APPLICATION OF CSDG MOSFET BASED ACTIVE HIGH PASS FILTER IN COMMUNICATION SYSTEMS

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by

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As the candidate’s supervisor, I have approved this thesis for submission.

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Plagiarism

I, **LLEWELLYN NAIDOO** with Student Number **211515870** with the thesis entitled ***APPLICATION OF CSDG MOSFET BASED ACTIVE HIGH PASS FILTER IN COMMUNICATION SYSTEMS*** hereby declare that:

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List of Abbreviations

Abbreviation	Full Form
AM	Amplitude Modulation
BJT	Bipolar Junction Transistor
CBJ	Collector-Base Junction
CMOS	Complementary Metal-Oxide-Semiconductor
CSDG	Cylindrical Surrounding Double Gate
CSG	Cylindrical Surrounding Gate
DG	Double Gate
DIBL	Drain Induced Barrier Lowering
EBJ	Emitter-Base Junction
EHF	Extremely High Frequency
ELF	Extremely Low Frequency
FinFET	Fin Field-Effect Transistor
FM	Frequency Modulation
GAA	Gate All Around
HPF	High Pass Filter
IF	Intermediate Frequency
LNA	Low-Noise Amplifier
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PC	Personal Computer
RDF	Random Dopant Fluctuations
RF	Radio Frequency
SCE	Short Channel Effects
SG	Single Gate
SHF	Super High Frequency
SOI	Silicon on Insulator
THF	Tremendously High Frequency

THz	Terahertz
VHF	Very High Frequency
VLSI	Very Large Scale Integration

List of Publications

The under listed journal and conference articles which is either published or accepted are found in this research work and constitutes the topics of the research work discussed in various chapters of this thesis.

Journal Publications

1. **Llewellyn Naidoo** and Viranjay M. Srivastava, "Effect of CSDG MOSFET based high pass filter on signaling," ***Int. J. of Innovative Technology and Exploring Engineering (IJITEE), vol. 8, no. 6C, pp. 91-96, April 2019.*** (in Chapter 4).

2. **Llewellyn Naidoo** and Viranjay M. Srivastava, "Application of CSDG MOSFET for Tera-Hertz range in high pass filtering," ***Far East Journal of Electronics and Communications (FJEC)***, vol. 18, no. 5, pp. 651-660, July 2018 (in Chapter 5).
(DOI: 10.17654/EC018050651) ***[DoHET, SCOPUS]***

Conferences Publications

3. **Llewellyn Naidoo** and Viranjay M. Srivastava**,** "Application of CSDG MOSFET based active high pass filter in satellite communications: A circuit perspective ," ***Int. Conf. on Advances in Big Data, Computing and Data Communication Systems (ICABCD),*** Durban, South Africa, 6 - 7 Aug. 2018, pp. 496-500 (in Chapter 3 and Chapter 6).
(DOI: 10.1109/ICABCD.2018.8465468) ***[IEEE Xplore]***

4. **Llewellyn Naidoo** and Viranjay M. Srivastava, "Application of high pass filter in robotics: a circuit perspective," ***8th IEEE Int. Conf. on Computer Communication and Informatics (ICCCI)***, India, 4-6 Jan. 2018, pp. 131-134 (in Chapter 4)

(DOI: 10.1109/ICCCI.2018.8441390) ***[IEEE Xplore]***

Abstract

This research work looks at the design of three active high pass filters. These filters have been designed for (i) robotic system, (ii) sensing device and (iii) satellite communication system. In this research work a high pass filter has been designed with a Cylindrical Surrounding Double Gate (CSDG) MOSFET. A CSDG MOSFET is a continuation of DG MOSFET technology. It is formed by rotation of a DG MOSFET with respect to its reference point to form a hollow cylinder. It consists of 2 gates, a drain and a source.

Electronic robotic systems have a section of transmitter and receiver. For the receiver, to provide the required selectivity of frequencies, a filter is used. There is a wide variety of these filters that can be used within the Radio Frequency (RF) range. Radio frequencies range from *3 kHz* to *300 GHz*. This particular filter is designed and simulated at a cutoff frequency of *100 GHz* (*0.1 THz*). It makes use both an operational amplifier and a transistor. This circuit was compared to a circuit that made use of 2 operational amplifiers and the results are discussed. In addition a CSDG MOSFET which makes use of a Silicon Dioxide dielectric is connected to the output of the transistor circuit to see what effect it has on the circuit. Using this model of filter a fine signal (command) can be given to robotic system.

The second filter is designed for remote sensing devices. These devices continuously send/receive signals and these signals or radio waves are transmitted/received via a transmission line to/from a receiver/transmitter which has a filter that selectively sorts out the signals and only passes a desired range of signals. The CSDG MOSFET being a capacitive model allows for better filtering of low frequencies and passes through a frequency range of *200 GHz* (*0.2 THz*) efficiently. By placing the capacitors in parallel, the design requires smaller capacitance values to be used. In addition the desired range of frequencies can be achieved from the inversely proportional relationship between frequency and capacitance.

Finally a filter has been designed to use in satellite communication systems. These systems consist of various subsystems to allow it to function efficiently. These subsystems require a number of electronic devices. In this research work, a CSDG MOSFET is added to the output of the transistor circuit and operates within the EHF band (*0.3 THz*). The CSDG MOSFET makes use of Hafnium Silicate ($HfSiO_4$) as a dielectric material due to its wide band-gap and lower dielectric constant makes it ideal for this design. The gain and other parameters of the three designed filters are analyzed.

In conclusion, it has been demonstrated that the third order active high pass filters performs better with the CSDG MOSFET.

Chapter-1

Introduction

A communication system is made up of a number of communication networks, transmission systems, relay systems, and tributary systems that form the basis for the efficient communication of information [1, 2]. Communication networks can be divided into two categories (i) analog communication and (ii) digital communication.

(i) Analog technology transmits data as radio signals at various frequency levels that are added to carrier waves at a certain frequency. This technology is widely used in the telecommunications industry. The telecommunication sector has evolved from the simple telegraph which was first commercially developed in 1837 by Sir William Fothergill Cooke and Charles Wheatstone [3]. It reduced communication time during the early 1800's from days to hour's just as modern technology as reduced the communication of large amounts of information from hours to seconds [4]. This is due to the rapid changing of technology which has allowed businesses to operate more efficiently and helps keep people connected to one another. One of the largest and thriving segments in telecommunications is wireless communications [5, 6].

Mobile technology is the most common type of wireless communication and is used in cellular communication [7, 8]. This form of communication consists of both consumer part (handset) and infrastructure part (radio base stations). The handset is made up of a transmitter and receiver and is discussed in more detail in Section 1.1 and Section 1.2 respectively.

(ii) Digital technology refers to the generation, storage, and processing of data. Applications for this type of technology include mobile phones, laptops, computers and other similar systems that make use of binary computational code in order to operate. The application of binary computational code can be extended to allow the efficient operation of social media platforms, media tools, cloud computing and productivity applications such as Microsoft Office. Some of the benefits of this type of technology are that it reduces man-hours of labor and it has enabled volumes of information to be compressed on compact storage devices which reduces the time taken for data transmission speed.

Figure 1.1. Simple communication system block diagram

Figure 1.1 above shows a basic block diagram of such a system. It consists of 3 essential components:

(i) Transmitter- Its purpose is to convert the input signal into a signal that is better suited for transmission through the communication channel. This method is known as Modulation.

(ii) Communication Channel- It serves as a medium for the signal to travel between the transmitter and receiver. The connecting link can either be classified as a guided or unguided medium. A guided medium refers to a physical connection such as a transmission line. Unguided medium refers to wireless transmission of signals. For Radio Frequency (RF) communication, the medium is air.

(iii) Receiver- It is responsible for converting the received signal into the original input signal. This process is called Demodulation. If all 3 components perform their respective functions, then the output signal will equal or differ slightly to the input signal.

1.1. Transmitter Systems

In the field of communications, transmitters are devices that send out data as radio waves within the electromagnetic spectrum in order to achieve a particular communication need. They are essential components of all electronic devices that communicate via radio waves such as broadcasting applications, cell phones, Bluetooth devices and keyless remotes, etc. A transmitter can either be a single portion of electronic equipment or a Very Large Scale Integration (VLSI) circuit in addition with another electronic device. There are various transmitter architectures that are used widely in the communications industry [9]. Some of these include Amplitude Modulated and Frequency Modulated transmitters, Single-Sideband, Radar, Satellite and Ultra Wideband transmitters. The process to transmit data is composed of the following elements:

(i) Power Supply- Provides the necessary power to the device to enable the broadcasting of information.

(ii) Electronic Oscillator- Generates a sine wave of stable amplitude and is referred to as the carrier wave as it serves to “carry” information through the air.

(iii) Modulator- Responsible for adding suitable information to the carrier wave. The two most common methods used are Amplitude Modulation (AM) and Frequency Modulation (FM). The former method increases or decreases the strength of the carrier wave whilst the latter increases or decreases the frequency of the carrier wave [10].

(iv) RF Amplifier- Power of the signal is increased which results in an increase in the range of radio waves.

(v) Antenna Tuner- Matches both the impedance of the transmitter and antenna in order for the efficient transfer of the signal and helps prevent a phenomenon known as standing waves [11].

Modern designs use a crystal oscillator which provides a stabilization of the operating frequency due to phase locking and provides more stable lower frequency which is used as a reference.

1.2. Receiver Systems

Receivers are devices that modify the received signal from a transmitter into a desired signal. This is achieved by allowing the received signal to undergo a number of processes. Figure 1.2 shows a superheterodyne receiver which was designed by Edwin Armstrong in 1918 is the most widely used today in communication systems. Superheterodyne receivers emit low-power radio signals during normal operation [12]. The incoming signal that is collected by the antenna enters the RF stage where it passes through an RF filter and then an amplifier to provide the initial filtration and amplification of the signal. Thereafter it enters a mixer where it is mixed with a generated signal from the local oscillator.

The output of the mixer passes through to the Intermediate Frequency (IF) stage where it undergoes a second filtration and amplification process [13]. Only signals within the pass band of the IF filter will pass through. The last stage involves demodulation which will recover the original signal. The receiver and transmitter combination is known as a transceiver system. Common applications for a transceiver system include cellular phones, telephones and two-way radios.

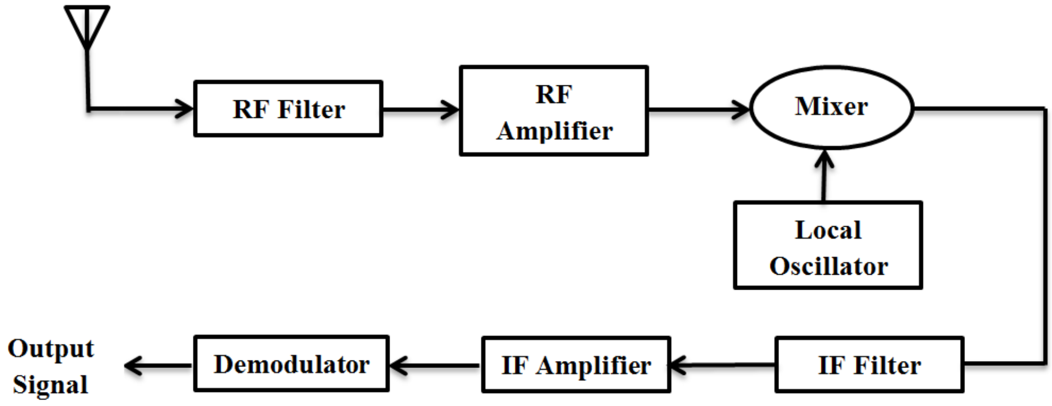

Figure 1.2. Super heterodyne receiver [13].

1.3. RF Filters

This research work looks at the design of a component for the receiver and transmitter viz. an RF filter. An RF filter is an electronic device that selectively sorts signals and passes through a desired range of signals while suppressing the others [14]. RF filters are common but critical components in the RF front-end [15]. It is designed to operate within the RF spectrum which includes frequencies between the Extremely Low Frequency (ELF) and extremely High Frequency (EHF) bands (Table 1.1). Filters are designed to satisfy an array of specifications. Although they use the same basic circuit components, circuit values vary when the proposed solution is designed to meet different criteria. They are used in a variety of applications such as television, radio and communications. These devices will use some form of filtering on the signal that is transmitted or received.

There are various types of RF filters. The four most common types are shown in Figure 1.3 [16, 17]:

(i) Low Pass Filter- Allows frequencies only below the cutoff frequency to pass.
(ii) High Pass Filter- Allows frequencies only above the cutoff frequency to pass.
(iii) Band Pass Filter- Allows frequencies through within a given pass band.
(iv) Band Elimination Filter- Rejects signals within a certain band.

The cutoff frequency of a filter refers to the point where the output level of the filter drops by 50% (-3dB) within the band level. The optimal filter, whether it is a low pass, high pass, or band pass filter will have a frequency band over which the magnitude is unity (pass band) and a frequency band over which the transmission is zero (stop band).

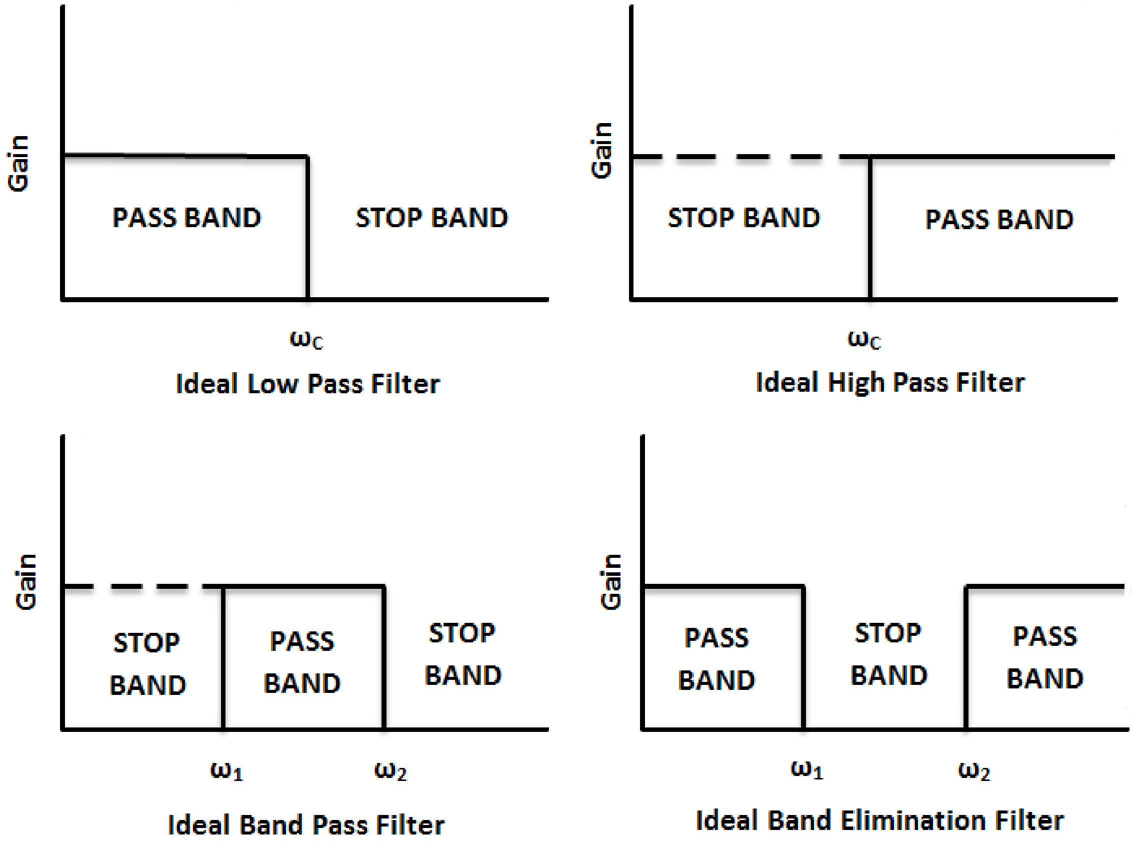

Figure 1.3. Amplitude characteristics of the various filters [18].

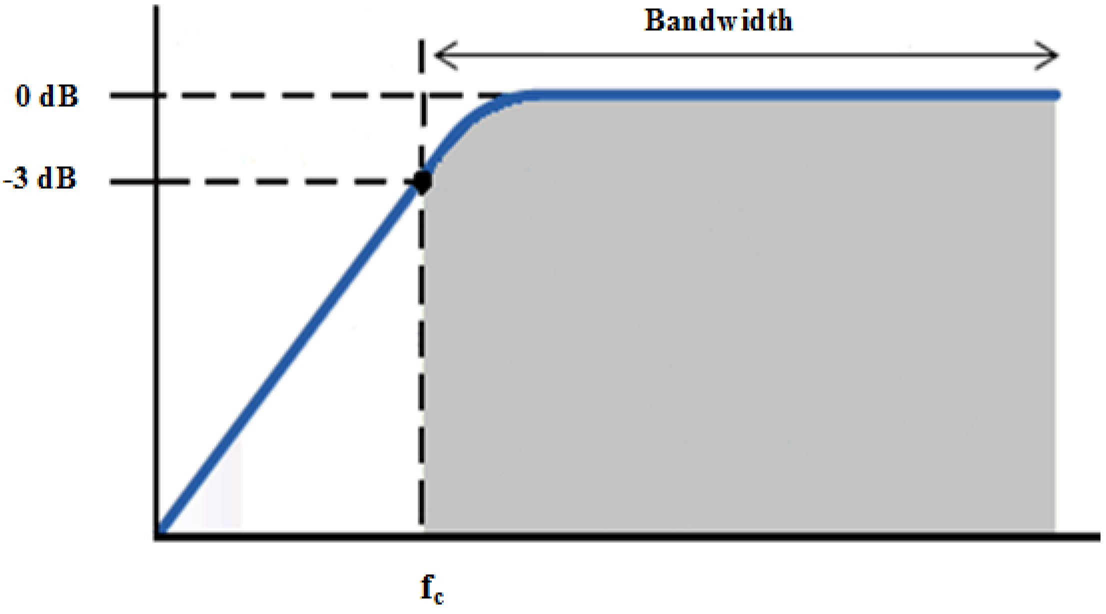

Figure 1.4. -3 dB Curve of high pass filter [18].

Table 1.1 Radio frequency spectrum [17]

Band Name	**Abbreviation**	**Frequency**	**Wavelength**
Extremely low frequency	ELF	3–30 Hz	10^5–10^4 km
Super low frequency	SLF	30–300 Hz	10^4–10^3 km
Ultra-low frequency	ULF	300–3000 Hz	10^3–100 km
Very low frequency	VLF	3–30 kHz	100–10 km
Low frequency	LF	30–300 kHz	10–1 km
Medium frequency	MF	300 kHz – 3 MHz	1 km – 100 m
High frequency	HF	3–30 MHz	100–10 m
Very high frequency	VHF	30–300 MHz	10–1 m
Ultra-high frequency	UHF	300 MHz – 3 GHz	1 m – 10 cm
Super high frequency	SHF	3–30 GHz	10–1 cm
Extremely high frequency	EHF	30–300 GHz	1 cm – 1 mm
Tremendously high frequency	THF	300 GHz – 3 THz	1 mm – 0.1 mm

1.4. RF Filter Challenges

RF passive and active components bear a burden of many design constraints and performance metrics thus the design of a filter poses a number of challenges to researchers and engineers. One of the biggest challenges includes the overall size of this component [19]. Since there are many subsystems in a communication system, space is limited so each subsystem needs to be designed in a way that will not affect the other subsystems design parameters as well as its efficiency. Hence, the footprint of a comprehensively designed filter must be capable of fitting into a predefined package size. This often causes the overall RF filter to be designed around this constraint.

Other challenges include the power handling capability and the ability to achieve higher frequency filtering [20]. The power handling capability is largely dependent on the frequency that a filter is designed for. As with most RF components they have a reduced power threshold compared to lower powered components. But with technology continuously improving, better components in the next few years will be available and higher frequencies will be achieved.

1.5. Research Questions

This research work looks at answering the following questions:

A. Which type of filter will be best suited to meeting our design specification?

B. What effect will using an alternative active component (transistor) have on the performance of a filter?

C. What components will best help us achieve the high frequencies the various active high pass filters are designed for?

D. Will the addition of a Cylindrical Surrounding Double Gate (CSDG) MOSFET have any effect on the performance of the filter?

1.6. Research Work Contribution

The following contributions are made to the field of RF filters:

A. By designing filters to operate within the upper regions of the RF spectrum a greater amount of data can be transmitted for a variety of applications.

B. The filters which are proposed are designed to be cost effective.

C. CSDG MOSFET’s are designed to provide better performance over other MOSFET structures.

1.7. Organization of the Thesis

This research work aims to design a filter that can operate at high frequencies. Various circuits have been simulated using different components to achieve the desired results with improved performance. The organization of the thesis is as follows:

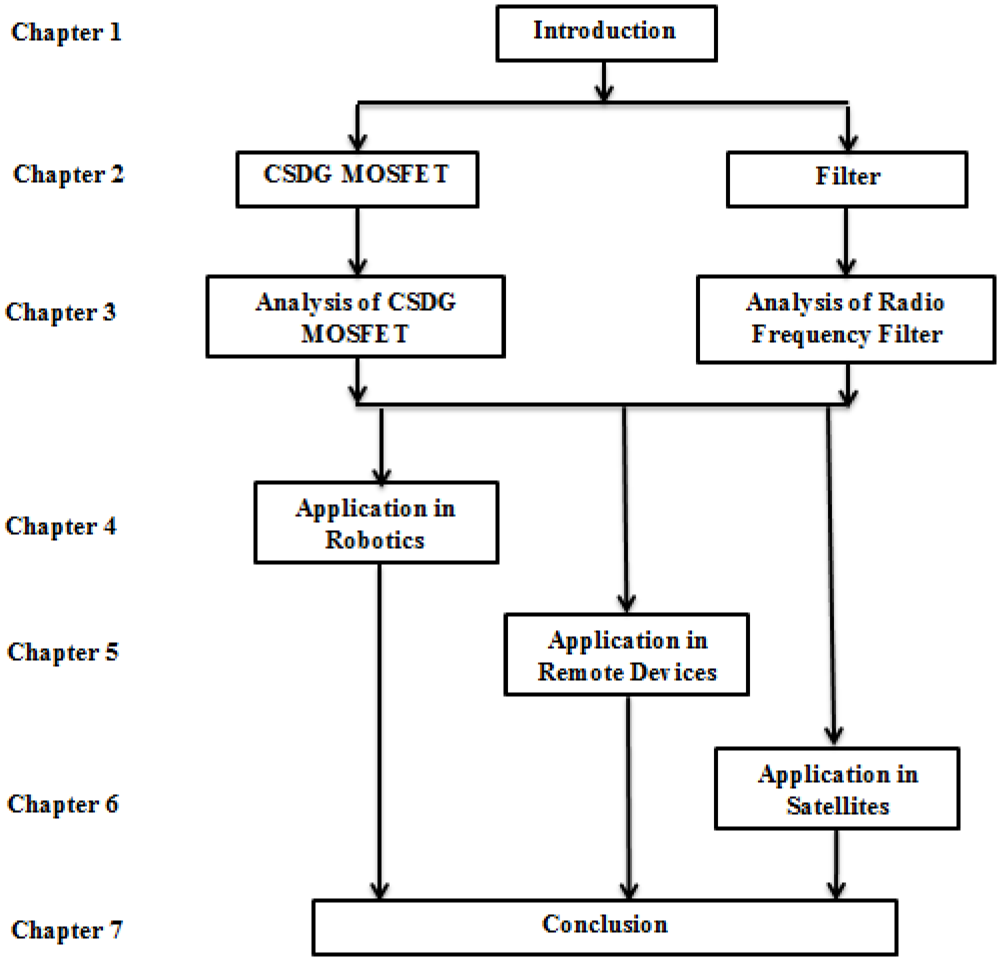

Figure 1.5. Research work structure.

Chapter 2 presents the literature review for this research work. The theories of the various types of filters and MOSFET’s have been discussed with their applications. The motivation for choosing a particular filter is detailed in this chapter as well. In addition we look at the previous work that has been done by other researchers in the electronic filter field.

Chapter 3 focuses on the various designs that are used for both the Cylindrical Surrounding Double-Gate (CSDG) MOSFET and active High Pass Filter (HPF) in this research work.

Chapter 4 discusses the design of an active HPF that can be used in a robotic system. This filter makes use of both a transistor and an operational amplifier to provide the necessary gain. The designed filter is simulated with the aid of a software tool. These results are discussed and compared to an active high pass filter that makes use of two operational amplifiers. In addition a CSDG MOSFET has been implemented and added to the filter circuit to see what improvements it has on the overall gain of the circuit.

Chapter 5 focuses on the design of a CSDG MOSFET that can be used in an active high pass filter circuit to provide an improvement in gain. The CSDG MOSFET makes use of parallel capacitors that connect the gate and drain. By doing this the overall capacitance is reduced and will allow higher frequencies to be achieved. Results have been discussed for both circuits with and without the use of a CSDG MOSFET.

Chapter 6 details the design of a filter that can be used in a satellite communication system. This design also makes use of a CSDG MOSFET but an additional oxide layer is added to the MOSFET. Hafnium Silicate has been chosen to complement the existing Silicon layer. In addition we look at the effect that varying the forward current gain has on the gain of the filter.

Finally, we conclude this research work and recommend the future scope of the work in Chapter 7.

Chapter-2

Literature Review

In continuation from Chapter 1 (were RF filters has been discussed), we are using the CSDG MOSFET to design the novel filter. Therefore this chapter deals with the theory behind the CSDG MOSFET.

2.1 Bipolar Junction Transistor

The development of the Bipolar Junction Transistor (BJT) in 1948 guided the field of electronics in a new direction. This crystalline silicon structure as made it possible to design and manufacture devices that are both cost effective and have minimal weight. A BJ T is made up of 3 separate layers of doped semiconductor materials which can either be of PNP or NPN configuration and is illustrated in Figure 2.1. The difference in functionality between these two configurations is the biasing of the junctions when they are in operation. The NPN bipolar transistor contains a thin p-region between two n-regions. In contrast, the PNP bipolar transistor contains a thin n-region sandwiched between two p-regions [21]. The three regions and their terminal connections are referred to as the emitter, base, and collector.

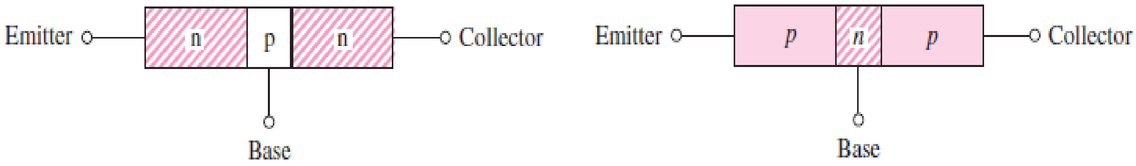

Figure 2.1. Simplified structure of bipolar transistors [21].

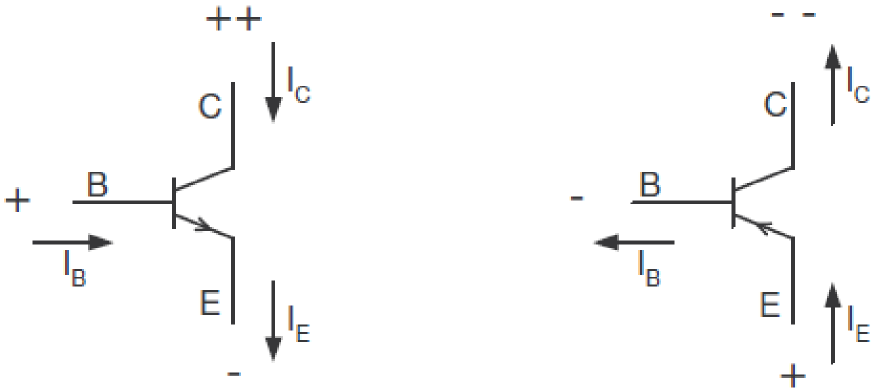

Figure 2.2. Circuit symbols of NPN (left) and PNP (right) BJT devices [22].

The BJT consists of a pair of PN junctions which are known has the emitter-base junction (EBJ) and the collector-base junction (CBJ). The different bias conditions of these junctions determine the various modes of operation. Some of these operations include active, cutoff, saturation and reverse-active modes [22]. Depending on the mode that the BJT operates at, it can either act as an amplifier or a switch.

2.2 MOSFET

Very Large Scale Integrated (VLSI) and Ultra Large Scale Integrated (ULSI) circuits make use of MOS technologies to make microprocessors, memory chips and analog integrated circuits (IC's). Since the late 1970's the MOSFET has been used extensively in electronic circuits for the following reasons:

- Compared to a BJT it is smaller in size and requires a smaller area of silicon or similar material.
- The process to manufacture these components is simple.
- Digital logic and memory can be made with MOSFET's only.

The heart of this structure is known as a MOS capacitor (Figure 2.3). This structure is composed of semiconductor substrate, an insulator film (SiO_2 is commonly used), and metal electrode (gate). The capacitance of the MOS structure depends on the voltage (bias) of the gate. Generally a voltage is applied to the gate (V_G) whilst the body of the component is grounded.

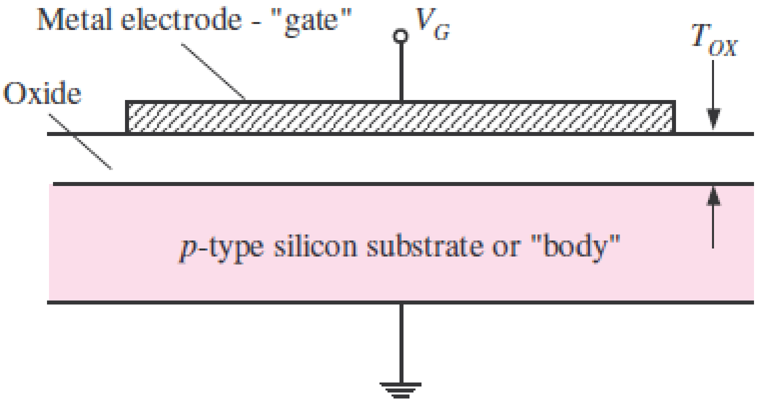

Figure 2.3. MOS capacitor [23].

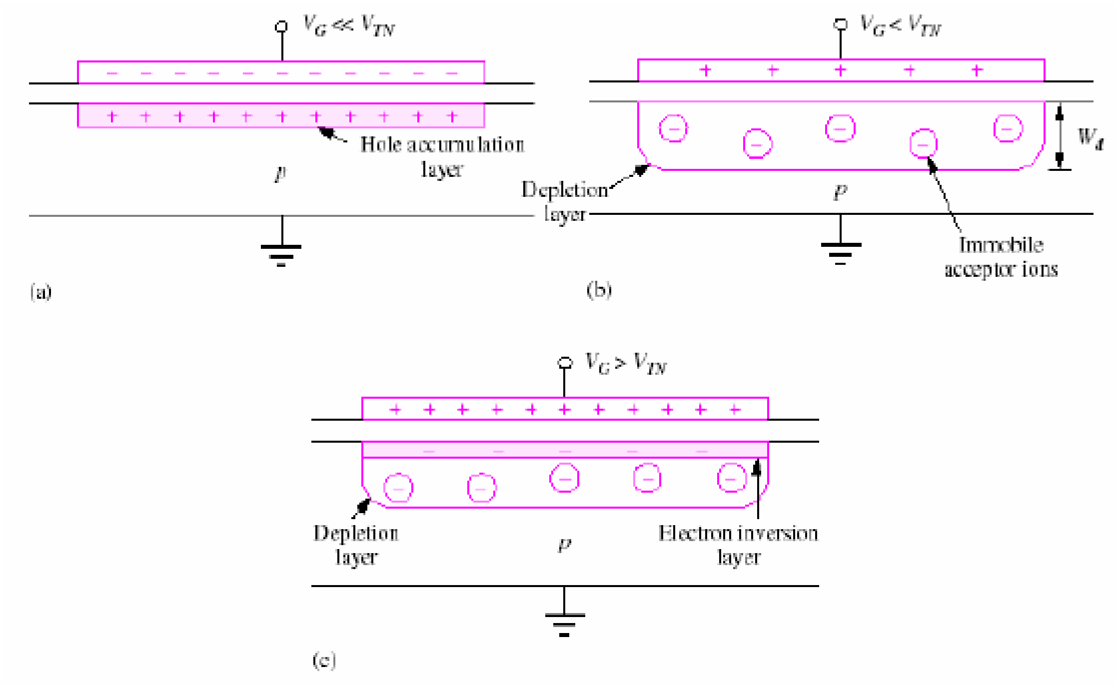

Figure 2.4. Three modes of operation (a) accumulation, (b) depletion and (c) inversion of MOS capacitor [24].

Figure 2.4 shows the *three* modes of operation of the MOS capacitor as accumulation, depletion and inversion modes respectively and is explained below:

(i) **Accumulation -** A positively applied gate voltage which is larger than the flat band voltage (V_{FB}) brings about positive charge on the metal electrode (gate) and negative charge in the semiconductor. V_{FB} is the voltage at which there is no charge in the MOS capacitor and hence there is no electric field across the oxide.

(ii) **Depletion -** If the applied V_G is brought below the V_{FB}, a negative charge is induced at the interface between the gate and the SiO_2 oxide layer. This results in a positive charge being induced at the oxide/semiconductor interface.

(iii) **Inversion -** If V_G is lowered below the threshold voltage (V_T); the semiconductor surface inverts its conduction type from n-type to p-type in our particular situation.

2.3 Double-Gate (DG) MOSFET

The DG MOSFET is an extension of the MOSFET concept and consists of two gates. The main idea of this improved type of MOSFET is to have a Si channel of very small width and to control the Si channel by applying gate contacts to both sides of the channel [25, 26]. The structure of the DG MOSFET consists of a conducting channel which is commonly undoped and is enclosed by gate electrodes at the top and bottom (Figure 2.5). These devices have an excellent gate control over the channel due to the sandwiching of Silicon on Insulator (SOI) between the two gates. The DG MOSFET makes use of volume inversion layer unlike the Single Gate (SG) MOSFET. Volume inversion carriers tend to experience less interference with the carriers than in the surface inversion layer due to more space and freedom of carrier and this leads to increase in the mobility of the DG MOSFET [27].

The DG MOSFET's family consists of *three* types (i) Planar, (ii) Vertical and (iii) FinFET. Planar has both horizontal gates and channels whilst a Vertical DG MOSFET has conduction in the vertical direction. A FinFET has a vertical channel and its conduction is parallel to the water surface. From the three mentioned types the FinFET device has the simplest fabrication process and is thus the most popular type of DG MOSFFET. A DG MOSFET has a number of advantages over CMOS devices and some of these include [28-30]:

- Nearly ideal subthreshold slope due to the voltage being applied on the gate terminals help to regulate the electric field which in turn determines the amount of supplied current through the channel.
- Circuit speed is improved.
- Small intrinsic gate capacitance and junction capacitances.
- Short Channel Effects (SCE) is better suppressed since the gate to channel coupling is doubled.
- Reduced Random Dopant Fluctuations (RDF) due to undoped or lightly doped body and reduced carrier mobility degradation.
- Design flexibility at circuit level by symmetric/asymmetric with tied and independent gate options.

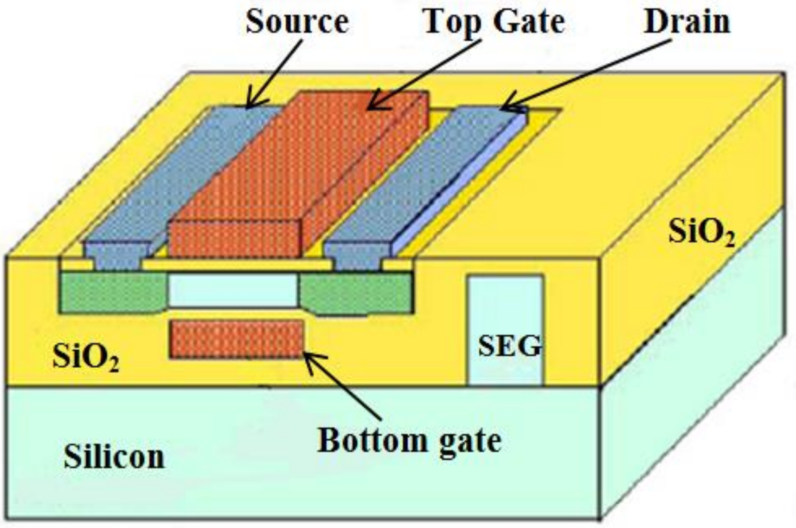

Figure 2.5. Double-Gate MOSFET structure [28].

- The current driving capability of DG MOSFETs is twice that of planar CMOS and thus these devices can be operated at reduced input and threshold voltages. Hence power consumption is less in DG MOSFETs.

2.4 Gate All Around (GAA) MOSFET

The scaling of MOSFET transistors makes the use of innovative device geometries a necessity in order to solve the limitations of the technology that is currently available on the market [31]. Several concepts have been designed in the GAA family of MOSFETs with the two most common being of cylindrical or square shape. A cylindrical shaped GAA MOSFET can be simplified since the device can be analyzed in 1D whereas a square GAA MOSFET has to make use of more challenging techniques because we need to take into account that the cross-sections of these devices do not form a traditional squared shape. This imperfection happens during the manufacturing process when the substances experience a chemical imbalance which results in the edges having a rounded corner. Due to the technology that is currently available this effect is unavoidable but with the rapid growth of technology we will soon have squared GAA MOSFETs readily available. Aside from these two mentioned shapes, a promising design for a GAA based MOSFET makes use of nanowire technology [32]. It provides excellent electrostatic control over the channel which is bounded by a conducting gate and provides higher transconductance compared to the devices mentioned earlier in this chapter [33]. The insulation layer (SiO_2) usually ranges from *1nm* to *5nm*.

2.5 Cylindrical Surrounding Gate MOSFET

MOSFET technology has already achieved perceptible level of performance by down scaling the dimensions [34]. However the problem arises when it comes to improving the devices electrostatic efficiency. A saturated device has dimensions which give rise to a number of issues such as high gate leakage current and various SCEs viz. threshold voltage roll-off, drain induced barrier lowering (DIBL) and increased substrate bias effect [35, 36]. However there have been numerous alterations to the general MOSFET devices structure in order to improve its performance and the geometry best suited to help minimize the above mentioned issues is in the form of a cylinder. This new device is known as the Cylindrical Surrounding Gate (CSG) MOSFET and provides exceptional gate controllability in comparison to single gate and other multi-gate structures. The CSG component in the fully depleted regime shows better robustness against SCEs and also reduces the threshold voltage and sub-threshold swing [37]. Figure 2.6 below shows a general CSG structure.

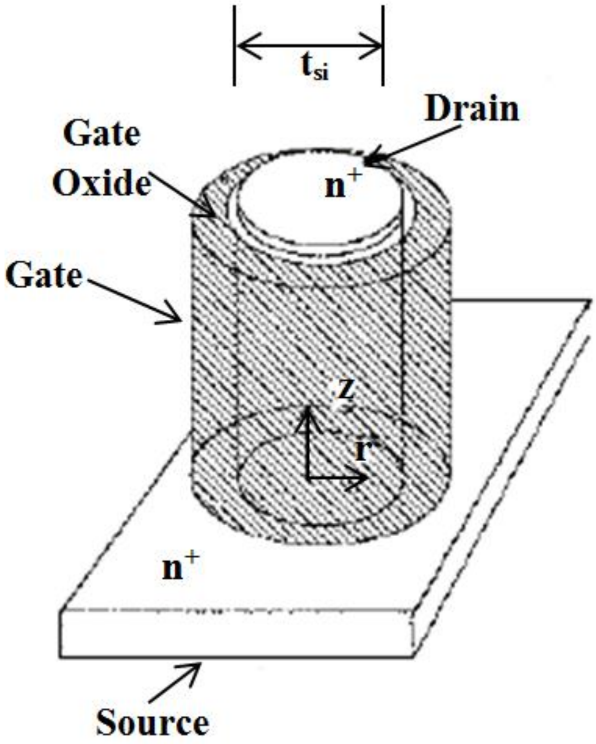

Figure 2.6. Cylindrical Surrounding Gate MOSFET structure [38].

2.6 Cylindrical Surrounding Double-gate (CSDG) MOSFET

(*This device is used and elaborated in this research work/thesis.*)

The CSDG MOSFET is extremely beneficial since it is composed of an undoped body which allows for the efficient controlling of the MOSFET channel by making use of a small channel width and due to its cylindrical structure, gate contact is applied to both the outer and inner sides of the MOSFET. This characteristic helps to reduce the SCE and will yield higher carrier mobility compared with the DG MOSFET or SG MOSFET and makes it an ideal choice for VLSI and nanotechnology designs. A CSDG MOSFET is an extension of the GAA device with scaling [38]. This type of MOSFET looked into how the use of circuit parameters such as capacitance, threshold voltage, frequency, switching speed and drain current can play a role in helping to improve shortcomings such as enhancing carrier mobility, current drive and reduce short channel effects [39].

The concept behind the operation of CSDG MOSFET is that it controls the Silicon channel width so that it has minimal contact with both sides of the channel. This idea helps to suppress the SCE and results in higher currents being achieved compared to a MOSFET that makes use of only a single gate. It is also observed that an n-doped layer in the channel reduces the threshold voltage and increases the drain current, when compared with a device of undoped channel. The reduction in the threshold voltage and the increase in the drain current occur with the level of doping [40, 41].

A larger leakage current is observed than that of an undoped channel but smaller than that of a uniformly doped channel. In particular, the CSDG MOSFET with an intrinsic channel is considered as the best option from the MOSFET family for device downscaling.

Figure 2.7 shows the basic model of combination of two MOSFETs attached to form an n-channel MOSFET. This structure is designed on a p-type semiconductor which serves as the Body (B) and comprises of two n-type semiconductors at the uppermost part of the Body and are known as the Source (S) and Drain (D). A metal electrode called the Gate (G_1) can be seen above the p-type semiconductor and is kept apart from the semiconductor by a thin layer of SiO_2 (Oxide 1). This thin layer acts as an electrical insulator and occupies the space between the Source and Drain which makes the Gate electrically insulated from the Body [42, 43]. The bottom portion of Figure 2.7 also represents the MOSFET but in this case it shows an inverted view and this structure is a

DG MOSFET. To form a CSDG MOSFET, Figure 2.7 is then rotated along its reference point to form a cylindrical shape and can be seen in Figure 2.8. The CSDG MOSFET has two gates (G_1 and G_2, blue), a drain (red), Oxides (Oxide-1 and Oxide-2, yellow), and the p-type substrate (green).

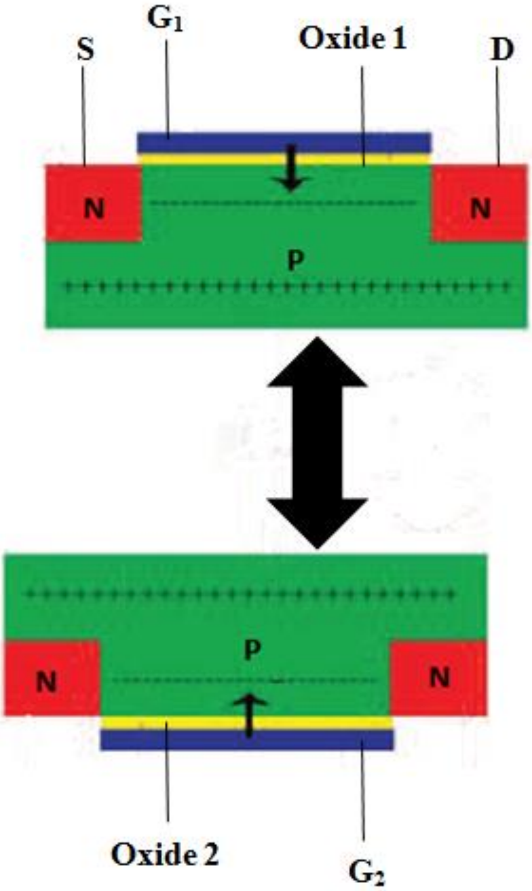

Figure 2.7. Basic model of combination of two MOSFETS back-to-back [38].

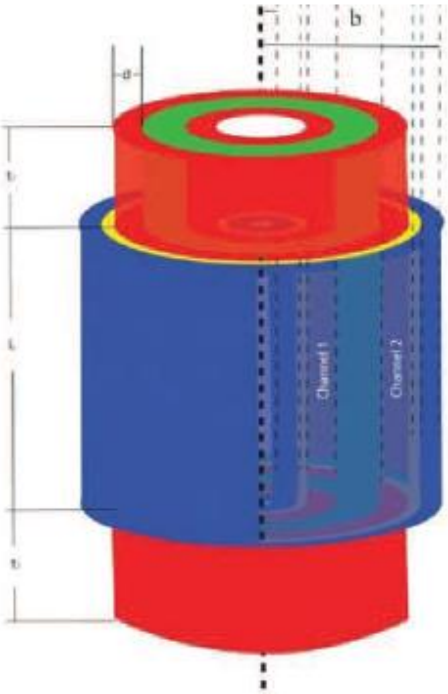

Figure 2.8. Schematic of Cylindrical Surrounding Double Gate MOSFET. [38].

Gate-1 is formed in the inner portion of the cylinder, followed by the thin oxide which helps minimize the effect of SCE whilst the extended element of the cylinder is the Drain and Source. In the CSDG MOSFET, when suitable positive voltages are applied to the gates G_1 and G_2, the body which has the majority carrier as hole and minority carrier as electron will have the holes repelling from the insulators Oxide-1 and Oxide-2 and electrons attracted toward the insulator [41]. This establishes a channel for which electrons at the n substrate can move through the source to the drain. This channel is called the inversion layer [42, 44]. An increase in voltage potentials at both G_1 and G_2 will create a larger electric field which in turn creates a larger n-channel between the drain and the source. This is referred to as the enhancement mode of the MOSFET.

CSDG MOSFET's have been used in a number of electronic circuits such as bridge rectifiers and boost regulators [45, 46]. In terms of a CSDG MOSFET being used in the RF and communications domain not much work has been done in this area. *Oyedeji et. al.* [47] recently proposed the design of an amplifier that made use of a CSDG MOSFET and can be seen in Figure 2.9. An amplifier is an electronic device that will increase a signal's voltage, current or power. They are widely used in wireless communication, broadcasting and in audio equipment.

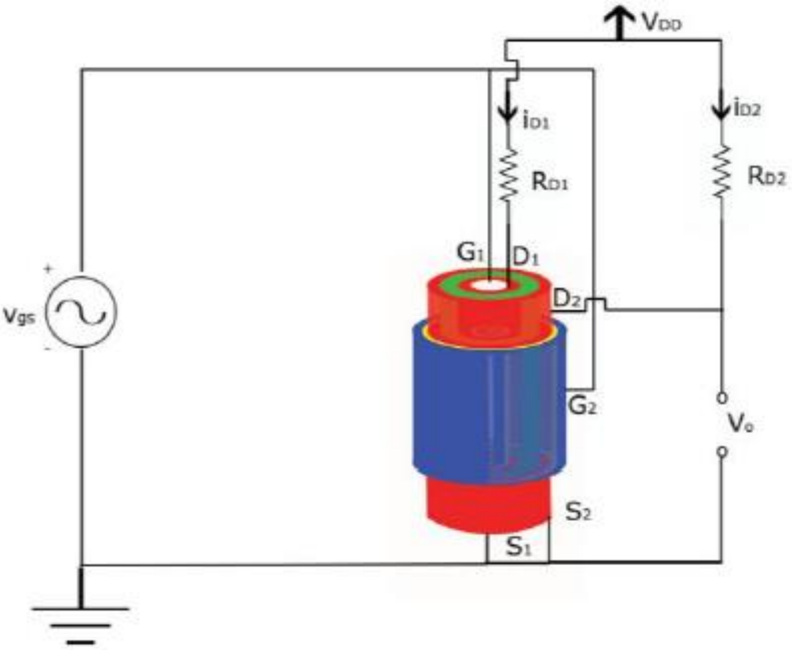

Figure 2.9. CSDG MOSFET based amplifier [47].

This work looked at addressing the operational transconconductance of an amplifier of small voltage in CSDG MOSFET. From the model that was created, it was found that the transconductance in a single CSDG MOSFET is more than that of a CSSG or any similar kind of DG MOSFET due to the structure of the device. This is another advantage of using a CSDG MOSEFT over another MOSFET structure. It was also found that the transconductance of the CSDG MOSFET is affected by the increase of the addition of both an inner and outer structure.

In conclusion, the CSDG MOSFET just like conventional MOSFET devices operates in three modes [48]:

- Cut-off mode: The applied voltage (V_{gs}) is lesser than the threshold voltage (V_T) and the device tends to be in the off state.
- Linear mode: The applied voltage at the gate (V_{gs}) is greater than the threshold voltage and drain voltage ($V_{gs}-V_T>V_{ds}$) which leads to the formation of weak inversion channels between the oxide and the p-substrate.
- Saturation mode: As the drain voltage increases, a saturation region will be reached ($V_{gs}-V_T<V_{ds}$). At this mode, the CSDG MOSFET is fully turned on, and the on-resistance reduces drastically. The CSDG MOSFET operates efficiently under this mode as a rectifier.

2.7 Filter

As explained in Chapter 1, filters perform the function of frequency selection by passing signals whose frequencies lie within a specified range whilst preventing the passing of those that fall outside this region. In addition to having low and high pass filters there are variations of these types of filters. Some of these include RC, RL, RLC, LC and LR filters. Each of the five mentioned filters consists of either a combination of a resistor, inductor or capacitor network and is driven by a voltage or a current source. These filters are known as passive filters. RC filters are commonly used for low and high pass filters whereas a RLC filter configuration is commonly used for band pass and band elimination filters.

Recently extensive research has been conducted to convert RC or RL circuits into an LC circuit [49]. This is done by LC circuit uniquely mapping the roots of either a RC or RL circuit so that it becomes easier to identify and extract the roots from the bode plot. In the analog circuit industry this accurate identification of roots can be used in applications ranging from amplifiers to filters [50, 51].

In addition to having passive filters we also have active filters. There have been a number of designs in the field of active filters and these filters make use of active components such as an operational amplifier and other electronic components like resistors and capacitors [52]. The advantage of using an active component is that it provides a filter circuit with amplification and gain control. Some of the other advantages include [53]:

- A reduction in size of the filter circuit and thus reduces the overall weight of the circuit.
- Performance and reliability of the filter are improved. These filters provide exceptional isolation between the separate stages since it has a high input impedance and a low output impedance.
- Simpler design that that of a passive filter and can be used in a wider range of applications.
- Cost of the circuit is minimized since operational amplifiers cost less and these circuits don’t make use of inductors.

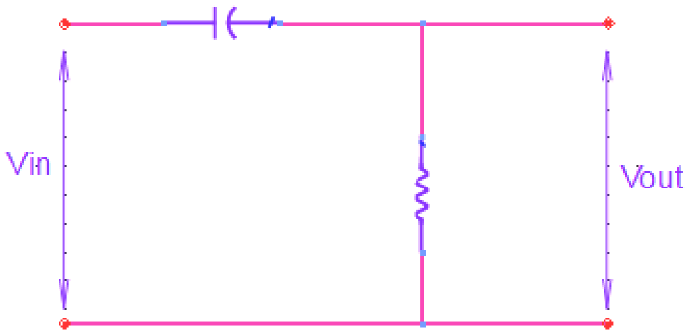

Figure 2.10. Passive high pass filter.

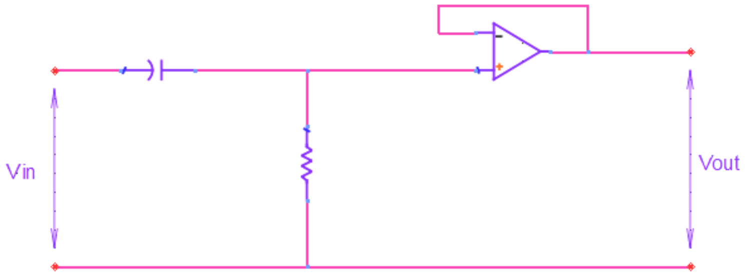

Figure 2.11. First order active high pass filter.

Figures 2.10 and 2.11 show a passive high pass filter and first order active high pass filter respectively.

2.8 Order of Filter

Filters are also designed for specific number of orders viz. first order, second order, third order, etc. [54]. The order of the filter refers to the number of components (either capacitors or inductors) that are part of the filter circuit. For an active circuit all the capacitors before the input of the active component are considered to have an effect on the order of the filter. For example, a first order RC high pass filter will consist of just a single capacitor and a second order filter will consist of two capacitors. A first and second order filter forms the basis for higher order filters (third, fourth, fifth, etc.).

An active high pass filter can be designed to meet a range of filter orders. Both first and second order filters are the building blocks for active filters that make use of orders that are greater than two. A general rule for the order for designing a filter, is an even order number will comprise of a number of cascaded second order filters only. An odd order filter will begin with a first order and then followed by a number of cascaded

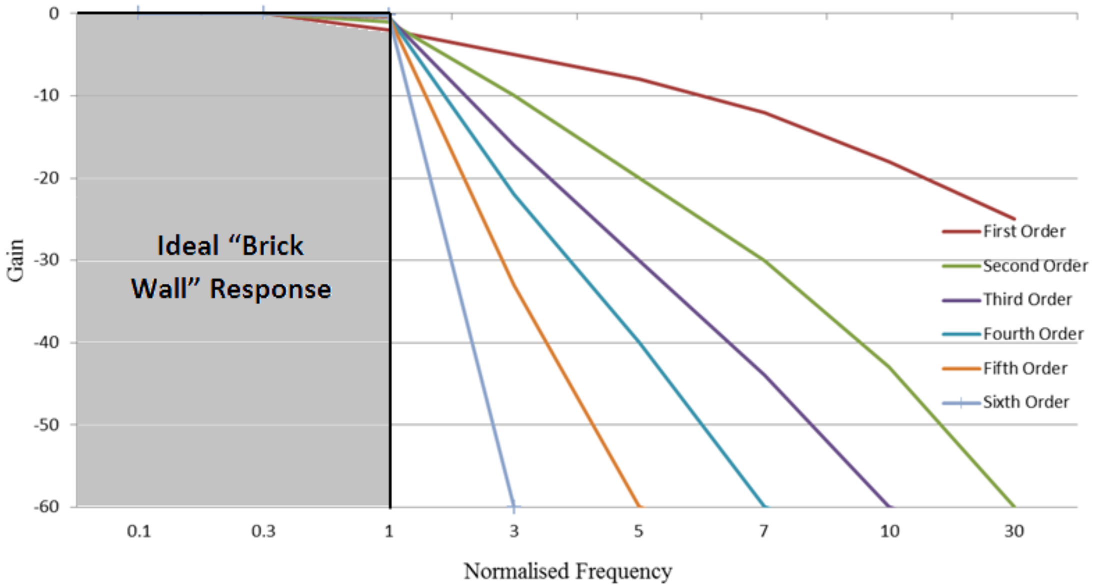

Figure 2.12. Ideal frequency response of different filter orders.

second order filters [55]. From Figure 2.12, it can be seen that the higher the filter order, the closer the filter is to the ideal "brick wall" response.

The order of the filter is referred to as the maximum amount of delay the filter will have and it is directly proportional to the number of components needed to fulfill a particular filter's specification. The advantages of using higher order filters include some of the following:

- Narrower transition band.
- More attenuation between the pass band and stop band.
- Flatter pass band (less ripple).

There are a number of disadvantages to increasing the order of the filter and some of these include:

- Longer group dely.
- Cost to manufacture is greater has the order of filter is increased.
- Higher chance of instability.

2.9 Components of Filter

The components that are used for a filter depends on what type of filter is being designed. There are three main types of filter circuits that are designed and these are (i) RC, (ii) RL and (iii) RLC circuits. The major difference between these two circuits is that the former circuit stores energy in the form of the electric field whilst the latter circuit stores energy in the form of a magnetic field [53]. Electronic filters are continues-time filters that can be implemented with basic components such as resistors, capacitors, amplifiers or more complicated components such as active devices, which have been used for a long time in the field of engineering [56]. An RC circuit consists of a resistor and capacitor combination whereas a RL circuit makes use of a resistor and inductor combination. An RLC circuit consists of a resistor, an inductor and a capacitor connected either in series or parallel [52]. For this research work we look at the RC network configuration. The advantages of using this type of filter are the following:

(i) Mitigation of noise as this circuit does not create a magnetic field.
(ii) Circuits are not bulky since it does not make use of an inductor.
(iii) Costs are kept to a minimum as capacitors use a more simple design compared to an inductor and they are more readily available.

Chapter-3

CSDG MOSFET and RF Filter Designs

This chapter looks at the detailed design of the CSDG MOSFET and 3rd order filters, which have been implemented in this research work. First we look at the design of the MOSFET's that have been used for a robotics systems (Chapter 4), remote controlled devices (Chapter 5), and satellite communication systems (Chapter 6). Thereafter we document the equivalent filters that make use of the CSDG MOSFET. To further improve the gains and other parameters of the designed active high pass filters CSDG MOSFET's are added to their outputs.

3.1 CSDG MOSFET Design

Three different configurations of CSDG MOSFET's are designed and this is detailed in the subsections to follow. In sections 3.1.1, 3.1.2 and 3.1.3 we have designed MOSFET's that can be used in robotic system, remote controlled devices, and satellite systems respectively.

From Equation 3.3 there are a number of parameters that can affect the overall capacitance of the CSDG MOSFET. The three parameters that were considered are length, circumference and permittivity of dielectric used. From Gaussian Law we can derive two equations (Equation 3.1 and Equation 3.2) that allows us to see what affect changing the three parameters over a desired range has on the electric field of a cylindrical device.

$$\Phi = E2\pi rL = \frac{\lambda L}{\varepsilon_o} \tag{3.1}$$

$$E = \frac{\lambda}{2\pi\varepsilon_o r} \tag{3.2}$$

The two equations above show us what type of relationship length, circumference and permittivity will have with the electric field. Circumference and permittivity both have an inversely proportional relationship with the electric field. This means that has the circumference or permittivity increases, the electric field will decrease and vice versa. Length is directly proportional to electric field and thus if length is increased or decreased so will the electric field.

3.1.1. Basic Capacitive Model

Since capacitance plays such an important role in the selectivity of frequencies, by using a CSDG MOSFET to act as an additional capacitor. It will allow for better frequency selection and thus improvements in gain will be observed. The Single-Gate (SG) MOSFET for a number of years has been the choice of semiconductor device for Very Large Scale Integrated (VLSI) circuits. As explained in Chapter 2 of this research work, the CSDG MOSFET is an extension of a DG MOSFET with numerous benefits. It is at the forefront of MOSFET technology and research within this field is consistently growing [57]. It requires a small area of substrate due to its basic design and its fabrication costs are kept to a minimum [58]. However it does have its drawbacks such as mobility limitations, gate oxide used and leakage current. To reduce these limitations a new MOSFET structure has been proposed by *Srivastava et al* [46] and is known as a CSDG MOSFET. A CSDG MOSFET is formed by rotation of a DG MOSFET with respect to its reference point to form a hollow cylinder. This design is equivalent to two Single-Gate MOSFET brought together back-to-back and is then rotated 360° with respect to one of the gates [59].

The basic concept of CSDG MOSFET is to control the Si channel width so there is a smaller contact point at both sides of the channel, which is of cylindrical shape as shown in Figure 3.1. This concept aids in suppressing the SCE and leads to higher currents as compared with a MOSFET using a single gate. It consists of two gates, one drain and one source. For this proposed solution we look at a basic CSDG MOSFET design that makes use of a SiO_2 layer and we analyse the results that are achieved after the newly designed filter has been simulated. The following six equations are analysed for the design of a CSDG MOSFET [59]:

$$\left.\begin{aligned}
C_{gs1} &= \frac{2\pi\varepsilon t}{\ln\left(\frac{a+d}{a}\right)} \\
C_{gd1} &= \frac{2\pi\varepsilon t}{\ln\left(\frac{a+d}{a}\right)} \\
C_{ds1} &= \frac{2\pi\varepsilon L}{\ln\left(\frac{a+d}{a}\right)} \\
C_{gs2} &= \frac{2\pi\varepsilon t}{\ln\left(\frac{b}{b-d}\right)} \\
C_{gd2} &= \frac{2\pi\varepsilon t}{\ln\left(\frac{b}{b-d}\right)} \\
C_{ds2} &= \frac{2\pi\varepsilon L}{\ln\left(\frac{b}{b-d}\right)}
\end{aligned}\right\} \tag{3.3}$$

Where, ε is the Dielectric permittivity, *a* and *b* are the inner and outer radius diameter respectively, *L*, *t* and *d* are length of cylinder, junction depth and depth of source respectively.

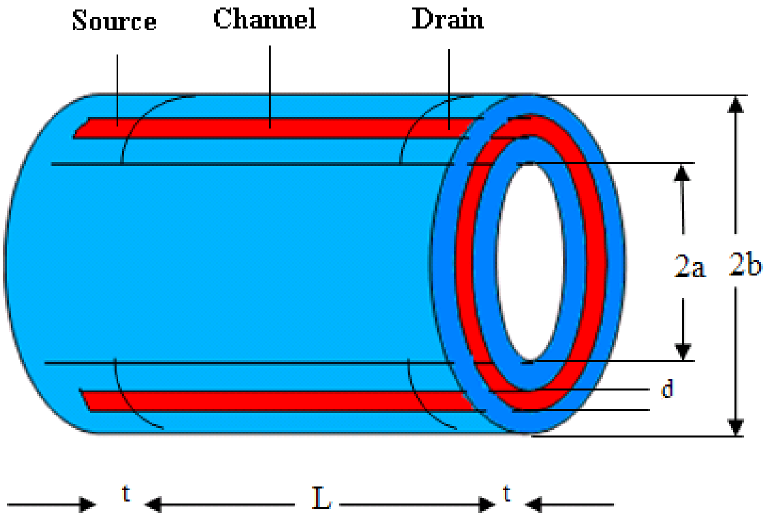

Figure 3.1. CSDG MOSFET [59].

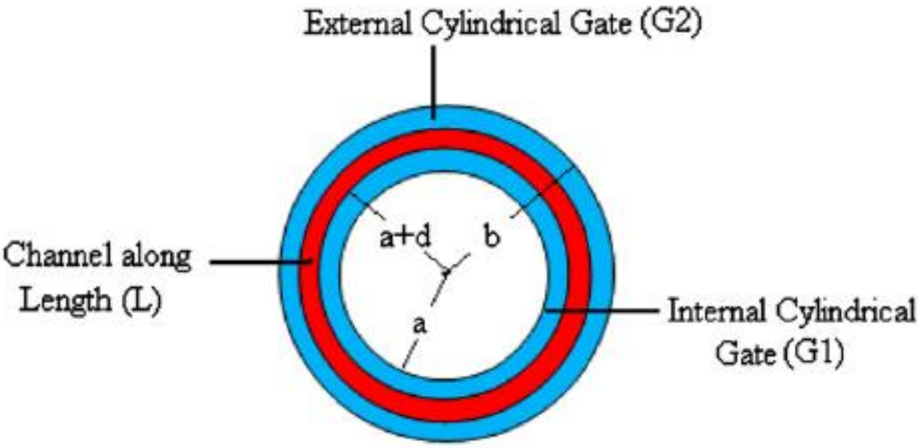

Figure 3.2. Cross section of CSDG MOSFET [59].

For this design we have selected *a = 5 nm*, *b = 12 nm*, *L = 20 nm*, *t = 10 nm*, and *d = 10 nm*. The calculations for the required component values are calculated using the equations above:

$$C_{gs1} = C_{gd1} = \frac{2\pi\varepsilon t}{\ln\left(\frac{a+d}{a}\right)} \tag{3.4}$$

$$= \frac{2\pi * 3.9 * 8.85 * 10^{-12} * 10 * 10^{-9}}{\ln\left(\frac{5*10^{-9} + 10*10^{-9}}{5*10^{-9}}\right)}$$

$$= 0.003\, fF$$

$$C_{gs2} = C_{gd2} = \frac{2\pi\varepsilon t}{\ln\left(\frac{b}{b-d}\right)} \tag{3.5}$$

$$= \frac{2\pi * 3.9 * 8.85 * 10^{-12} * 10 * 10^{-9}}{\ln\left(\frac{12*10^{-9}}{12*10^{-9} - 10*10^{-9}}\right)}$$

$$= 0.002\, fF$$

$$C_{ds1} = \frac{2\pi\varepsilon L}{\ln\left(\frac{a+d}{a}\right)} \tag{3.6}$$

$$= \frac{2\pi * 3.9 * 8.85 * 10^{-12} * 20 * 10^{-9}}{\ln\left(\frac{5*10^{-9} + 10*10^{-9}}{5*10^{-9}}\right)}$$

$$= 0.006\, fF$$

$$C_{ds2} = \frac{2\pi\varepsilon L}{\ln\left(\frac{b}{b-d}\right)} \tag{3.7}$$

$$= \frac{2\pi * 3.9 * 8.85 * 10^{-12} * 20 * 10^{-9}}{\ln\left(\frac{12*10_{-9}}{12*10^{-9} - 10*10^{-9}}\right)}$$

$$= 0.006\, fF$$

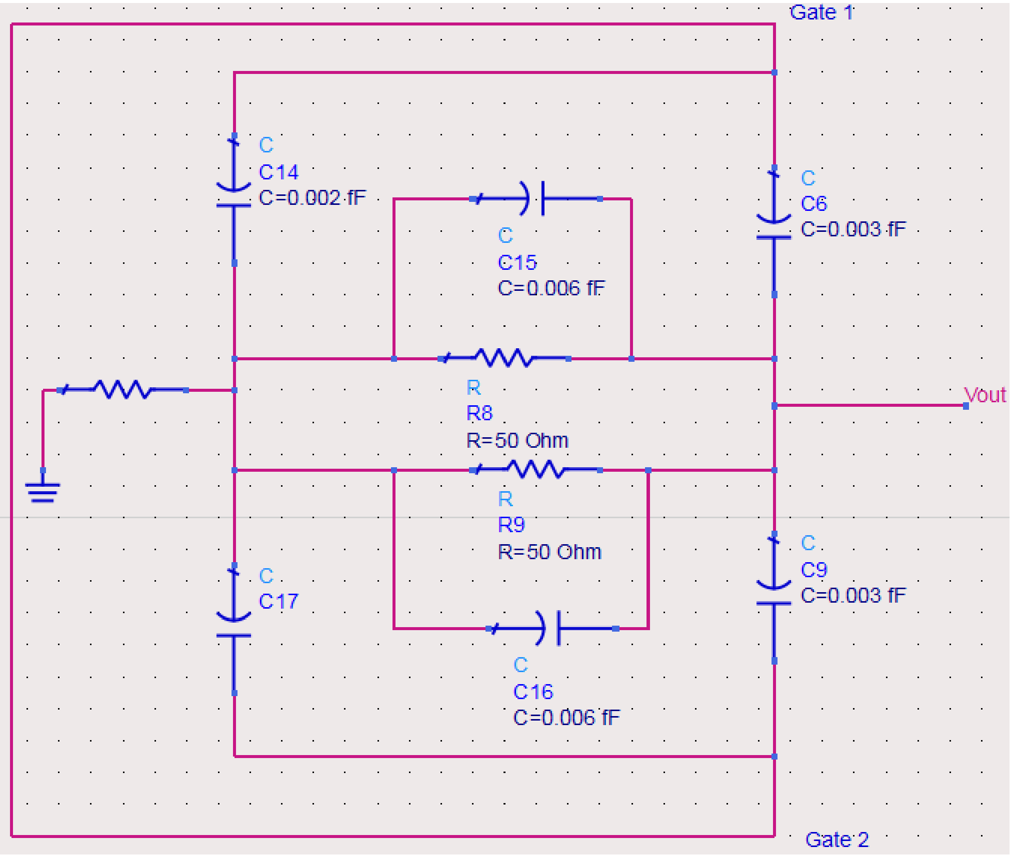

Figure 3.3. CSDG MOSFET schematic.

3.1.2. Parallel Gate Capacitors

The capacitors that connect the gate and source are placed in parallel and are of equal capacitance as this will remove lower frequencies, because capacitance is inversely proportional to cutoff frequency as in Figure 3.4 [60].

For this design we have selected *a = 5 nm*, *b = 12 nm*, *L = 20 nm*, *t = 10 nm*, and *d = 10 nm*. For this design since parallel capacitors are used the following equations apply:

$$C_{gs1} = C_6 + C_8 \qquad (3.8)$$

$$= 2C_6\left(C_6 + C_8\right)$$

$$C_{gs2} = C_9 + C_{10} \qquad (3.9)$$

$$= 2C_9\left(C_9 = C_{10}\right)$$

The total capacitance across source to drain is given by the following expression:

$$C_{CSDG} = C_{ds1} + C_{ds2} + \frac{C_{gs1} * C_{gd1}}{C_{gs1} + C_{gd1}} + \frac{C_{gs2} * C_{gd1}}{C_{gs2} + C_{gd2}} \qquad (3.10)$$

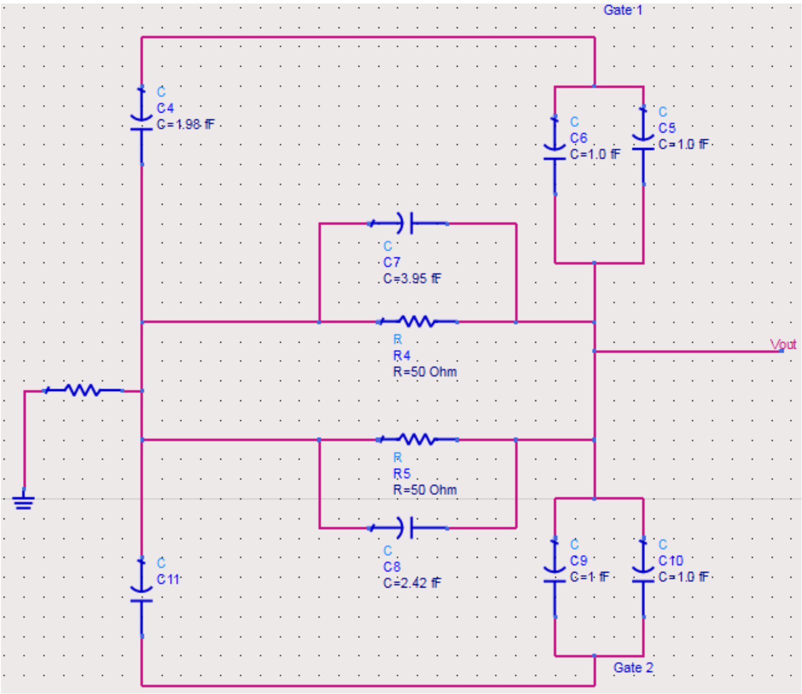

Figure 3.4. Parallel gate capacitive model of CSDG MOSFET.

3.1.3. Hafnium Silicate Based CSDG MOSFET Model

The gate oxide that is most commonly used is SiO_2 but due to the demand for circuits to be more compact, the SiO_2 layer produces high leakage current as the layer becomes thinner (*1.4 nm*) [61]. To overcome leakage currents, high-k gate oxides (Table 1) are being used. *Robertson* [62] has proposed Hafnium Oxide (HfO_2) or Hafnium Silicate ($HfSiO_4$) as an additional oxide layer. The CSDG MOSFET that is being designed (Figure 3.8) makes use of $HfSiO_4$ which has a lower dielectric constant and wider band-gap compared to HfO_2. The advantage of the former will allow the designed filter to operate at higher frequencies and operate more efficiently since the need to store energy is linearly reduced.

In addition the overall capacitance of the MOSFET is reduced due to the lower dielectric constant and results in higher frequencies being achieved (frequency is inversely proportional to capacitance). Another advantage of using $HfSiO_4$ is that, when it is interfaced with the SiO_2 layer, SCE is minimized. Since satellites operate at such extreme temperatures, $HfSiO_4$ can operate at temperatures above *2000°C* and thus makes it an ideal addition to the SiO_2 layer.

A CSDG MOSFET makes use of two gates viz. an inner gate (G_1) and an external gate (G_2). The newly designed component has a layer of $HfSiO_4$ between the gate and the Silicon layer (Figure 3.5 to Figure 3.7) to provide a better dielectric constant whilst providing an increase in performance. The gates on the silicon substrate will help to control the channel better compared to other CMOS devices.

Table 3.1 Table of High K Dielectric Materials

Dielectric Material	Dielectric Constant (K)	Gap (eV)
Silicon (Si)		1.1
Silicon Dioxide (SiO_2)	3.9	9
Aluminium Oxide (Al_2O_3)	9	8.8
Titanium Oxide (TiO_2)	80	3.5
Zirconium Dioxide (ZrO_2)	25	5.8
Hafnium Oxide (HfO_2)	25	5.8
Hafnium Silicate ($HfSiO_4$)	11	6.5
Strontium Titanate ($SrTiO_3$)	2000	3.2
Yttrium Oxide (Y_2O_3)	15	6
Lanthanum Oxide (La_2O_3)	30	6

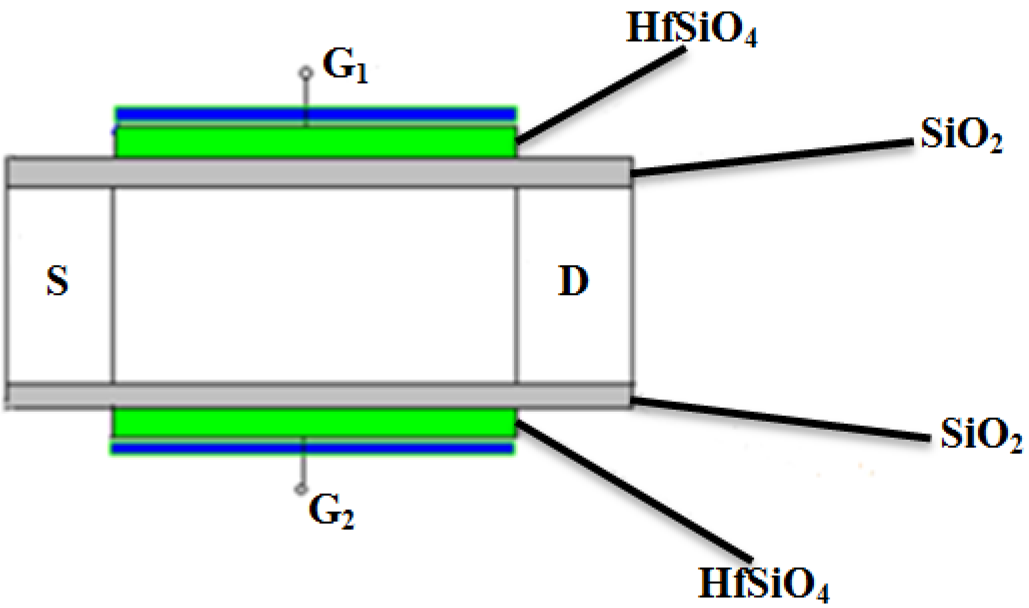

Figure 3.5. Basic model of $HfSiO_4$ based Double-Gate MOSFET.

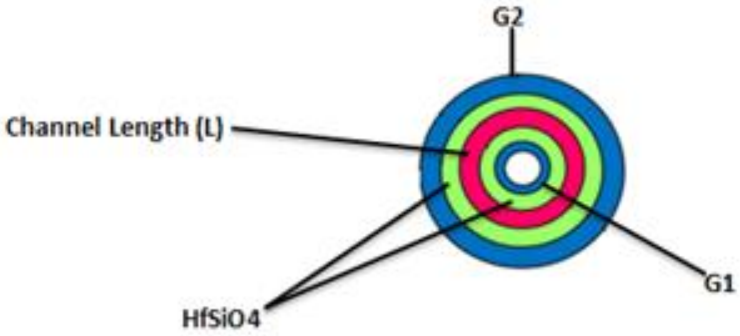

Figure 3.6. Side view of CSDG MOSFET.

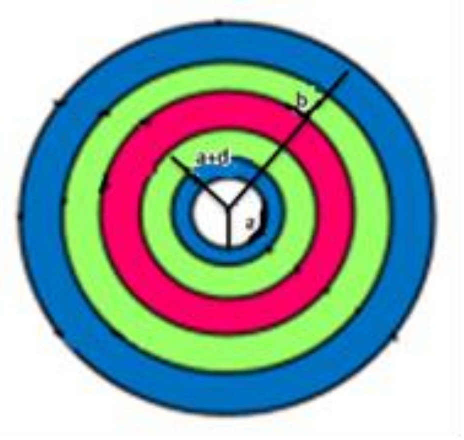

Figure 3.7. Cross section area of CSDG MOSFET with parameters.

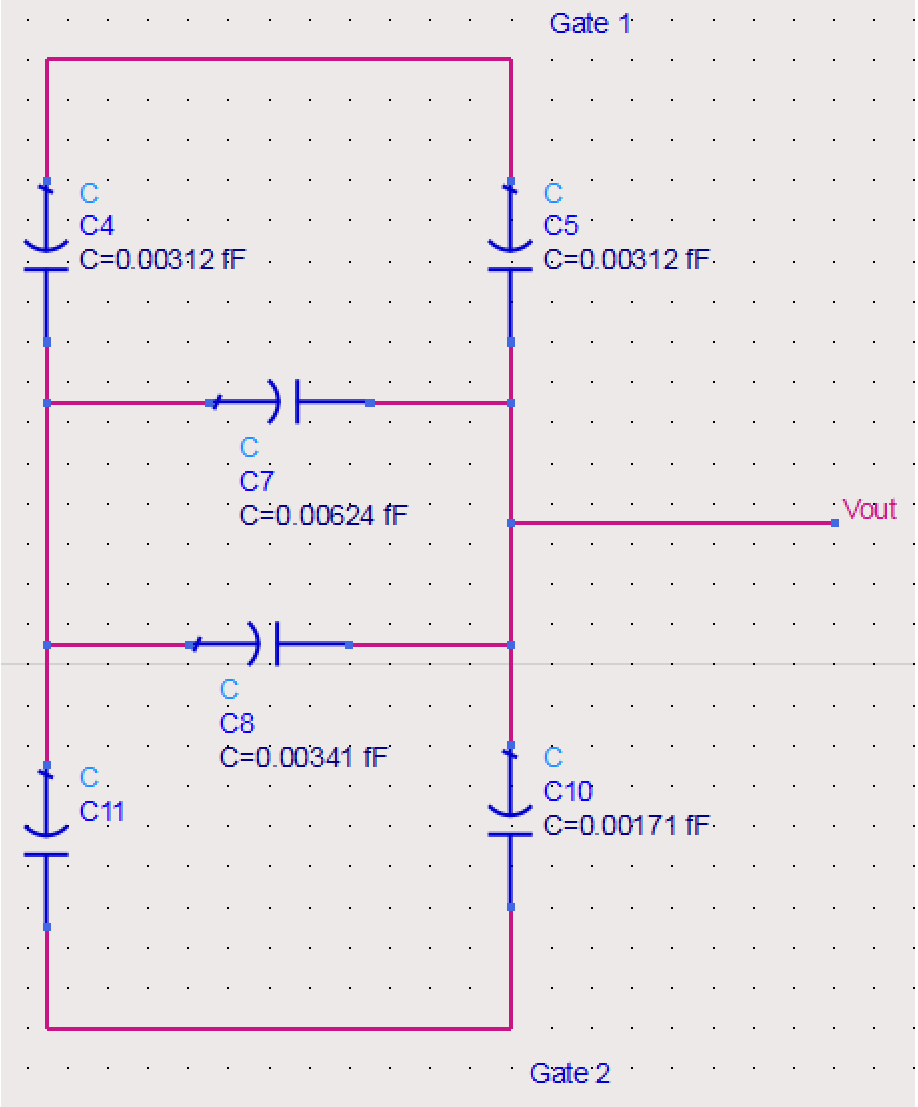

Figure 3.8. Capacitive model of CSDG MOSFET using $HfSiO_4$.

Since satellite systems consist of a number of components, each component needs to be designed for a particular size whilst delivering the levels of performance that are required for the satellite to operate in an efficient manner. The designed CSDG MOSFET makes use of the following parameters to ensure that the filter remains compact: $a = 3\ nm$, $b = 6\ nm$, $L = 10\ nm$ *and* $d = 5\ nm$.

Since this newly designed CSDG MOSFET makes use of two dielectric materials it results in the following effective dielectric material (K_{eff}) and equivalent capacitance (C_{eq}) equations:

$$K_{eff} = \frac{K_{SiO_2} * K_{HfSiO_4}}{K_{SiO_2} + K_{HfSiO_4}} \tag{3.11}$$

$C_{eq} = \frac{C_{SiO_2} * C_{HfSiO_4}}{C_{SiO_2} + C_{HfSiO_4}}$, where C_{SiO_2} and C_{HfSiO_4} are defined as:

$$C_{SiO_2} = \frac{2\pi * K_{SiO_2} * L}{t_{SiO_2}} \tag{3.12}$$

$$C_{HfSiO_4} = \frac{2\pi * K_{HfSiO_4} * L}{t_{HfSiO_4}} \tag{3.13}$$

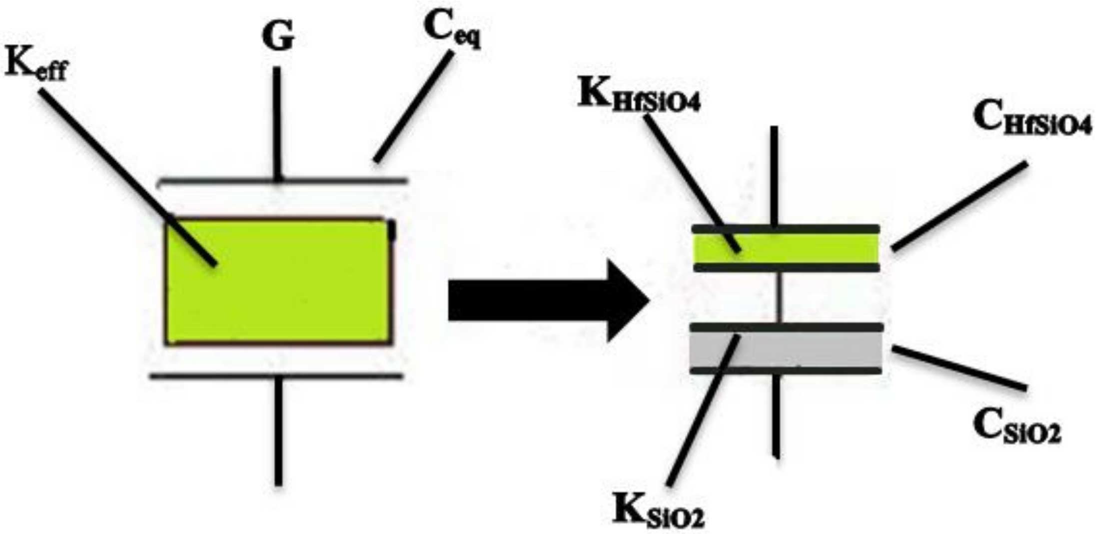

Figure 3.9. The oxide region of the MOSFET showing the materials used.

3.2 RF Filter Design

RF filters of all types are important elements in a number of applications ranging from audio to RF. This section will look at the design of a third order active high pass filter. Designing this type of filter is considered to be a difficult process but it can be simplified once the full specifications of the design are known. This allows decisions to be made on topology, filter type and components that can be used to meet the filter specifications.

Two significant parameters which illustrate the change in signal are known as gain (G) and phase shift (θ). Since both the gain and phase shift are parameters that depend on frequency they are said to be functions of frequency [63, 64]. They can thus be expressed by the following equations:

$$G = G(f) \tag{3.14}$$

$$\theta = \theta(f) \tag{3.15}$$

These two above functions represent the frequency response and the phase response of the designed active high pass filter respectively. In addition to these 2 parameters we also look at the return loss of the various third order filters that have been designed. To design this type of filter we simply cascade both first and second order active high pass filters. Below is the derivation for the cutoff frequency a first order filter [65, 66]:

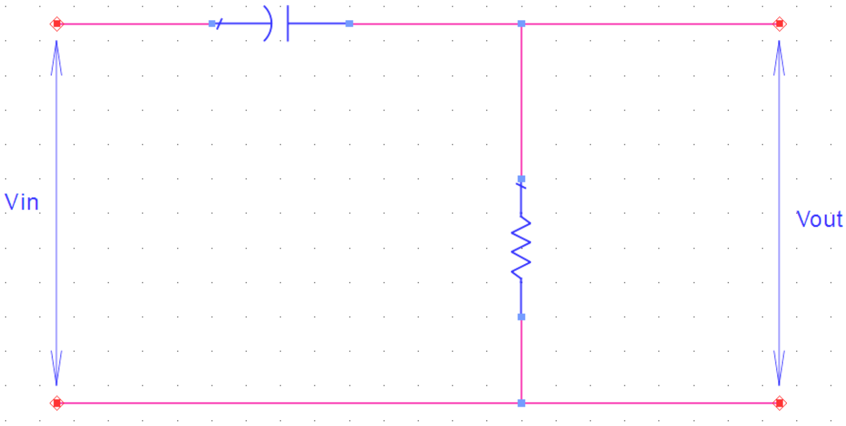

Figure 3.10. First order filter.

$$V_{out} = \frac{V_{in} * \left(-j\frac{1}{C\omega_c}\right)}{R - j\frac{1}{C\omega_c}} \tag{3.16}$$

It is known that the cutoff frequency should be equated to a value of $\frac{1}{\sqrt{2}}$.

$$\frac{-j\frac{1}{C\omega_c}}{R - j\frac{1}{C\omega_c}} = \frac{1}{\sqrt{2}}$$

$$\frac{\frac{1}{\omega_c C}}{\sqrt{R^2 + \left(\frac{1}{\omega_c C}\right)^2}} = \frac{1}{\sqrt{2}}$$

$$\sqrt{2} * \frac{1}{\omega_c C} = \sqrt{R^2 + \left(\frac{1}{\omega_c C}\right)^2}$$

$$2 * \left(\frac{1}{\omega_c R}\right)^2 = R^2 + \left(\frac{1}{\omega_c R}\right)^2$$

$$R^2 = \left(\frac{1}{\omega_c C}\right)^2$$

$$R = \frac{1}{\omega_c C}$$

$$\text{Since, } \omega_c = 2\pi f_c$$

$$f_c = \frac{1}{2\pi RC}$$

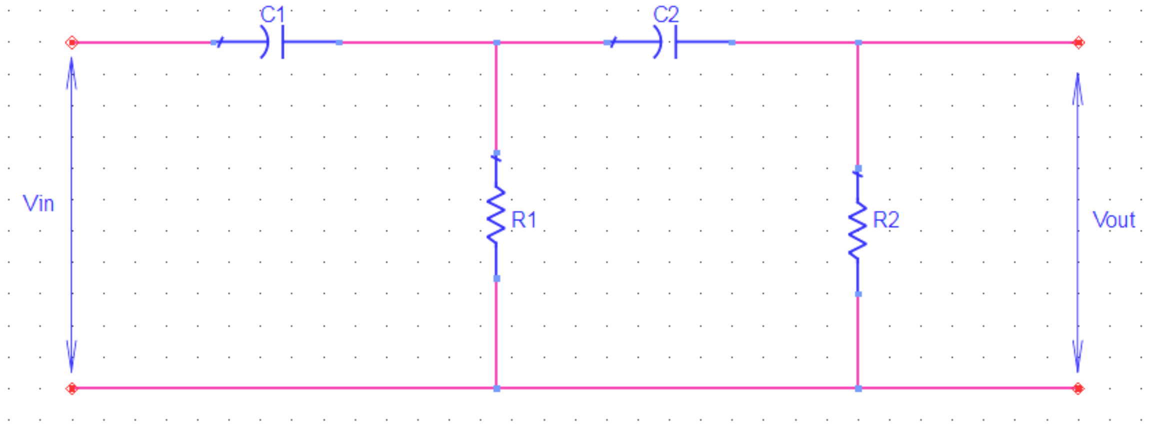

Figure 3.11. Second order filter.

The next derivation is of a second order filter and makes use of Kirchoff’s Current Law. The circuit shown in Figure 3.11 helps with this derivation.

$$\frac{V_{out} - V_{node}}{R_2} + sC_2 V_{out} = 0$$

$$\therefore V_{node} = V_{out}\left(1 + sR_2 C_2\right) \tag{3.17}$$

$$\frac{V_{node}-V_{in}}{R_1}+\frac{V_{node}-V_{out}}{R_2}+sC_1V_{node}=0$$

$$\therefore V_{node}\left(R_1+R_2+sR_1R_2C_1\right)-R_2V_{in}-R_1V_{out}=0 \tag{3.18}$$

Substitute equation 3.17 into equation 3.18 and rearranging we end up with following resulting equation:

$$\frac{V_{out}}{V_{in}}=\frac{R_2}{\left(1+sR_2C_2\right)\left(R_1+R_2+sR_1R_2C_1\right)-R_1}$$

$$=\frac{1}{s^2R_1R_2C_1C_2+s\left(R_1C_1+R_1C_2+R_2C_2\right)+1}$$

Substituting $s=j\omega$ the resulting equation is:

$$\frac{1}{\sqrt{\omega^4\left(R_1R_2C_1C_2\right)^2+\omega^2\left[(R_1C_1+R_1C_2+R_2C_2)^2-2\left(R_1R_2C_1C_2\right)\right]+1}}$$

It is known that the cutoff frequency should be equated to a value of $\frac{1}{\sqrt{2}}$.

$$\frac{1}{\sqrt{2}}=\frac{1}{\sqrt{\omega^4\left(R_1R_2C_1C_2\right)^2+\omega^2\left[(R_1C_1+R_1C_2+R_2C_2)^2-2\left(R_1R_2C_1C_2\right)\right]+1}}$$

$$2=\omega^4\left(R_1R_2C_1C_2\right)^2+\omega^2\left[(R_1C_1+R_1C_2+R_2C_2)^2-2\left(R_1R_2C_1C_2\right)\right]+1$$

$$1=\omega^2\left(R_1R_2C_1C_2\right)\left[\omega^2\left(R_1R_2C_1C_2\right)+\left(R_1C_1+R_1C_2+R_2C_2\right)^2-2\right]$$

$$1=\omega^2\left(R_1R_2C_1C_2\right)$$

$$\omega^2=\frac{1}{R_1R_2C_1C_2}\text{ , hence }\omega=\frac{1}{\sqrt{R_1R_2C_1C_2}}$$

Since, $\omega=2\pi f_c$ so $\therefore\ f_c=\frac{1}{2\pi\sqrt{R_1R_2C_1C_2}}$

After considering the advantages and disadvantages and doing extensive research, the order of filter that was chosen was a third order active high pass filter as this best allowed us to meet our specification targets. A factor is of paramount importance in the electronics industry is one of cost to manufacture and produce such equipment. After simulating other filters that made use of a fourth or fifth order, we observed that the differences in gain were not significant enough to warrant the extra cost and complexity of the design.

3.3 Analysis of Parameters

This section of the chapter looks analyzing the effect that length and radius will have on both the gain and cutoff frequency of a filter. When doing the analysis on length, other parameters such has radius, permittivity and depth of source were kept constant. Figures 3.12 and 3.13 show the gain and cutoff frequency respectively.

These results agreed with the theory learnt from Sections 3.1 and 3.2 of this chapter. From equation 3.3 we see that length is directly proportional to capacitance. Has the length of the cylinder is increased so does the capacitance. Since capacitance is inversely proportional to frequency, the frequency of the filter is decreased when capacitance is increased. This can be clearly seen in Figure 3.13. The difference in the frequency value may be a mere 0.25 but this small value can alter the bandwidth and the throughput of a device.

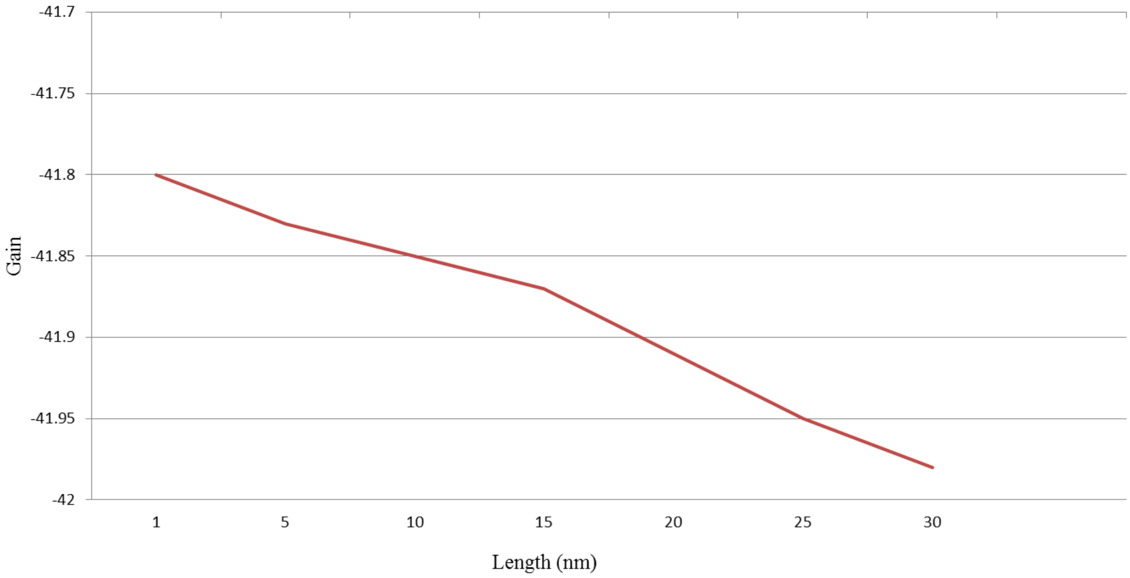

Figure 3.12. Length vs. Gain.

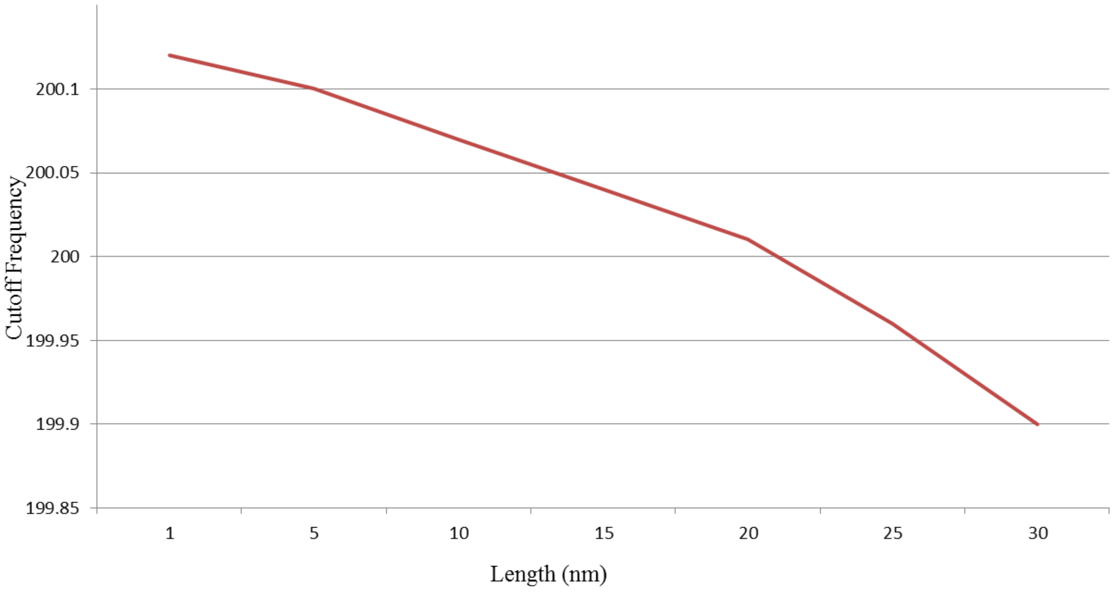

Figure 3.13. Length vs. Cutoff Frequency.

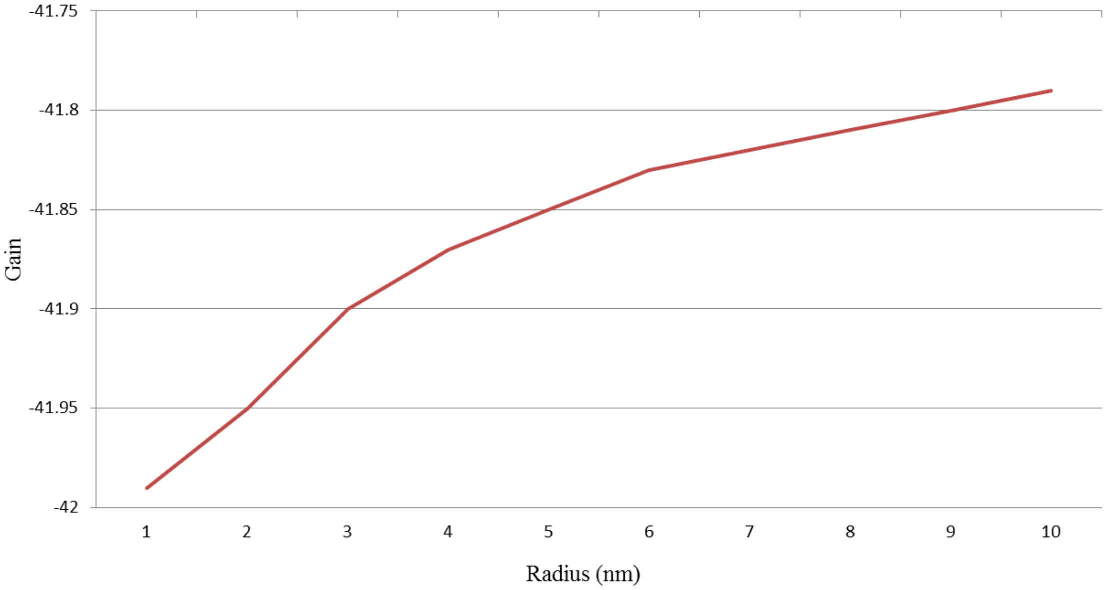

Figure 3.14. Radius vs. Gain.

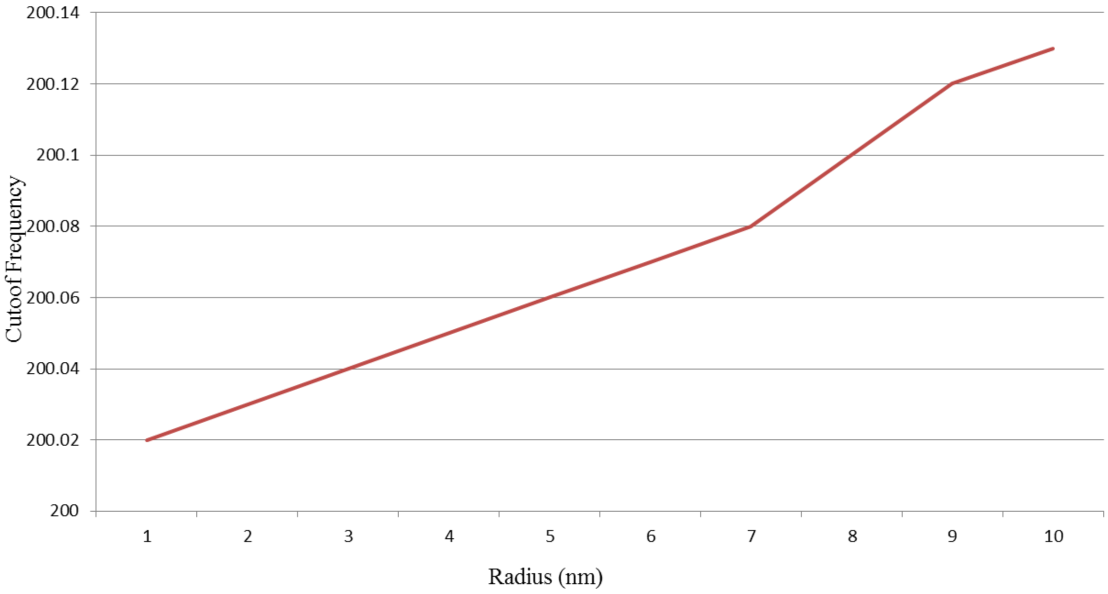

Figure 3.15. Radius vs. Cutoff Frequency.

When doing the analysis on radius, other parameters such has length, permittivity, junction depth and depth of source were kept constant.

These results also agreed with the theory learnt from Sections 3.1 and 3.2 of this chapter. Since radius is inversely proportional to capacitance, increasing the radius will decrease the capacitance and will lead to higher frequencies being achieved. Finding a balance between these two parameters will ensure that more efficient and higher frequency filters can be designed.

Chapter-4

Application of High Pass Filter in Robotics: A Circuit Perspective

This chapter deals with the design of a filter that could be implemented in a robotics system. After extensive research it has been found that by using a high pass filter we can achieve the high frequencies that the robotic design requires. The cutoff frequency for this design was chosen to be *0.1 THz*. To further improve the gain (an important parameter of filter design) of the proposed circuit, a CSDG MOSFET (as discussed in Section 3.1) has been added to the output of the filter.

4.1 Introduction

Robotics is a field of engineering and science that includes mechanical engineering, electrical engineering, computer sciences, and mechatronics [67-69]. This field deals with the design, construction, operation, and use of robots. Basically, robots are machines which reduce the human efforts in heavy works in industries, building etc. [70-72]. They are especially useful in situations where humans have to be in dangerous environments such as bomb/explosive detection and deactivation, high temperatures in industry, and mining.

The mechanical structure of a robot can be controlled by human to perform certain tasks [73]. There are various ways that one can control the robot e.g. Personal Computer (PC) control, direct wired control (the controller is physically connected to the robot via a cable), wireless or by means of Radio Frequency (RF). To use the RF method of control, industrial robotics make use of remote control units which consist of microcontrollers within the transmitter and receiver to send and receive data through RF. Main advantage of using RF is that it does not require line-of-sight (unobstructed path) communication and thus range of communication can be up to *50 meters*. In addition, robots can be used in defense, mining, surveying and other similar applications.

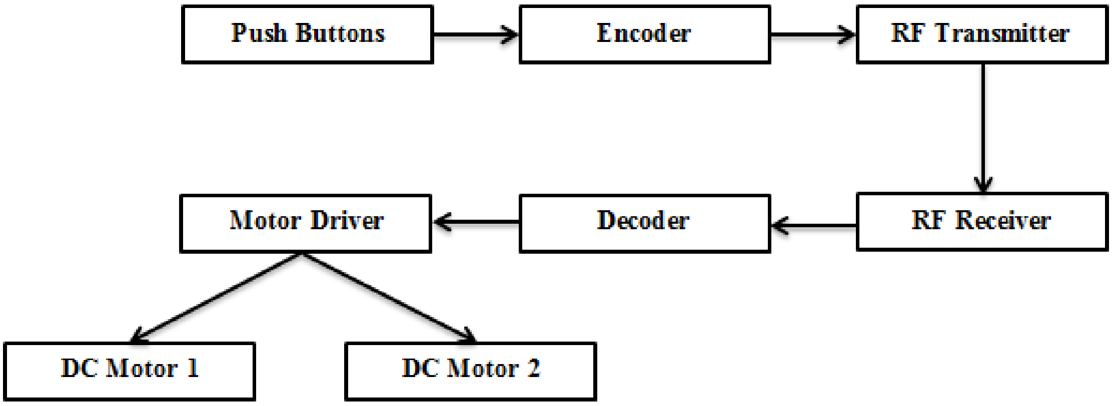

Figure 4.1. Block diagram of a robot system.

4.2 Filter use in Robotics

A robotic system cannot operate efficiently without a highly selective filter. These filters are placed between the transmitter and preamplifier and ensure that only signals from the appropriate frequency band will be amplified and the correct signals are received during important functions in the manufacturing industry such as welding and assembling of cars. If filters are not designed properly it will lead to problems during the manufacturing process and this will have an effect on production numbers which will lead to a loss of profits.

The newly designed filter is designed to operate at frequencies around 100 GHz. This will allow robotic systems to complete multiple functions at once as there is a greater bandwidth to operate within. With a greater demand from industry for their robots to be more function rich, robot manufacturers need their systems to work in the EHF Band [74-76].

4.3 Proposed Solution

For a robotic system which employs a high pass filter, radio waves from the transmitter pass through the air simultaneously without impeding each other. These radio waves can be separated at the receiver end because they have different frequencies. To separate the unwanted signal from the desired signal, the high pass filter allows only the frequency of the transmitter to pass through. For this design an active high pass filter has been implemented. The advantages of using an active filter (over a passive filter) are that there are no loading problems between the source and the load, lower cost and minimum weight.

An active high pass filter order larger than second will require cascading first and second order high pass filters. For this design the first order system consists of an operational amplifier followed by a transistor based circuit. The transistor based circuit consists of a few components viz. a pair of capacitors and three resistors. Resistors R_4 and R_5 create a bias point for the base of the transistor whilst resistor R_e sets the transistor current.

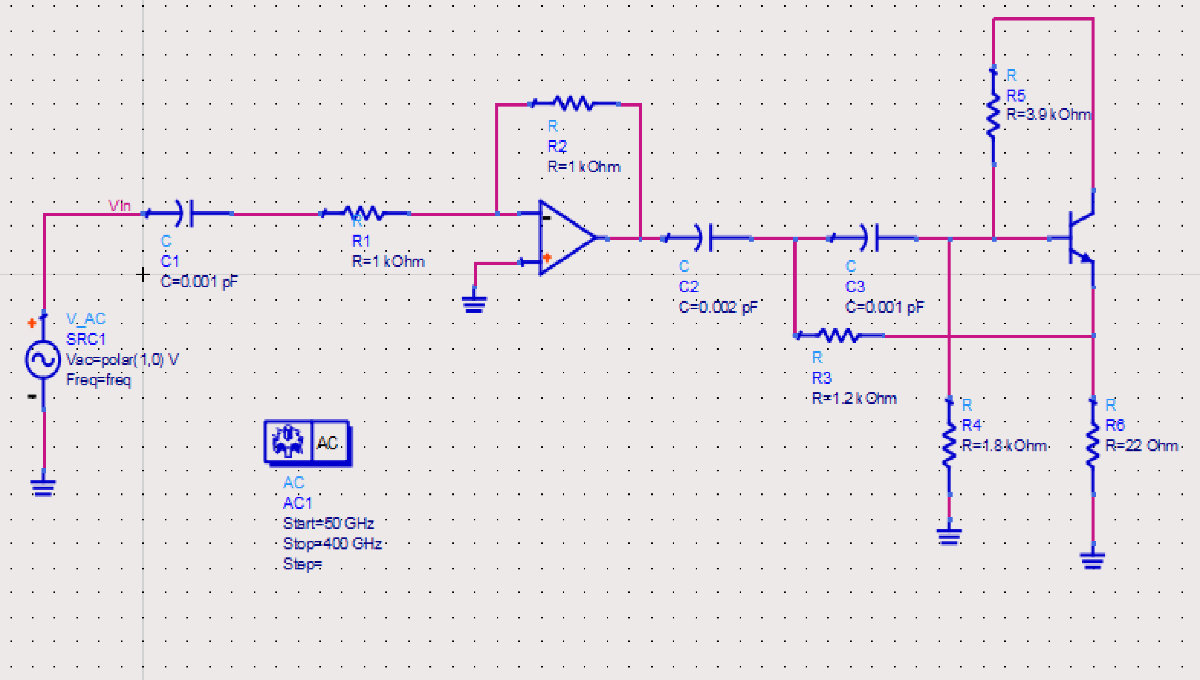

Figure 4.2. Circuit design of a 3rd order active high pass filter

4.4 RF Filter Design

The main objective of this work is to design a filter that can operate at a frequency that is close to the terahertz range. As such a cut-off frequency of *100 GHz* (*0.1 THz*) has been considered. The following equations are relevant for the design of the op-amp based circuit [65, 66]:

$$f_c = \frac{1}{2\pi R_2 C_1} \tag{4.1}$$

Furthermore, the following equations are relevant for the design of the transistor based circuit:

$$C_2 = 2C_3 \tag{4.2}$$

$$R_3 = \frac{R_4 * R_5}{R_4 + R_5} \tag{4.3}$$

$$R_e(\mathrm{B}+1) \gg R_2 \tag{4.4}$$

$$f_c = \frac{1.414}{4\pi R_3 C_3} \tag{4.5}$$

In this application we have taken the value of $C_1 = 0.001\ pF$

$$f_c = \frac{1}{2\pi R_2 C_1}$$

$$100 * 10^9 = \frac{1}{2\pi R_2 * 0.001 * 10^{-12}}$$

$$\therefore R_2 = 1k\Omega$$

$$R_1 = 1k\Omega$$

For this application we have taken the value of $C_3 = 0.001\ pF$

$$C_2 = 2C_3$$

$$\therefore C_2 = 0.002\, pF$$

$$f_c = \frac{1.414}{4\pi R_3 C_3}$$

$$100 * 10^9 = \frac{1.414}{4\pi R_3 * 0.001 * 10^{-12}}$$

$$\therefore R_3 = 1.2k\Omega$$

The value for R_4 was chosen has *1.8 k Ω*.

$$R_3 = \frac{R_4 * R_5}{R_4 + R_5} \tag{4.6}$$

$$1.2k = \frac{1.8k * R_5}{1.8k + R_5}$$

$$\therefore R_3 = 1.2k\Omega$$

$$\therefore R_5 = 3.9k\Omega$$

β is the forward current gain of the transistor and has a value of 60.

$$R_e(\text{B}+1) \gg R_2$$

$$R_e(60+1) \gg 1.2k$$

$$\therefore R_e = 22\Omega$$

The transfer function of a filter circuit is defined as being a mathematical expression relating the output voltage (V$_o$) of the filter circuit to the input voltage (V$_i$). For the operational amplifier circuit the transfer function can be written as:

$$T_0(s) = \frac{V_o}{V_i} \tag{4.7}$$

$$= \frac{\boldsymbol{R_2}}{\frac{\mathbf{1}}{\boldsymbol{C_1 s}} + \boldsymbol{R_1}}$$

$$= \frac{\boldsymbol{R_2 C_1 s}}{\mathbf{1} + \boldsymbol{R_1 C_1 s}}$$

The transfer function for the transistor part of the filter is given as:

$$T_t(s) = \frac{V_o}{V_i} \tag{4.8}$$

$$= \frac{R_e}{1 + \frac{1}{R_3 C_2 s} + \frac{1}{R_3 C_3 s} + \frac{1}{R_3 C_2 s R_7 C_3 s}}$$

Since, $R_7 = \dfrac{R_4 * R_5}{R_4 + R_5}$

$$= \frac{\boldsymbol{R_e}}{1 + \frac{1}{s}\left(\frac{1}{\boldsymbol{R_3 C_2}} + \frac{1}{\boldsymbol{R_3 C_2}}\right) + \frac{1}{s^2}\left(\frac{1}{\boldsymbol{R_3 C_2 R_7 C_3}}\right)}$$

$$= \frac{s^2 \boldsymbol{R_e}}{s^2 + s\left(\frac{1}{\boldsymbol{R_3 C_2}} + \frac{1}{\boldsymbol{R_3 C_2}}\right) + \left(\frac{1}{\boldsymbol{R_3 C_2 R_7 C_3}}\right)}$$

Substituting R_7 back into the above equation we get:

$$T_t(s) = \frac{s^2 R_e}{s^2 + s\left(\frac{1}{R_3C_2} + \frac{1}{R_3C_2}\right) + \left(\frac{1}{R_3C_2 * \frac{R_4 * R_5}{R_4 + R_5} * C_3}\right)}$$

$$= \frac{s^2 R_e}{s^2 + s\left(\frac{1}{R_3C_2} + \frac{1}{R_3C_2}\right) + \left(\frac{R_4 + R_5}{R_3C_2R_4R_5C_3}\right)}$$

By combining the operational amplifier and transistor equations, the overall transfer function for the filter is realized and is given by:

$$T(s) = T_o(s) * T_t(s) \tag{4.9}$$

$$= \frac{R_2C_1s}{1 + R_1C_1s} * \frac{s^2 R_e}{s^2 + s\left(\frac{1}{R_3C_2} + \frac{1}{R_3C_2}\right) + \left(\frac{R_4 + R_5}{R_3C_2R_4R_5C_3}\right)}$$

$$\begin{aligned} &= \frac{R_2C_1R_es^3}{s^3(R_1C_1) + s^2\left(1 + \frac{R_1C_1}{R_3C_2} + \frac{R_1C_1}{R_3C_3}\right)} \\ &+ \frac{R_2C_1R_es^3}{s\left(\frac{1}{R_3C_2} + \frac{1}{R_3C_3} + \frac{R_1C_1(R_4 + R_5)}{R_3C_2R_4R_5C_3}\right)} + \frac{R_2C_1R_es^3}{\left(\frac{R_4 + R_5}{R_3C_2R_4R_5C_3}\right)} \end{aligned}$$

4.5 Results and Analysis of 3rd Order Filter

The designed active high pass filter shown in Figure 4.2 has been simulated using a software tool that is used commonly to design electronic circuits. The gain and phase of the circuit has been observed and are shown in the graphs. Figure 4.3 represents the overall gain of the filter and we can see that has the frequency increases, the gain of the filter approaches closer to *0 dB*. This agrees with the theory of how a high pass filter should behave [77]. At the cutoff frequency of *0.1 THz* we observe a gain of *-56.17 dB*.

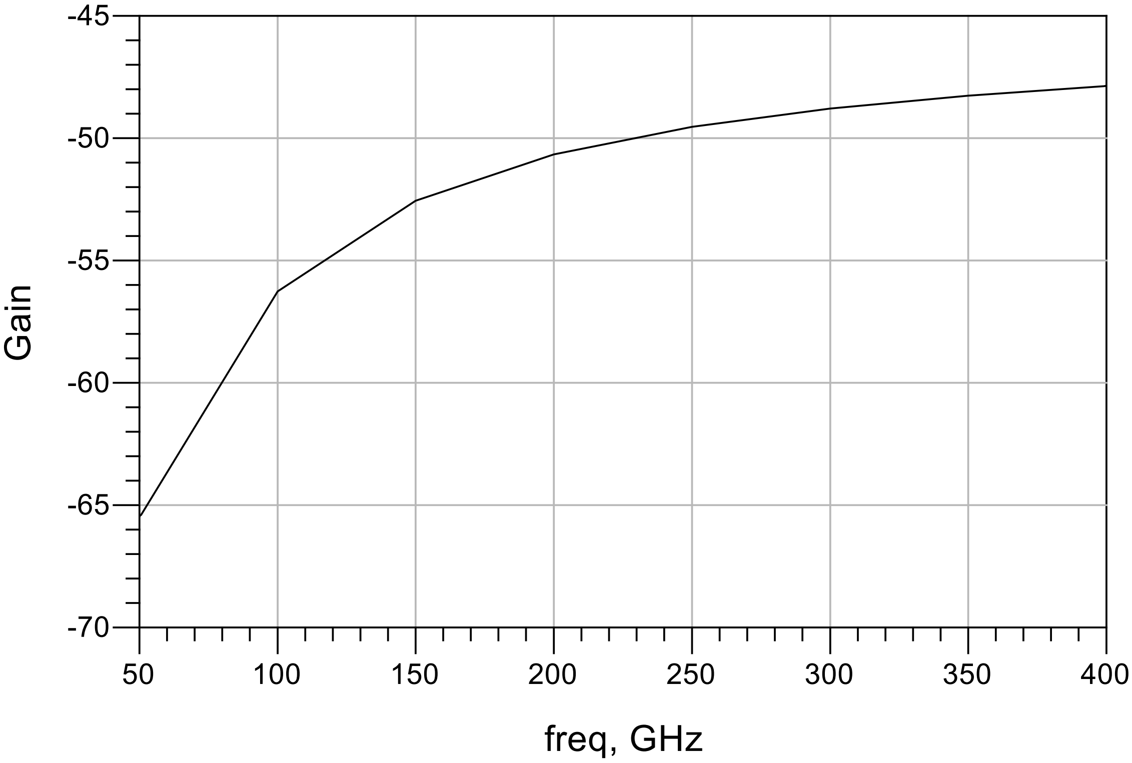

Figure 4.3. Frequency response of proposed 3rd order filter.

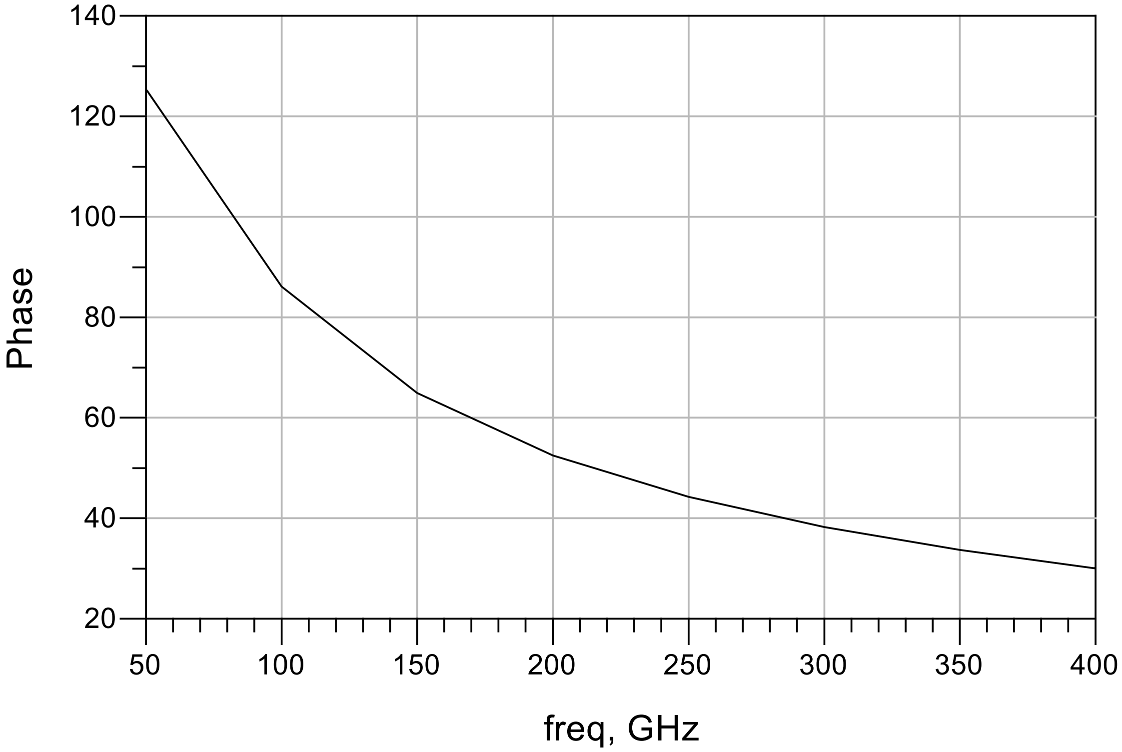

Figure 4.4. Phase response of the proposed 3rd order filter.

The graph shows a *-3 dB* difference in gain between the cutoff frequency and the frequency which provides the maximum gain. This region is referred to as the roll off region. The designed active high pass filter achieves its maximum gain at a frequency of *0.23 THz.*

Figure 4.4 shows the phase response of the filter and has a phase shift of *90°* at the cutoff frequency. This result also agrees with filter theory behavior and thus we can say that the proposed filter solution has been designed correctly [77].

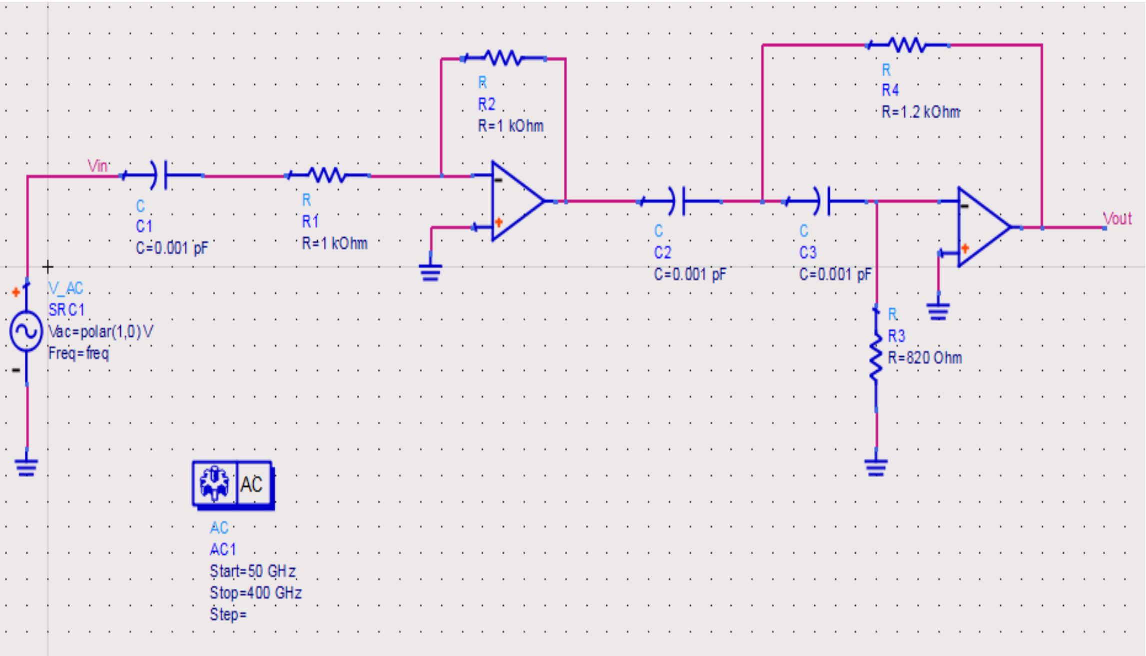

Figure 4.5. Active high pass filter with two operational amplifiers.

Table 4.1 Frequency response for both transistor and operational amplifier based active high pass filters

Frequency (GHz)	**Gain (dB)**		
	Operational Amplifier	**Transistor**	**Difference**
50	-64.40	-63.48	0.92
60	-63.48	-61.37	1.94
70	-62.35	-59.68	2.73
80	-61.06	-58.29	2.64
90	-59.80	-57.13	2.55
100	-58.55	-56.17	2.75
110	-58.28	-55.40	3.02
120	-57.92	-54.80	3.52
130	-57.02	-54.35	2.67
140	-56.60	-54.02	2.58
150	-56.35	-53.79	2.45

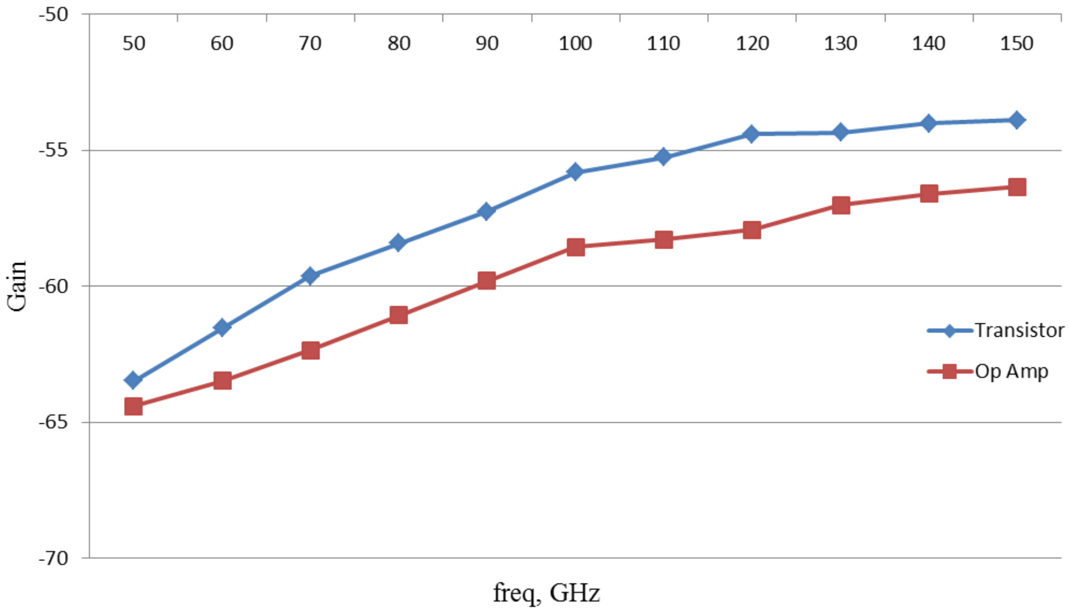

Figure 4.6. Comparison of gains of third order active high pass filters.

Comparing the designed filter with an equivalent active high pass filter that uses two operational amplifiers (Figure 4.5), the benefits in terms of gain is obvious when using a transistor at high frequencies. From this result we can see that if an active filter needs to be designed at frequencies above the VHF band it will be better if a transistor is added to the basic active high pass filter configuration. Table 4.1 and Figure 4.6 illustrate the difference in gains of the two circuits. The gain at the cutoff frequency of *100 GHz* for the transistor based circuit is *-55.80 dB* compared to *-58.55 dB* of the operational amplifier based circuit. This shows that the newly designed circuit which uses a transistor performs better at higher frequencies as it is closer to achieving unity gain.

4.6 Implementation of CSDG MOSFET to the Filter

So far we have seen the benefits that a transistor as over an operational amplifier in terms of the gain an active high pass filter circuit has. To further improve the gain of this designed filter we add a CSDG MOSFET that has been designed in Section 3.2.1 and illustrated in Figure 3.3 is connected to both gates (Gate 1 and Gate 2) to the output of the transistor circuit (Figure 4.2). Figure 4.7 shows the proposed solution of CSDG MOSFET based active high pass filter. This circuit has been simulated and the results which have been observed are compared to the active high pass filter that did not make use of the CSDG MOSFET.

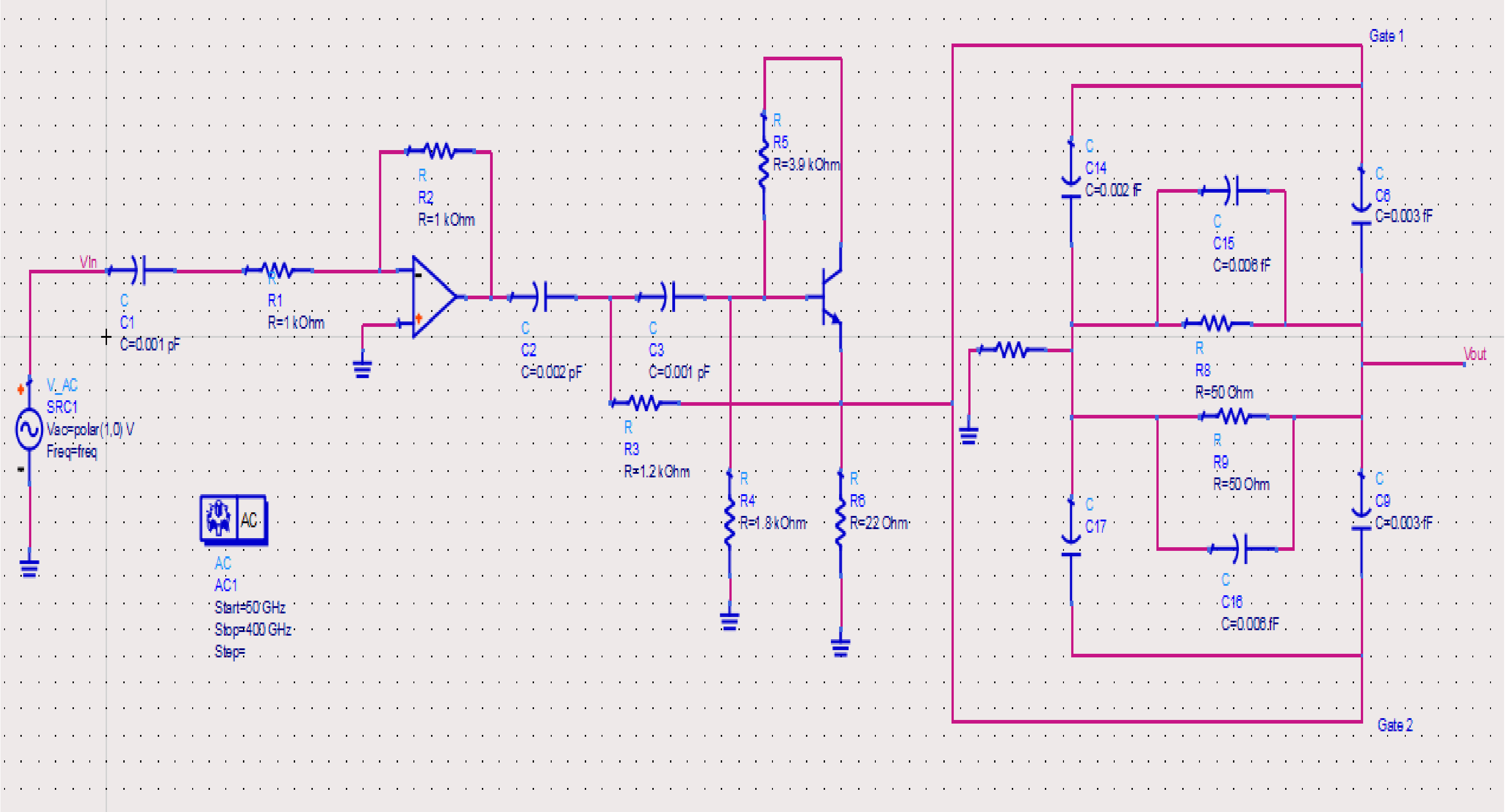

Figure 4.7. CSDG MOSFET based 3rd order active high pass filter for robotics.

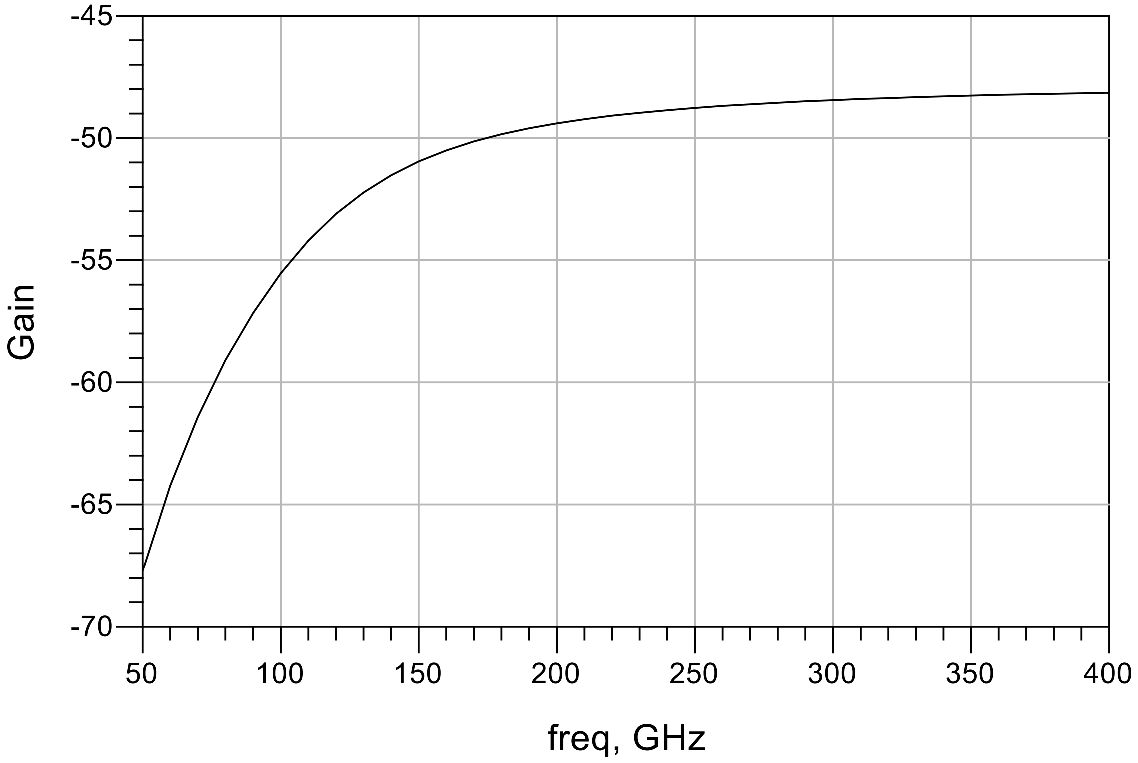

Figure 4.8. Gain of CSDG MOSFET based 3rd order filter.

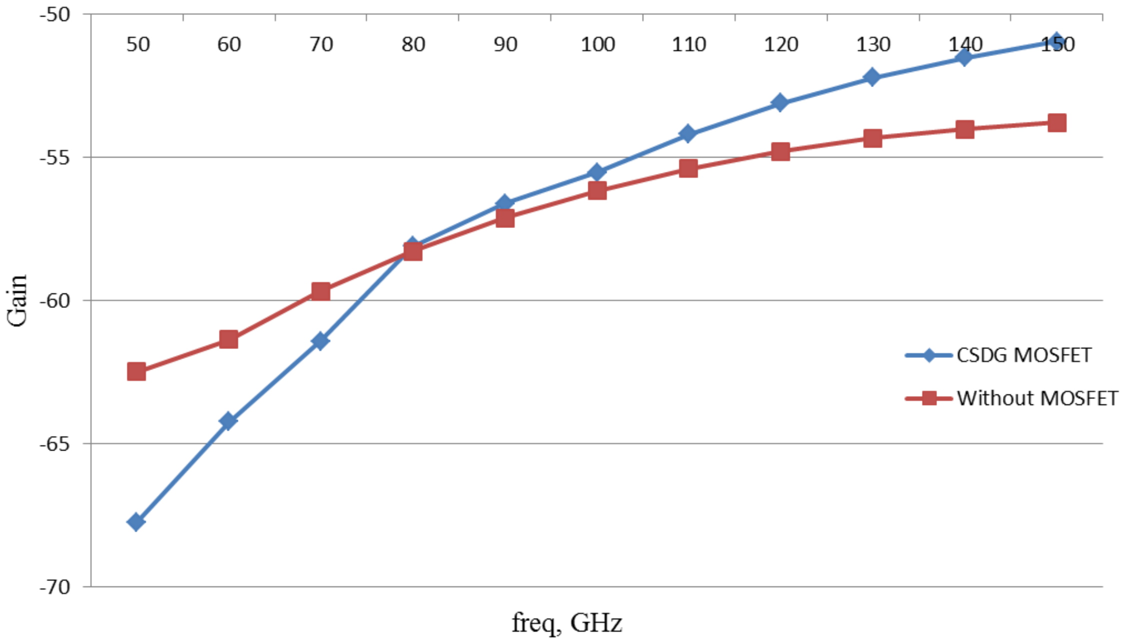

Figure 4.9. Comparison of filter with and without CSDG MOSFET.

Figure 4.8 shows the gain of the filter with the addition of CSDG MOSFET. Since a MOSFET is a capacitive model and one of the components that contributes the most to the working of an active filter is a capacitor, the results achieved during simulations is as expected. At the cutoff frequency of 100 GHz we observed a gain of *-55.54 dB*. The difference in gain was found to be *0.63 dB* and has the frequency increased the difference in gains only gets larger until it reaches its maximum gain. From Table 4.2 and Figure 4.9 we can conclude that there are improvements in terms of gain with CSDG MOSFET. In this case the frequency is approximately *500 GHz*.

In Figure 4.9 we have observed that there is a steeper slope for the filter that made use of the CSDG MOSFET compared to the filter that didn’t. From theory it is known that the steeper the slope of a frequency response graph the greater its ability to provide effective filtering. This means the frequencies below the cutoff frequency will be rejected faster and will thus allow the passband signals to be received more efficiently.

The ratio of reflected signal to input signal is known as return loss. Often return loss is expressed has a positive integer such as *20 dBm*. But it’s really meant to be a negative integer because return loss is always lower than the input signal. From the above figure we observe a return loss of *-58.4 dBm*. This is the power ratio which is in decibels (dB) of the measured power and is then associated with one milliwatt. The closer the value is to *0 dBm* the stronger the signal will be. Figure 4.11 shows a comparison of the return loss of the designed filter with and without CSDG MOSFET.

Table 4.2 Frequency Response for Active High Pass Filters With and without the use of CSDG MOSFET

Frequency (GHz)	**Gain (dB)**		
	Without CSDG MOSFET	**With CSDG MOSFET**	**Difference**
50	-63.48	-67.74	-4.26
60	-61.37	-64.23	-2.36
70	-59.68	-61.42	-1.74
80	-58.29	-58.10	0.19
90	-57.13	-56.62	0.51
100	-56.17	-55.54	0.63
110	-55.40	-54.20	1.2
120	-54.80	-53.11	1.69
130	-54.34	-52.23	2.11
140	-54.02	-51.52	2.50
150	-53.79	-50.96	2.83

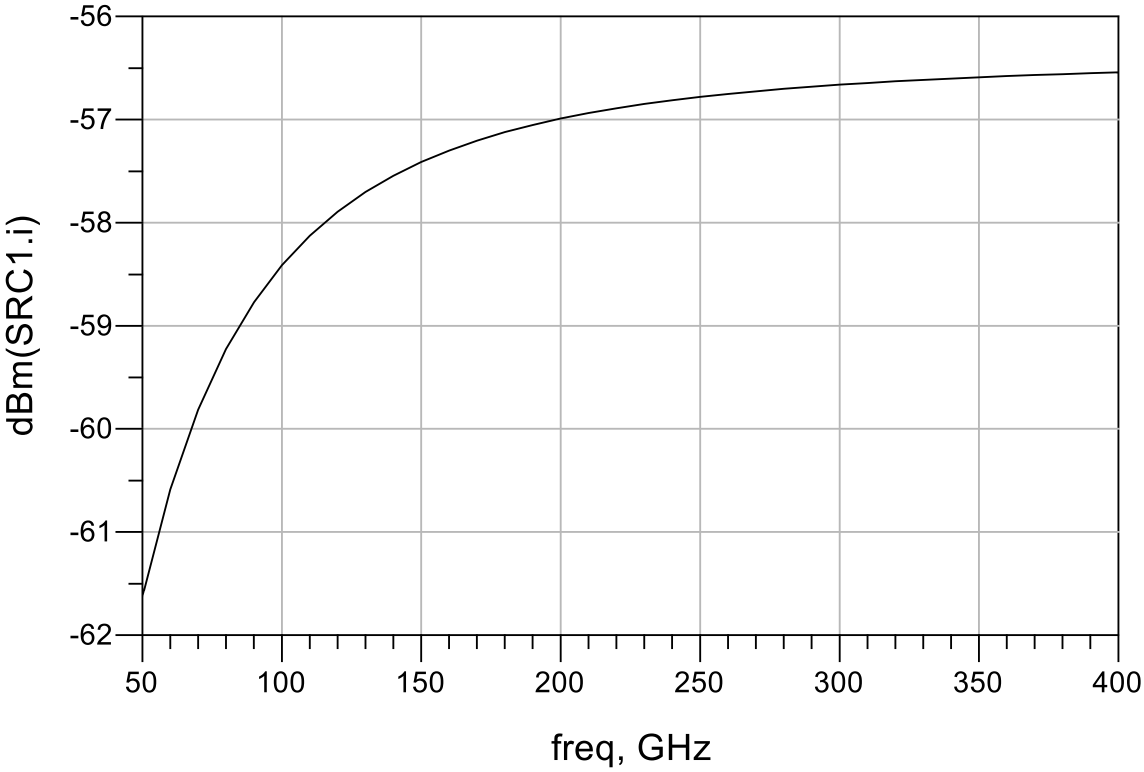

Figure 4.10. Return loss of 3rd order active high pass filter.

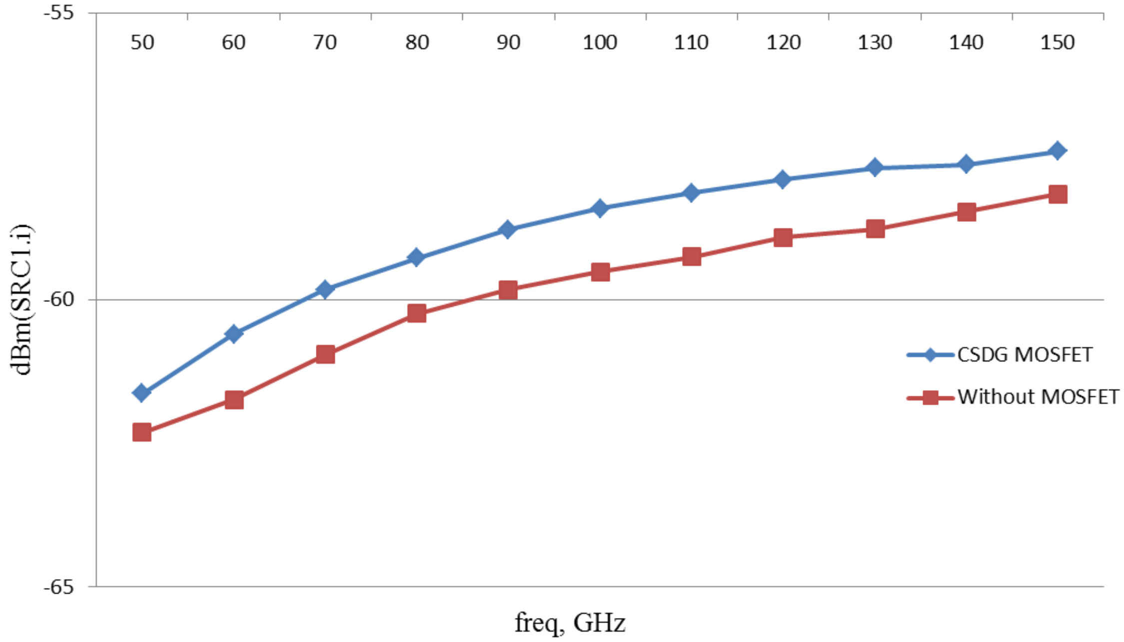

Figure 4.11. Comparison of return loss with and without a CSDG MOSFET.

4.7 Chapter Conclusions

This work explains the design and simulation of an active high pass filter. This designed filter plays an important role in today’s technologically advanced world as they are widely used in applications related to communications and robotics. An active filter has been chosen to be designed over a passive filter since it is efficient, costs and its weight is kept to a minimum and one can control the overall gain of the filter. This particular filter was designed to be used in robotics system that made use of RF method of control.

The design of the active filter made use of two active components (operational amplifier and transistor). The transistor was implemented in this design as we wanted to achieve frequencies that are higher of the RF spectrum whilst providing the levels of gain that are required for a filter to deliver it’s information efficiently and an operational amplifier helped with this aspect of the design. A software tool was used and it aided in designing a successful active high pass filter.

The newly designed filter offers better gain compared to a filter that uses an operational amplifier and transistor to form an active filter. In addition the benefits in gain and return loss were observed when a CSDG MOSFET was implemented. Using this type of filter allows a fine signal (command) to be sent to the robotics system.

Chapter-5

Application of CSDG MOSFET for High Pass Filtering (THz)

A filter is an important component of a communication system and thus this chapter looks at the designing of such a device. The proposed device is a third order active high pass filter and makes use of an operational amplifier. Operational amplifiers are the most common type of active component that is used in filter design but from the previous chapter and the chapter to follow we can also use transistors. This filter has been designed to operate at a cutoff frequency of *0.2 THz* and made use of CSDG MOSFET to further improve the gain of the filter.

5.1 Introduction

Remotely controlled electronic devices generate a number of signals which are transmitted and received by various electronic devices that allow information to be transmitted in an efficient manner. Common applications for these types of devices include television remotes, electric garage door openers, burglar alarm systems, boom gates and automation systems that can be used in industry [78]. An RF remote control is for the most part a convenience feature that can be used to operate various appliances from a short distance. It consists of two parts viz. a transmitter and a receiver [79-84].

The transmitter part in remote controlled devices is divided into two parts, the RF remote control and the transmitter module. This allows the transmitter module to be used as a component in larger applications. The transmitter module is small but a user needs to fully understand how it operates but combined with the RF remote control it is much simpler to use.

The receiver is either made up of a super-regenerative or a superheterodyne receiver. The super-regenerative receiver works like that of an intermittent oscillation detection circuit. The superheterodyne receiver works like the one in a radio receiver. The superheterodyne receiver is commonly used for the following advantages:

- Stability.
- High sensitivity.

- Relatively good anti-interference ability.
- Small package.
- Lower price.

The generated signals of remote controlled devices are sent from the transmitter via wireless communication to the receiver [79, 80]. Within a receiver there are various components that ensure the efficient communication of information or signals. Some of these components include amplifiers, mixers, oscillators, and filters etc. [81, 82]. The latter component is used to ensure that the desired range of frequencies is achieved. Filters are used in various communication, instrumentation and audio systems [83, 84]. An active high pass filter is considered to be the ideal choice for this research work as it allows us to best meet our design goal of achieving frequencies that is in the Extremely High Frequency (EHF) range [52].

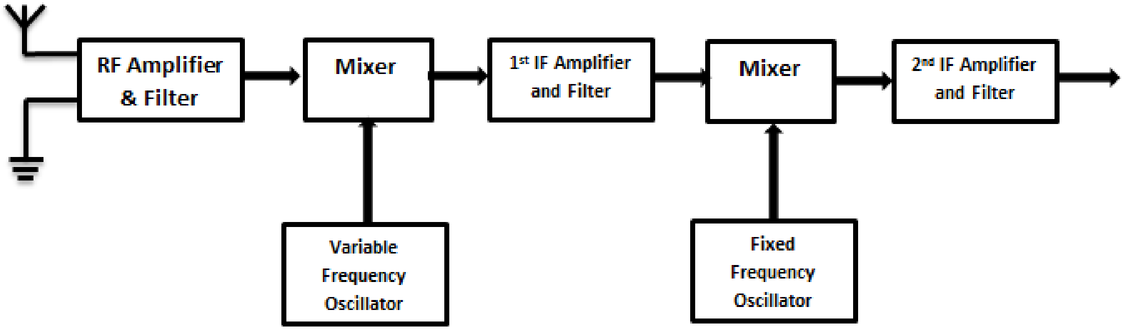

Figure 5.1. Generalized block diagram of receiver circuit

5.2 Model of 3rd Order Filter

There have been a number of designs in the field of active high pass filters [73]. They are similar in design to a RC passive high pass filter circuits, except that it makes use of an active component such as an operational amplifier in conjunction with a number of electronic components such as resistors and capacitors for its functioning and is illustrated in Figure 5.2. For this design a third order active high pass filter has been designed and operates at a frequency of *0.2 THz*.

A third order active high pass filter is created by cascading both first and second order high pass filters which makes use of an operational amplifier. These types of filters mainly use two operational amplifiers but the proposed solution makes use of just a single operational amplifier. The main advantages of using an active filter over a passive filter are its ability to provide a gain and their absence of inductors. The latter reduces the problems associated with these components and since inductors are bulky components the overall size of the circuit is reduced, hence heat generation reduces/heat sink.

The following equations are relevant for the design of the first order filter [65, 66]:

$$f_c = \frac{1}{2\pi R_1 C_1} \tag{5.1}$$

The value for C1 was chosen to be *0.001 pF*.

$$f_c = \frac{1}{2\pi R_1 C_1}$$

$$200*10^9 = \frac{1}{2\pi R_1 * 0.001*10^{-12}}$$

$$\therefore R_1 = 820\Omega$$

The following equations are relevant for the design of the second order filter:

$$f_c = \frac{1}{2\pi\sqrt{R_2 R_3 C_2 C_3}} \tag{5.2}$$

$$200*10^9 = \frac{1}{2\pi\sqrt{R_2{}^2 * 0.0001*10^{-12} * 0.0001*10^{-12}}}$$

$$\therefore R_2 = 8.2k\Omega$$

$$R_3 = 8.2k\Omega$$

The output and input voltages for the third order high pass filter is given as:

$$V_o = s^3 \tag{5.3}$$

$$V_i = 1 + \frac{1}{C_1 s R_1} + \frac{1}{C_1 s R_3} + \frac{1}{C_2 s R_3} + \frac{1}{C_3 s R_3} + \frac{1}{C_1 s R_1 C_2 s R_3} \tag{5.4}$$

$$+ \frac{1}{C_1 s R_1 C_3 s R_3} + \frac{1}{C_1 s R_2 C_3 s R_3} + \frac{1}{C_2 s R_2 C_3 s R_3} + \frac{1}{C_1 s R_1 C_2 s R_2 C_3 s R_3}$$

$$= 1 + \frac{1}{s}\left(\frac{1}{C_1 R_1} + \frac{1}{C_1 R_3} + \frac{1}{C_2 R_3} + \frac{1}{C_3 R_3}\right) + \frac{1}{s^2}\left(\frac{1}{C_1 R_1 C_2 R_3} + \frac{1}{C_1 R_1 C_3 R_3} + \frac{1}{C_1 R_2 C_3 R_3}\right)$$

$$+ \frac{1}{s^2}\left(\frac{1}{C_2 R_2 C_3 R_3}\right) + \frac{1}{s^3}\left(\frac{1}{C_1 R_1 C_2 R_2 C_3 R_3}\right)$$

The transfer function for the third order high pass filter is given as:

$$T(s) = \frac{V_o}{V_i} \tag{5.4}$$

$$= 1 + \frac{s}{\left(\frac{1}{C_1R_1} + \frac{1}{C_1R_3} + \frac{1}{C_2R_3} + \frac{1}{C_3R_3}\right)}$$

$$+ \frac{s^2}{\left(\frac{1}{C_1R_1C_2R_3} + \frac{1}{C_1R_1C_3R_3} + \frac{1}{C_1R_2C_3R_3} + \frac{1}{C_2R_2C_3R_3}\right)}$$

$$+ \frac{s^3}{\left(\frac{1}{C_1R_1C_2R_2C_3R_3}\right)}$$

$$= 1 + \frac{s}{2.56 * 10^{12}} + \frac{s^2}{4.61 * 10^{12}} + \frac{s^3}{1.81 * 10^{36}}$$

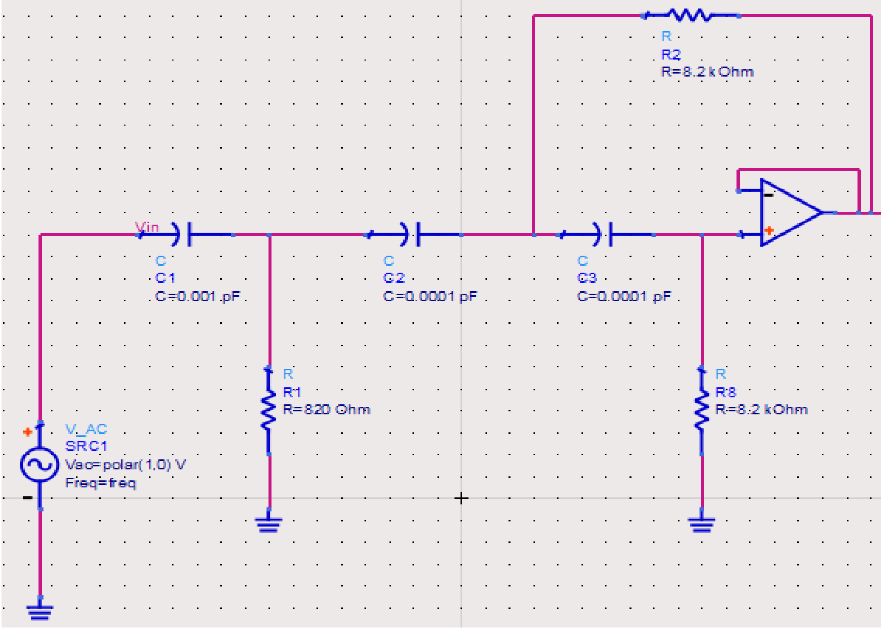

Figure 5.2. Active 3rd order high pass filter.

The designed filter (Figure 5.2) has been simulated and the following result have been observed. Figure 5.3 shows the gain of the third order filter that forms the basis of this design. The shape of the curve is of importance and does agree with the theory of how this type of filter should behave.

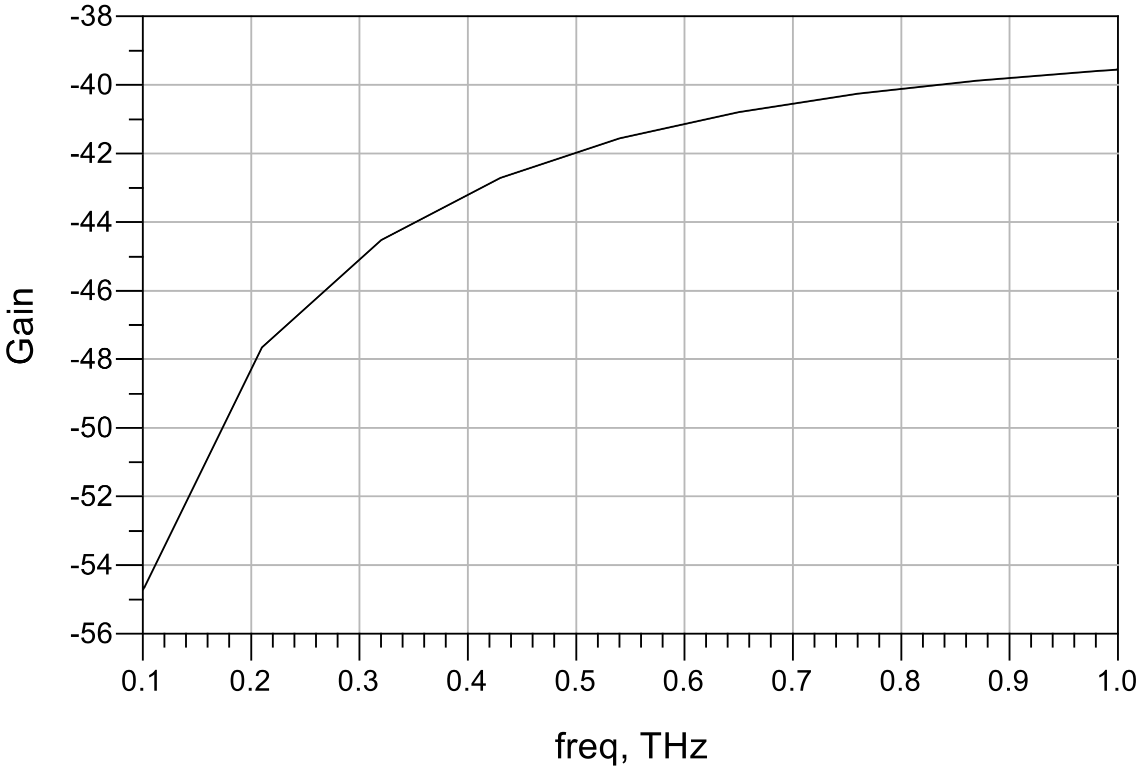

Figure 5.3. Gain of 3rd order active high pass filter

From the graph it is imperative that between the cutoff frequency and the highest point on the graph the response falls by *9 dB* and this is one of the defining characteristics of a filter for a certain order. For each order of filter there are *3 dB* differences in response and increases by a factor of 3 for each additional order. In addition when the graph is extrapolated to reach the x-axis, a roll-off of *60 dB/decade* has been observed.

5.3 Proposed Solution

The proposed design is a combination of both an active high pass filter (Figure 5.2) and CSDG MOSFET (Figure 3.4). By connecting the MOSFET to act as an additional capacitor at the output we have analyzed the benefits of gain as this is one of the most important parameters when designing a filter. The designed third order active high pass filter with internal capacitive model of CSDG MOSFET (Figure 5.4) and has been simulated using an electronic device simulator. The gain, phase, and return loss of the circuit have been observed in Figures 5.5, 5.6 and 5.8 respectively. These three parameters are considered to be critical in the design and overall working of a filter.

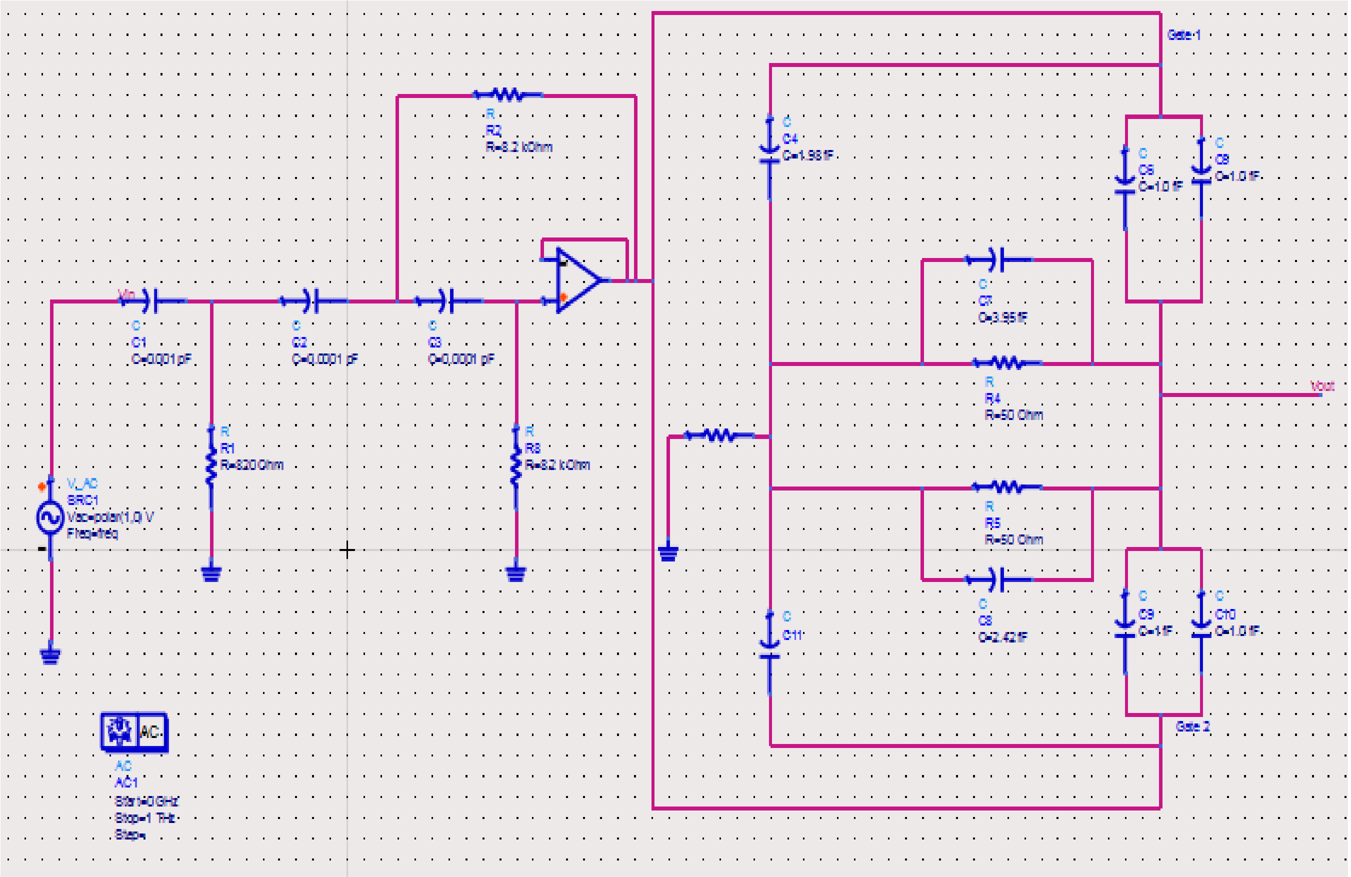

Figure 5.4. Proposed solution (3rd order filter combined with small signal capacitive model of CSDG MOSFET).

5.4 Results and Analysis of 3rd Order Filter

Comparing both Figure 5.3 with Figure 5.5, there are benefits in terms of gain of the CSDG MOSFET as on the designed filter. At the cutoff frequency of *0.2 THz,* the filter that made use of the CSDG MOSFET has a gain of *-46.78 dB* compared to *-48.06 dB* without the MOSFET. From Table 5.1, it has been observed that as the frequency increases above the cutoff frequency, the difference in gains between the two circuit's increases as well. At frequency *1 THz* the difference in gain is a significant 3.77 and at this frequency it approaches the passband of the filter where it reaches its maximum gain.

Figure 5.6 shows the phase of the filter. This filter has an effect on both the amplitude and phase of the signal. From Fourier analysis theory we know that a square wave is made up of a fundamental frequency and odd order harmonics [85]. The phase responses of these harmonics are accurately characterized. If there is a change in the phase relationship the sum of these harmonics will not be equivalent to the square wave. This will result in overshoot has the wave is seen has being distorted.

Each pole of a filter will add 45° of phase shift at the cutoff frequency. The phase will vary from 0° (well below the cutoff frequency) to 90° (well beyond the cutoff frequency) [86]. For filters that make use of multiple poles, each of the poles will add a phase shift, so that the total phase shift will be multiplied by the number of poles. Since this design is a third order active high pass filter, a phase shift of *270°* occurs at the cutoff frequency of *0.2 THz*. Figure 5.6 agrees with the theory of how a phase response should look.

The analyzed results and Figure 5.7 show that the circuit which uses CSDG MOSFET performs better at higher frequencies as it is closer to achieving unity gain i.e. when a particular signal goes into a device at one level and comes out of that device at the same level. This is due to the CSDG MOSFET being a capacitive model and from theory; capacitance plays an important role in how a filter operates to achieve efficiency.

At the cutoff frequency the difference in gain of the two circuits (Figure 5.2 and Figure 5.4) is *1.28 dB* and has the frequency of the graph is increased the difference gets larger until we reach a frequency of *1 THz.* At this frequency we observe a difference of *3.77 dB.*

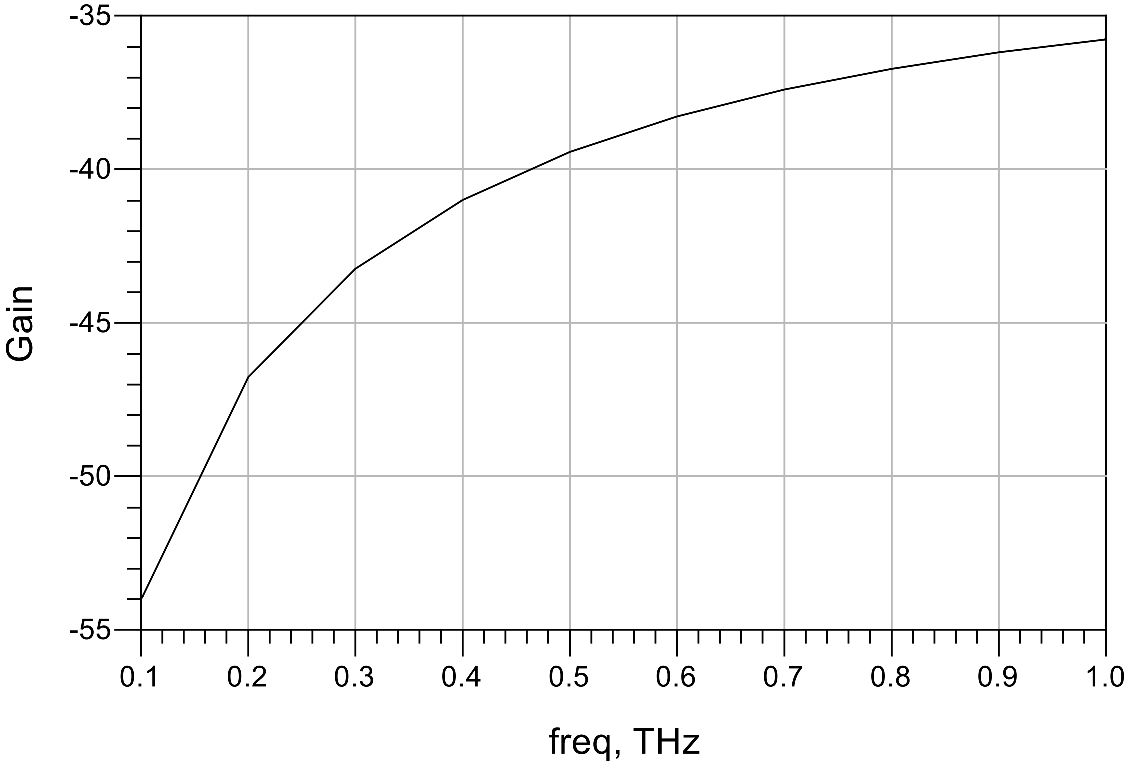

Figure 5.5. Gain of CSDG based 3rd order active high pass filter

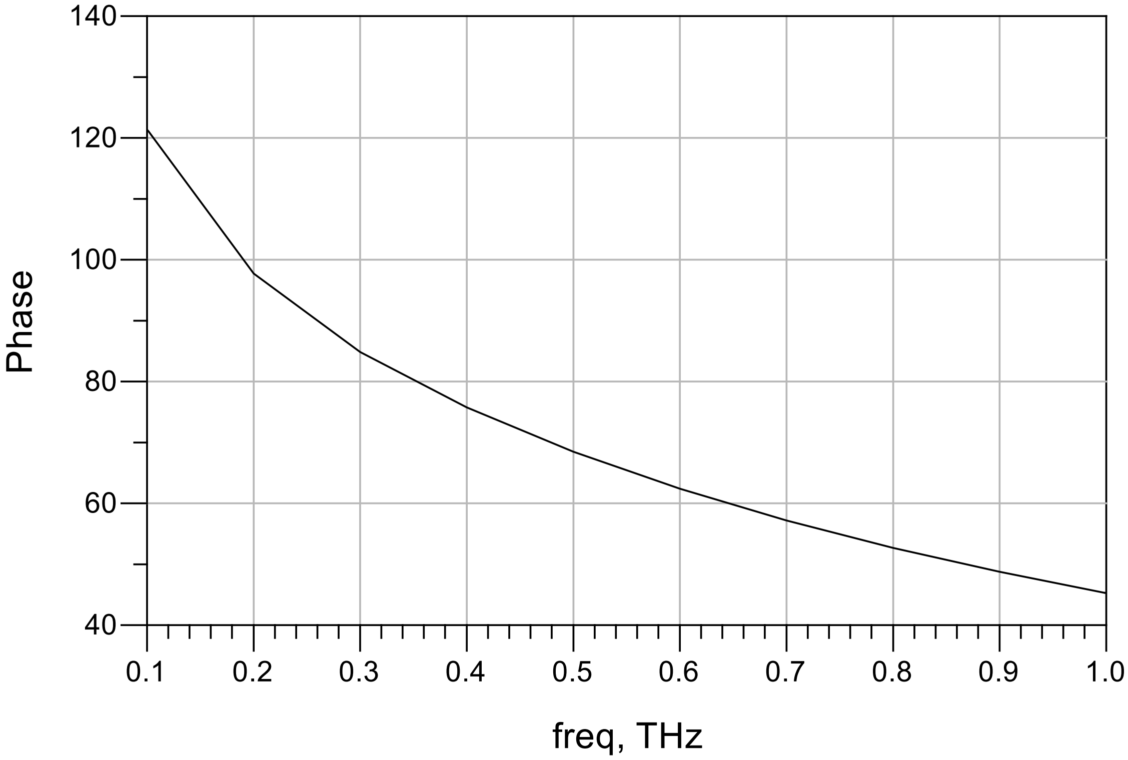

Figure 5.6. Phase response of CSDG based 3rd order active high pass filter

Table 5.1 Frequency response for both designed circuits

Frequency (GHz)	Gain (dB)		
	Without CSDG MOSFET	**With CSDG MOSFET**	**Difference**
100	-54.74	-54.02	0.72
150	-52.23	-49.57	2.66
200	-48.06	-46.78	1.28
250	-46.44	-44.78	1.66
300	-44.97	-43.25	1.72
350	-44.08	-42.02	2.06
400	-43.13	-41.01	2.12
500	-41.93	-39.44	2.49
600	-40.87	-37.98	2.89
800	-40.24	-36.84	3.40
1000	-39.55	-35.78	3.77

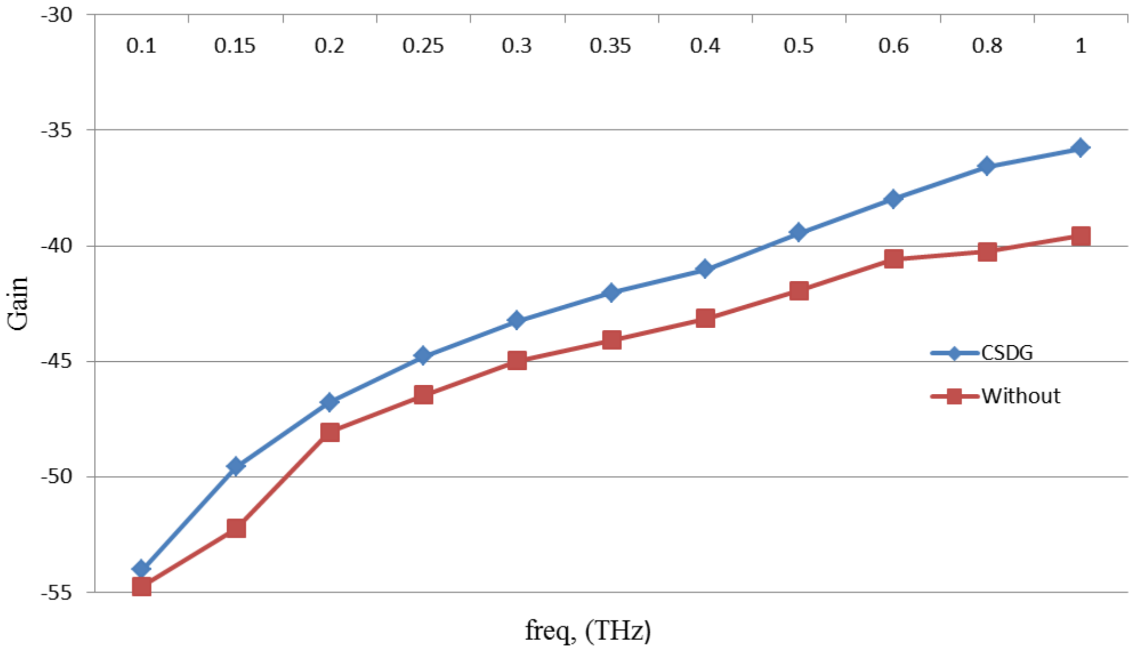

Figure 5.7. Comparison of gains of circuits with and without CSDG MOSFET

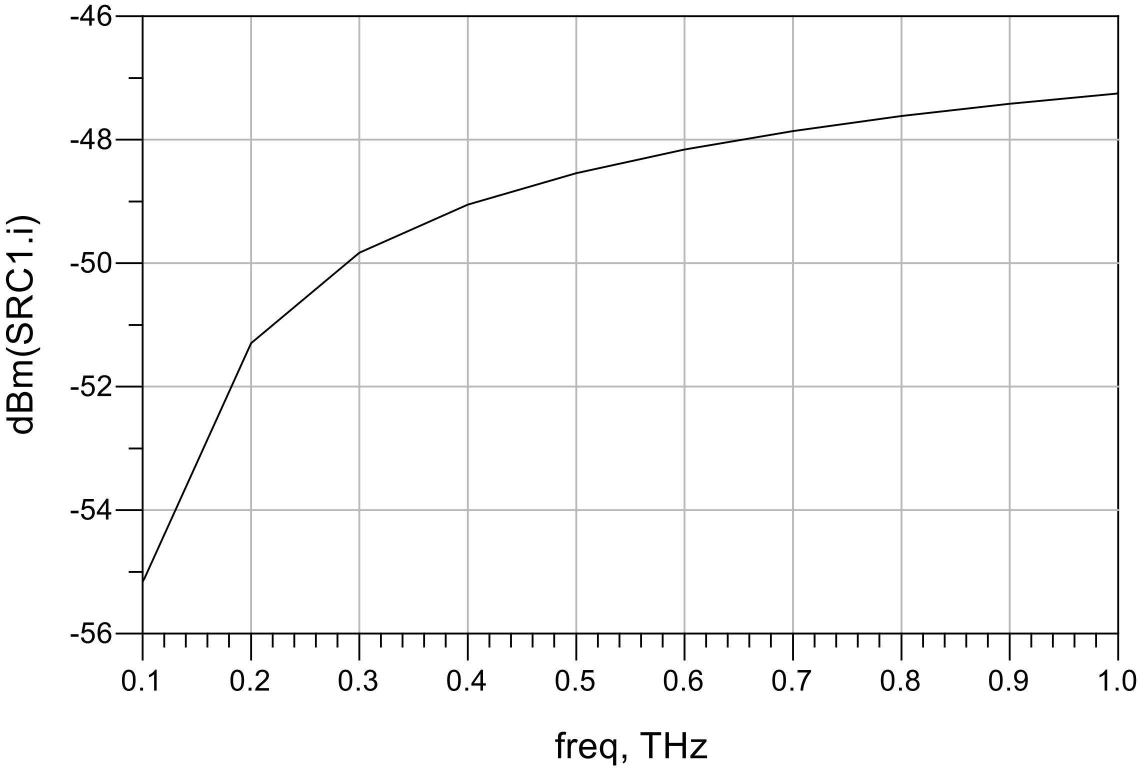

Figure 5.8. Return loss of 3rd order high pass filter

Figure 5.8 shows the return loss of the designed filter that can be implemented in a remote controlled device. The return loss is given by the following equation [87]:

$$RL = 10\log\left(\frac{P_{reflected}}{P_{in}}\right) \tag{5.5}$$

From the graph we observe a return loss of *-51.84 dBm* at the cutoff frequency. Comparing this result with a return loss of *-52.36 dBm,* the benefits in return loss can be seen when the filter is implemented using CSDG MOSFET. From this result we note that the CSDG based filters percentage reflected power is *2.5%* of the input power. The filter that did not make use of the MOSFET has *2.8%.* Figure 5.9 shows a comparison graph of return loss for the filter that made use of the CSDG MOSFET and the one that didn't. The average difference between return losses of these two filters was obtained to be *2.4 dBm.*

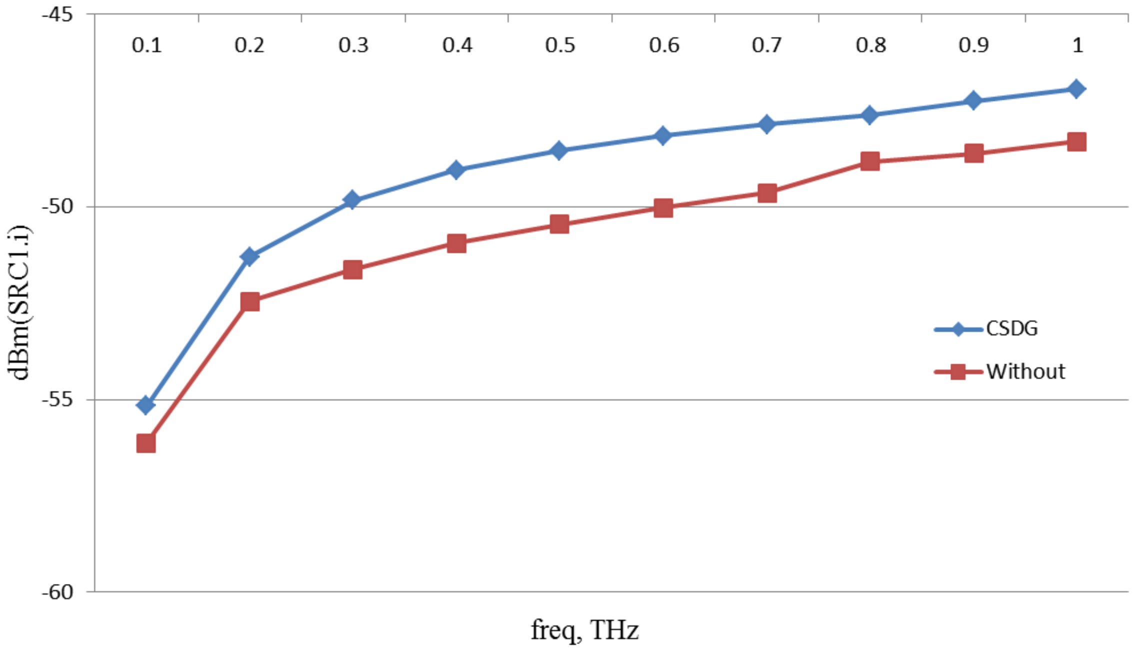

Figure 5.9. Comparison of return loss of filter with and without CSDG MOSFET

5.5 Chapter Conclusions

This chapter explains the design and simulation of an active high pass filter of third order that can be used in remote sensor devices such as remote controls and garage door openers. In the field of communications a filter is one of the most important components in a system. They provide the necessary range of frequencies that will ensure the system works in the most efficient way. An active filter has been chosen to be designed since it is efficient, costs and weight are kept to a minimum and one can control the overall gain of the filter.

The designed active filter operated at a cutoff frequency of *0.2 THz* and made use of a CSDG MOSFET and results were compared with and without the use a MOSFET. The CSDG MOSFET was designed by placing the capacitors that connect the gate and source in parallel. This resulted in the design requiring smaller capacitance values to be used. The newly designed filter offered better gain compared to a third order filter that did not make use of the MOSFET.

Chapter-6

Application of CSDG MOSFET Based Active High Pass Filter in Satellite Communications

In the context of increasing the number of satellites that orbit Earth, developing satellites that are more cost effective becomes very important in order to receive and transmit more information. For a satellite system to function correctly it needs various combinations of subsystems and one of these subsystems is an electronic RF filter. This chapter presents a relatively simple and cost effective filtering solution for the various signals that are being transmitted. The designed filter operates at a cutoff frequency of *0.3 THz.*

6.1 Introduction

Satellite communications are used in a variety of applications such as military, navigation, weather and mobile communication services as shown in Figure 6.1 [88, 89]. There are a number of subsystems that allow the efficient communication of radio signals within the satellite. Each subsystem has its own functions and is crucial to the overall operation of the satellite. Some of these subsystems include amplifiers, converter, oscillators, multiplexers and filters. The satellite communicates with Earth based antennas via radio signals [90]. It has a transmitter and sends these signals to a receiver that is in the ground station. The signals arriving from satellites are often very weak, requiring high sensitivity for the receiving equipment. These ground stations are capable of receiving signals in the Super High Frequency (SHF) and Extremely High Frequency (EHF) bands.

Overall satellite communication system has to overcome several challenges in order to become mainstream. One of these challenges is the cost to manufacture to make them more viable [91]. Another challenge is that the frequency bands adjacent to the ones used for satellite communications are becoming increasingly congested. By using a number of simulation tools this challenge is slowly being eliminated has designs of filters are continuously improving. This research work looks at designing a component of receiver viz. a filter in the EHF band. In the satellite industry, the driving force behind any new

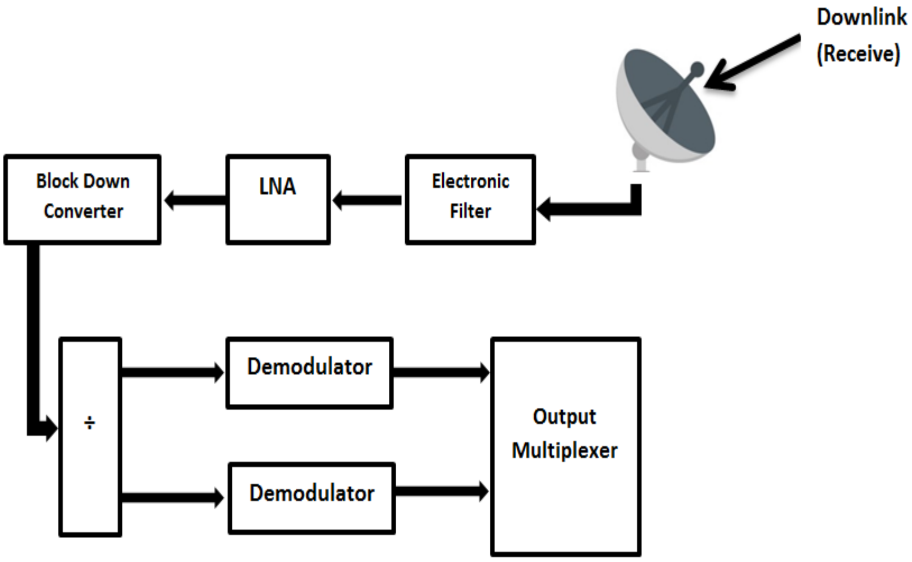

Figure 6.1. Generalized block diagram of satellite communication system.

development is profit, or the economic enticement. The newly implemented filter addresses this issue by designing a cost effective solution without sacrificing much in terms of the performance of the filter and suitable to use in satellite communications.

6.2 Satellite Communication with Filter

RF components, especially filters are fundamental elements that exist in a satellite communication system. A filter's function is to separate the desired signal from the unwanted signal and will be used for front end tuning to provide the main selectivity of frequencies. Thus a well-designed filter can provide the necessary level of performance and may also aid solutions for in-band interference, as the low loss of these devices allows their placement before the first Low-Noise Amplifier (LNA) in the system [92]. Radio signals (downlink) from the satellite are received from an antenna and these signals are sent through the various components (Figure 6.1) within the ground station in order to attain the relevant information. So in this chapter we have designed the CSDG MOSEFT based filter suitable for satellite communication systems.

6.3 Active 3rd Order High Pass Filter Design

The third order active high pass filter is implemented (as in Figure 6.2) which operates at a cutoff frequency of *0.3 THz* and makes use of a transistor instead of an operational amplifier [93, 94]. A transistor is chosen as it will allow us to achieve the high frequencies that are needed for this design since an operational amplifier will provide a reduction in performance as the frequency of the filter is increased. This design requires a frequency within the EHF band the transistor is an ideal active component to use. In addition they are more cost effective and the overall weight of the circuit is reduced since it requires fewer components.

The following equations are relevant for the design of the first order filter and a value of *0.0001 pF* for C_1 was chosen [65]:

$$f_c = \frac{1}{2\pi R_1 C_1} \tag{6.1}$$

$$300*10^9 = \frac{1}{2\pi R_1 * 0.0001*10^{-12}}$$

$$\therefore R_1 = 5.6k\Omega$$

The value for C_3 was chosen has *0.0001 pF*.

$$C_2 = 2C_3 \tag{6.2}$$

$$\therefore C_2 = 0.0002 pF$$

$$f_c = \frac{1.414}{4\pi R_3 C_3} \tag{6.3}$$

$$300*10^9 = \frac{1.414}{4\pi R_2 * 0.0001*10^{-12}}$$

$$\therefore R_2 = 3.9k\Omega$$

The value for R_3 was chosen has *8.2 k Ω*.

$$R_2 = \frac{R_3 * R_4}{R_3 + R_4} \tag{6.4}$$

$$3.2k = \frac{8.2k * R_4}{8.2k + R_4}$$

$$\therefore R_4 = 8.2k\Omega$$

β is the forward current gain of the transistor and has a value of 50.

$$R_e(\beta + 1) \gg R_2 \tag{6.5}$$

$$R_e(50+1) \gg 3.9k$$

$$\therefore R_e = 82\Omega$$

$$R_e(\mathrm{B}+1) \gg R_2$$

The following two equation (V_o and V_i) aid in determining the transfer function of the proposed active 3rd order filter. Equation 6.6 is used to determine the output voltage.

$$V_o = R_e s^3 \tag{6.6}$$

Equation 6.7 is used to determine the input voltage of the designed filter.

$$\begin{aligned} V_i &= 1 + \frac{1}{s}\left(\frac{1}{C_1R_1} + \frac{1}{C_1R_2} + \frac{1}{C_2R_2} + \frac{1}{C_3R_5}\right) \\ &+ \frac{1}{s^2}\left(\frac{1}{C_1C_2R_1R_2} + \frac{1}{C_1C_3R_1R_2} + \frac{1}{C_1C_2R_2R_5} + \frac{1}{C_2C_3R_2R_5}\right) \\ &+ \frac{1}{s^3}\left(\frac{1}{C_1C_2C_3R_1R_2R_5}\right) \end{aligned} \tag{6.7}$$

$$\mathrm{Since}, R_5 = \frac{R_3 * R_4}{R_3 + R_4}$$

$$\begin{aligned} V_i &= 1 + \frac{1}{s}\left(\frac{1}{C_1R_1} + \frac{1}{C_1R_2} + \frac{1}{C_2R_2} + \frac{1}{C_3\frac{R_3 * R_4}{R_3 + R_4}}\right) \\ &+ \frac{1}{s^2}\left(\frac{1}{C_1C_2R_1R_2} + \frac{1}{C_1C_3R_1R_2} + \frac{1}{C_1C_2R_2\frac{R_3 * R_4}{R_3 + R_4}} + \frac{1}{C_2C_3R_2\frac{R_3 * R_4}{R_3 + R_4}}\right) \\ &+ \frac{1}{s^3}\left(\frac{1}{C_1C_2C_3R_1R_2\frac{R_3 * R_4}{R_3 + R_4}}\right) \end{aligned}$$

$$V_i = 1 + \frac{1}{s}\left(\frac{1}{C_1R_1} + \frac{1}{C_1R_2} + \frac{1}{C_2R_2} + \frac{R_3+R_4}{C_3R_3R_4}\right)$$
$$+\frac{1}{s^2}\left(\frac{1}{C_1C_2R_1R_2} + \frac{1}{C_1C_3R_1R_2} + \frac{R_3+R_4}{C_1C_2R_2R_3R_4} + \frac{R_3+R_4}{C_2C_3R_2R_3R_4}\right)$$
$$+\frac{1}{s^3}\left(\frac{R_3+R_4}{C_1C_2C_3R_1R_2R_3R_4}\right)$$

Therefore,

$$T(s) = \frac{V_o}{V_i} \qquad (6.8)$$

$$= \frac{R_e s^3}{\left[\begin{array}{l} s^3 + s^2\left(\frac{1}{C_1R_1} + \frac{1}{C_1R_2} + \frac{1}{C_2R_2} + \frac{1}{C_3R_5}\right) + \\ s\left(\frac{1}{C_1C_2R_1R_2} + \frac{1}{C_1C_3R_1R_2} + \frac{1}{C_1C_3R_2R_5} + \frac{1}{C_2C_3R_2R_5}\right) \\ +\left(\frac{1}{C_1C_2C_3R_1R_2R_5}\right) \end{array}\right]}$$

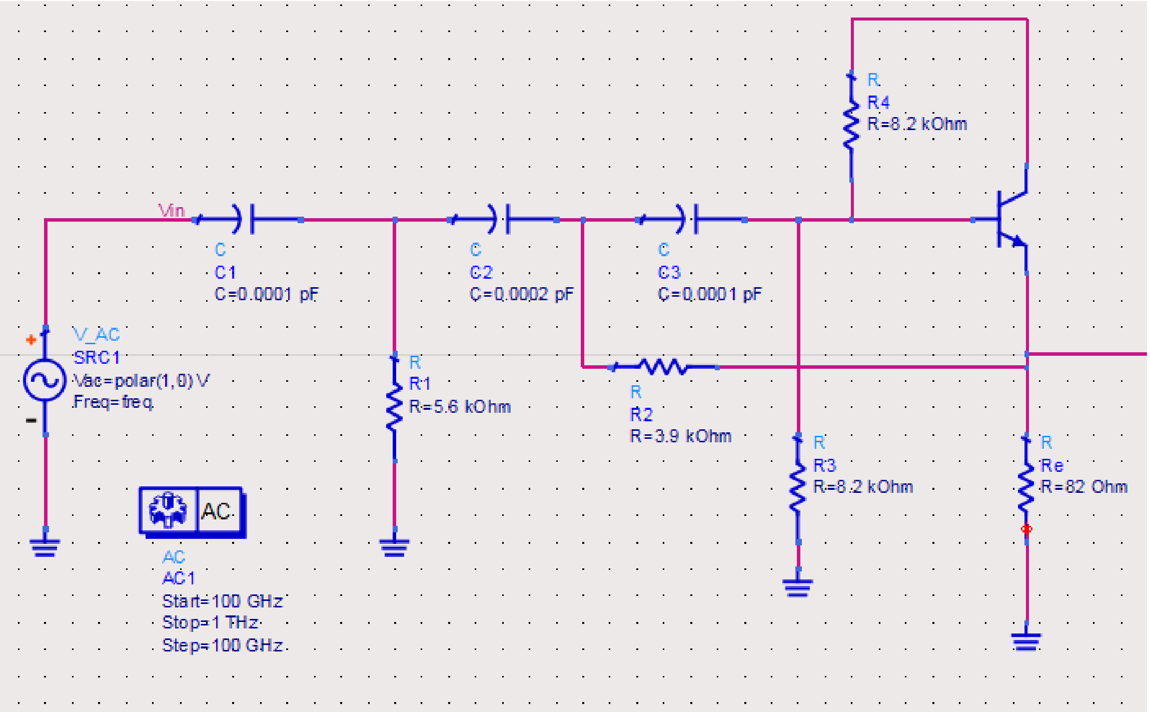

Figure 6.2. Active 3rd order active high pass filter.

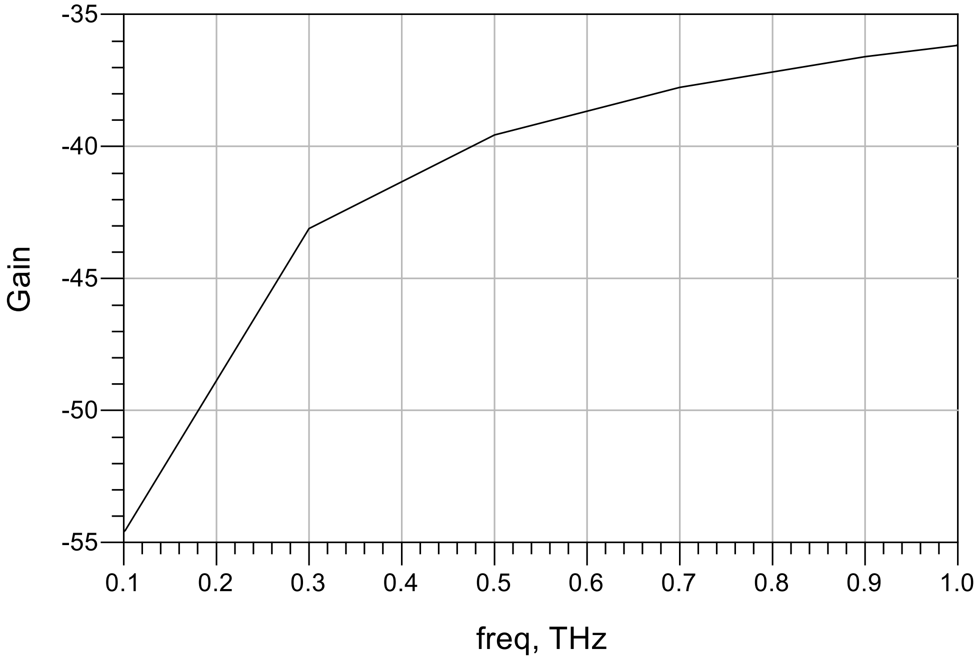

Figure 6.3. Gain of 3rd order active high pass filter.

Figure 6.3 shows the frequency response of the transistor based filter which has been designed and is illustrated by Figure 6.2. The frequency response allows us to observe explicitly how the gain (ratio of output signal to input signal) of the filter changes for a range of frequencies. From the graph it can be seen that the gain at the cutoff frequency of *0.3 THz* is *-43.12 dB*. One of the defining features of a third order filter is a *9 dB* fall between the maximum gain *(-33.499 dB* at *1.5 THz*) and the gain at the cutoff frequency [77].

6.4 Model of CSDG MOSFET Based Filter for Satellite Communications

The proposed design (Figure 6.4) is combination an (i) active high pass filter and (ii) CSDG MOSFET. The transistor consists of resistors R_3 and R_4 which create a bias point for the base of the transistor whilst resistor R_e sets the transistor current. By connecting the MOSFET to the output of the transistor to act as an additional capacitor at the output we will analyze the benefits of the gain as this is one of the most important parameters when designing a filter. The MOSFET has been designed in such a way as to produce as little capacitance as possible and will thus allow us to achieve the desired frequency range.

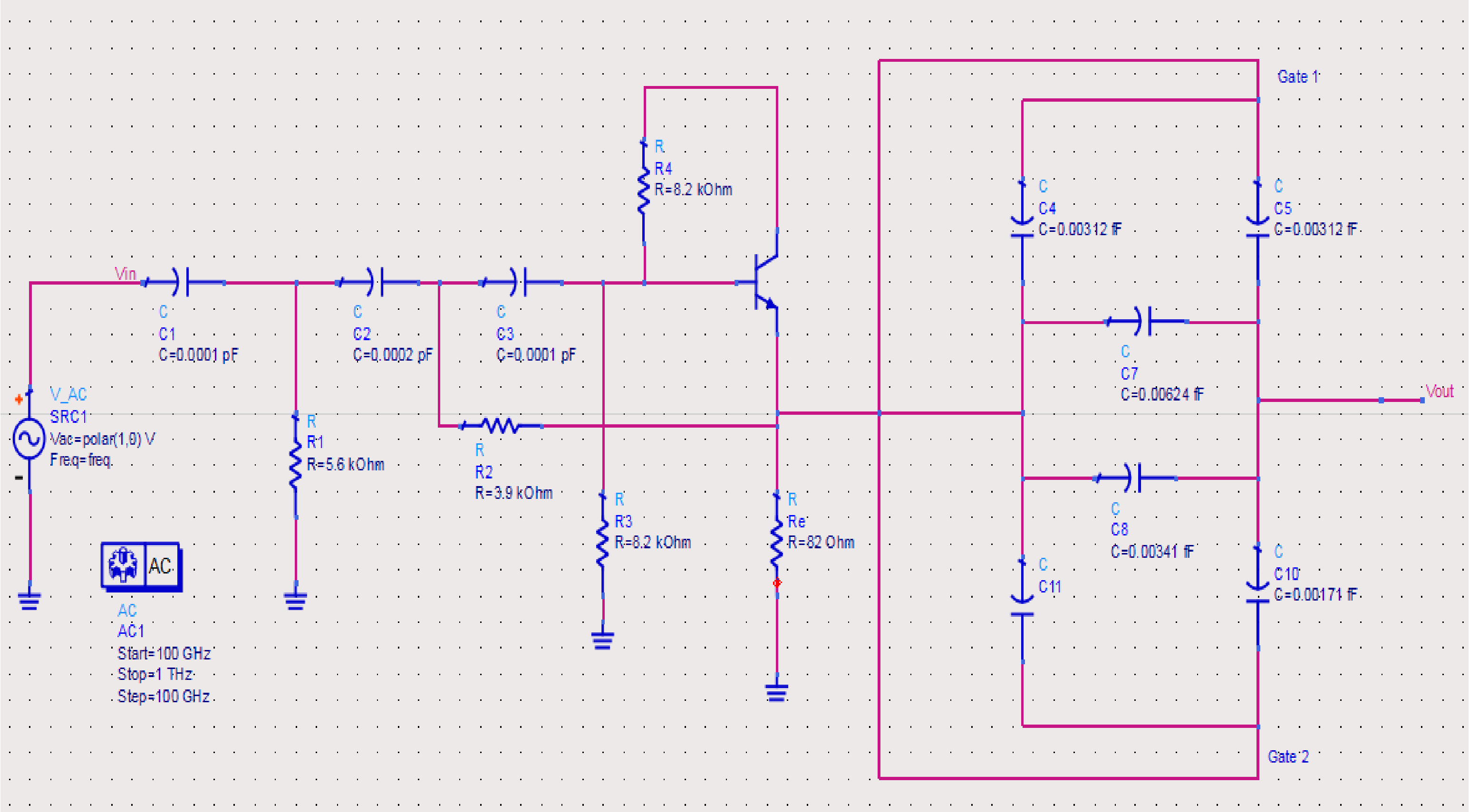

Figure 6.4. Proposed solution of 3rd order high pass filter with CSDG MOSFET.

6.5 Simulations Results and it's Analysis

The designed third order active high pass filter with CSDG MOSFET as shown in Figure 6.3 has been simulated using an electronic device simulator. The gain and phase of the circuit have been observed and are shown in Figure 6.5 and Figure 6.7, respectively.

Figure 6.5 shows the gain of the designed filter. At the cutoff frequency of *0.3 THz*, a gain of *-41.848 dB* was observed. Comparing this gain with the gain of *-43.12 dB* that was achieved with the transistor based circuit (Figure 6.3), the increase in performance the CSDG MOSFET has on gain can be seen. Once again we can observe *9 dB* drop between the maximum gain and the gain at the cutoff frequency.

Figure 6.6 shows a comparison of the gains of both circuits. The differences in gain may only be a mere *1.5 dB* but considering the frequencies this filter is designed for, the proposed solution ensures that a significant amount of additional information is able to be transmitted. The MOSFET was designed in a way that made the overall circuit have minimal capacitance and from the inversely proportional relationship with cut-off frequency. The decrease in capacitance will allow high frequency filtering to be achieved whilst achieving improvements in gain.

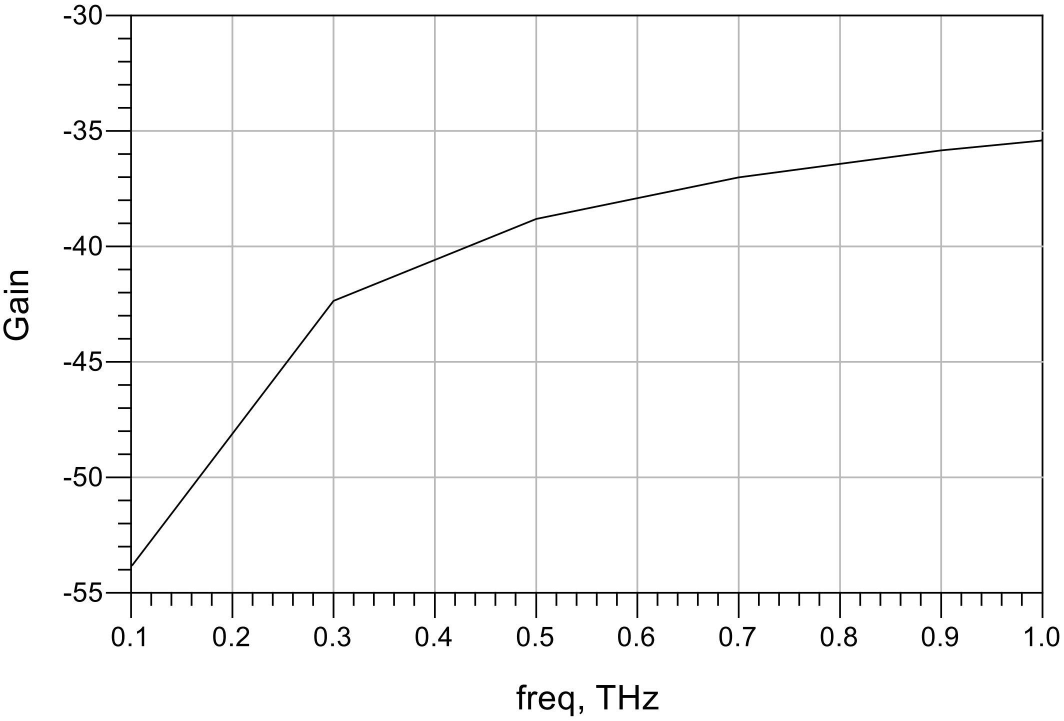

Figure 6.5. Gain of 3rd order high pass filter with CSDG MOSFET.

Table 6.1 Frequency response for active high pass filters with and without the use of a CSDG MOSFET

Frequency (THz)	**Gain (dB)**		
	Without CSDG MOSFET	**With CSDG MOSFET**	**Difference**
0.1	-54.64	-53.36	0.72
0.2	-49.78	-47.68	2.66
0.3	-43.12	-41.85	1.28
0.4	-41.56	-40.15	1.66
0.5	-39.57	-38.51	1.72
0.6	-38.83	-37.63	2.06
0.7	-37.77	-36.61	2.12
0.8	-37.15	-35.90	2.49
0.9	-36.61	-35.34	2.89
1	-36.18	-34.91	3.40

The phase response (Figure 6.7) of the filter is simply defined as being the argument of the transfer function. It can also be defined has the phase of the output with respect to the input as reference. The input is referred to having a phase of zero degrees. Since phase can accumulate to any amount of time, the phase response has no restrictions and can lie in the region between 0° and 360°. For higher order filters, the phase response of each additional section is cumulative, adding to the total. A second order filter will have a phase shift of *180°* and a third order filter will have a phase shift of *270°*.

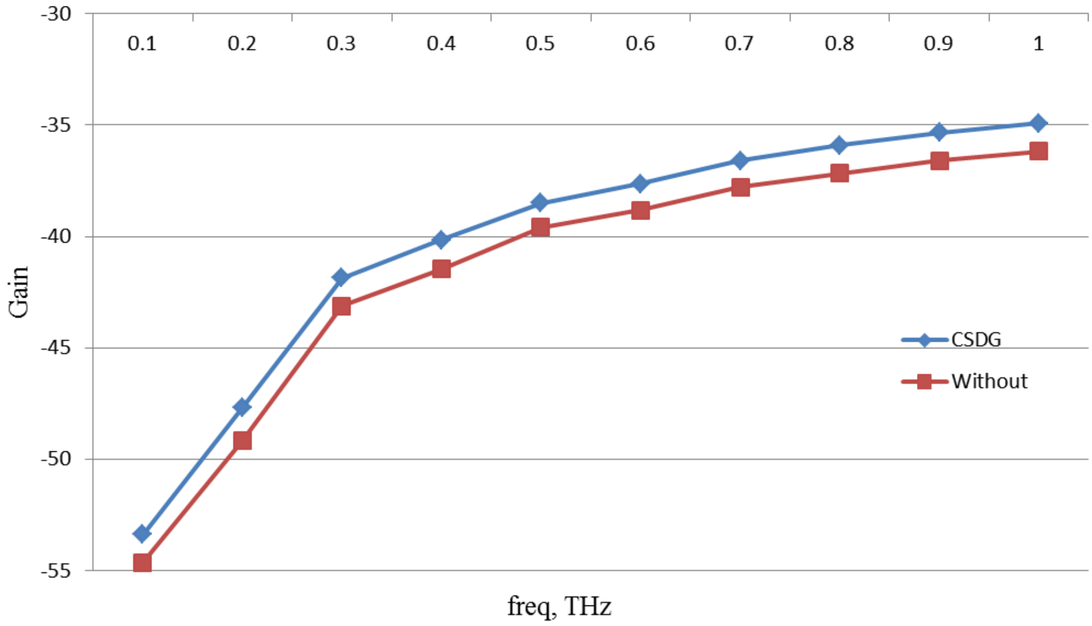

Figure 6.6. Comparison of gain with and without CSDG MOSFET.

The designed third order filter has a phase shift of *270°* when the graph is extended to the minimum frequency which agrees with theory of how a third order active high pass filter should behave. At the cutoff frequency of *0.3 THz,* a phase response of *85.6°* can be seen. Has the graph of Figure 6.7 approaches the maximum frequency of operation, its phase response is approximately *41.2°*.

Satellite communication systems are continuously evolving and the need to achieve a higher range of frequencies is demanding. These results show that the designed filter can operate at a frequency of *0.3 THz* and with this high frequency the bandwidth is increased. A larger bandwidth for a satellite system is beneficial as more information can be received at once in the ground station.

Table 6.1 shows what affect forward current gain (β) has on the overall gain of the circuit. Forward current gain is responsible for the amplification of the transistor. Practically β exists between the ranges of 50 to 400 but recently these values have dropped below the 50 mark. By increasing the β value, the emitter resistance is reduced and thus provides an increase in gain. This design made use of a value of 50 instead of 30 or 40 as this type of transistor is more feasible, readily available and more cost effective.

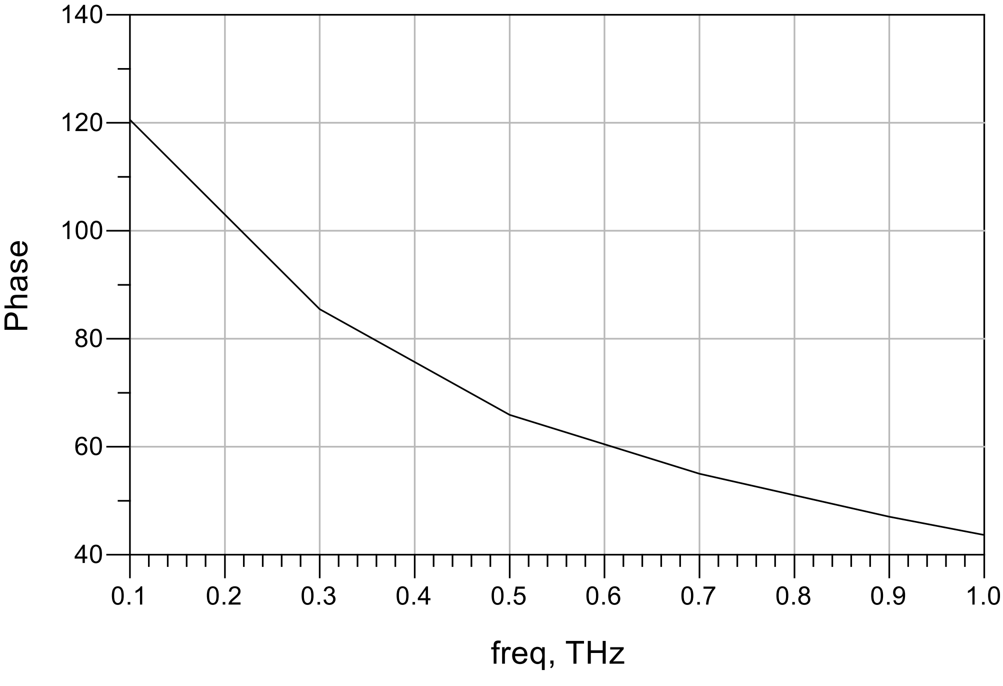

Figure 6.7. Phase response of 3rd order high pass filter with CSDG MOSFET

Table 6.2 Forward current gain vs. gain

Forward Current Gain (β)	**Gain (dB)**
30	-39.109
40	-40.660
50	-41.848
60	-43.956
70	-45.623
80	-46.415
90	-47.129
100	-48.737
110	-49.326
120	-49.951
130	-50.428
140	-51.247
150	-51.91

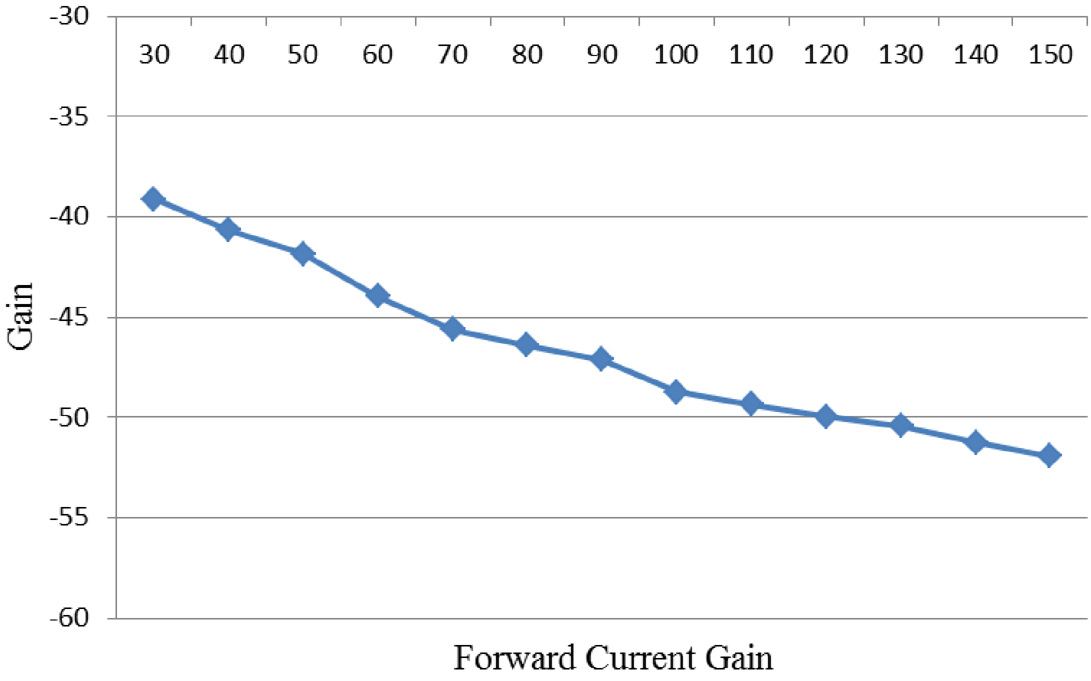

Figure 6.8. Forward current gain vs. gain.

Achieving gains that are closer to unity will ensure that whatever information is received from the satellite via an antenna at one level will be transmitted at the same level to various communication systems based on Earth. Basically if we use an input of 1V then a 1V output will be received, which is said to equal a gain of one or unity. Another advantage of achieving unity is that a significantly cleaner and undistorted signal is delivered. If each piece of the communications equipment in a satellite system adds even a tiny bit of distortion, the accumulated effects degrade the signal and eventually lead to the system not achieving its desired functions. Thus as transistor technology improves and β values are reduced (Figure 6.8), active high pass filters can be designed with better gain.

Figure 6.9 illustrates the return loss of the RF filter. From the graph we observe a return loss of *-67.37 dBm*. Comparing this result with a return loss of *-69.24 dBm* we can see what improvement the CSDG MOSFET has on this parameter. This result may be far from the desired result of *0 dBm* but with technology and components rapidly improving we can achieve results that are closer to the desired result and thus ensuring that the signal delivered is of a more considerable strength. However, considering the frequency domain the designed active high pass filter is operating in this is a good start to research work relating return loss to cutoff frequency.

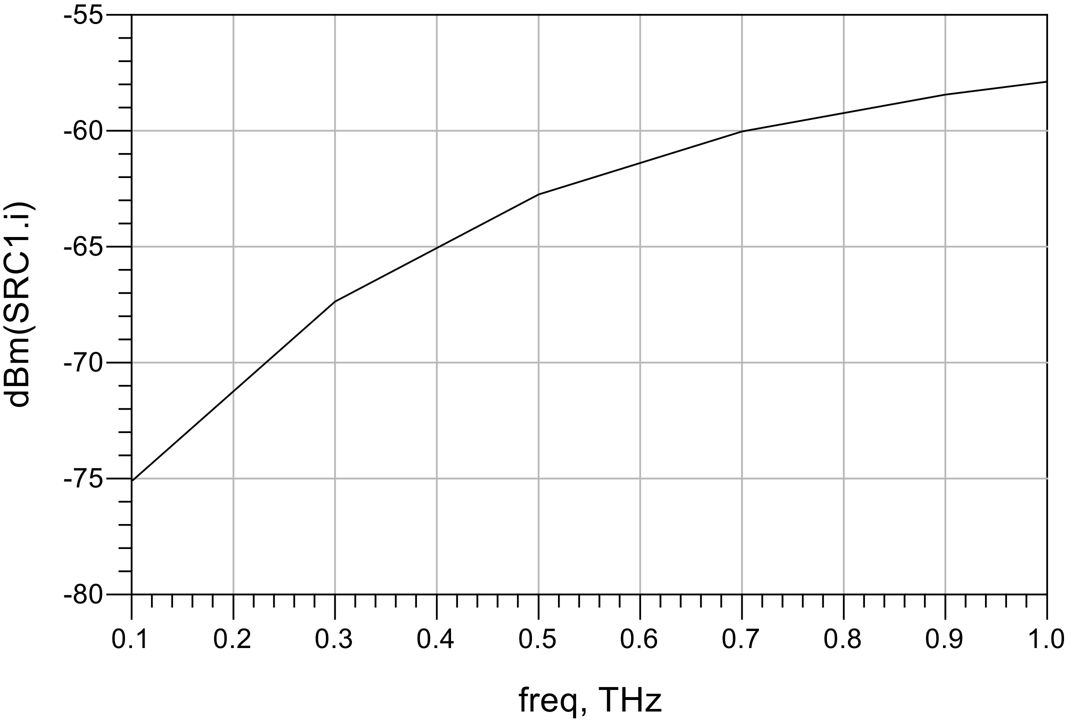

Figure 6.9. Return loss of 3rd order high pass filter with CSDG MOSFET.

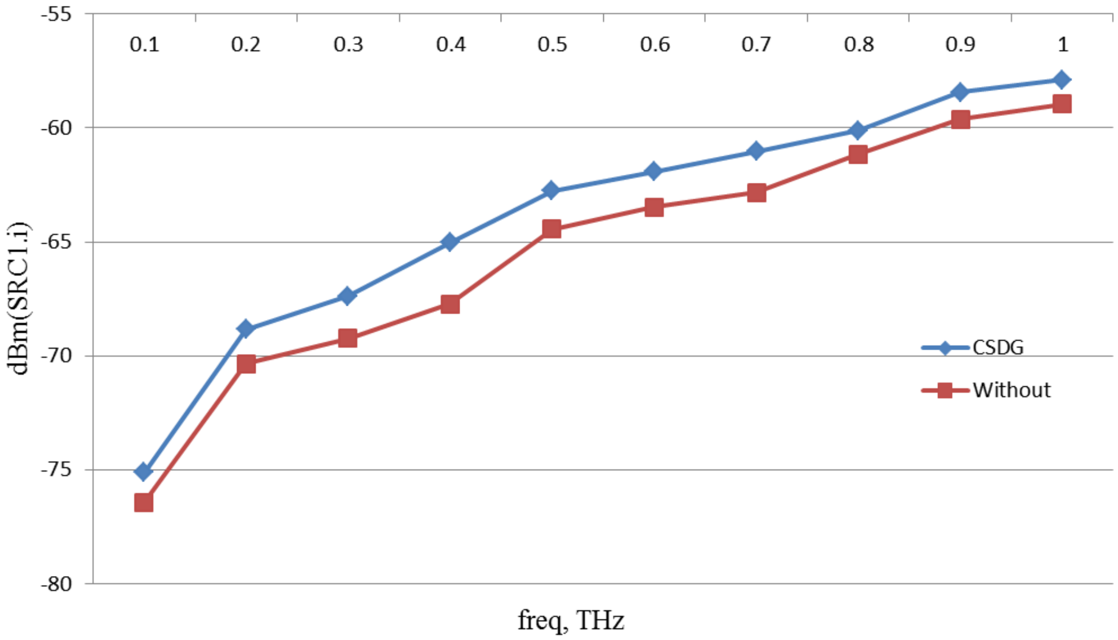

Figure 6.10. Comparison of return loss of both circuits with and without CSDG MOSFET

Figure 6.10 shows a comparison graph of return loss for the filter that made use of the CSDG MOSFET and the one that didn't. The average difference between return losses of these two filters was found to be *1.8 dBm*.

6.6 Chapter Conclusions

RF filters are an essential component in communication systems. This filter is designed for satellite communication systems. There are various types of filters that are currently available and this section looked at the design and simulation of a third order active high pass filter. This type of filter has been chosen since it allowed us to achieve the high frequencies that the design required. The designed filter operated at a cutoff frequency of *0.3 THz* and made use of a CSDG MOSFET to further eliminate lower frequencies whilst improving gain. The CSDG MOSFET made use of a high-k gate oxide known as $HfSiO_4$. The main reasons for choosing this oxide were its lower dielectric constant and wider band gap compared to HfO_2 (Section 3.3).

The results were obtained using an RF simulation software tool for both the circuits with and without the CSDG MOSFET and a comparison graph was plotted in addition to its table of results. From these results we can conclude that the overall gain and return loss of the circuit was improved. In addition we looked at the affect that changing the forward current gain had on the filter.

Chapter-7

Conclusions and Future Recommendations

7.1 Conclusions

This research work looked at the design and simulation of a number of active filters. These filters have been designed for use in communication systems such as robotics, remote sensor devices as well as satellites. A filter is a device that selectively sorts out signals whilst passing through a desired range of signals. The 4 most commons types of filters are low pass, high pass, band pass and band reject filters. Low pass and high pass filters can further be designed using passive or active components. For this research work we looked at the design of an active high pass filter as it allowed us to achieve frequencies within the EHF band. The advantages of using an active filter over a passive filter are its lower cost and the overall size of the circuit is kept to a minimum. The latter is critical to the design of VLSI circuits.

Chapter 3 detailed the design of the 3 CSDG MOSFET's and active high pass filters that were used throughout this research work. A number of materials and components were used in order to get desired results. Parameters such as length, circumference and permittivity were looked at to see what effect they had on the electric filed. In addition the length and radius of the CSDG MOSFET was modified. These results were plotted on a graph in terms of gain and cutoff frequency for both length and radius.

Chapter 4 looked at the design of an active high pass filter that could be used in a robotics system. The designed circuit made use of both an operational amplifier and a transistor. Results of the circuit were obtained using a simulation software tool and these results were compared to a circuit that made use of two operational amplifiers. The benefits in terms of gain were observed when these results were plotted on a comparison chart. To further improve the gain of the circuit a CSDG MOSFET was added to the output at the transistor. The gain was improved by *1 dB* at the cutoff frequency of *0.1 THz*. In addition to gain improvements there were also improvements in the return loss of the system.

Chapter 5 presented a third order active high pass filter that made use of an operational amplifier and a CSDG MOSFET. The designed MOSFET made use of parallel capacitors between the gate and the source. This allowed the overall capacitance of the circuit to be reduced and this aided in the filter achieving a cutoff frequency of *0.2 THz*. The gain of the filter at the cutoff frequency was found to be -46.78 dB whilst the return loss was found to be.

Chapter 6 focused on the design of a CSDG based filter that could be implemented in a satellite system. This filter operated at a cutoff frequency of *0.3 THz*. The CSDG MOSFET made use of a high-k gate oxide known as $HfSiO_4$ in addition to the SiO_2 layer. This oxide was chosen for its low dielectric constant and wider band gap. The results obtained using the CSDG MOSFET showed an improvement in all the relevant parameters.

7.2 Future Recommendations

Future work for this type of filter will involve designing not only active high pass filters but filters in general that can operate at higher frequencies closer to the Tremendously High Frequency (THF) range whilst achieving gains that are closer to unity. Achieving these higher frequencies will ensure that a larger bandwidth is available and thus a greater amount of information can be transmitted. In addition other related filter parameters could be analyzed such as temperature.

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