Stimulated Optical Radiation in Ruby,” *Nature*, 187(4736), 493–494.
- [21] C. Research, (2025), “Lidar: Foundations and Frontiers,” Technical Report.
- [22] Keller J. B., (2002), “History and Development of Military Lasers,” *Medical Aspects of Harsh Environments*, Vol. 2, Office of the Surgeon General, U.S. Army, 23–42. Available: <https://medcoeckapwstorprd01.blob.core.usgovcloudapi.net/pfwimages/dbimages/Laser%20Ch%202.pdf> (Accessed: June 10, 2025).
- [23] IR Systems Engineering, (n.d.), *Photonics Project*, Vol. 4. Available: <https://photonicsproject.org/wp-content/uploads/IR-Systems-Engineering-Vol-4.pdf> (Accessed: May 1, 2025).
- [24] Infiniti Electro-Optics, “LRF Performance: Ranging Limitations of Laser Range Finders.” Available: <https://www.infinitioptics.com/whitepapers/lrfperformance-ranging-limitations> (Accessed: December 31, 2024).
- [25] Candan C., Tiken M., Berberoglu H., Orhan E., Yeniay A., (2021), “Experimental Study on km-Range Long-Distance Measurement Using Silicon Photomultiplier Sensor with Low Peak Power Laser Pulse,” *Applied Sciences*, 11(1), 1–13.
- [26] Dandawate Y. H., Upadhyay P., Jaywant S., (2015), “FPGA Based Low Power Laser Range Finder,” 1st International Conference on Computing, Communication, Control and Automation (ICCUBE), pp. 984–988, Pune, India, 26–27 July 2015.
- [27] Wang J., Shi H., Wang C., Hu M., Song Y., (2022), “Impact of Laser Intensity Noise on Dual-Comb Absolute Ranging Precision,” *Sensors*, 22(15), 1–10.

- [28] Kraftmakher Y., (2006), "Noise Reduction by Signal Accumulation," *The Physics Teacher*, 44, 528–530.
- [29] Poularikas A. D., (2009), *Discrete Random Signal Processing and Filtering Primer with MATLAB*, CRC Press/Taylor & Francis.
- [30] Kumngern M., Aupithak N., Khateb F., Kulej T., (2020), "0.5 V Fifth-Order Butterworth Low-Pass Filter Using Multiple-Input OTA for ECG Applications," *Sensors*, 20(24), 1–16.
- [31] Sun C. Y., Lee S. Y., (2018), "A Fifth-Order Butterworth OTA-C LPF with Multiple-Output Differential-Input OTA for ECG Applications," *IEEE Transactions on Circuits and Systems II: Express Briefs*, 65(4), 421–425.
- [32] Hintikka M., Kostamovaara J., (2018), "Experimental Investigation into Laser Ranging with Sub-ns Laser Pulses," *IEEE Sensors Journal*, 18(3), 1047–1053.
- [33] Sun X., Tan J., Xu J., Huang S., (2013), "Research on Key Technology for Phase-Shift Laser Range Finder," 11th IEEE International Conference on Dependable, Autonomic and Secure Computing (DASC), pp. 235–237, Chengdu, China, 21–23 December 2013.
- [34] Deliyannis T. L., Sun Y., Fidler J. K., (1999), *Continuous-Time Active Filter Design*, CRC Press.
- [35] Razavi B., (2017), *Design of Analog CMOS Integrated Circuits*, 2nd Edition, McGraw-Hill Education.
- [36] Schaumann R., Van Valkenburg M. E., Ghausi M. S., (2009), *Design of Analog Filters*, 2nd Edition, Oxford University Press.
- [37] Mancini R., (2002), "Active Filter Design Techniques," *Op Amps for Everyone*, 2nd Edition, Elsevier, Chapter 16.
- [38] Hayt W. H., Kemmerly J. E., Durbin S. M., (2012), *Engineering Circuit Analysis*, 8th Edition, McGraw-Hill Education.
- [39] Sedra A. S., Smith K. C., Carusone T. C., Gaudet V., (2021), *Microelectronic Circuits*, 8th Edition, Oxford University Press.
- [40] Podder P., Hasan M. M., Islam M. R., Sayeed M., (2020), "Design and Implementation of Butterworth, Chebyshev-I and Elliptic Filter for Speech Signal Analysis," *arXiv preprint*, arXiv:2002.03130.
- [41] Laghari W. M., Baloch M. U., Mengal M. A., Shah S. J., (2014), "Performance Analysis of Analog Butterworth Low Pass Filter as Compared to Chebyshev Type-I Filter, Chebyshev Type-II Filter and Elliptical Filter," *Circuits and Systems*, 5(9), 8–18.

- [42] Jagtap S. K., Uplane M. D., (2012), “A Real-Time Approach: ECG Noise Reduction in Chebyshev Type II Digital Filter,” *International Journal of Computer Applications*, 50(20), 1–5.
- [43] Kumngern M., Khateb F., Kulej T., (2022), “0.5 V Current-Mode Low-Pass Filter Based on Voltage Second Generation Current Conveyor for Bio-Sensor Applications,” *IEEE Access*, 10, 12201–12207.
- [44] Jung M., Min B. W., (2019), “A Widely Tunable Compact Bandpass Filter Based on a Switched Varactor-Tuned Resonator,” *IEEE Access*, 7, 95178–95185.
- [45] Mancini R., (2002), *Op Amps for Everyone: Design Guide*, Elsevier.
- [46] George Washington University, (2011), “Filter Design – ECE121.” Available: <https://www2.seas.gwu.edu/~ece121/Spring-11/filterdesign.pdf> (Accessed: February 18, 2025).
- [47] Electronics Tutorials, (2025), “Sallen-Key Filter Tutorial.” Available: <https://www.electronics-tutorials.ws/filter/sallen-keyfilter.html> (Accessed: February 16, 2025).
- [48] Razavi B., (2017), *Design of Analog CMOS Integrated Circuits*, 2nd Edition, McGraw-Hill Education.
- [49] Al-Absi M. A., Al-Suhaibani E. S., Abuelma’atti M. T., (2017), “A New Compact CMOS C-Multiplier,” *Analog Integrated Circuits and Signal Processing*, 90(3), 653–658.
- [50] Andreani P., Sjöland H., (2002), “A Comparison Between Two 1.8-GHz CMOS VCOs Tuned by Different Varactors,” *IEEE Journal of Solid-State Circuits*, 37(5), 693–697.
- [51] Zhang R., Shao C.-H., Peroulis D., (2018), “A New Adaptive Reconfigurable Bandpass Filter with Flexible Resonance Control,” *48th European Microwave Conference (EuMC)*, pp. 539–542, Madrid, Spain, 23–27 September 2018.
- [52] Arslanalp R., Yücehan T., (2014), “Capacitance Multiplier Design by Using CFOA,” *Elektrik-Elektronik ve Bilgisayar Sempozyumu (ELECO)*, pp. 225–229, Bursa, Turkey, 27–29 November 2014.
- [53] Bonteanu G., (2017), “A Wide Range Fine Tuning Capacitance Multiplier,” *2017 IEEE 23rd International Symposium on Design and Technology in Electronic Packaging (SIITME)*, pp. 251–256, Constanța, Romania, 26–29 October 2017.

BIOGRAPHY

Emrah BÖLÜK completed his Bachelor of Science (B.Sc.) degree in Electrical and Electronics Engineering in 2022. Following his graduation, he held positions as an Analog Electronics Design Engineer in several prominent defense industry organizations. Throughout his academic and professional career, he has actively participated in numerous national and international competitions, thereby enhancing his technical and project-based competencies. His primary areas of interest and research include analog circuit design, hardware design engineering, and integrated circuit (IC) design.



PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

[1] Bölük. E., Uygur A., “Implementing Analog Filter Applications in Electro-Optical Sensors”, 8th GTU Graduate Research Symposium, 30-31 May. 2024

[2] Bölük E., Uygur A., “A Smart Analog Filtering Approach for Laser Range Finder Systems,” in Proceedings of the 9th International Symposium on Innovative Approaches in Smart Technologies (ISAS 2025), Gaziantep, Türkiye, 27-28 Jun. 2025

