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# Low Frequency Filter design Using Gyrator for Biomedical Applications

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***ABSTRACT*: This paper deals with the design of low frequency filter using gyrator for biomedical applications. The dynamic range of filter cut off frequency is between 1HZ to 100 HZ, which coincides with the biomedical constrains. The paper is organized as follows. In section I, an introduction of the biomedical signals, filter considerations and the existing methods for LPF are discussed. In section II, the gyrator and how it is used to simulate a capacitor is introduced. In section III, we present some results of the proposed method. Finally, conclusions and suggestions for future work are included in section IV.**

***Index Terms* — Biomedical application, capacitor scaling, , gyrator, IC implementation, Low frequency filter.**

## I. INTRODUCTION

Biomedical signals are time records of biomedical events such as contracting heart or stimulated neuron. Biomedical signals are produced as a result of electrochemical activity of excitable cells including nervous, muscular, or glandular tissue evoked potential. When millions of these cells are generated, an electric potential is generated and can be measured at the body surface. Examples of such potentials are the Electrocardiogram (ECG) generated by the heart and the Electroencephalogram (EEG) generated by the brain. Biomedical signals contain useful information that can be used to interpret or understand some underlying physiological events. Biomedical signals recorded at the body surface are usually in the range of micro to millivolt range. Large amplification is therefore necessary followed by signal pre-filtering prior digitization. The bandwidth of such signals is very low and usually less than 1KHz. Clinical ECG signals for example occupy a frequency bandwidth 0.01-100Hz while it is 0.1-30Hz for EEG signal [1]. Therefore, analog filters are needed in order to attenuate undesired high frequency noise. Furthermore, biopotential electrodes generate low frequency drift signal which if not removed can swamp the desired biomedical signals.

High performance integrated circuit building blocks are necessary for biomedical applications. Despite the many advancements in analog integrated circuit design, there are still some problems to solve in biomedical electronics such as minimizing the number of external components [2]. Most biomedical signals are less than 1kHz, while the IC implementation of analog filters between 1KHz-10KHz can be carried out by standard analog IC circuit design [2]. Designing IC filter circuits less that 1KHz is not trivial. To design a first order low pass filter with a cut-off frequency of 100 HZ, and if we use 1 1kΩ resistor, then, 1.59μF is needed. This amount of capacitance is too large to be used on a chip. The usual capacitors used on a chip are below 50 pF. Therefore, most biomedical signal pre-filtering is performed using external resistor and capacitor components. To solve this problem, several techniques have been proposed including switched-capacitor topology, and OTA-C techniques [3-7]. All of proposed methods have their own disadvantages and advantages. The switched-capacitors are used to enlarge the capacitance of the network and as a result to decrease the filter central frequency. The main disadvantages of such method are the need for pre and post filtering, aliasing and switching problem. In OTA filters, the frequency is directly proportional to the OTA transconductance and inversely proportional to the capacitance. There are some methods used to decrease the transconductance or increasing the capacitance using current mirror, current cancellation or Triode biased transistor. The main disadvantage of using current mirror is the Large amount of silicon required for the transistors. The current cancellation technique has a high sensitivity to transistor mismatch while the triode biased transistor suffers from saturation voltage being highly sensitive to the threshold voltage and relatively harmonic distortion.

The Miller's effect method is also used to enlarge the capacitive impedance of the network. A voltage amplifier of gain $A_v$ is used which is fed back to a capacitor. Consequently, the overall capacitance is increased to $(1+ A_v)C_L$. The main disadvantage of such technique is the reduction in the signal swing and additional amplifier.

In this paper, we present an alternative solution based on increasing the capacitance of the network using a gyrator. The gyrator introduced by Tellegen in 1948 as an ideal model for devices which interchange the role of the electric field and the magnetic field. The simulated capacitor is composed of two gyrators.

The paper is organized as follows. In section II, the gyrator and how it is used to simulate a capacitor is introduced. In section III, we present some results of the proposed method. Finally, conclusions and suggestions for future work are included in section IV.

## II. METHODOLOGY

The gyrator model is defined by currents and voltages as depicted in Fig. 1:

$$V_1 = Ri_2 \tag{1}$$

$$V_2 = -Ri_1 \tag{2}$$

where R is the gyre resistance

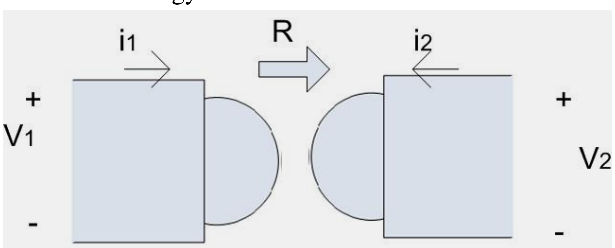


Fig. 1, The gyrator block diagram

If we connect a load impedance to the output extremity of the gyrator, looking from the input extremity, the input impedance will be:

$$Z_i = R^2 \frac{1}{Z_L} \tag{3}$$

Fig. 2 shows the connection of two gyrators one by one. The load at the output extremity is terminated by a capacitor. Looking from the input side:

$$C_{eq} = \frac{R_2^{\,2}}{R_1^{\,2}} C \tag{4}$$

where $R_1$ indicates the gyre resistance of the first gyrator and $R_2$ indicates the gyre resistance of the second one [8].

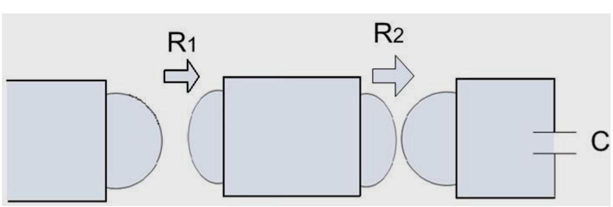


Fig. 2, Two grade gyrators connected one by one

Clearly as (4) states, we can obtain a scaled capacitor from the two gyrators. The proposed circuit by [8], in Fig.3 is in fact an equivalent capacitor. We can use this circuit in series with a resistor to obtain a low pass filter.

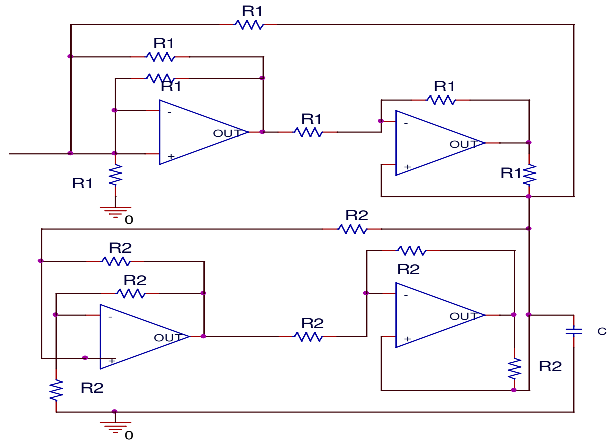


Fig. 3, The circuit of using two gyrators to realize larger capacitance

The circuit in Fig. 3 operates similarly as a low pass filter [8]. However, instead of using two gyrators connected together, we can obtain an equivalent capacitor from a single gyrator as well. Fig. 4 shows the realization of the gyrator introduced by Riordan [9].

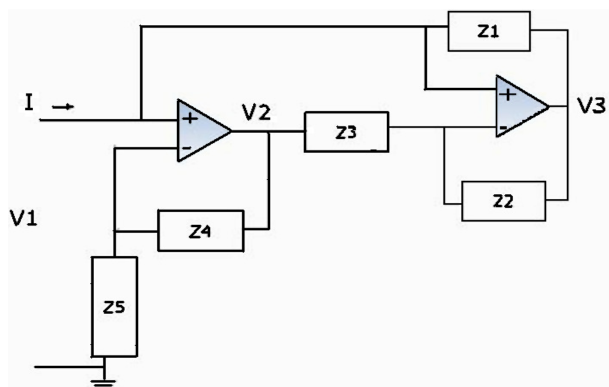


Fig. 4, Realization of gyrator introduced by Riordan

It can be readily shown that the input impedance of this circuit is given by:

$$Z_{in} = \frac{V_1}{I} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4} \tag{5}$$

The other circuits introduced for the gyrator, like the ones by Antoniou [9], also represent identical input impedance as (5). One can notice by using $Z_1$, $Z_3$ or $Z_5$ as a capacitor, while all other components are resistors, the input impedance will be a capacitor. For example, let:

$Z_1 = \frac{1}{jwC_1}$, $Z_2=R_2$, $Z_3=R_3$, $Z_4=R_4$, $Z_5=R_5$, so:

$$Z_{net} = \frac{R_3 R_5}{R_2 R_4 S C_1} \tag{6}$$

Since $R_2$, $R_3$, $R_4$ and $R_5$ are constants, we refer to $Z_{net}$ as a capacitor where:

$$C_{net} = \frac{R_2 R_4}{R_3 R_5} C_1 \tag{7}$$

Overall, when using gyrators, we have two alternatives to scale a capacitor and use it in a low pass filter. One is via two gyrators connected together, and the second one is with a single gyrator. Due to the cost consideration, we chose the second option to get an equivalent capacitor.

We tested and compared all the alternative circuits in [9], which realize a gyrator, in the frequency range of 1-100 HZ. The comparison criteria are capacitor location and capacitance range. The frequency response of each of these circuits is compared to the frequency response of a basic 1st order RC low pass filter. Among all the circuits, the one shown in Fig. 4 proved to be superior.

## III. RESULTS

To investigate the performance of the proposed low pass gyrator filter, different cases are considered:

- Gyrator performance with different capacitor locations
- Gyrator performance with different capacitor values
- Gyrator performance with different resistor values

We used Pspise for simulations. Fig. 5 shows the under test circuit and Fig. 6 shows the reference.

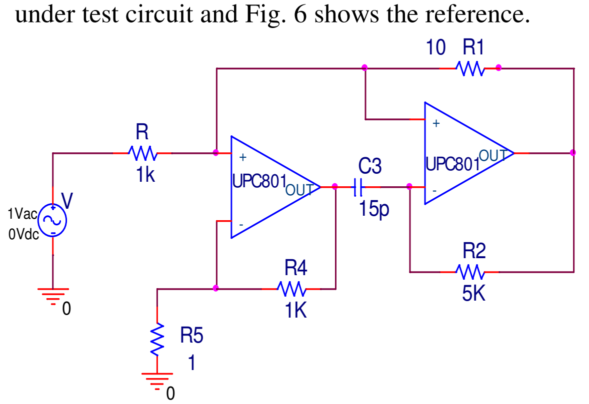


Fig. 5, The under test circuit in a LPF

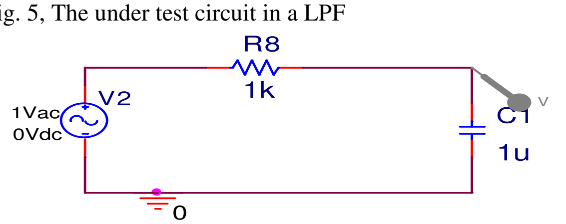


Fig. 6, The basic RC low pass filter used as the reference

For a good response of the gyrator filter, the operational amplifiers need to have high input resistance and low output resistance [10]. Op amps of family UPC are generally good for active filter design and have a very high input resistance, and low output resistance compared to the general purpose LM741. In our analysis we used the operational amplifier UPC 801 with unity gain bandwidth of 3 MHZ, and input resistance of 2.5 GΩ.

Location of the capacitor in the gyrator filter changes its gain. The reason is that, since we are dealing with low frequencies and small capacitor values, the capacitor will act as an open circuit. Consequently, to avoid an undesirable response, the capacitor is to be located where least amount of current is to flow. To simulate a capacitor, in (5) we replace Z1, Z3 or Z5 as a capacitor, while all other components are resistors. In this test, we compare the response of the gyrator filter, in different capacitor locations with the response of the reference. The aim is to find out the location at which the frequency response accuracy is the lowest. The frequency response accuracy is measured using:

$$\%\,\text{accuracy} = \frac{|A_R - A_M|}{A_R} \times 100 \qquad (8)$$

where $A_R$ is the gain of the reference circuit at the cut off frequency, and $A_M$ is the gain of the gyrator filter at its cut off frequency.

The passive element values are chosen arbitrary, but for the capacitance, as already mentioned it has to be less than 50 pF. Let:

$C_1$=15pF; $Z_3$= 10Ω; $Z_2$=5KΩ; $Z_4$=1KΩ; $Z_5$=1Ω

From (7), the equivalent capacitance of the network is 7.5 μF. This capacitor value is to be used in the referenced circuit. Apparently using the above values in series with a resistor of 1KΩ in the LPF circuit corresponds to a low pass filter of 20 HZ cut off frequency.

Fig. 7 shows the result of the comparison between the response of the basic RC filter and the gyrator filter with different capacitor locations.

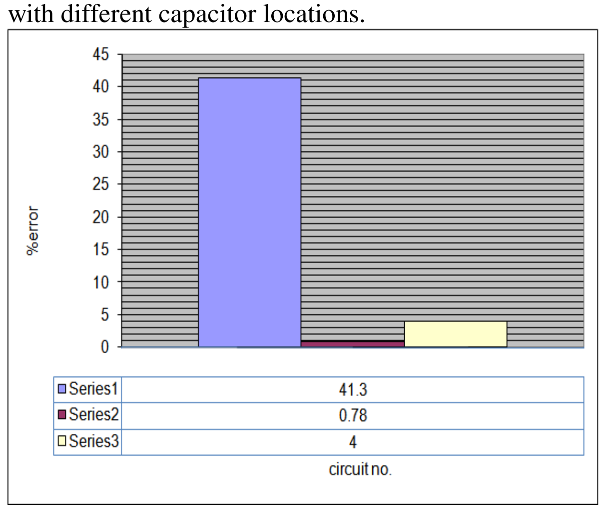


Fig. 7. %accuracy in the gyrator filter response for f = 20HZ

From Fig. 7, we can readily observe that the circuit performs better if the capacitor is located in $Z_3$ or $Z_5$.

*III.B) Performance of the gyrator with different capacitor values.*

In this test, the effect of the different capacitor values on the circuit response is evaluated. To have a complete inspection on the attenuation rate of the gyrator filter, the response of the circuit is examined on wide rage, covering two decades after the cut off frequency.

This test is carried out by, first studying the gyrator filter when $Z_3$ is placed by a capacitor. The capacitor value is altered from 1 pF to 50 pF. For each change in C, the result is compared with the response of the reference circuit. The same test is performed on $Z_5$. Fig. 8 shows the gyrator filter response in the cut off frequency, for the two capacitor location.

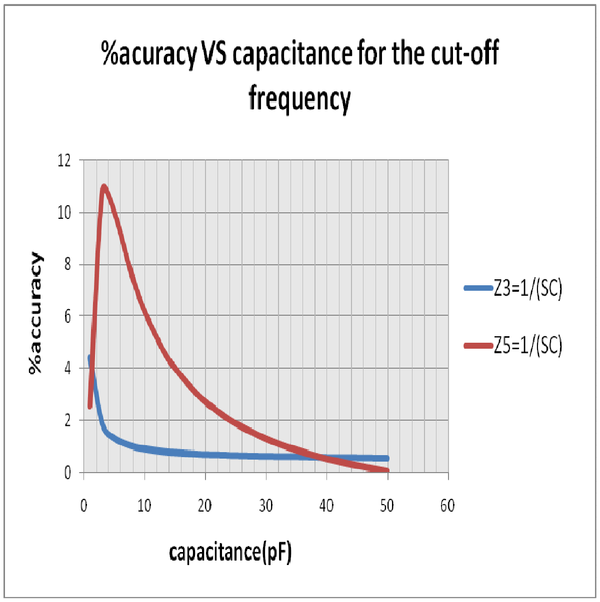


Fig. 8, %accuracy VS capacitance for the cut-off frequency

Fig. 8 shows that the circuit with $Z_3$ performs better than with $Z_5$. The response is less than 2% accuracy for the cut off frequency when $Z_3$ is placed by a capacitor valued between 4-50 pF.

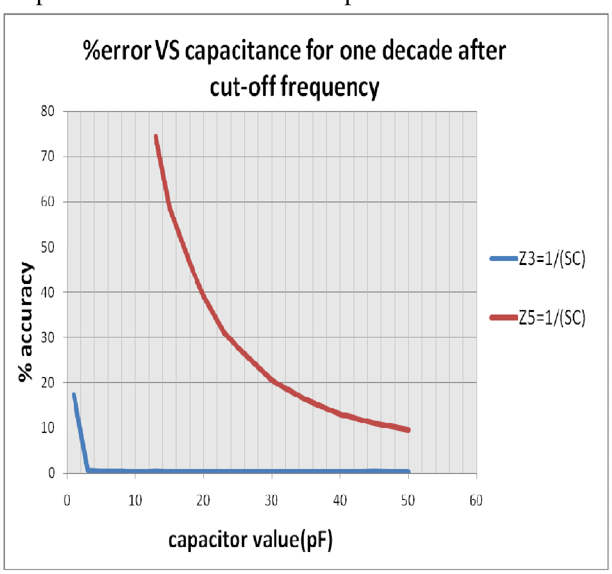


Fig. 9 %accuracy VS capacitance for the one decade after cut-off frequency

Fig. 9 shows that the %accuracy one decade after the cut off frequency is essentially zero when $Z_3$ is placed by a capacitor valued between 5-50 pF. Whereas using $Z_5$ as a capacitor, we do not get low %accuracy. Hence $Z_3$ performs more effectively as a reactance.

To investigate the capacitor values which can be used for $Z_3$, we take the %accuracy for two decades after the cut-off frequency. Fig. 10 shows that for capacitor values of 15-50 pF, the high frequencies are attenuated with less than 10% accuracy. As we increase the capacitance towards the 50 pF, the gyrator filter response gets more similar to the referenced response.

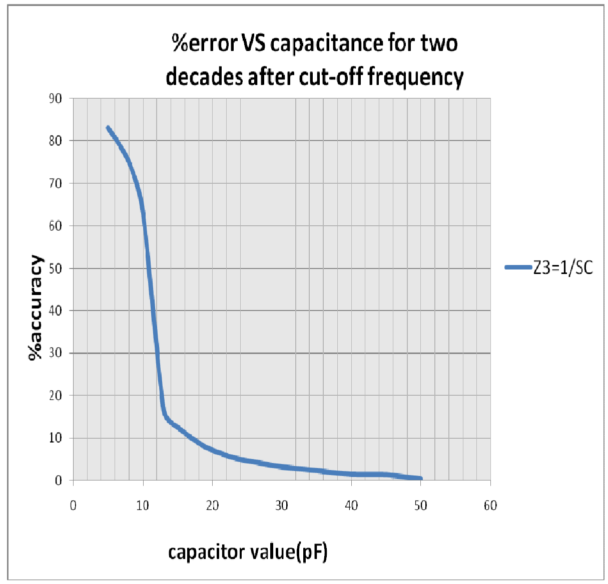


Fig. 10, %accuracy VS capacitance for two decades after cut-off frequency

To sum up the results obtained in the tests conducted so far, we found the location $Z_3$ to be the most efficient one to place the capacitor in, and the best capacitor values to be used are within 15-50 pF.

*III.C) Performance of the gyrator with different Resistor values.*

Equation (7) states in order to increase the net capacitance, we should decrease the value of $R_1$ and $R_5$; at the same time, increase $R_2$ and $R_4$. In this test, we investigate the effect of resistor values on the response of the system.

First, conducting the test for $R_1$ and $R_5$, we set $R_5 = 1\Omega$ and increment $R_1$ to investigate its effect. Then, we exchange values of $R_1$ and $R_5$, and do the same thing to study the effect of $R_5$ on the response. We found out that, small values of $R_1$ and $R_5$ lead to a huge frequency shift of about 7KHZ.

A Similar test was performed on $R_2$ and $R_4$. To gain a frequency range of 1-100 HZ, we need an equivalent capacitance of 1-150 µF. Since we are using C in the range of pF, according to (7) R2 and R4 need to be in the range of KΩ to compensate the effect of the small capacitance. To start the test on $R_2$ and $R_4$, we set $R_4$=1KΩ and increment the $R_2$. We do the same to detect the effect of the $R_4$. We got that if $R_4$ exceeds 2KΩ, we get a huge error in the circuit response. Table.1 represents the results we obtained for this test.

TABLE I

Summary of the resistors value test result

| Applicable range for R1(Ω) | Applicable range for R2(Ω) | Applicable range for R4(Ω) | Applicable range for R5(Ω) |
|---|---|---|---|
| 5 – 20 | 1K – any | 1K -3K | 1 |

To sum up the results we got in the test C, despite our desire of having minimum values for $R_1$ and $R_5$, there are minimum boundaries for them. In theory, we can set $R_1=1\Omega$. In practice, however this will lead to a cut-off frequency shift. Allocating values lower than $5\Omega$ for $R_1$, which is located in the main feedback branch and plays and important roll in determining the gain of the filter, corresponds to a short circuit. By placing zero for $R_1$ in the gain equation, we get non-defined gain. The best response, considering the least cut-off frequency shift and the gain loss, is acquired when $R_1=10\Omega$, and $R_5=1\Omega$. Moreover, the maximum resistance value for $R_4$ is $3K\Omega$; however, we can increase the resistance of $R_2$ to higher values without much error, or gain loss. As a result, in our design, we set $R_4 = 1K\Omega$, and having $R_2 = 5\ K\Omega$ is adequate. However, we can increase value of $R_2$ to $M\Omega$, without much significant negative effect on the circuit response.

## CONCLUSION

The proposed gyrator filter in Fig. 5 proved to act as a low pass filter. This circuit responds similarly to a basic RC Low pass filter. The op amps used in the circuit are chosen to be UPC 801. The current location of the capacitor in Fig. 5 proved to be the best one and its value was found to be within 15 pF and 50 pF. The resistor values to be used in the circuit verified to be within a specific range and are shown in table. 1. Fig.11 shows the frequency response of the gyrator filter.

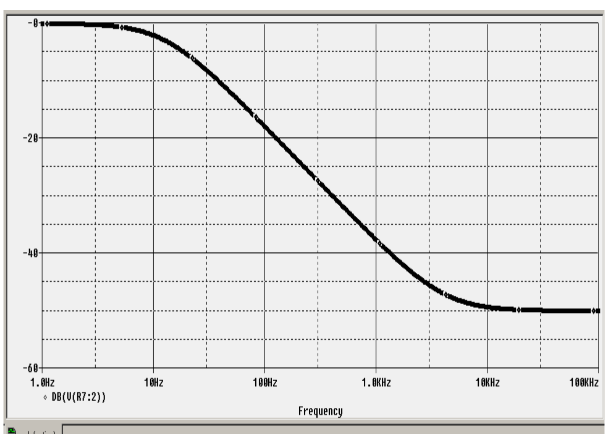


Fig. 11. Frequency response of the proposed circuit for C=25pF

The component values used in the circuit to obtain the frequency response in Fig. 11 are:

$C_3$=25 pF; $R_1$= 10Ω; $R_2$=5KΩ; $Z_4$=1KΩ; $Z_5$=1Ω

Advantages of this method over the previous methods mentioned in the introduction could be:

- Due to the large dynamic range of R2, we can easily vary its value to obtain any arbitrary equivalent capacitance and consequently have a filter with a variable cut off frequency.
- There is no switching problem, and no need for pre and post filtering.

Next in this project is to design a second order filter using the gyrator circuit and construct it as a chip using active loads instead of the solid resistors.

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