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Design of Low Power Notch Filter for Biomedical Applications

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Abstract: The most important constraint in the design of Biomedical circuits is suppression of the power line frequency of 60 Hz which is a major interference in proper read out of low frequency ECG and EEG signals. This paper presents the design of low power Notch filter for biomedical applications using 180nm CMOS technology. The filter implementation is based on Tow-Thomas Topology. The filter design is based on highly linear fully differential Operational amplifier having a gain of 96.8dB. A filter design methodology wherein a second order continuous time (CT) filter is designed using a R – 2R ladder resistor is proposed in this paper which reduces the overall silicon area requirement for the resistor implementation. It is demonstrated that a notch depth of 84.79dB is achieved using CT filers. The CT filter consumes a very low power of less than 10.67 µW making it more suitable for bio-medical applications. The proof of concept is demonstrated by post layout simulations on Cadence analog design environment.

Keywords: Notch filter, Low frequency, Tow-Thomas Topology, Operational Amplifier, Resistor ladder, Low power.

I. INTRODUCTION

With the technology taking new leaps and bounds, there has been growing interest in biomedical applications. The applications include EEG (Electroencephalogram) [1] EMG (Electromyogram) [2] and ECG (Electrocardiogram) [3], and whose measurements are recorded at very low frequencies. While recording the measurements from an ECG of a patient, the major problem faced is the interference of a 60Hz low frequency signal generated from the ac power line [4].The resultant ECG signal/waveform is a noisy signal as it is interrupted by an unwanted frequency. The methods and remedies to overcome the interfering signal has been the topic for research and researchers have come up with various solutions [4-6] to combat this unwanted frequency. One way to suppress this frequency is by designing a notch filter having with high rejection rate at 60 Hz. This high Quality factor notch filter is capable of suppressing the unwanted powerline frequency.

The notch filter also called as Band reject filter does the opposite of the bandpass filter and is a preferred choice for suppressing the powerline interference signal. It will pass all the frequencies except the noise band frequency of 60Hz.This requires a high Q-factor for the filter with a very narrow bandwidth.

The Notch filter is designed by using Tow-Thomas Topology in which a continuous time filter using RC components is designed. A highly linear Operational amplifier is the basic building block of the notch filter. The amplification of notch filter is of crucial importance as for the entire filter design as the input signals from ECG, EEG or EMG will be very small in the range of µV or mV.

The paper is organized as follows- Section II describes the basics of ECG signal and impact of powerline interference on the ECG signal. In section III, the detailed design of operational amplifier is presented. In section IV, the design of Continuous time notch filter using ladder resistor network is described. Section V presents the design of discrete-time notch filter. In Section VI, the conclusion and comparison of this work with other works is discussed.

II. EFFECT OF POWERLINE FREQUENCY ON ELECTROCARDIOGRAM (ECG) SIGNAL

Electrocardiogram (ECG) is a test performed to obtain the electrical activity of a patient's heart. It is quite difficult to obtain accurate results while the activity is being recorded. The ECG of a patient is recorded by connecting skin electrodes at different locations on human body. A typical ECG signal is shown in figure 1.

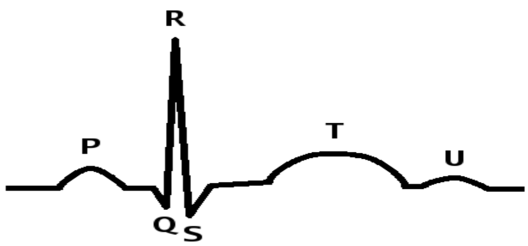

Figure 1: ECG Signal - the PQRSTU complex

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The signal is labelled as P,Q,R,S,T and U [8]. The p wave results from the contraction of right atrium followed by left atrium. The QRS complex has the highest amplitude as it indicates the time when the heart muscles are in action[9]. The T wave indicates the polarization of ventricles. Figure 2 represents a human heart.

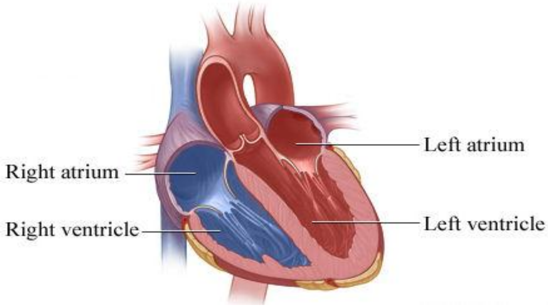
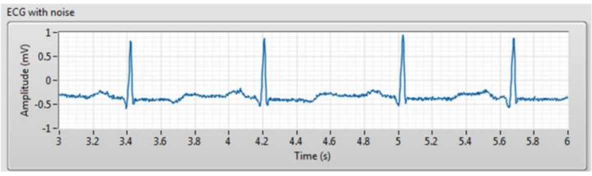
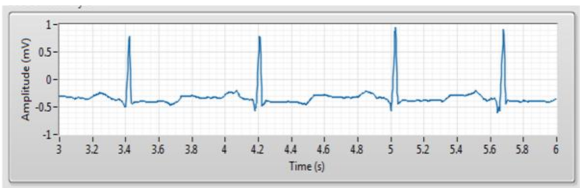


Figure 2: Human heart showing atria and ventricles.

ECG signal is a low frequency signal and to record this signal is not an easy task as most of the time the signal gets corrupted by various kinds of noise[6]. The sources that contribute to noise are - Powerline interference, Electrode contact noise, muscle contraction etc,. The powerline interference is often encountered when the a.c mains power is turned on and harmonics are generated.



(a)



(b)

Figure 3: (a) Powerline interference in ECG signal (b) ECG signal with powerline interference cancelled.

Electrode contact noise results from loose contact. Muscle noise arises from contraction of muscles. Figure 3 (a) shows an ECG signal corrupted by powerline interference and 3(b) shows an ECG signal with the 60 Hz powerline interference being cancelled.

This paper focuses on proposing a low power robust design of notch filter for removal of powerline interference.

III.OPERATIONAL AMPLIFIER

The most crucial block in design of an active filter is the opamp, which determines the overall power consumption and the notch depth of the filter. A fully differential operational amplifier is preferred for Bio medical applications as it effectively eliminates the inter electrode noise from various leads of ECG machine. This paper implements a fully differential version of a two stage class AB opamp is shown in Fig. 4 [10]. Since both input and output stages are class-AB, it can work with very low biasing currents, hence consumes very less power.

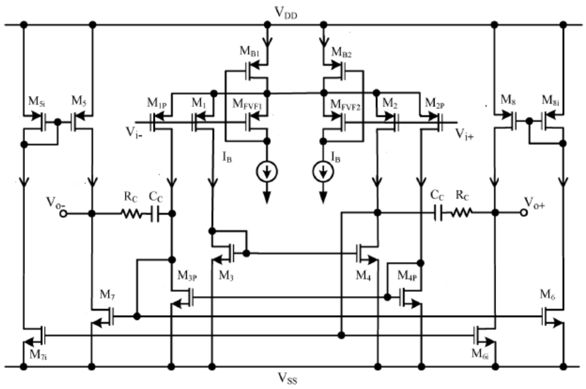


Figure 4: Circuit Diagram of fully differential Class AB Operational Amplifier

Table 1 enlists the transistor dimensions of the various NMOS and PMOS devices used in the design. A current source of 100nA is used to bias the opamp for a Supply voltage of 1.2 V.

TABLE 1: OPAMP DEVICE DIMENSIONS

DEVICE	LENGTH	WIDTH	DEVICE	LENGTH	WIDTH
M1	720 NM	720 NM	M12	900 NM	360 NM
M2	720 NM	720 NM	M13	5.85 M	815 NM
M3	720 NM	720 NM	M14	5.85UM	815 NM
M4	720 NM	720 NM	M15	5.85UM	815 NM
M5	720 NM	720 NM	M16	5.85UM	815 NM
M6	720 NM	720 NM	M17	3.65UM	3.5 UM
M7	900 NM	360 NM	M18	3.65UM	3.5 UM
M8	900 NM	360 NM	M19	3.65UM	3.5 UM
M9	900 NM	360 NM	M20	3.65UM	3.5 UM
M10	900 NM	360 NM	M21	9 UM	220 NM
M11	900 NM	360 NM	M22	9 UM	220 NM

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Figure 5 represents the Gain and Phase plot of Operational Amplifier. The Simulation results show a Gain of 96.8 dB and a unity gain bandwidth of 2.435 MHz with a phase margin of 64.6 degrees and slew rate of 25 V/u Sec.

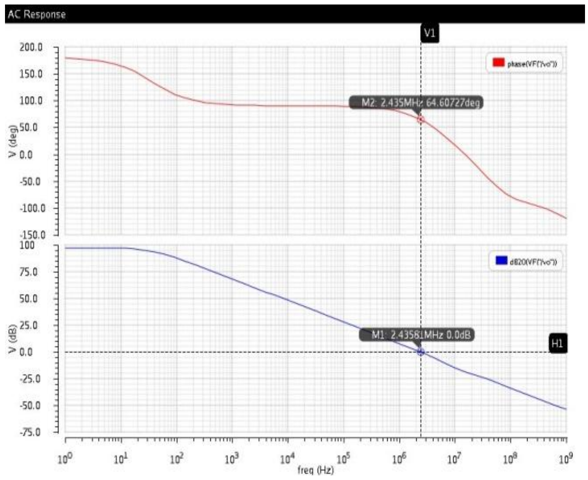

Figure 5: Gain and Phase plot of Operational Amplifier

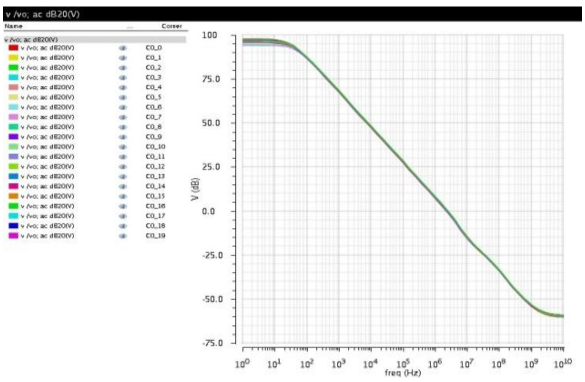
Figure 6: Corner analysis of Opamp

Corner Analysis is performed for temperatures -40°c, 0°c, 27°c, 120°c to check the robustness of the design. The performance of opamp at all corners is satisfactory as shown in figure 6, thus indicating that the designed Operational Amplifier meets the specifications for all the technology corners.

IV. DESIGN OF CONTINUOUS-TIME NOTCH FILTER

The filter is implemented using the Tow Thomas biquad filter depicted in figure 7. It consists of three main parts – the first opamp based circuit implementing a simple transfer function, the second opamp based circuit implements an inverting integrator and the third opamp implements a unity gain inverter.

The transfer function of a second order notch filter is given by

$$H(s) = K\frac{s^2+\omega_0^2}{s^2+\frac{\omega_0}{Q}s+\omega_0^2} \quad (1)$$

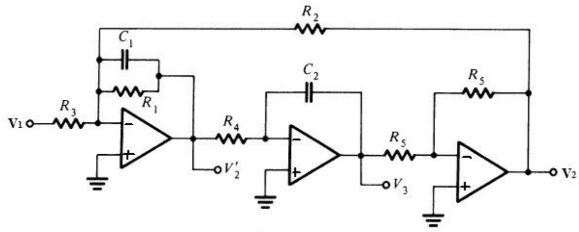
Figure 7: Structure of Tow Thomas biquad filter

where ω_0 is the pole frequency, as well as the notch frequency (zeroes at $\pm j\ \omega_0$), Q is the pole quality factor, and K is the gain. As this filter has to reject the power line frequency of 60 Hz, the values of resistor and capacitor can be calculated using the equation 2.

$$\text{Fo}= \frac{1}{2.\pi.R.C} \quad (2)$$

For a frequency of 60 Hz, the time constant RC will be very high. The Capacitor is chosen with a value of 5.2 pF thereby resulting in a resistor value of 510.3707 MΩ. We observe that the design of low frequency notch filter requires large value of resistor which is of the order of Mega ohms. Such a high value of resistance cannot be realized practically in silicon as it occupies large area. An alternate way of designing a high value of resistor is the use of a R-2R ladder shown in figure 8. The maximum resistance can be increased by increasing the size of the ladder network.

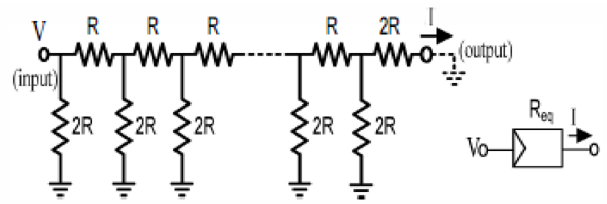

Figure 8: R-2R Ladder Network

The high resistance value of 510.3707 MΩ is replaced by R-2R ladders [7] so that a high value resistor can be implemented using many smaller value resistors. The overall value of ladder network is obtained using equation (3), hence saving huge area and providing linearity. The value of R depends on the number of ladders(n). If the value of n is 12 then R will be calculated as below

$$R_{eq} = 2^n(R) \quad (3)$$

Here R_{eq}= 510.3707 MΩ then

$$R = \frac{R_{eq}}{2^n} = \frac{510.3707 \times 10^6}{2^{12}} = 124.602k\Omega$$

Therefore R ≈ 124.602 kΩ and 2R ≈ 249.2 kΩ

The continuous time notch filter is implemented using the ladder structure resistors as shown in figure 9 where R1, R2, R3, R4 represent the equivalent resistance obtained from R-2R ladder network. The total area needed to make an n-bit R-2R would be that of $R_{tot} = (3n-1)R$.

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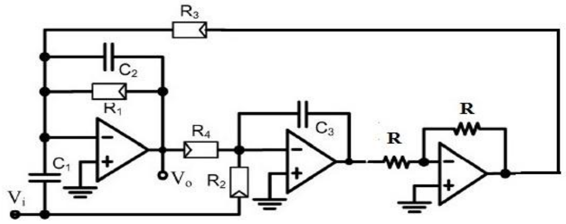
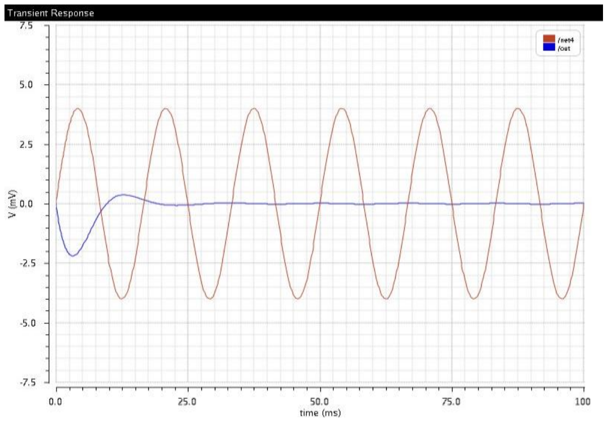
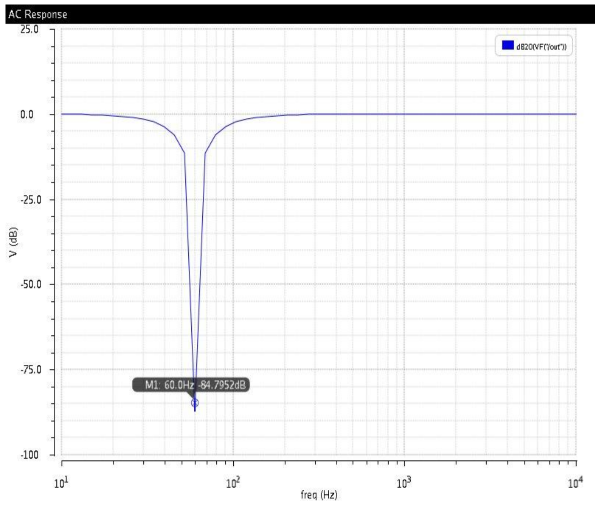


Figure 9: Implementation of tow Thomas filter using ladder resistors

Transient analysis of the filter is shown in figure 10(a) which indicates that when a 60 Hz sine wave of 4mV amplitude is applied as input to the filter the output totally diminishes, indicating the effective functionality of the filter. The AC analysis of the tow Thomas filter shows a notch at 60 Hz with a notch depth of -84.79dB as shown in figure 10(b).



(a)



(b)

Figure 10: (a) Transient analysis of continuous time notch filter (b) AC analysis of CT notch filter

The complete layout design of the continuous time notch filter is shown in figure 11. The Area occupied by the filter is 405.415 µm × 307.37 µm = 0.1247 $(mm)^2$. Table 2 indicates the performance summary of the designed filter.

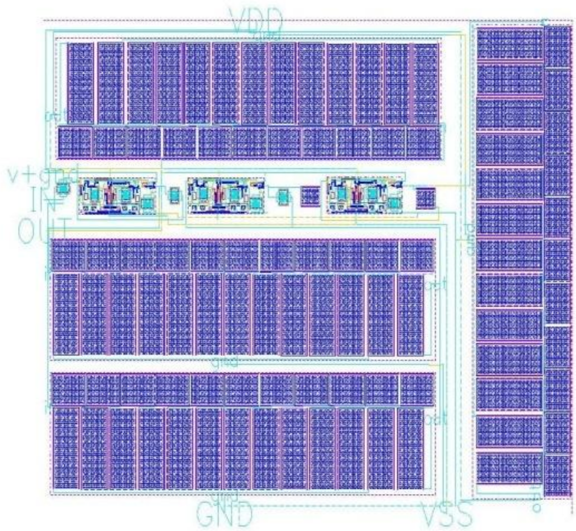


Figure 11 : Layout of Continuous time Notch Filter

Table 2: Performance summary of proposed filter

Parameter	CT Notch Filter
Application	ECG
Notch Frequency	60 Hz
Notch Depth	84.79 dB
Power consumption @ 1.2 V	10.67 µW
Area	0.1247 $(mm)^2$

V. CONCLUSION

The notch filter is implemented using 0.18 um CMOS technology at a power supply of 1.2V in both continuous time domain. The Large resistance is replaced by a R-2R ladder network in order to minimize the resistance tolerance effect and save a huge area. Table 3 compares the performance of the proposed notch filter with existing works and it is observed that the proposed design achieves maximum notch depth and minimum power consumption in contrast with the other published works.

Table 3 Performance Comparison with other works

Reference	[7]	[8]	[9]	This Work
Technology	0.18 µm	0.9 µm	0.35 µm	0.18µm
Notch frequency	50 Hz	50 Hz	60 Hz	60 Hz
Notch Depth	55.4 dB	41 dB	66 dB	84.79 dB
Power Supply	1.8 V	3 V	3 V	1.2 V
Power Consumption	25.2 µW	75 µW	11 µW	10.67 µW

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