Tunable Class AB CMOS Gm-C Channel Filter for a Bluetooth Zero-IF Receiver

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***Abstract*— A novel tunable third order low-pass Gm-C filter is introduced. Programmable transconductors operating in class AB have been used for its implementation hence featuring low quiescent power consumption. The operation in class AB is achieved using quasi-floating gate transistors. This filter is suitable for channel filtering of highly integrated, ultra low power wireless receivers e.g. for Bluetooth and Zigbee. Measurement results for a test chip prototype in a low-cost 0.5µm standard CMOS process are presented.**

***Index Terms*—Transconductor, linear OTA, class AB circuits, analog CMOS circuits, analog integrated circuits.**

I. INTRODUCTION

CHANNEL filtering is required in receivers in order to separate the desired signal from other undesired signals, interferences, and out-of-band noise. It is usually carried out by a continuous-time band-pass filter if the Intermediate Frequency (IF) of the receiver is not zero, or a continuous-time low-pass filter in direct conversion receivers (having zero IF). Current trend in wireless receivers is toward solutions featuring high integration density and low power consumption. To achieve these requirements active filter implementations are used. However, large interferers near the desired signal demand high linearity, which is often difficult to achieve together with low area and low power consumption. While usually active-RC filters were employed due to their high linearity, now transconductance-C (Gm-C) topologies have been proposed [1]. Due to their open-loop operation, Gm-C filters usually achieve lower power consumption for a given bandwidth, but they also feature less linearity. In order to solve this limitation, the basic trend is designing the transconductors by going back to the classic approach to achieve highly linear circuits, i.e., using feedback and passive resistors, providing a highly linear *V-I* conversion.

A disadvantage of conventional Gm-C filters is that transconductors usually operate in class A, which makes that the maximum current they can provide is limited by the bias current increasing. This leads to relatively high quiescent power consumption.

In this paper we propose a novel Gm-C filter which uses a transconductor suitable to the demands in terms of linearity and power consumption of channel filters in highly integrated low power receivers. It achieves high linearity by the use of a passive resistor for voltage-to-current conversion and the use of negative feedback in the voltage followers that translate the input voltage to the resistor terminals. Besides, the transconductor operates in class AB, which means that the maximum current is not limited by the bias current. This allows low quiescent power consumption without degrading dynamic performance. Moreover, its transconductance tunability allows guaranteeing that the cut-off frequency and the quality factor of the filter will have the desired value. The filter has been designed and implemented in a 0.5µm CMOS technology, and measurement results are presented. The paper is organized as follows: Section II describes the voltage follower employed in the transconductor, which is presented in section III. In section IV the third order low-pass filter is explained. Measurement results of a test chip prototype are presented in Section V. Finally, some conclusions are given in Section VI.

II. VOLTAGE FOLLOWER

The proposed voltage follower structure used in the transconductor is shown in Fig. 1. Transfer of the input voltage from the input terminal Y to the low-impedance terminal X is very accurate since a high-gain negative feedback loop is employed, which is formed by the source follower M1 with negative feedback provided by transistor M2. This feedback loop improves accuracy in the voltage transfer as it allows transistor M1 to carry a constant current I_B, as opposed to conventional source followers where the drain current is dependent on the input voltage. Hence the gate-to-source voltage of M1, V_{GS1}, is also constant neglecting body effect and channel-length modulation [2].

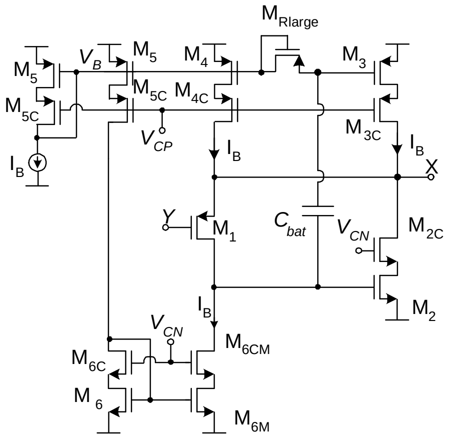

Fig. 1. Proposed class AB Voltage Follower using QFG techniques

Class AB operation has been achieved just by adding a floating capacitor and a large resistance R_{large} implemented by a minimum-size diode-connected MOS transistor M_{Rlarge} in cutoff region, whose common terminal is the gate of transistor M3. Hence, as its gate is weakly connected in dc to the bias voltage V_B through a large resistance, M3 becomes a "quasi-floating gate" (QFG) transistor [3].

The operation of the circuit is as follows. During quiescent operation, the capacitor C_{bat} has no effect and the voltage at the gate of M3 is V_B as no current flows through the resistor. Therefore, quiescent currents and voltages, and thus quiescent power consumption, are the same as those of the equivalent circuit operating in class A.

However, when a positive input voltage is applied to terminal Y, a negative voltage swing appears at the gate of M2. This negative voltage swing is translated to the gate of M3, as the floating capacitor cannot be rapidly discharged through R_{large}. This capacitor acts as a floating battery. The negative voltage swing allows M3 to provide a large current to the output, which is not limited by the bias current. Hence the circuit operates in class AB and can have high current driving capability and, at the same time, very low quiescent power consumption.

It must be mentioned that R_{large} and C_{bat} form a first-order high-pass filter from the gate of M2 to the gate of M3. Hence the DC level and frequency components below $1/(2\pi R_{large}C_{bat})$ in the gate voltage of M2 are not transferred. Due to the very large value of $R_{large}C_{bat}$ employed, this cutoff frequency is in practice below 1 Hz.

III. TRANSCONDUCTOR

The design of the transconductor employed is shown in Fig. 2. It employs two second-generation current conveyors (CCIIs) [4], whose voltage follower is the one already explained and its current follower is a simple current mirror, and two passive resistors in series. The CCIIs transfer the differential input voltage to the resistor terminals, thus yielding V-I conversion. Then current at terminals X is conveyed to the high-impedance output terminals Z.

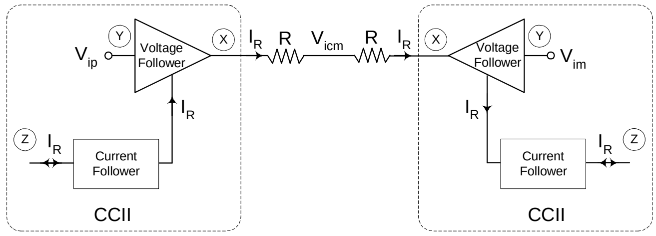

Fig. 2. CCII-based transconductor with high input resistance

While the advantage of this scheme is its high input resistance, the main disadvantage is that the voltage follower must process rail-to-rail input signals to achieve rail-to-rail operation. Common-mode input voltage V_{icm} is sensed by the matched resistors and hence it can be used for output common-mode control of the driving stage. Fig. 3 shows the implementation of the proposed transconductor.

However, continuous transconductance tuning is needed for the Gm-C filter to feature continuous tuning. The tuning method employed is the one shown in Fig. 4 [5].

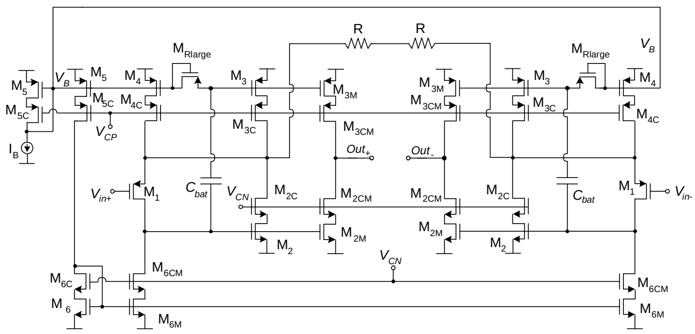

Fig. 3. Differential transconductor operating in class AB

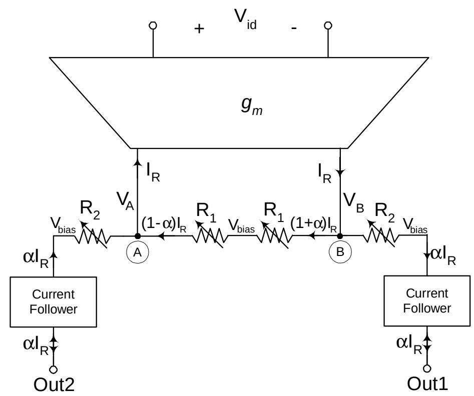

Fig. 4. Current-division tuning method

According to it, the current generated in the V-I conversion suffers an attenuation due to the resistive divider. As a result, the current that goes through the current followers, αI_R, is less than the total amount of current obtained from the V-I conversion, I_R. The value of α is:

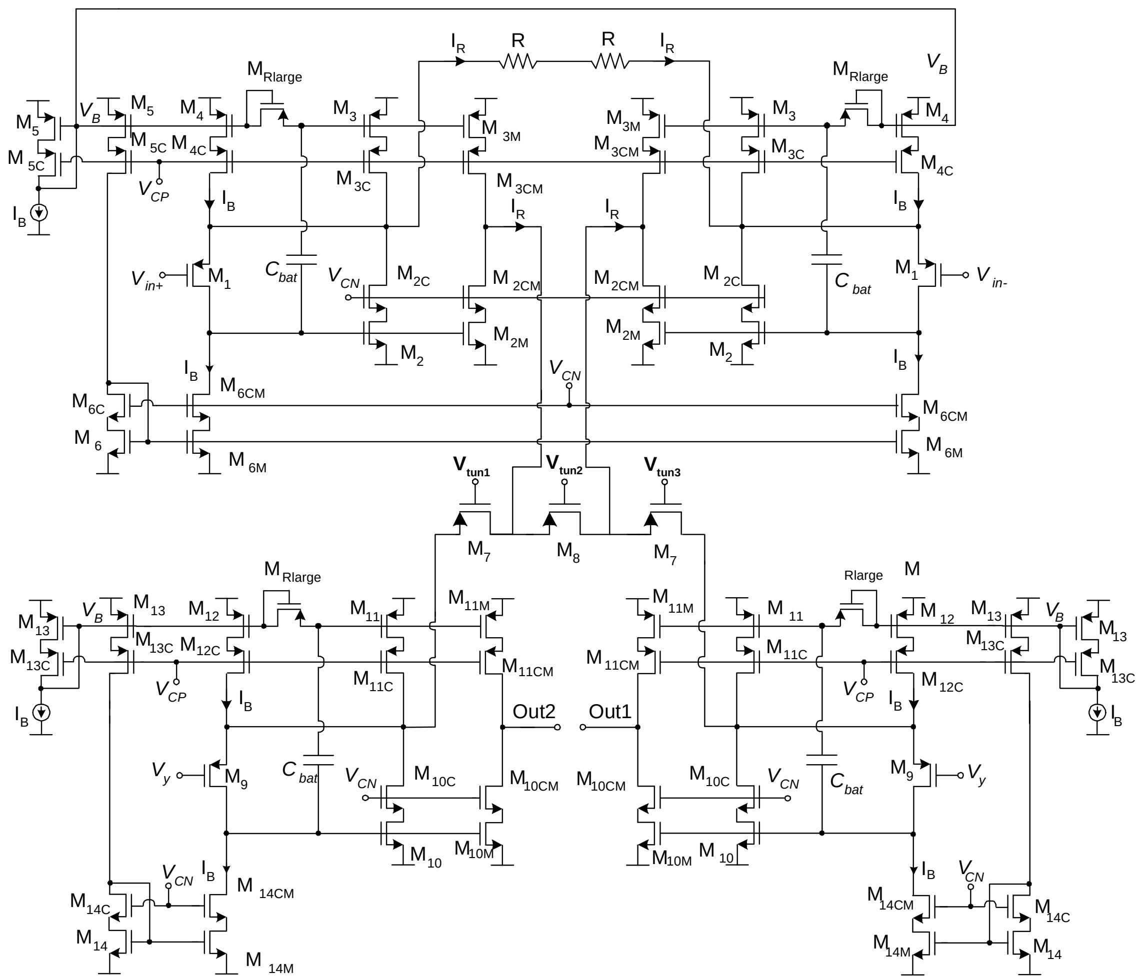

Fig. 5. Schematic of the proposed tunable class AB transconductor

$$\alpha = \frac{1}{1 + R_2/R_1} \qquad (1)$$

As the transconductance value becomes as follows

$$G_m = \frac{2\alpha I_R}{V_{id}} = \frac{\alpha}{R} \qquad (2)$$

it is possible to adjust it by changing *α*, and to do that, programmable resistors R_1 and R_2 are needed. These resistors are implemented with MOS transistors in the triode region that can be tuned by changing their gate voltages.

Although this tuning method employs MOS transistors in the resistive divider, it provides good linearity results due to the fact that passive resistors are still used to do the *V-I* conversion. Triode transistors are just used for current splitting.

In view of the previous ideas, the resulting programmable transconductor is the one in Fig. 5.

The upper part of the circuit, which involves transistors M1 to M6, is a non-tunable fully-differential transconductor that uses passive resistors for highly linear *V-I* conversion and has class AB operation. Connected to their outputs, transistors M7 and M8 form the resistive divider in charge of controlling the amount of current that goes through the output current followers. And finally, the last part of the circuit, which covers all the transistors from M9 to M14, includes the current followers that operate also in class AB and provide the transconductor with high-impedance outputs. Note that the same class AB CCIIs employed in the transconductor have been used to implement the current followers.

IV. Third-order Low-pass Filter

The chosen filter is a 1MHz tunable third order low-pass filter suitable for Bluetooth applications and its specifications are given in Table I. Its schematic is shown in Fig. 6.

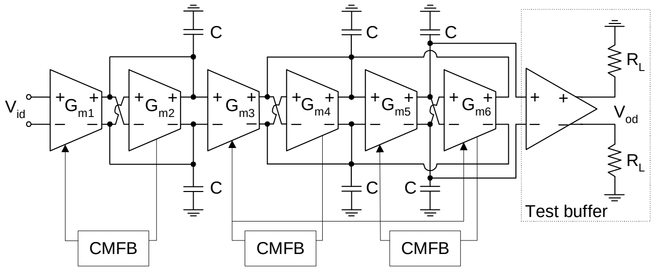

Fig. 6. Schematic of the low-pass filter

According to the figure, this Gm-C filter is constituted by six equal tunable transconductors, already explained, as well as six grounded capacitors. Besides, as it is a differential implementation, common mode control circuitry is needed at some nodes. The scheme of this circuit is based on sensing the output common-mode voltage of a transconductor in the next one and feed it back. Conventional techniques have been used to implement the CMFB circuit. Finally, there is a voltage follower in order to measure the output, avoiding loading the filter with the bonding pad capacitance.

The first two transconductors along with the first pair of grounded capacitors is a first-order filter, and the subsequent four transconductors plus the other four capacitors form a Tow-Thomas second order section. The transfer function of this filter is as follows

$$H(s)=\frac{V_{od}(s)}{V_{id}(s)}=\frac{G_{m1}/C}{s+G_{m2}/C}\cdot\frac{G_{m3}G_{m5}/C^2}{s^2+(G_{m4}/C)s+G_{m5}G_{m6}/C^2} \qquad (3)$$

Transconductance values are set to $G_{m1} = G_{m2} = G_{m4}$ and $G_{m3} = G_{m5} = G_{m6}$, so two different transconductance values are employed.

V. Measurement Results

The proposed tunable transconductor and the Gm-C filter were fabricated in a standard 0.5µm CMOS n-well process with nominal nMOS and pMOS threshold voltages of 0.64 V and –0.92 V respectively. For their implementation three metal layers, poly-poly capacitors, and high resistance polysilicon resistors were used. The microphotograph of the circuit can be seen in Fig. 7. The silicon area employed by the filter is 2.22 mm^2. Capacitor C_{bat} was implemented with two polysilicon layers and has a nominal value of 1 pF while resistor R was implemented with high-resistance polysilicon and has a value of 10 kΩ. The supply voltages employed for all the measurements were V_{DD} = 1.65 V and V_{SS} = -1.65 V.

The dimensions of the transistors employed in the six tunable transconductors of the filter are listed in Table II. The value of the grounded capacitors of the filter is 15 pF.

In Fig. 8. the harmonic distortion measured for a differential input sinusoid of 120 kHz and different amplitudes is shown. The bias current was I_B = 10 µA.

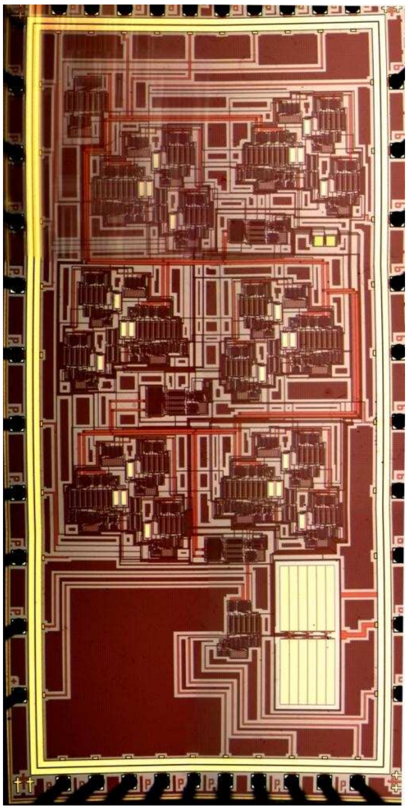

Fig. 7. Filter microphotograph.

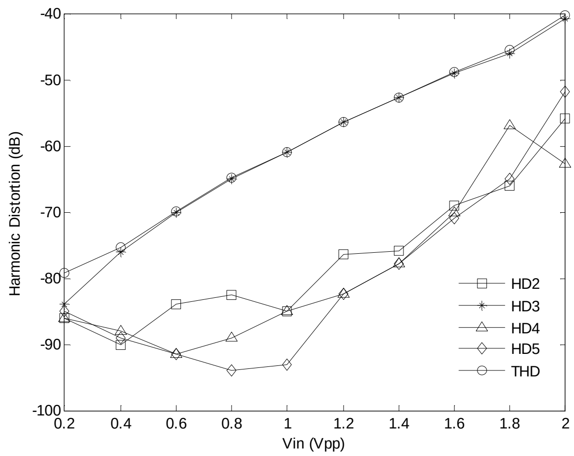

Fig. 8. Measured harmonic distortion vs input voltage at 120kHz

Harmonic distortion is dominated by the third-order harmonic, as expected from a fully differential filter. For peak-to-peak differential input voltages larger than $4RI_B$=4·10µA·10kΩ = 0.4 V the output currents are larger than the bias current I_B. Beyond this point in Fig. 8 linearity is not degraded abruptly, confirming the class AB operation of the circuit. As can be seen, Total Harmonic Distortion (THD) is lower than -55 dB for an input of 1.2Vpp (36% of the supply voltage), which corresponds to peak currents 300% larger than the bias current.

The frequency response of the filter is shown in Fig. 9 for different values of the frequency tuning voltage, where its tuning capability is proved.

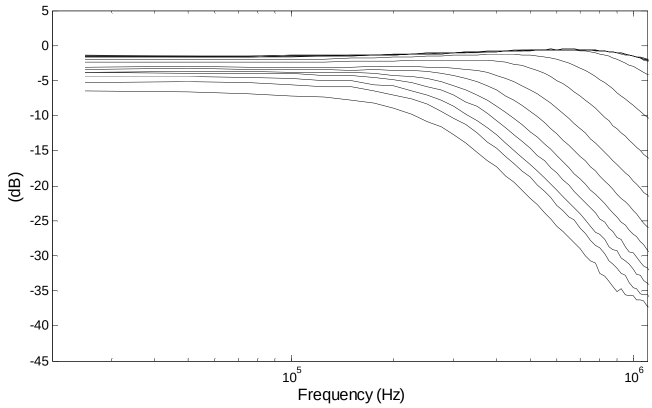

Fig. 9. Measured filter magnitude response

It can be observed that the DC gain changes between the different tuning voltages. However, the difference between the highest and the lowest values is lower than 7dB. The -3dB cutoff frequency range, which is quite wide, goes from 200 kHz to 1.45 MHz. This range is enough to compensate for process variations.

Finally, Table III summarizes the main measured performance parameters of the filter.

VI. Conclusion

A novel tunable highly linear third order low-pass Gm-C filter has been introduced. Very low quiescent power consumption has been achieved thanks to the programmable transconductors operating in class AB employed for its implementation. Quasi-floating gate transistors have been used in order to obtain this class AB operation. As a result, the circuit is able to have high current driving capability and, at the same time, very low quiescent power consumption. Besides, each transconductor of the filter includes in its design a technique for tuning the transconductance. This allows, once the filter is complete, to adjust the cutoff frequency as well as the quality factor.

Measurement results of the filter show a quiescent power consumption of 4.62mW and a THD lower than -50dB for 120 kHz inputs up to 1.6Vpp. Therefore, it is suitable for channel filtering of highly integrated, ultra low power wireless receivers.

Acknowledgment

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TABLE I
FILTER SPECIFICATIONS

Type	Butterworth
Order	3
3-dB Frequency range	1.4 MHz – 200 kHz
THD	< -50 dB
Quiescent power consumption	< 5 mW

TABLE II
TRANSISTOR ASPECT RATIOS FOR TRANSCONDUCTORS

TRANSISTOR	**DIMENSIONS**
M_1, M_3, M_{3M}, M_4, M_5, M_{6C}, M_{6CM}, M_9, M_{11}, M_{11M}, M_{12}, M_{13}, M_{14C}, M_{14CM}	W = 25.05μ ; L = 1.05μ ; m = 4
M_2, M_{2M}, M_{10}, M_{10M}	W = 15μ ; L = 1.05μ ; m = 4
M_{2C}, M_{2CM}, M_{10C}, M_{10CM}	W = 15μ ; L = 0.6μ ; m = 4
M_{3C}, M_{3CM}, M_{4C}, M_{5C}, M_{11C}, M_{11CM}, M_{12C}, M_{13C}	W = 49.95μ ; L = 0.6μ ; m = 4
M_6, M_{6M}, M_{14}, M_{14M}	W = 25.05μ ; L = 3μ ; m = 4
M_7	W = 49.95μ ; L = 1.05μ ; m = 4
M_8	W = 49.95μ ; L = 1.05μ ; m = 8
M_{Rlarge}	W = 1.5μ ; L = 0.6μ ; m = 1

TABLE III
SUMMARY OF EXPERIMENTAL RESULTS

Technology	0.5μm CMOS
Supply Voltage	±1.65 V
Bias Current	10 μA
Filter	
Cutoff frequency range	1.4MHz - 200kHz
Die area	2.22 mm^2
CMRR @ 125 kHz	54 dB
PSRR+ @ 125 kHz	59 dB
PSRR- @ 125 kHz	53 dB
Quiescent power consumption	4.62 mW