A 1.5 V, 50 nA, 100 Hz, 73 dB-DR, Subthreshold Lowpass Filter for EEG/ECG Recording

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***Abstract*—This paper presents a subthreshold lowpass biquad circuit suitable for the design of EEG/ECG Lowpass filter. The proposed circuit is designed to obtain an input referred noise of 25 µV$_{\mathrm{rms}}$ and a cutoff frequency of 100 Hz. Circuit simulations, using 0.35 micron CMOS model parameters, verify that the filter operated from a 1.5 V single supply consumes 75 nW and provides a dynamic range of 73 dB (measured from 1% total harmonic distortion) well compatible to EEG and ECG acquisition requirements.**

***Keywords*—analog filter; biomedical filter; ECG; EEG; Recordingt; gm-C; manpower.**

I. INTRODUCTION

Wearable and implantable medical devices that record physiological signals require very low-power analog front-end (AFE) interface. Typically in bio-signals AFE such as EEG and ECG require a lowpass filter (LPF) that discriminates signal in the range of a few hundreds Hz with quite high dynamic range (DR) in order to relax the front-end amplifier specifications, [1-7]. Designing an integrated LPF to meet the aforementioned requirements is thus challenging when power consumption and chip area are concerned. The LPF filter based on source-follower circuits has been implemented [8]. This type of filter contains local feedback loops that lead to good linearity in the passband without linearization. It has been designed and implemented using subthreshold CMOS devices [9] consuming only 15 nW from a supply voltage of 3 V and attains a dynamic range (DR) of 56 dB. Based on the local feedback concept of the source-follower filter mentioned above, inventing a novel transistor-level circuit architecture that operates from a lower supply voltage and having greater DR will help relax further the specification of the front-end amplifier.

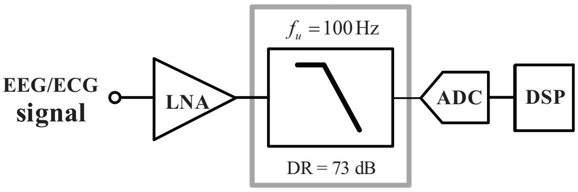

Fig. 1. Portabel EEG/ECG detection concept.

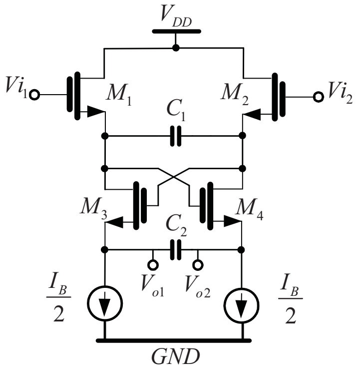

Fig. 2. Transistorized G_m-C Lowpass biquad filter [8].

Figure 1 shown an EEG/ECG detection concept. The EEG/ECG signals enlarged by a low-noise instrumentation amplifier (LNA) will enter the LPF to separate the required signal from interferences and noise. The LNA is the most power-hungry part since it needs to achieve low input-referred noise (IRN). The cutoff frequency response of the filter should be adjustable in the range of 50 to 250 Hz. If the DR of the LPF is sufficiently high, the LNA's DR can be relaxed and eventually leads to lower power consumption. In this paper, we propose a 2$^{\mathrm{nd}}$-order LPF that inherits the local feedback structure of [8] and [9] to achieve good linearity but operates from a lower supply voltage (1.5 V). The proposed filter structure employs a source-coupled differential pair as a transcoductor instead the source-follower circuit. For this reason, with acceptable additional power consumption, a two-time larger linear input voltage range is expected. The filter also achieves DR greater than the design of [9].

II. BASIC SOURCE-FOLLOWER LOWPASS BIQUAD

The transistorized source-follower based lowpass biquad is shown in Fig.2. All the transistor sizes are identical and conducting the same drain currents. Thus they are approximately having the same values of transconductance;

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$g_{m1} = g_{m2} = g_{m3} = g_{m4} = g_m$. The transfer function of the biquad filter is then given by

$$H(s) = -\frac{1}{s^2 \frac{C_1 C_2}{g_m^2} + s\frac{C_1}{g_m} + 1} \tag{1}$$

where the body effect is negligible. The second-order filter parameters extracted from (1) are:

$$\omega_o = \frac{g_m}{\sqrt{C_1 C_2}} \tag{2}$$

$$Q = \sqrt{\frac{C_2}{C_1}} \tag{3}$$

and

$$|K| = 1 \tag{4}$$

where ω_o, Q, and K are the pole frequency, the quality factor and the dc-gain, respectively.

We take this biquad structure to develop further in order to obtain a low-voltage circuit structure that is able to handle a larger input voltage for the same level of distortion. This is possible by considering the circuit in Fig. 2 as a G_m-C filter. For a MOSFET biased in subthreshold region, a differential G_m cell connected in negative feedback as shown in Fig. 3 can represents the small signal operation of a transistor [10]. Considering Figs. 2 with 3, it shows that the filter topology in Fig. 2 can be represented by a G_m-C filter topology shown in Fig. 4. In the next section, we will describe a low-voltage transistor-level circuit of this G_m-C prototype.

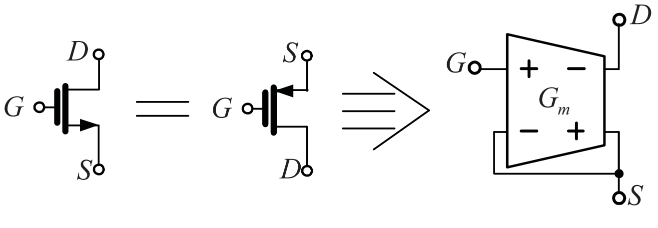

Fig. 3. Single transistor and its small-signal macro-model.

III. PREPARE YOUR PAPER BEFORE STYLING

For a PMOS source-coupled-pair (SCP) transconductor connected in negative feedback fashion shown in Fig. 5 can also be considered as a feedback transconductor of Fig. 3. Compared with the single transistor, the SCP transconductor in Fig. 5 offers 200% linear input range extension. As the transconductor is formed by two transistors, noise and mismatch are the reasonable prices to pay for. Figure 6 shows the possible realization of the proposed lowpass biquad. Transistors M_9 and M_{18} form bias circuits by means of simple current mirroring to supply dc currents I_B and $I_B/2$ to the biquad core circuit. With this bias arrangement, the total static current consumption of this circuits is $5.5I_B$.

Figure. 7 show the proposed biquad circuit with different bias arrangement that can reduce the total current consumption to be $5I_B$. Here the drain currents, of M_1 and M_4 are combined and the opposite direction of their ac components are cancelled. The resulting dc-only current can then be scaled and re-used as sinking bias current $I_B/2$.

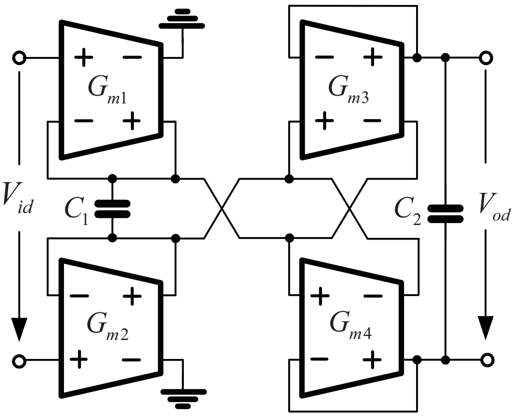

Fig. 4. The proposed lowpass filter for EEG/ECG recording.

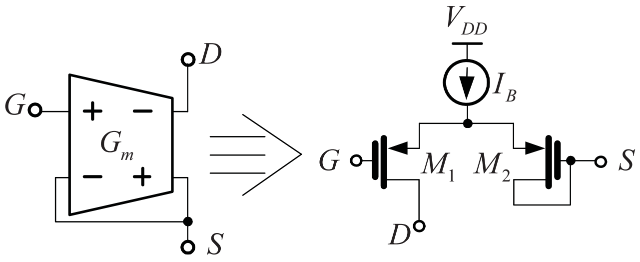

Fig. 5. Differential SCP transconductor and its macro-model.

IV. USING THE TEMPLATE

The proposed lowpass filter circuit Fig. 8 has been designed and simulated using 0.35μm AMS CMOS technology. The following results obtained from the condition shown in Table. I. Figure 8 shows the simulated magnitude of frequency response of the proposed filter. The cutoff frequency f_c is 100 Hz. The input-referred noise (IRN) density is shown in Fig. 9. Integrated over f_c, an average noise voltage of 25 μV_{rms} is obtained. Transient simulation is also performed to estimate the biquad's linearity when a sinusoidal input voltage with frequency of 100 Hz is applied. The total harmonic distortion

(THD) has been calculated and plotted in Fig. 10. A THD of 1.1% is obtained for the input amplitude of $0.125\mathrm{V_{rms}}$. According to the THD and IRN obtained from these two simulations, the proposed filter's DR equals 73 dB.

The term 'figure of merit (FoM)' that has been introduced in [11] defined by (6) is used here to compare the proposed biquad circuit with other relevant LPFs (all operated in subthreshold region). The common parameters including P, N, and f_c are the power consumption, filter order, and cutoff frequency, respectively.

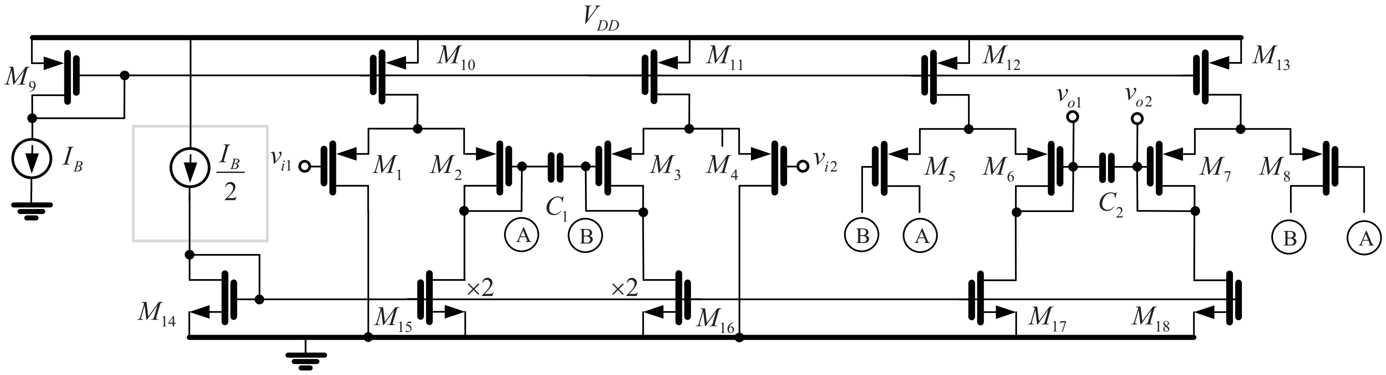

Fig. 6. The subthreshold lowpass filter for EEG/ECG recording.

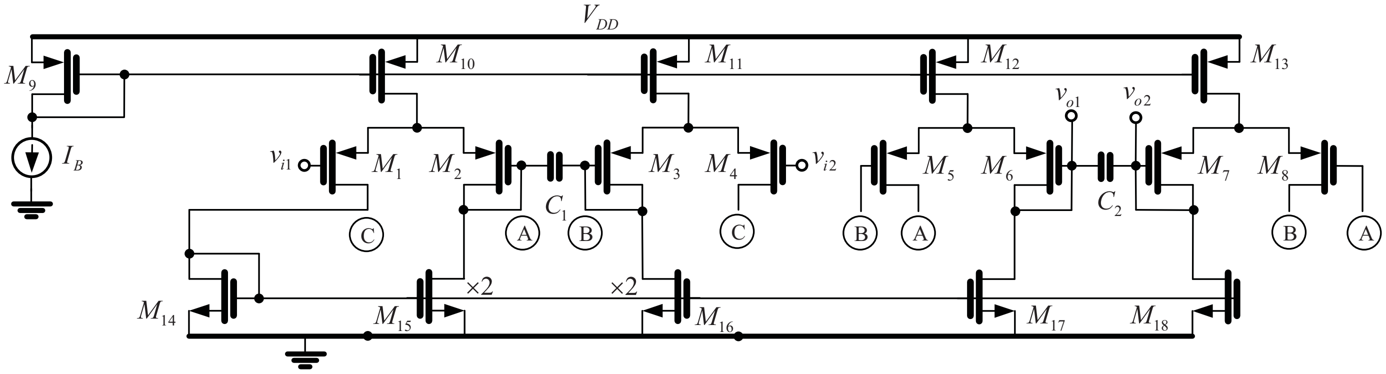

Fig. 7. The proposed subthreshold lowpass filter for EEG/ECG recording.

$$\mathrm{FoM} = \frac{P}{N \times f_c \times DR} \tag{6}$$

TABLE I. FILTER DESIGN PARAMETERS

Parameter	Value
I_B	12 nA
V_{DD}	1.5V
V_{cm}	0.5 V
C_1, C_2	80 pF, 40 pF
All CMOS	$W = L = 10$ µm,

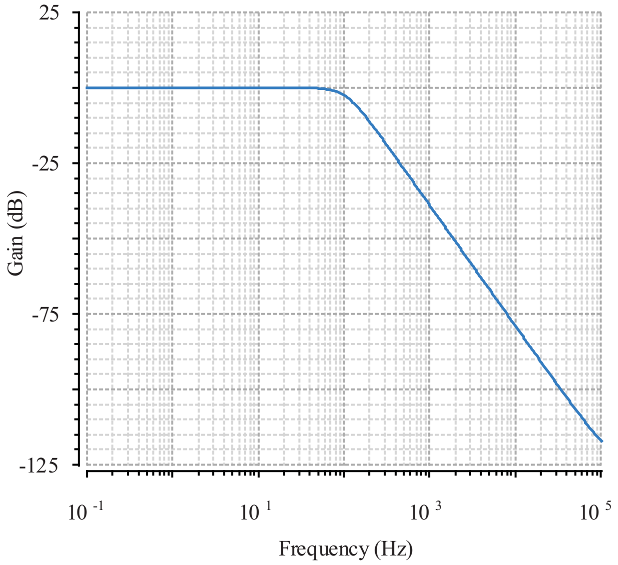

Fig. 8. Frequency response of the proposed filter.

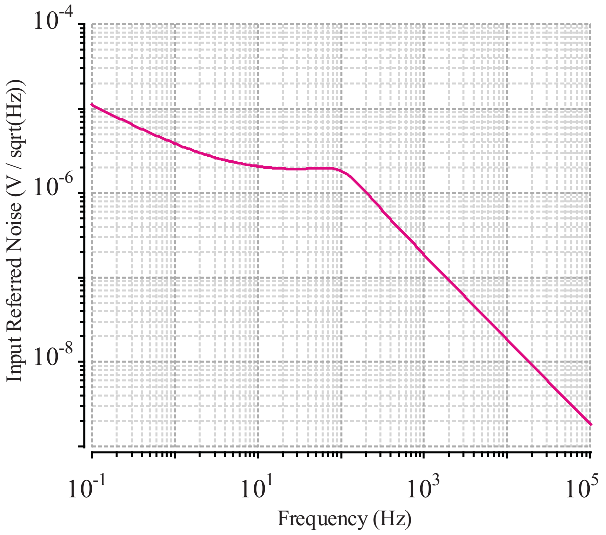

Fig. 9. Simulated input-referred noise spectrum of the proposed filter.

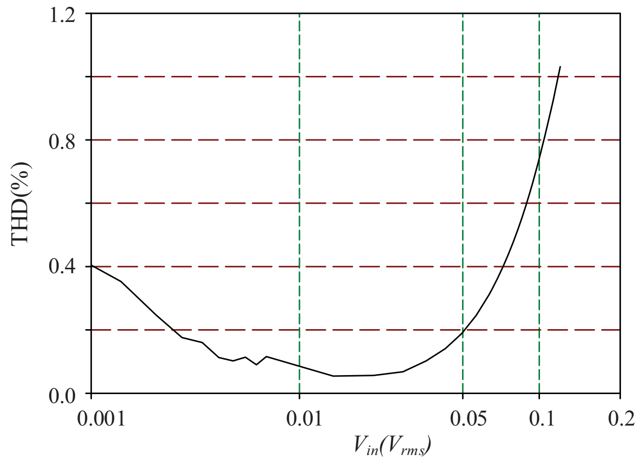

Fig. 10. Simulated THD of the proposed filter for various input amplitudes.

TABLE II. PERFORMANCE SUMMARY AND COMPARISON

Parameter	Reference				
	This work	**[4]**	**[6]**	**[7]**	**[9]**
V_{DD} (V)	1.5	0.6	1.5	0.9	3
Tech. (µm)	0.35	0.35	0.35	0.35	0.35
Order	2	4	2	4	4
f_c (Hz)	100	101	250	100	100
IRN (µV_{rms})	25	46.27	59.6	80.5	36
DR (dB)	73	47	59.6	48.2	66.7
Power (nW)	75	0.9	1.93	4.26	15
FoM (J)	5.137p	46.5a	0.052p	0.16f	0.562p

V. CONCLUSION

This paper has described a second-order lowpass filter that is constituted by four SCP transconductors. The filter core's linearity relies on local the feedback mechanism of each transconductor. It provides good linearity despite operating from a low-voltage supply. The circuit simulations of the proposed LPF with a 100 Hz cutoff frequency using 0.35µm process parameters confirm that the proposed filter can operate properly and be compatible with EEG/ECG acquisition requirements.

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