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The Study and Design Techniques of CMOS Based Analog Filters: An Overview

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***Abstract*— The MOSFETs are three terminal devices which are working on the principle involved and is the use of the voltage between two terminals so as to control the current flowing in the third terminal. It has now become by so far the most widely used electronic device especially, in the design of integrated circuits, which are the circuits fabricated on a single silicon chip. These devices can be made quite small as far as possible such that their manufacturing process is relatively simple and their operation requires comparatively small consumption of the power. It can be used in enormous number of applications which are ranging from the signal amplification to digital logic and memory designs for the mixed signal based applications. On the contrary, the CMOS device which performs the various Boolean operations on the multiple input variables and thus, determines the outputs as Boolean functions of the inputs, becomes the basic building blocks of all the mixed signal processing based applications. The basic application of the CMOS is the inverter circuit that utilizes two different matched enhancement type MOSFETs with n channel and other with p channel.**

***Index Terms*—MOSFET, Analog Filters, Active Filters, Butterworth Filters, Chebyshev Filters, Design Approach, CMOS, LPF, HPF.**

I. INTRODUCTION

A. MOSFETs

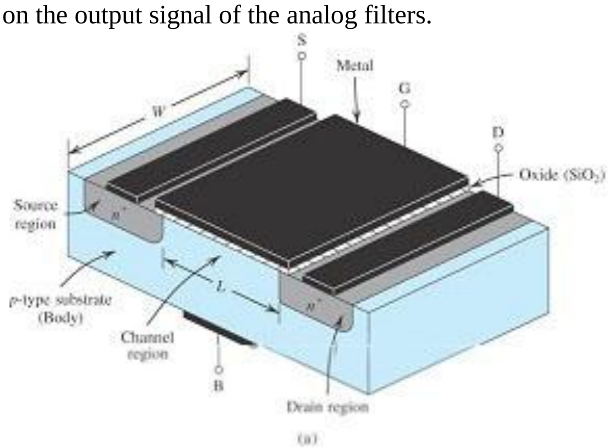
The MOSFET has become by far the most widely used integrated circuits (ICs), which are circuits fabricated on a single silicon chip. MOSFETs can be made quite small and their manufacturing process is relatively simple, also their operations require comparatively little power. All these properties have made it possible to pack large numbers of MOSFETS on a single IC chip to implement very sophisticated, very large scale integrated (VLSI) circuits such as those for memory and microprocessors. The analog circuits such as various amplifiers and filters are also implemented using the MOS technology. Both the analog and digital functions are implemented on the same IC chip, in what is known as mixed signal design used for the various ASP applications. The figure 1 shows the physical structure of a n-channel enhancement type MOSFET which is basically, a three terminal device i.e. gate (G), the source (S), and the drain (D).

In this device, an input voltage is applied to the gate that controls the current flow between source and drain in the region labeled "channel region" which has a length (L) and width (W) as the two most important parameters of the MOSFET.

It has been also observed that the MOSFET is an asymmetrical device, thus, its source and drain can be interchanged with no change in the device characteristic, as shown in the figure 2, which depicts the I_D-V_{DS} characteristics of the MOSFET [1-5].

The body of each of this device is connected to its source and thus, there is no body effect phenomenon arises in the applications. Because of this comparative analysis, it has been observed that the analog filters have been designed for the mixed signal ASP application using the CMOS as the main contributing devices. The filters are the circuit arrangement that has been designed so as to perform the frequency selection from range of frequencies. In particular, linear, time-invariant (LTI) analog filters can be characterized by their (continuous) impulse response, h(t) where t is time in seconds. Instead of a difference equation, analog filters may be described by a differential equation. Instead of using the z transform to compute the transfer function, we use the transform.

In this present work, the active analog filters are implemented using a combination of passive and active components that require an outside power source and resonance is achieved without the inductor. Thus, finally, it has been observed in this study that there are basically two different types of analog filters that have been used in the implementation of the most of the applications i.e. Butterworth filter and Chebyshev filter, with the use of various simulation software, say, MatLAB, LabVIEW, etc. In this simulation of the analog filters, the various dominant parameters of the filters are observed that have great impact on the output signal of the analog filters.



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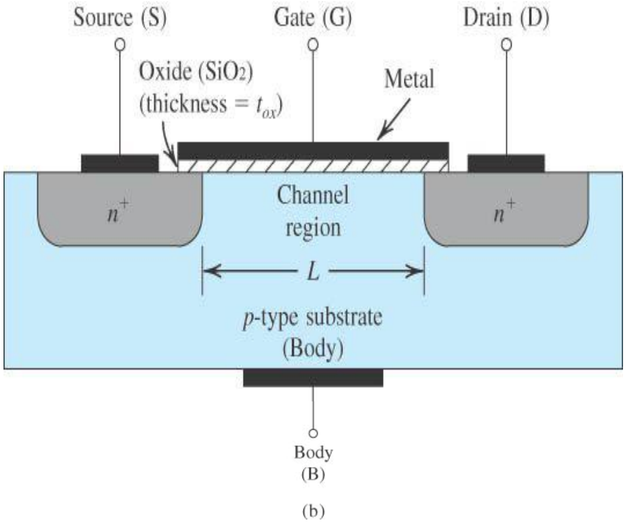

Fig 1: Physical structure of the enhancement-type NMOS transistor: (a) perspective view; (b) cross-section [1].

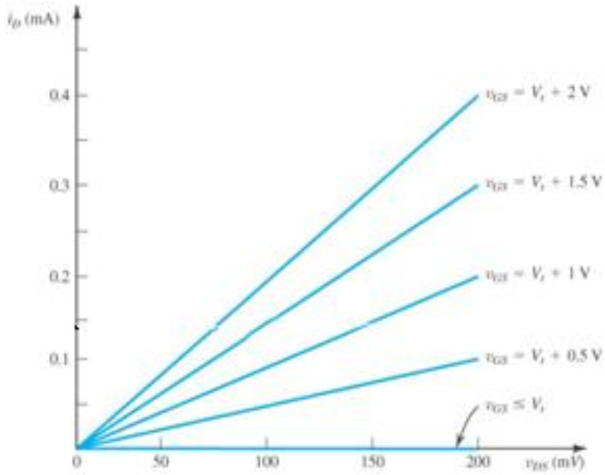

Fig 2: i_D–v_{DS} characteristics of the MOSFET [2]

As V_{DS} is increased the channel will no longer be in uniform depth, rather the channel will take the tapered form shown in Fig 1.3, being deepest at the source end and shallowest at the drain end, which increases the resistance correspondingly. Thus I_D-V_{DS} curve does not continue as a straight line but bends as shown in Fig 1.4. Eventually, when V_{DS} is increased to the value, at which the channel depth at the drain end decreases to almost zero, and the channel is said to be pinched off. Increasing V_{DS} beyond this value saturates the drain current and the MOSFET is said to be entered the saturation region of operation.

The voltage V_{DS} at which saturation occurs is denoted by V_{Dsat},

$$V_{DSat} = V_{GS} - V_t \qquad (1)$$

I_D-V_{DS} expression for MOSFET can be written as,

$$i_D = \frac{1}{2}(\mu_n C_{ox})\left(\frac{W}{L}\right)(v_{GS} - V_t)^2 \qquad (2)$$

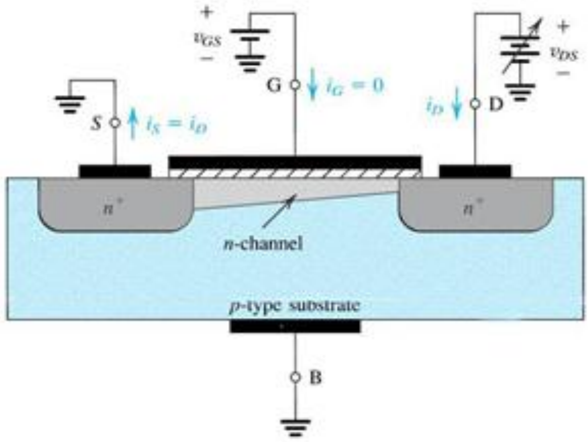

Fig 3: Operation of the enhancement NMOS transistor as v_{DS} is increased [3].

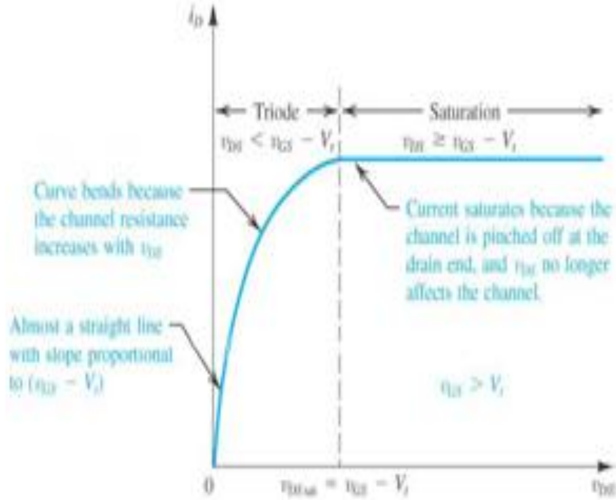

Fig 4: i_D versus v_{DS} for an enhancement-type NMOS [4].

B. CMOS

The complementary MOS technology employs MOS transistors of both polarities. Although CMOS circuits are somewhat more difficult to fabricate than NMOS, the availability of complementary devices makes possible many powerful circuit design possibilities. This statement applies to both analog and digital circuits. CMOS technology has virtually replaced designs based on NMOS transistors alone. Figure 5 shows a cross-section of a CMOS chip illustrating how the PMOS and NMOS transistors are fabricated. CMOS is a technology for constructing integrated. CMOS technology is used in microprocessor, microcontroller, static RAM, and other digital logic circuits. CMOS technology is also used for several analog circuits as image sensors (CMOS sensor), data converters, and highly integrated transceivers for many types of communication. Two important characteristics of CMOS devices are high noise immunity and low static power consumption. Since one transistor of the pair is always off, the series combination draws significant power only momentarily during switching between on and off states. Consequently, CMOS devices do not produce as much waste heat as other forms of logic, for

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example Transistor logic (TTL) or NMOS logic, which normally have some standing current even when not changing state. CMOS also allows a high density of logic functions on a chip.

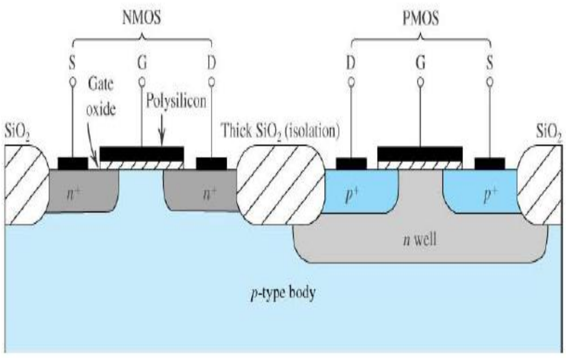

Fig 5 Cross-section of a CMOS integrated circuit [5]

An important characteristic of a CMOS circuit is the duality that exists between its PMOS transistors and NMOS transistors. A CMOS circuit is created to allow a path always to exist from the output to either the power source or ground. To accomplish this, the set of all paths to the voltage source must be the complement of the set of all paths to ground. This can be easily accomplished by defining one in terms of the NOT of the other. Due to the De Morgan's laws based logic, the PMOS transistors in parallel have corresponding NMOS transistors in series while the PMOS transistors in series have corresponding NMOS transistors in parallel. More complex logic functions such as those involving AND and OR gates require manipulating the paths between gates to represent the logic. When a path consists of two transistors in series, both transistors must have low resistance to the corresponding supply voltage, modeling an AND. When a path consists of two transistors in parallel, either one or both of the transistors must have low resistance to connect the supply voltage to the output, modeling an OR. To speed up designs, manufacturers have switched to constructions that have lower voltage thresholds but because of this a modern NMOS transistor with a V_{th} of 200 mV has a significant sub threshold leakage current. Designs (e.g. desktop processors) which include vast numbers of circuits which are not actively switching still consume power because of this leakage current. Leakage power is a significant portion of the total power consumed by such designs. Multi threshold CMOS (MTCMOS), now available from foundries, is one approach to managing leakage power. With MTCMOS, high V_{th} transistors are used when switching speed is not critical, while low V_{th} transistors are used in speed sensitive paths. Further technology advances that use even thinner gate dielectrics have an additional leakage component because of current tunneling through the extremely thin gate dielectric. Using high-k dielectrics instead of silicon dioxide that is the conventional gate dielectric allows similar device performance, but with a thicker gate insulator, thus avoiding this current. Leakage power reduction using new material and system designs is critical to sustaining scaling of CMOS.

II. FILTERS

In circuit theory, a filter is an electrical network that alters the amplitude and/or phase characteristics of a signal with respect to frequency. Ideally, a filter will not add new frequencies to the input signal, nor will it change the component frequencies of that signal, but it will change the relative amplitudes of the various frequency components and/or their phase relationships. Filters are often used in electronic systems to emphasize signals in certain frequency ranges and reject signals in other frequency ranges. Such a filter has a gain which is dependent on signal frequency. Since filters are defined by their frequency-domain effects on signals, it makes sense that the most useful analytical and graphical descriptions of filters also fall into the frequency domain. Thus, curves of gain vs. frequency and phase vs. frequency are commonly used to illustrate filter characteristics, and the most widely-used mathematical tools are based in the frequency domain. The frequency-domain behavior of a filter is described mathematically in terms of its transfer function or network function. This is the ratio of the Laplace transforms of its output and input signals. The voltage transfer function H(s) of a filter can therefore be written as:

$$H(s) = \frac{V_{OUT}(s)}{V_{IN}(s)} \quad (3)$$

Where, $V_{IN}(s)$ and $V_{OUT}(s)$ are the input and output signal voltages and s is the complex frequency variable. The transfer function defines the filter's response to any arbitrary input signal, but we are most often concerned with its effect on continuous sine waves. Especially important is the magnitude of the transfer function as a function of frequency, which indicates the effect of the filter on the amplitudes of sinusoidal signals at various frequencies. Knowing the transfer function magnitude (or gain) at each frequency allows us to determine how well the filter can distinguish between signals at different frequencies. The transfer function magnitude versus frequency is called the amplitude response or sometimes, especially in audio applications, the frequency response. Similarly, the phase response of the filter gives the amount of phase shift introduced in sinusoidal signals as a function of frequency. Since a change in phase of a signal also represents a change in time, the phase characteristics of a filter become especially important when dealing with complex signals where the time relationships between signal components at different frequencies are critical.

$$|H(j\omega)| = \left|\frac{V_{OUT(j\omega)}}{V_{IN(j\omega)}}\right| \quad (4)$$

and the phase is:

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$$\arg H(j\omega) = \arg \frac{V_{OUT(j\omega)}}{V_{IN(j\omega)}} \qquad (5)$$

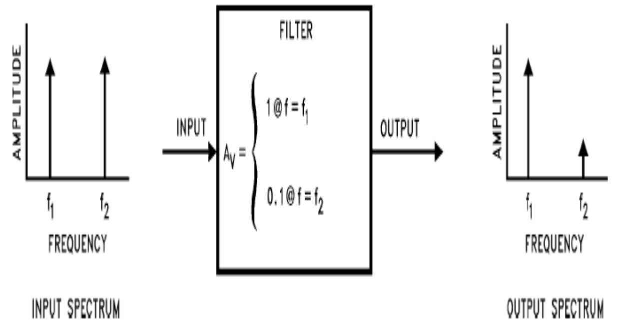

Fig: 6 Using a Filter to Reduce the Effect of an Undesired Signal [6]

The order of a filter is the highest power of the variable s in its transfer function. The order of a filter is usually equal to the total number of capacitors and inductors in the circuit. (A capacitor built by combining two or more individual capacitors is still one capacitor.) Higher-order filters will obviously be more expensive to build, since they use more components, and they will also be more complicated to design. However, higher-order filters can more effectively discriminate between signals at different frequencies.

A. FILTER SPECIFICATION

The five parameters of a practical filter are defined in Fig 7. The cutoff frequency (F_c) is the frequency at which the filter response leaves the error band (or the −3 dB point for a Butterworth response filter). The stop band frequency (F_s) is the frequency at which the minimum attenuation in the stop band is reached. The pass band ripple (A_{max}) is the variation (error band) in the pass band response. The minimum pass band attenuation (A_{min}) defines the minimum signal attenuation within the stop band. The steepness of the filter is defined as the order (M) of the filter. M is also the number of poles in the transfer function. A pole is a root of the denominator of the transfer function. Conversely, a zero is a root of the numerator of the transfer function. Each pole gives a –6 dB/octave or –20 dB/decade response. Each zero gives a +6 dB/octave, or +20 dB/decade response. The process of obtaining a transfer function that meets given specification is known as filter approximation. The filter transfer function T(s) can be written as the ratio of two polynomials as :

$$H(s) = \frac{a_m s^m + a_{m-1} s^{m-1} + ...+ a_1 s + a_0}{b_n s^n + b_{n-1} s^{n-1} + ...+ b_1 s + b_0} \qquad (6)$$

Therefore, H(s) is a rational function of s with real coefficients with the degree of m for the numerator and n for the denominator. The degree of the denominator is the order of the filter. For the filter circuit to be stable, the degree of the numerator must be less than or equal to that of the denominator.

The numerator and denominator coefficients, a_0, a_1, …, a_m and b_0, b_1, …,b_{n-1} , are real numbers. These roots can be real or complex. When they are complex, they occur in conjugate pairs. These roots are plotted on the s plane (complex plane) where the horizontal axis is σ (real axis) and the vertical axis is ω (imaginary axis). How these roots are distributed on the s plane can tell us many things about the circuit. In order to have stability, all poles must be in the left side of the plane. If we have a zero at the origin, that is a zero in the numerator, the filter will have no response at dc (high-pass or band pass).

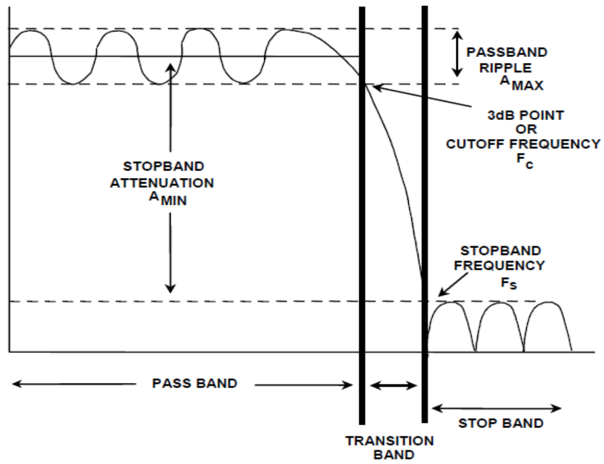

Fig: 7 Specification of the transmission characteristics of a low pass filter [7].

III. ACTIVE FILTERS

The filters use amplifying elements, especially op amps, with resistors and capacitors in their feedback loops, to synthesize the desired filter characteristics. Active filters can have high input impedance, low output impedance, and virtually any arbitrary gain. They are also usually easier to design than passive filters. Possibly their most important attribute is that they lack inductors, thereby reducing the problems associated with those components. Still, the problems of accuracy and value spacing also affect capacitors, although to a lesser degree. Performance at high frequencies is limited by the gain-bandwidth product of the amplifying elements, but within the amplifier's operating frequency range, the op amp-based active filter can achieve very good accuracy, provided that low-tolerance resistors and capacitors are used. Active filters will generate noise due to the amplifying circuitry, but this can be minimized by the use of low-noise amplifiers and careful circuit design. By cascading two or more of these circuits, filters with orders of four or greater can be built. The two resistors and two capacitors connected to the op amp's non-inverting input and to V_{IN} determine the filter's cutoff frequency and affect the Q(Quality factor); the two resistors connected to the inverting input determine the gain of the filter and also affect the Q. Since the components that determine gain and cutoff frequency also affect Q, the gain and cutoff frequency can't be independently changed.

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Figures 8(b) and 8(c) are multiple-feedback filters using one op amp for each second-order transfer function. Note that each high-pass filter stage in Figure 1.8(b) requires three capacitors to achieve a second-order response. As with the Sallen-Key filter, each component value affects more than one filter characteristic, so filter parameters can't be independently adjusted. The second-order state-variable filter circuit in Figure 1.8(d) requires more op amps, but provides high-pass, low-pass, and band pass outputs from a single circuit.

By combining the signals from the three outputs, any second-order transfer function can be realized. When the center frequency is very low compared to the op amp's gain-bandwidth product, the characteristics of active RC filters are primarily dependent on external component tolerances and temperature drifts.

For predictable results in critical filter circuits, external components with very good absolute accuracy and very low sensitivity to temperature variations must be used, and these can be expensive.

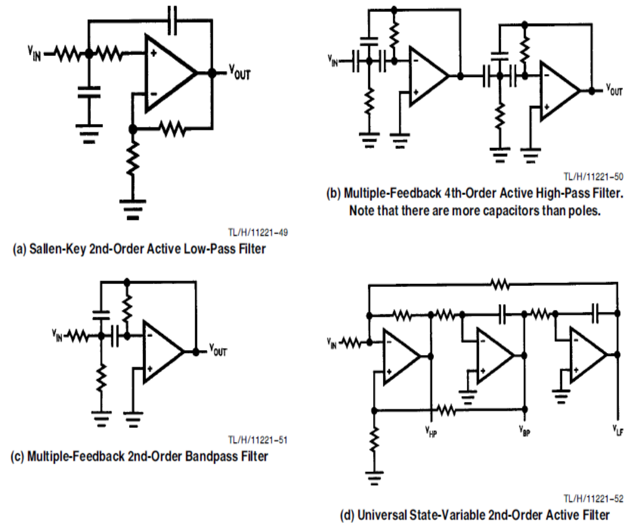

Fig: 8 Examples of Active Filter Circuits Based on Op Amps, Resistors, and Capacitor.

B. BUTTERWORTH LOW-PASS FILTERS

The Butterworth low-pass filter provides maximum pass band flatness. Therefore, a Butterworth low-pass is often used as anti-aliasing filter in data converter applications where precise signal levels are required across the entire pass band. Figure 1.9 plots the gain response of different orders of Butterworth low-pass filters versus the normalized frequency axis, Ω (Ω = f / f_C); the higher the filter order, the longer the pass band flatness.

C. CHEBYSHEV LOW-PASS FILTERS

The Chebyshev low-pass filters provide an even higher gain roll off above f_C. However, as Fig 1.10 shows, the pass band gain is not monotone, but contains ripples of constant magnitude instead. For a given filter order, the higher the pass band ripples, the higher the filter's roll off. With increasing filter order, the influence of the ripple magnitude on the filter roll off diminishes.

Each ripple accounts for one second-order filter stage. Filters with even order numbers generate ripples above the 0-dB line, while filters with odd order numbers create ripples below 0 dB. Chebyshev filters are often used in filter banks, where the frequency content of a signal is of more importance than a constant amplification.

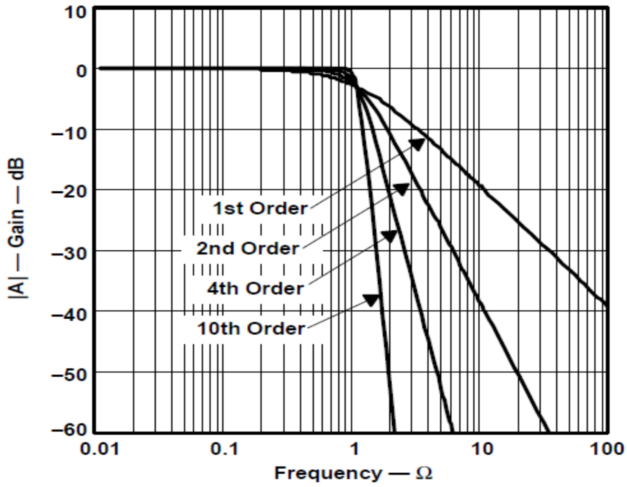

Fig: 9 Amplitude Responses of Butterworth Low-Pass Filters

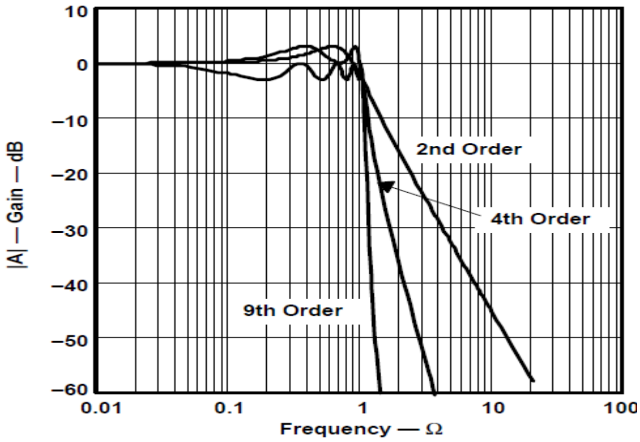

Fig: 10 Gain Responses of Chebyshev Low-Pass Filters

IV. CONCLUSION & DISCUSSIONS

In this paper, we have done literature study on MOSFETS, CMOS, and Filters. Their properties are studied thoroughly and the drawbacks are identified to design a filter with improvised filtering action. This improvisation in the designing of CMOS Analog filters can be done using software like MATLAB and LABVIEW.

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