0.13-µm CMOS Tunable Transconductor Based on the Body-Driven Gain Boosting Technique with Application in Gm-C Filters

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***Abstract*— We present a low-voltage low-power CMOS tunable transconductor exploiting body gain boosting to increase the small-signal output resistance. As a distinctive feature, the proposed scheme allows the OTA transconductance to be tuned via the current biasing the gain-boosting circuit. The proposed transconductor has been designed in a 0.13-µm CMOS technology and powered from a 1.2-V supply. To show a possible application, a 0.5-MHz tunable third order Chebyshev low pass filter suitable for the Ultra Low Power Bluetooth Standard has been designed. The filter simulations show that all the requirements of the chosen standard are met, with good performance in terms of linearity, noise and power consumption.**

***Keywords*-Transconductor; filter; body-driven; CMOS; Gm-C filters; gain boosting.**

I. Introduction

High-performance Transconductors (OTAs) offering, as main features, linear and tunable transconductance with wide frequency bandwidth and high output resistance, are key elements in the design of continuous-time integrated filters adopting the Gm-C (or OTA-C) approach. Moreover, the increasing number of portable electronic applications requires circuits with ultra low-power capabilities. While frequency operation and power consumption issues are addressed by adopting low-threshold deep-submicron CMOS technologies, other performance parameters like linearity and output resistance result to be severely degraded by the same technologies [1]. More specifically, the maximum achievable small-signal output resistance of a nanometer MOS device is becoming unsatisfactorily low as it falls in the range of a few kilohms. Cascoding techniques are customarily adopted to face this problem, however standard cascoding approaches increase the supply voltage demand for a given output voltage swing to an extent that the advantage of using the advanced technology is almost lost.

To achieve very low voltage operation, approaches that exploit the MOS body terminal have been investigated until recently [2]-[9]. In this context, a gain boosted technique that exploits the body of the auxiliary gain-boosting transistor as input terminal was discussed in [10]. Compared to the standard low-voltage cascode approach, the body-driven one reduces the minimum supply requirement by two thresholds in a rail-to-rail structure adopting two complementary n-channel and p-channel sections [10].

In this paper, we will exploit this body-driven gain-boosting approach to design a low-voltage OTA whose tunability is achieved by varying the current that biases the gain boosting auxiliary circuit. No similar technique has been presented in the literature to the knowledge of the authors. The OTA is then used in the implementation of a third-order low-pass channel filter for a receiver based on the Ultra Low Power (ULP) Bluetooth Standard [11]. The OTA and the whole filter are designed in a 0.13-µm technology powered from a 1.2-V supply and simulated performances meet the stringent specifications of the chosen standard.

II. Body-Driven Gain-Boosted OTA

The basic transconductor that will be used for reference in the design of the Bluetooth filter is depicted in Fig. 1a. It is a conventional pseudo differential cascode topology in which transistors M_1 (left and right side) are kept in their triode region (through V_{CN} and M_2). Transistors M_2-M_4 are in saturation. Voltage V_{CTRL} is generated by the common-mode feedback circuit (described later) and sets the branch current through bias current generators M_4. Unfortunately, this simple OTA provides an unacceptable low output resistance since it is dominated by $g_{m2}r_{d2}r_{d1}$, where r_{d1} is that of a triode-biased MOS. This low output resistance, coupled with the filter integrating capacitor, will severely impair the ultimate filter frequency performance.

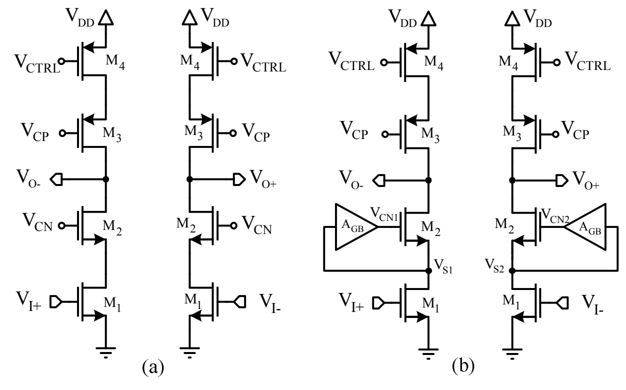

Figure 1. Basic pseudo-differential cascode OTA: (a) simple and (b) gain-boosted.

The gain-boosting technique [12] allows increasing the resistance seen at the drain of the cascode transistors. If A is the gain of the (inverting) auxiliary amplifier in Fig. 1b, then the output resistance of each terminal is given by

$$r_{out} = A g_{m2} r_{d2} r_{d1} \,//\, g_{m3} r_{d3} r_{d4} \tag{1}$$

Hence, the gain A allows compensating for the low value of r_{d1}. Besides, linearity is improved since the drain of the triode-biased transistor is kept to a nearly constant voltage irrespectively of the flowing current. At this purpose, the higher is the gain A, the higher is the linearity obtained. Of course, the bandwidth of the auxiliary amplifier must be higher than that of the main OTA for effective operation.

The auxiliary amplifier cannot be implemented with a conventional gate-driven transistor as it will unacceptably reduce the maximum signal swing. The body driven amplifier stage depicted in Fig. 2b can be profitably used to implement the auxiliary amplifiers in Fig. 1.

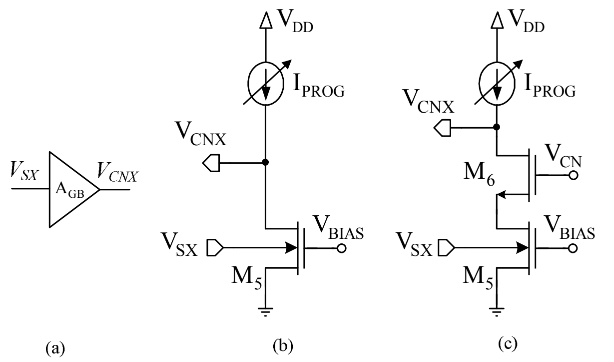

Figure 2. Body-driven amplifier stage (a) symbol (b) simple and (c) cascoded.

The gain of this stage is given by the source-bulk transconductance, g_{mb}, times the output resistance. Since the g_{mb} is lower than the gate transconductance, we can increase the dc gain by cascoding the body-driven transistor (and of course also the bias current generator, I_{PROG}). This option is illustrated in Fig. 2c. Both configurations need a bias voltages V_{BIAS} (V_{CN} is not critical) that is obtained through a suitable auxiliary circuit.

The complete scheme for the proposed pseudo-differential OTA is shown in Fig. 3. This figure includes the common-mode feedforward (CMFF) circuit required to set the common-mode current and a common-mode feedback circuit (CMFB) to fix the common-mode output voltage [13]-[14]. The CMFB circuit is composed of a branch similar to the CMFF circuit. The novel scheme proposed for the implementation of CMFF and CMFB performs a comparison of current to provide the control voltage V_{CTRL}. As node V_{CTRL} is a high impedance node, two Miller compensation capacitances are needed between node V_{CTRL} and the transconductor outputs (Vo+ and Vo-) in order to guarantee the OTA stability. Moreover, the active load formed by transistors M_3 and M_4 is a voltage-controlled current source that ensures high output impedance.

Linear voltage to current conversion is achieved by applying the input voltage to the gate of the triode-operated transistor M_1 whereas remaining transistors are in saturation. Input transistors are kept in triode region by means of a regulated-cascode topology whose feedback loop is made by the body-driven amplifier stage.

The programmability of the OTA is performed by the drain to source voltage V_{DS1}. Voltage V_{DS1} can be set by two parameters of the gain boosting amplifier: the current generator I_{PROG} and the biasing voltage V_{BIAS}. In this design we have selected the first option as voltage V_{BIAS} should be kept controlled in order to avoid forward biasing of the bulk junction. V_{BIAS} can be obtained through replica-bias circuitry.

An approximate expression for the large-signal drain current of the input transistors operating in strong inversion and the ohmic region is given by:

$$I_{D1} = \beta_1 \left[\left(V_{GS1} - V_{TN} \right) \cdot V_{DS1} - \frac{V_{DS1}^2}{2} \right] \tag{2}$$

where $\beta_1 = \mu_n C_{ox}(W/L)_{M1}$ is the transconductance factor of transistor M_1, and V_{GS1} is the input voltage V_i formed by the applied ac signal v_{in} superimposed to a common-mode voltage $V_{i,CM}$. The linear dependence of the transconductance on the control voltage is expressed as:

$$G_m = I_{out} / V_{id} = \beta_1 \cdot V_{DS1} \tag{3}$$

This ideal assumption is degraded in modern small geometry technologies. Large-channel input transistors have been used to reduce this effect.

III. CHANNEL FILTER OF THE ULP BLUETOOTH RECEIVER

The filter specifications for the channel filter of the receiver fulfilling the ULP Bluetooth Standard are summarized in the Table I.

TABLE I. FILTER SPECIFICATIONS FOR ULP BLUETOOTH

Specification	Value
Maximum peak to peak input voltage	140 mVpp
Maximum peak to peak output voltage	446 mVpp
Nominal current (under 1.2V supply)	250 µA
Inband gain	10 dB
Cut-off frequency	500 kHz
Attenuation at 1 MHz (0 dB reference)	> 15 dB
Attenuation at 3 MHz (0 dB reference)	> 45 dB
Noise figure	< 40 dB
THD (in the bandpass and Vin= 140mVpp)	< −40 dB

In order to satisfy the attenuation constraints, a third order Chebyshev filter was found to be enough. The block diagram of the filter is shown in Fig. 4.

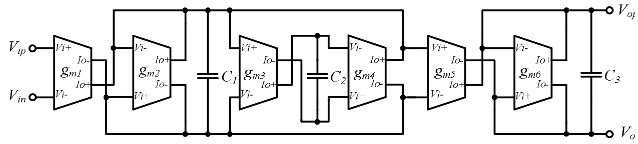

Figure 4. Third order Chebyshev low pass filter block diagram.

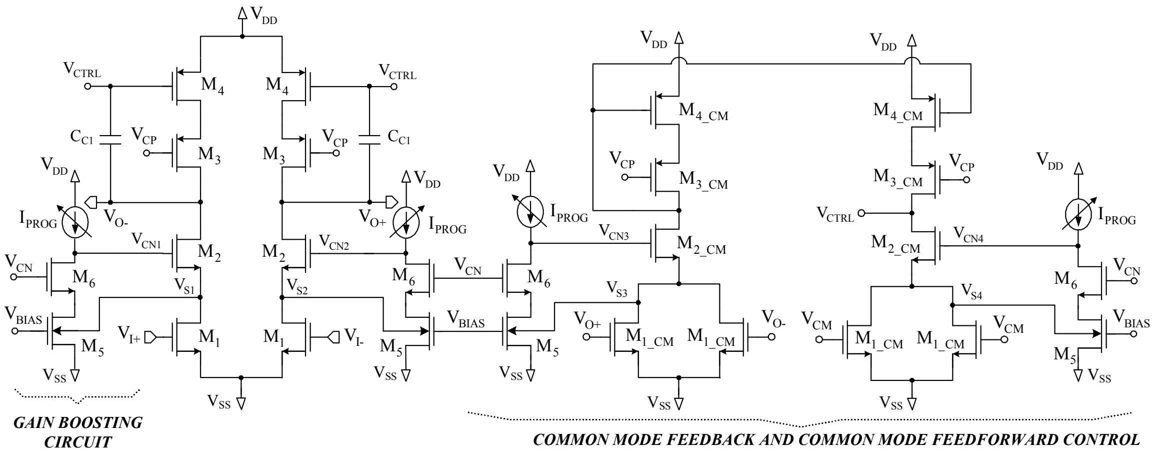

Figure 3. Complete scheme of the OTA.

The transfer function of this filter is reported in (4):

$$H(s)=\frac{2.219\cdot 10^{19}}{s^3+3.936\cdot 10^6\cdot s^2+1.515\cdot 10^{13}\cdot s+2.219\cdot 10^{19}}=\frac{1.128\cdot 10^{13}}{s^2+1.968\cdot 10^6\cdot s+1.128\cdot 10^{13}}\cdot\frac{1.968\cdot 10^6}{s+1.968\cdot 10^6} \tag{4}$$

IV. Design and Simulations

The OTA shown in Fig.1b, with the auxiliary amplifier in Fig. 2c and the bias and common-mode circuits (in Fig. 3) was designed in a 0.13-μm CMOS technology supplied with 1.2 V. Transistor dimensions are summarized in Table II. The compensation capacitances values are 300 fF.

TABLE II. OTA DESIGN SETTINGS AND TRANSISTOR DIMENSIONS

Transistor	W/L (μm/μm)
M_1	0.8μ/2.4μ
M_2	0.4μ/0.4μ
M_3	9μ/0.4μ
M_4	24μ/1.6μ
M_5	8μ/2.4μ
M_6	2μ/0.26μ
M_{1_CM}	0.2μ/2.4μ
M_{2_CM}	0.2μ/0.4μ
M_{3_CM}	4.5μ/0.4μ
M_{4_CM}	12μ/1.6μ

The linear performance of the OTA is given by the input voltage range for which the transconductance is constant. Fig. 5 illustrates the simulated dc transfer characteristic of the differential output current (I_{od}) versus the differential input voltage (V_{id}) for the tuning interval from I_{PROG} = 18.5 μA to 20.5 μA. For this tuning interval, the transconductance (dI_{od}/dV_{id}) ranges from 24 μA/V to 34 μA/V. Note the good linearity obtained in the tuning range for an input voltage range from -300 mV to +300 mV.

The main OTA performance parameters are summarized in Table III, first column (OTA1). The other two columns report for comparison the performance of the gain-boosted OTA using the auxiliary amplifier circuit in Fig. 2b (OTA2) and of the simple non gain-boosted OTA in Fig. 1a (OTA3).

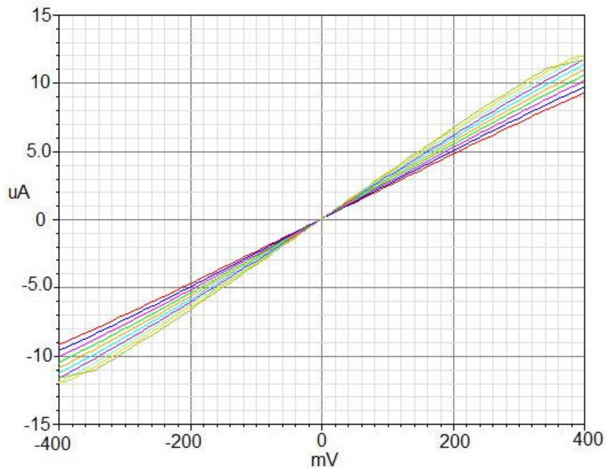

Figure 5. Programmability range for the proposed OTA. Differential output current versus differential input voltage.

TABLE III. MAIN OTA PERFORMANCE

Parameter	OTA1	OTA2	OTA3
G_m (μA/V)	27.4	26.9	22.2
R_{out} (MΩ)	54.4	15.2	1.84
THD @ 446mVpp, 100kHz	–52.7	–52.2	–44.5
NF @500kHz (dB)	42	42	39.8
Current consumption (μA)	101	103.5	24.7

It is apparent that the first OTA is superior in terms of output resistance and linearity obtained with a limited increase in current consumption. Hence, this OTA was used in the design of the filter. Table IV summarizes the transconductance and capacitor values adopted for the filter design.

TABLE IV. FILTER TRANSCONDUCTANCES AND CAPACITORS

Parameters	Values
G_{M1}	87 μA/V
G_{M2}	29 μA/V
G_{M3}	29 μA/V
G_{M4}	29 μA/V
G_{M5}	29 μA/V
G_{M6}	29 μA/V
C_1	7.37 pF
C_2	2.53 pF
C_3	7.37 pF

Fig. 6 illustrates the simulated frequency response at the nominal frequency of 0.5 MHz. The cut-off frequency can be tuned from 436 kHz to 594 kHz. A detail around the cut-off frequency has been also included. Fig. 7 shows the simulated output spectrum for a 100-kHz input signal of 140 mV peak-to-peak amplitude. We obtain −49 dB of THD for the nominal transconductance at $I_{PROG} = 19.1$ µA.

The main filter performance is summarized in Table V. ULP Bluetooth specifications are met.

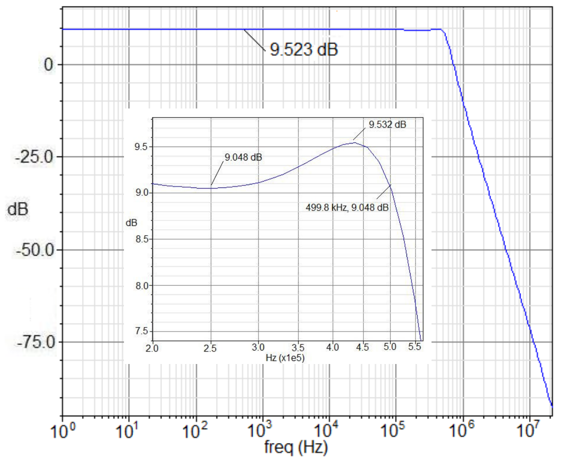

Fig. 6. Filter frequency response magnitude for an I_{PROG}= 19.1 µA

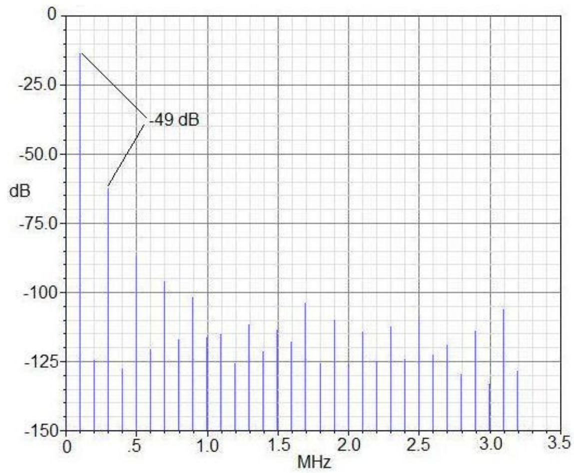

Fig. 7. Total harmonic distortion of the filter for a 70mVp input signal with a tone located at 100 kHz.

TABLE V. MAIN FILTER PERFORMANCE

Parameter	Value
Gain	9.52 – 9.5 dB
Cut-off frequency	436 – 594.3 kHz
Tunability current	18.3 – 20.5 µA
Noise figure	42 – 37 dB
Vin	140 mVpp
Maximum output voltage	414.8 – 418 mVpp
THD@100kHz for Vo	51.3 – 46.8 dB

V. CONCLUSIONS

We presented a gain boosting scheme based on bulk-driven transistors. This technique was exploited to design a linear pseudo-differential transconductor. The solution allows inherently to control the common-mode output voltage and provide tuning through the bias current of the boosting circuit. The properties of the transconductor make it very attractive for linear applications, especially at low supply voltages. In order to validate and find an application for the proposed 1.2-V 0.13-µm CMOS transconductor, a Gm-C filter for ULP Bluetooth applications has been implemented. Simulations results show that the filter meets the stringent standard specifications.

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