Memristor-based Tunable Analog Filter for Physiological Signal Acquisition for Electrooculography

Abstract. In this paper we demonstrate that Memristors can be used in conjunction with MOSFETs to implement a continuous-time tunable analog bandpass filter for use in the area of biomedical signal acquisition. The idea here is to implement a single band pass filter which can provide frequency tuning between EEG, EOG and ECG signals. Frequency tuning is achieved by varying the resistance of the Memristor (memristance). The proposed circuit promises lower power dissipation and smaller-sized implementations than CMOS counterparts. This circuit is capable of filtering out biomedical signals (specifically Electrooculography (EOG) signals) and the same is demonstrated for the frequency range of 6 Hz to 16 Hz. The power consumption of the band pass filter designed was found to be 127 nW at ±0.25V supply. The HSPICE simulation results were found in accordance to the qualitative discussion.

1. Introduction

The idea of combining the design and problem solving skills of engineering with medical/biological sciences for health-care purposes has lead to the emergence of the (relatively) new field of research known as the biomedical engineering. Most of the work in this field consists of research and development of bio-compatible prostheses, various diagnostic and/or therapeutic medical devices ranging from clinical equipment to ultra-miniaturized implants, resonance imaging and tomography set-ups etc. Almost all of the above mentioned techniques and equipment work on the fact that a human body constantly communicates information about its health, and this data can be captured and used through physiological-signal acquisition instruments that can measure heart rate, blood pressure, brain state, eye movements, heart activity etc. These biomedical indicators are very low voltage and low frequency signals which need to be suitably processed before recording and monitoring.

Processing of such biomedical signal involves the analysis of signal measurements to provide useful information upon which clinicians can make decisions. Technological advancements have led to miniaturization of monitoring devices and power sources opening up a whole new world of possibilities and innovations. An approach in this direction is the employment of wearable and implantable technologies which sense parameters of various diseases or disorders and are capable to transfer data to a remote center; direct the patient to take a specific action; or automatically perform a function based on the sensor reading. The idea of wearable and implantable electronics on human body poses restriction on the power consumption and size, and demands efficient operations at reduced power supply voltages. The major concerns of currently active research on such devices and instruments are therefore: reducing the size; lowering the power consumption; and to make the instruments measure the minutest potential difference. This is where the new device Memristor is expected to enable the chips to be smaller and better, because it is smaller in size (as compared to an on-chip resistor, or even transitor-based resistance emulators); retains memory; and is two orders of magnitude more efficient from power perspective as compared to traditional resistor technology [1–29].

A typical block diagram of a biomedical signal processing unit is shown in Fig. 1 where the band-pass filter (BPF) forms an important block. In this paper the idea is move the bandpass filter from the domain of discrete time filtering to the analog signal processing domain, and thereafter to implement a single tunable band pass filter which can select different frequencies corresponding to various physiological signal types.

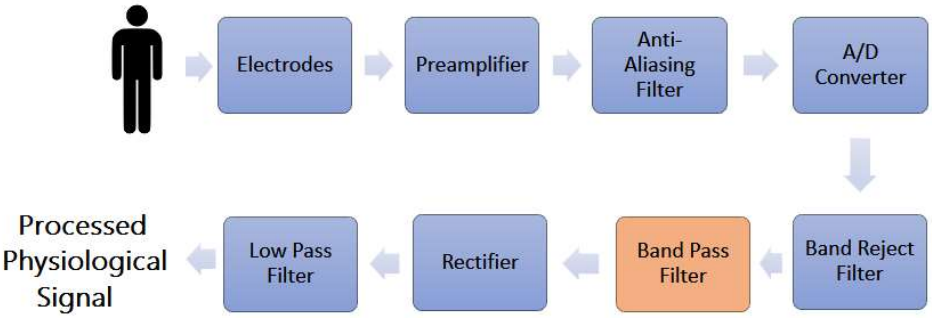


Figure 1. Typical physiological signal acquisition and processing flow

This paper includes a brief introduction in Section 1 explaining the need and advantages of incorporating Memristors with typical transistors in analog front-end design to obtain the desired benefits . Section 2 briefly reviews the literature presented on Memristor and their rapid rise to importance in the field of biomedical engineering. Section 3 includes an overview of a previously presented work [28], of which this paper is an improved version with qualitative discussion on how the frequency tunablity is much more advantageous than the gain tunability offered in the reference paper. Section 4 includes the HSPICE simulation results for Memristance programming and frequency tunable bandpass filter proposed in this work. Section 5 concludes the paper by presenting a summary and concluding remarks.

2. Existing Works

In 1971 Leon Chua, came out with the seminal paper titled *'Memristor - The Missing Circuit Element'* in which he proposed a new two-terminal circuit element-called the *Memristor* characterized by a relationship between the charge and flux linkage [1]. He introduced it as the fourth basic circuit element (the other three being R, L and C). It is to be noted that a physical Memristor device was not feasible at that time, and that became a reality later in 2008 when Strukov *et. al.* reported an actual working prototype in *'The Missing Memristor Found'* where they showed, using a simple analytical example, that Memristance arises naturally in nanoscale systems in which solid-state electronic and ionic transport were coupled under an external bias voltage [2]. These results served as the foundation for understanding a wide range of hysteresis exhibiting current–voltage behavior observed in many nanoscale electronic devices.

After the physical Memristor was made realizable in 2008, a significant quantum of research work in this field was carried out including the Memristor modeling and implementation of digital and analog circuits thereby reducing the complexity of the circuits. This was possible because the Memristor was supposed to have a striking feature of memory as it was capable of remembering the amount of current passed through it. Various Memristor models were also put forward to enable researchers to design simple and efficient circuits. In 2010, Mahvash and Parker presented a SPICE model for the Memristor which was fabricated at HP Labs in 2008 and validated it by simulating simple circuits [13]. The proposed model opened avenues to design and simulate Memristor circuits using SPICE. In the same year, Rak and Cserey came out with a new simulation program with integrated circuit emphasis macromodel of the physically implemented Memristor [10]. It proved to be a powerful tool for engineers to design and experiment new circuits with Memristors. In 2013, Biolek *et. al.* presented mechanisms for reliable SPICE simulations of Memristors, Memcapacitors And Meminductors wherein they proposed a collection of models of different memory circuit elements and provided a methodology for their accurate and reliable modeling in SPICE [21]. To aid the aspiring researchers in this field, the authors were generous enough to provide netlists for these models in various popular SPICE versions (PSpice, LTspice, HSpice).

While Memristor models were being developed as soon as its physical implementation came into existence, another dimension of research progressed to practically implement the Memristor in analog and digital domains using existing ICs. The first approach in this direction was in 2010 when Pershin and Ventra presented a practical approach to obtain programmable analog circuits with Memristors [14]. The approach was to apply low voltages to Memristors during their actual operation as analog circuit elements and significantly higher *programming* voltages to set/alter the Memristor's states. They demonstrated that the state of Memristors did not change during analog mode of operation provided all the signal levels were kept much lower than the programming voltage levels. A year later, in 2011 Shin, Kim & Kang presented various Memristor applications for programmable analog ICs [11]. A fine-resolution programmable resistance was achieved by varying the amount of flux across Memristors. Resistance programming was achieved by controlling the input pulse width and its frequency. A Memristor was subsequently designed for a pulse-programmable mid-band differential gain amplifier with high resolution.

A research contribution demonstrating the Memristor characteristics and Memristance variation with frequency was presented by Lee & Nickel in 2012, wherein they presented the idea of Memristor resistance modulation for analog applications [17]. It was shown that the linear resistance can be randomly programmed with accuracy and reproducibility. Analog circuits of tunable memristive low-pass and high-pass filters demonstrated frequency tuning by resistance modulation.

As the research progressed on Memristor to implement analog filters, their application in the field of biomedical signal acquisition and conditioning came into existence. A major step in this direction was in 2014 when Yener *et. al.* presented analytical and dynamical models for a Memristor-based high-pass filter and amplifier [23]. In the same year, the same authors also presented their work on frequency– and time–domain characteristics of a Memristor-based continuous-time low-pass and high-pass filters [22].

More recently, Yener *et. al.* put forward an ultra-low-voltage ultra-low-power Memristor-based band-pass filter and its application to EEG signal acquisition [28]. Several analog applications of Memristor, its SPICE macro-models and 'Memristor Emulators' with Memristor-like behavior were presented. This paper was an extended version of the study where the design of an ultra-low-voltage, ultra-low-power DTMOS-based (emulated) Memristor was presented especially for the Memristor based low frequency biomedical and chaotic applications, which was then used in a second-order SallenKey band-pass filter for EEG data processing.

3. Memristor-based Continuous-Time Analog Filter

The band pass filter forms a basic building block of a biomedical signal processing system as shown in Fig. 1. This section includes: *(i)* a brief overview of the filter topology used (Sallen-Key); *(ii)* a discussion on the previously published works on this topology, and how the existing circuits offer limited advantage; and *(iii)* the proposed band-pass filter circuit which can be employed to select pertinent frequencies for different types of physiological signals.

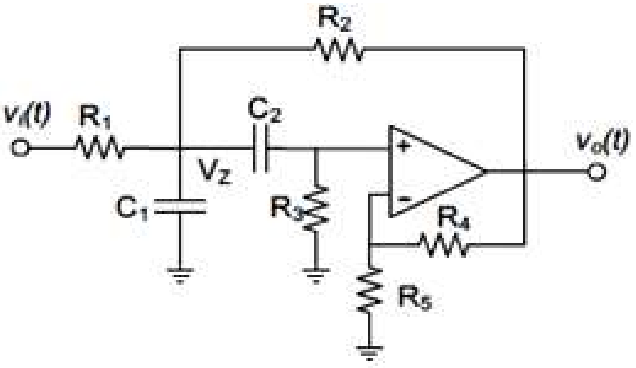


Figure 2. Traditional Sallen-Key band pass filter.

3.1. Traditional Sallen-key band-pass filter

A conventional Sallen-key band-pass filter is shown in Fig. 2. The transfer function for such a second-order band-pass filter can be expressed as

$$H(s) = \frac{\frac{1}{R_1C_1}\left(1+\frac{R_4}{R_5}\right)s}{s^2 + s\left(\frac{1}{R_1C_1}+\frac{1}{R_3C_1}+\frac{1}{R_3C_2}-\frac{R_4}{R_2R_5C_1}\right)+\frac{R_1+R_2}{R_1R_2R_3C_1C_2}} \tag{1}$$

Further, the gain can be expressed as

$$H_o = K = 1 + \frac{R_4}{R_5} \tag{2}$$

The center frequency (ω_o) and the quality factor (Q) of the are given in (3) and (4) respectively.

$$\omega_o = 2\pi f_o = \sqrt{\frac{R_1+R_2}{R_1R_2R_3C_1C_2}} \tag{3}$$

$$Q = \frac{\sqrt{\frac{R_1+R_2}{R_1R_2R_3C_1C_2}}}{\frac{1}{R_1C_1}+\frac{1}{R_3C_1}+\frac{1}{R_3C_2}-\frac{R_4}{R_2R_5C_1}} \tag{4}$$

From (2) through (4), it is evident that there is no tunability in the circuit of Fig. 2. To obtain electronic tuning of one or more filter parameters, some modifications/additions are required in the circuit.

3.2. An existing Sallen-Key BPF with gain tunability

As discussed in the previous section, Yener *et. al.* proposed a Memristor-based BPF, wherein the gain was made tunable by replacing the resistor R_5 in Fig. 2 with a Memristor as shown in Fig. 3, and demonstrated that this resulted in an electronic control over gain as becomes evident from (5) [28].

$$H_o = K = 1 + \frac{R_4}{M(q)} \tag{5}$$

However as was also mentioned in the previous section, having the gain controlled electronically by varying the Memristance is not of significance, as the signal level may be amplified at several other points in the block diagram of Fig. 1, if so required. The capability of tuning the center frequency of the band-pass filter appears to be more advantageous in the sense

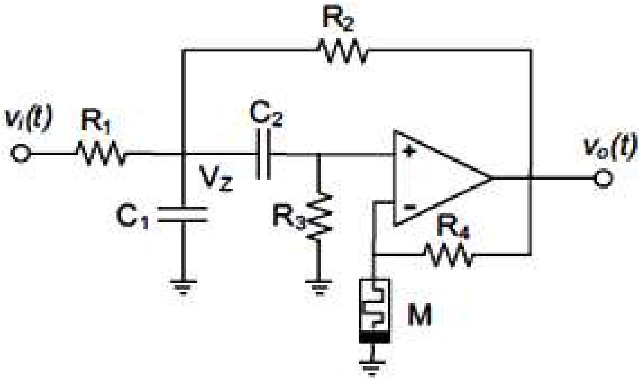


Figure 3. Memristor based Sallen-Key band pass filter proposed by Yener *et. al.* for gain control [28].

that the same filter circuit could then be used for acquisition of different physiological signals. A simple but effective technique to obtain such a tuning is presented next.

3.3. Proposed Memristor-based Sallen-Key BPF with electronic frequency tuning

The proposed Memristor-based circuit for a continuous-time analog band-pass filter with electronic frequency control is presented in Fig. 4. A comparison between the circuits of Fig. 2 and Fig. 4 leads to the fact that for the latter circuit, the center frequency of the BPF would now be governed by the Memristance $M(q)$ instead of the resistance R_3 (with the dependence on all other passive components remaining the same as in (3)). Hence, the center frequency of the proposed BPF can now be given by (6). The expression for the quality factor for the proposed filter is now given by (7). The expression for H_o remains the same as before *i.e.* as given by (2).

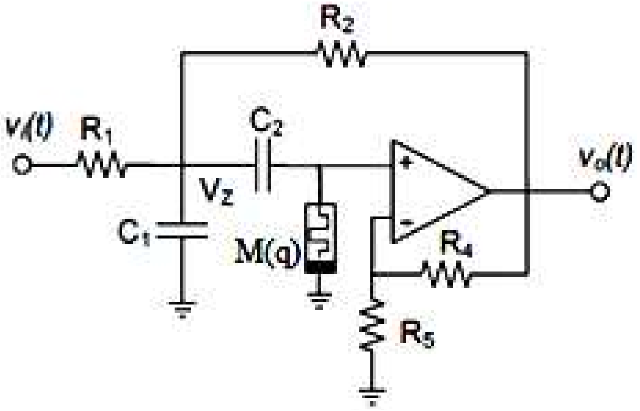


Figure 4. Proposed Memristor based Sallen-Key band-pass filter with electronic frequency tuning.

$$\omega_o = 2\pi f_o = \sqrt{\frac{R_1 + R_2}{R_1 R_2 M(q) C_1 C_2}} \tag{6}$$

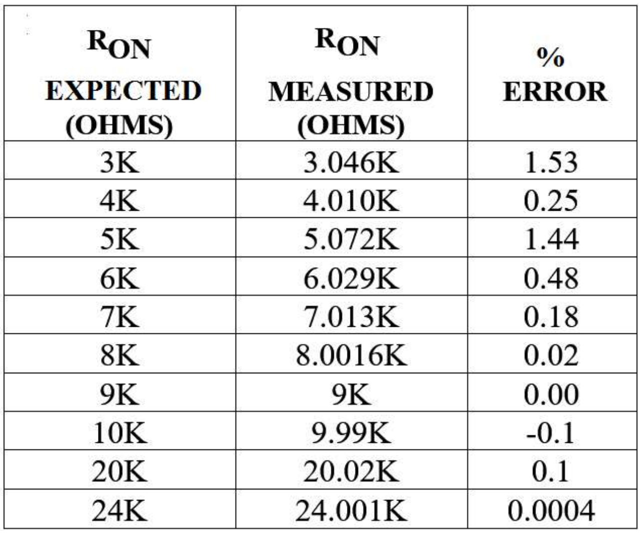
$$Q = \frac{\sqrt{\frac{R_1+R_2}{R_1 R_2 M(q) C_1 C_2}}}{\frac{1}{R_1 C_1} + \frac{1}{M(q) C_1} + \frac{1}{M(q) C_2} - \frac{R_4}{R_2 R_5 C_1}} \tag{7}$$

It can be observed from (6) that in order to tune the center frequency of the proposed filter, the Memristance $M(q)$ needs to be first set to an appropriate value using the so-called programming voltage signal. Thereafter, the input signal (to be filtered) may be applied at the input terminal of the circuit of Fig. 4. It is assumed that the input signal amplitude is several orders of magnitude smaller than the programming voltage, and therefore the value of the Memristance $M(q)$ remains unaltered on the application of the input signal.

4. Simulation Results

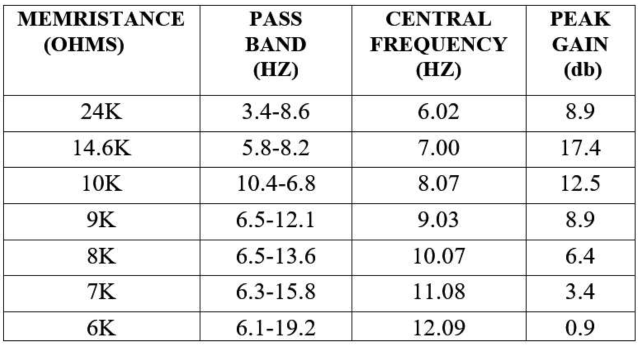
HSPICE simulations have been performed to get a performance evaluation of the proposed BPF of Fig. 4. $0.18\mu m$ TSMC models were utilized to implement the same sub-threshold DTMOS operational amplifier which was used in [28]. Variable Memristance $M(q)$ was obtained by varying the amplitude of the programming voltage applied across the Memristor. The values of expected and obtained ON resistances after programming the Memristor are listed in Table 1. The average percentage error in Memristance variation was found to be 0.04%.

Table 1. Actual and measured values of resistances for the Memristor model.



R_{ON} EXPECTED (OHMS)	R_{ON} MEASURED (OHMS)	% ERROR
3K	3.046K	1.53
4K	4.010K	0.25
5K	5.072K	1.44
6K	6.029K	0.48
7K	7.013K	0.18
8K	8.0016K	0.02
9K	9K	0.00
10K	9.99K	-0.1
20K	20.02K	0.1
24K	24.001K	0.0004

Table 2. Frequency Tuning for Different Memristance.



MEMRISTANCE (OHMS)	PASS BAND (HZ)	CENTRAL FREQUENCY (HZ)	PEAK GAIN (db)
24K	3.4-8.6	6.02	8.9
14.6K	5.8-8.2	7.00	17.4
10K	10.4-6.8	8.07	12.5
9K	6.5-12.1	9.03	8.9
8K	6.5-13.6	10.07	6.4
7K	6.3-15.8	11.08	3.4
6K	6.1-19.2	12.09	0.9

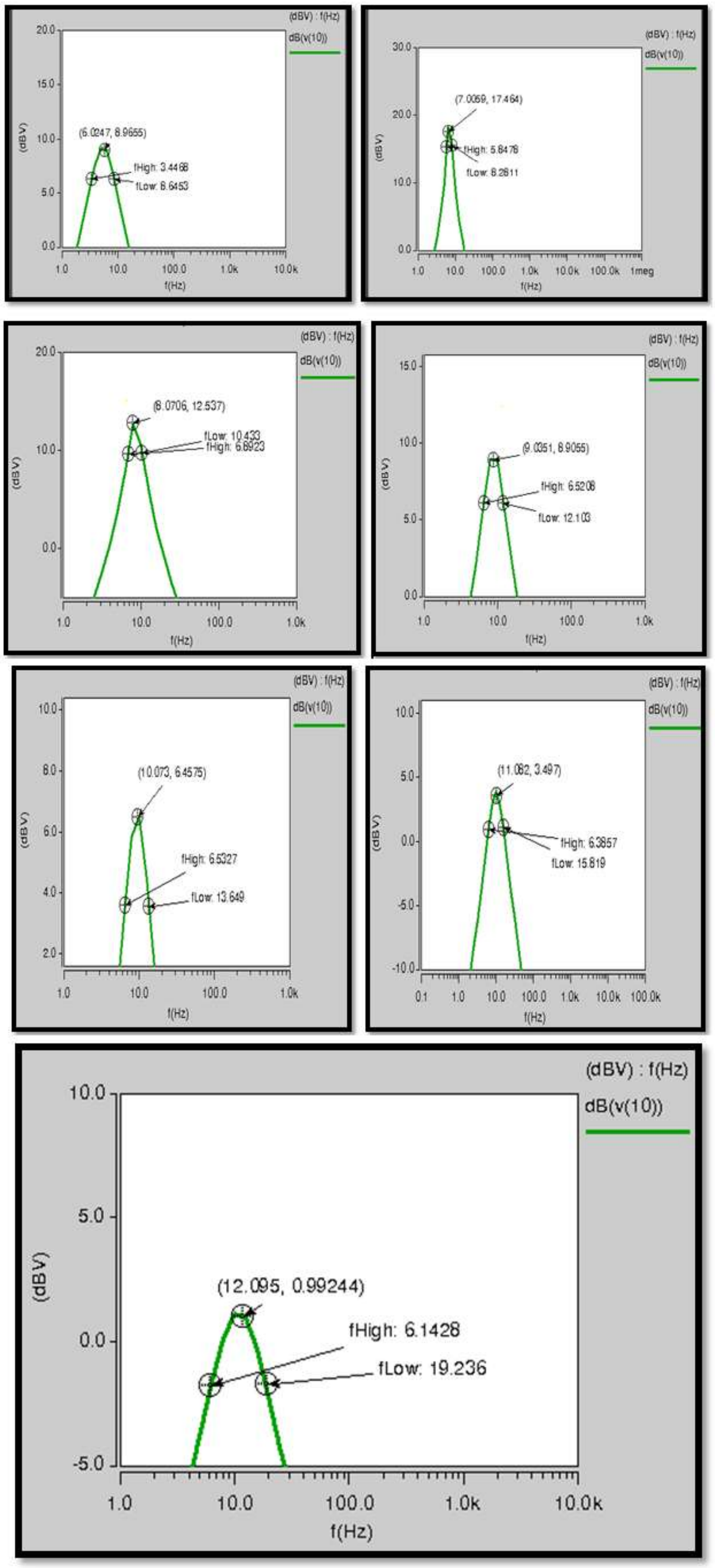


Figure 5. Simulation results for frequency tuning for the proposed bandpass filter.

The values of resistances and capacitances used during simulations were: $R_1 = 17.5\ K\Omega; R_2 = 12.4\ K\Omega; R_5 = 7.2\ K\Omega; C_1 = 2.2\ \mu F; C_2 = 2.2\ \mu F$. The Spice model for Memristor put forward by Biolek was used [[21]]. Power supplies were kept at $\pm 0.25V$.

The feature of electronic tuning of the center frequency of the proposed BPF was further tested using the HSPICE simulations. Table 2 lists the pass-bands obtained for the circuit of Fig. 4 with the Memristance $M(q)$ set to different values as mentioned in the table. The results of center frequency tuning simulations are also presented in Fig. 4. With a judicious selection of the Memristance value, the center frequency may be set as per the requirement of the physiological signal to be acquired. The estimated power consumption of the circuit as returned by HSPICE simulation software was approximately 127 nano-watts.

5. Conclusion

In this paper, we present a frequency tunable band-pass filter capable of selecting the biomedical signals which are low voltages and low frequency signals. The proposed filter designed is simulated using HSPICE wherein $0.18\mu m$ CMOS TSMC models were used during simulations along with the Biolek Spice model for Memristors. The designed circuit is found to have a pass-band range of 6hz to 16hz which can be employed in the filtering of EOG signals. The total power consumed was found to be 127 nano watts. Hence the designed circuit can efficiently be used in biomedical signal filtering due to low voltage low frequency operation with low power consumption and small size.

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