A 1V Low-Power Low-Noise Biopotential Amplifier Based on Flipped Voltage Follower

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***Abstract*— This paper presents a low-voltage low-power low-noise amplifier suitable for neural recording applications. Based on the flipped voltage follower (FVF) topology, the amplifier is able to operate under a 1V supply by alleviating the tradeoff between the noise and the voltage headroom. A gm-cell was built using FVF, its effective transconductance is not a function of the bias current, so the noise contribution of the output transistors can be decreased without increasing the bias current. This amplifier is designed and simulated in a 130 nm CMOS process. The amplifier consumes 2.2 µW from 1V supply voltage. The input referred noise is 3.7 μV_{rms}. The amplifier has a BW from 25 Hz to 9.9 kHz.**

Keywords—biopotential amplifier, low noise, low power circuit design, neural amplifier.

I. INTRODUCTION

Biopotential amplifiers are used to sense very weak signals from an electrode. The performance of the system used in neural recording depends on the performance of the amplifier because it is the very first stage of the system. The bio potential amplifier rejects the DC offset voltage developed at the electrode body interface. The signal amplitude of the extracellular action potential is up to 500 µV, with energy in the 100Hz–7kHz band [1], so the amplifier must provide low input referred noise to maintain a reasonable dynamic range. The biopotential amplifier should achieve a low power low voltage operation to minimize heat dissipation, avoiding frequent battery replacement and reduce the size of the power source.

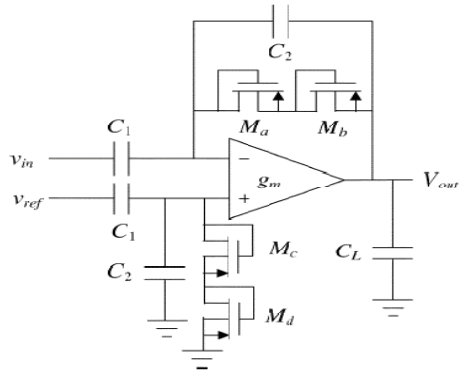

Fig. 1. Schematic of neural amplifier [1]

One of the most popular techniques used for designing biopotential amplifiers is the circuit reported in [1] as shown in Fig. 1. This technique includes the usage of capacitive coupling to reject DC offset, using $M_a - M_d$ as a pseudo-resistors with capacitive feedback around the operational transconductance amplifier (OTA) to achieve a low cut-off frequency of the high-pass filter. It uses a one-stage current mirror OTA to achieve a low noise operation by making the noise contribution of the input transistors more dominant. In fact, the aspect ratio of the output transistors should be made much smaller than that of the input transistors. However, for a certain bias current decreasing the aspect ratio of the output transistors results in increasing the overdrive voltage which decreases the available headroom. Thus, a tradeoff between the noise and the voltage headroom is required at the output. Also, decreasing the noise contribution of the output transistors can be achieved by increasing the transconductance of the input transistors but the transconductance is limited by the given bias current. To overcome this problem, the OTA contains a gm-cell with a overall transconductance Gm independent of the bias current as in [2].

In this paper, a low-voltage low-power low-noise OTA is proposed as a further enhancement of that presented in [2]. Section II introduces the proposed OTA. Section III shows the simulation results of the whole biopotential amplifier with the proposed OTA. Finally, section IV concludes the paper.

II. THE PROPOSED OTA

The proposed OTA is based on the flipped voltage follower (FVF) [3]. As shown in Fig.2, the FVF is used to build a gm-cell whose effective transconductance (Gm) is not a function of the bias current.

The current of M1, M2 is held constant equal to I_B.

$$V_{S1} = V_{in+} - V_{GS1} \ , \ V_{S2} = V_{in-} - V_{GS2} \quad (1)$$

$$V_{S1} - V_{S2} = V_{in+} - V_{in-} = v_{ind} \quad , \quad I_R = v_{ind}/R \quad (2)$$

The negative feedback adjusts I_3, I_4 as follows

$$I_3 = I_B - I_R \quad , \quad I_4 = I_B + I_R \quad (3)$$

$$i_{od} = I_4 - I_3 = 2I_R \quad (4)$$

$$G_m = \frac{i_{od}}{v_{ind}} = \frac{2}{R} \quad (5)$$

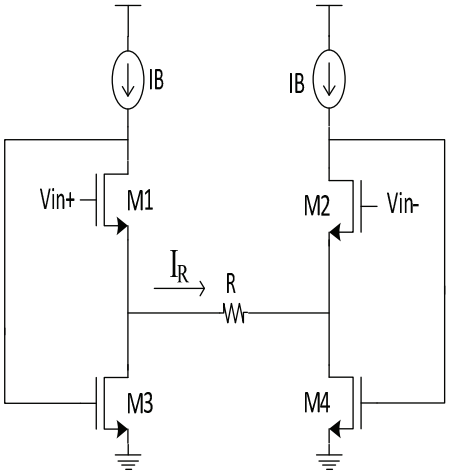

Fig. 2. A gm-cell based on FVF [3]

Fig. 3 shows the proposed OTA where the output current of the gm-cell is converted to a single ended output by M5-M8. The level shifter is a common drain voltage follower as shown in Fig. 4, it consumes 0.1 µA. It is used to ensure that the input transistors operate in the saturation mode.

The input referred noise can be given by

$$\overline{V_{n.in}^2} = 4KT\left[\frac{4}{3g_{m1}} + R + \frac{2}{3}\frac{4g_{m3}+2g_{m7}}{G_m^2} + \frac{4}{3}g_{m9}\left(\frac{1}{g_{m1}}+\frac{R}{2}\right)^2\right] \quad (6)$$

$$\overline{V_{n.in}^2} \approx \frac{16KT}{3g_{m1}}\left[1+\frac{g_{m9}}{g_{m1}}\right] + \frac{16KT}{3G_m}\left[\frac{2g_{m3}+g_{m7}}{G_m}\right] \quad (7)$$

The noise contribution from the transistors M3-M8 can be extremely reduced by increasing Gm (decreasing R). There is no need to decrease the aspect ratio of the output transistors, so the tradeoff between the noise and the voltage headroom is eliminated. The overdrive voltage of the output transistors is kept under 50mV, which allows a rail to rail operation. The noise contribution of the level shifter transistors can be neglected because its input referred noise is proportional to g_{mL}/G_m where g_{mL} is the transconductance of the level shifter transistor. The only two transistors that is needed to decrease their aspect ratios are M9 and M10 because their input referred noise is proportional to g_{m9}/g_{m1}, but their overdrive voltage will not affect the available headroom at the output.

The proposed OTA is similar in concept to the circuit reported in [2]. In fact, the input transistors operate in saturation mode, [2] used a topology with four transistors as current sources, which increase the input referred noise. In the proposed OTA, only two transistors are used for biasing; namely M9 and M10, which leads to a lower overall noise while maintaining low-voltage operation.

III. SIMULATION RESULTS OF THE BIOPOTENTIAL AMPLIFIER

The amplifier shown in Fig. 1 using the proposed OTA shown in Fig. 3 is designed and simulated in a 130 nm CMOS process. The mid-band gain $A_m = C_1/C_2$ is 39.7dB. The high pass cutoff frequency $f_{hp} = 1/2\pi R_{eq}C_2$ is 25 Hz. The low pass cutoff frequency $f_{lp} = G_m/2\pi A_m C_L$ is 9.9 kHz. Where R_{eq} is the equivalent resistance of the pseudo-resistors, G_m is the equivalent transconductance of the OTA. Fig. 5 shows the frequency response of the amplifier.

Table I shows the dc operating points and the dimensions of the transistors used in the OTA. The total current consumption is 2.2µA from a 1V supply, which means the power consumption is 2.2µW.

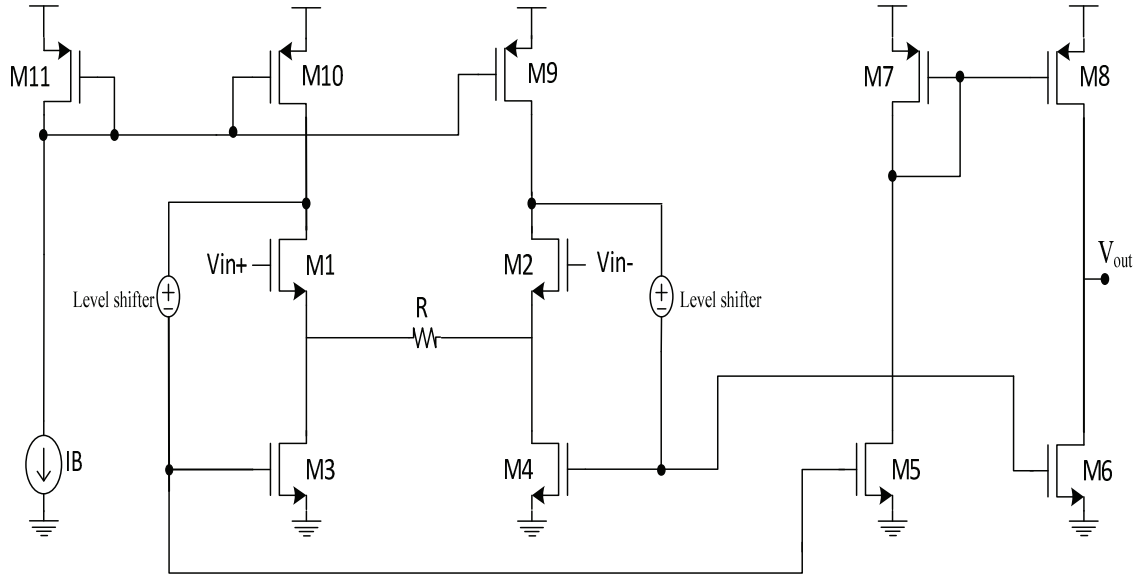

Fig. 3. The proposed OTA

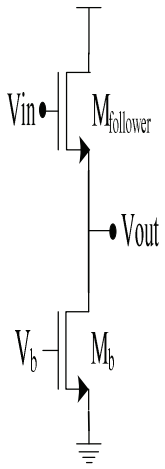

Fig. 4. Level shifter

TABLE I.

DEVICES GEOMETRY AND DC BIAS CURRENT FOR OTA

Devices	W/L(μm)	I_D(μA)
M1,M2	300/1.5	0.5
M3, M4, M5, M6	2/4	0.5
M7, M8	4/2	0.5
M9, M10, M11	2/40	0.5
M_b, $M_{follower}$	1/8	0.1

Fig. 6 shows the simulated input-referred voltage noise spectrum. The thermal noise level is 29 nV/√Hz and the noise corner occurs around a few hundred Hz. Integration of the output voltage noise from 0.1 Hz to 100 kHz then dividing the result over the amplifier mid-band gain yields an input referred noise voltage of 3.7 μVrms.

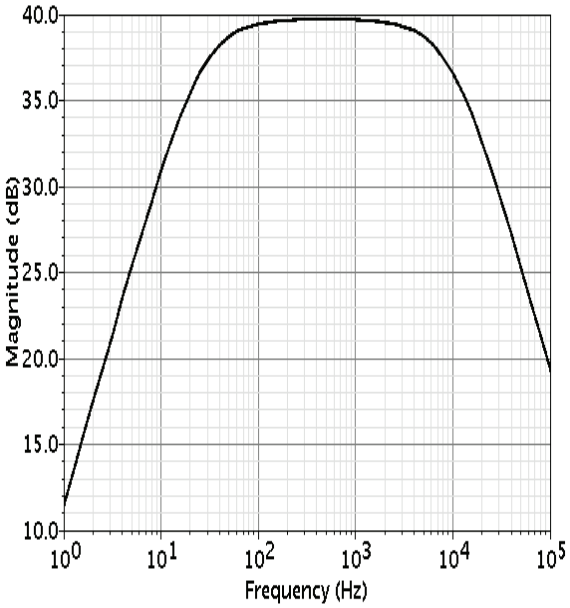

Fig. 5. The frequency response of the amplifier.

The noise efficiency factor (NEF) is used as a figure of merit to compare the noise and power performance with other amplifiers [4].

$$NEF = V_{ni,rms}\sqrt{\frac{2I_{tot}}{\pi.V_T.4kT.BW}} \quad (8)$$

where $V_{ni,rms}$ is the input referred rms noise voltage, I_{tot} is the total amplifier supply current, and BW is the amplifier bandwidth. The proposed OTA achieves NEF of 2.13.

Table II compares this amplifier with previous reported amplifiers. All of these amplifiers in the table use the same topology shown in Fig. 1 to reject DC offset, except [5] which uses active low frequency suppression. The proposed amplifier achieves a low input referred voltage noise with a low power consumption and can operate under 1V power supply with rail to rail output swing, it achieves the lowest NEF.

TABLE II. PERFORMANCE COMPARISON OF BIOPOTENTIAL AMPLIFIERS

		BW (Hz)	Gain (dB)	NEF	$V_{in,rms}$ (μV)	Supply (V)	Power (μW)	Tech. (μm)
Harrison 2003	[1]	0.025-7.2k	39.5	4	2.2	5	80	1.5
Wu 2006	[2]	0.003-245	40.2	3.8	2.7	1	2.3	0.35
Wattanapanitch 2007	[6]	45-5.3k	40.9	2.7	3.1	2.8	7.56	0.5
Gosselin 2007	[5]	105-9.2kHz	52	4.9	5.6	1.8	8.6	0.18
Rezaee 2011	[7]	300-10k	57.5	3	2.4	1.8	20.8	0.18
Majidzadeh 2011	[8]	10-7.2k	39.4	3.35	3.5	1.8	7.92	0.18
Qian 2011	[9]	0.36-1.3k	39.4	3.09	3.07	2.8	2.4	0.13
Zhang2012	[10]	0.05-10.5k	40	2.9	2.2	1	12.1	0.13
This work 2015		25-9.9k	39.7	2.13	3.7	1	2.2	0.13

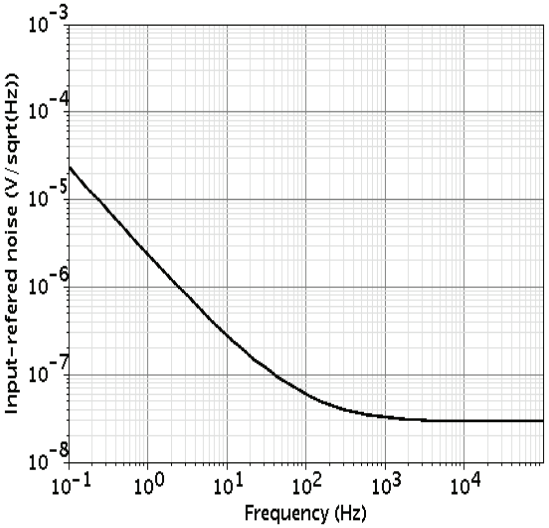

Fig. 6. The input-referred voltage noise spectrum

The total harmonic distortion (THD) of the amplifier stays below 1% for input signals smaller than 6mV peak to peak. Hence, the amplifier achieves a dynamic range of about 55 dB.

IV. CONCLUSION

The flipped voltage follower cell is used to build a gm-cell with effective transconductance Gm independent of the bias current. Using this gm-cell a low-voltage low-power low-noise amplifier suitable for neural recording has been designed. The amplifier has an input referred voltage noise of 3.7 μV_{rms}. It consumes 2.2 μW. it is able to operate at 1V supply voltage. Its bandwidth is 25-9.9k Hz. The NEF is 2.13.

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