A FULLY BALANCED, CCII-BASED TRANSCONDUCTANCE AMPLIFIER 
AND ITS APPLICATION IN HIGH FREQUENCY FILTERS

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Abstract: This paper presents an approach to OTA-C filter design that is suitable for developing fully integrated, highly linear filters, intended for modern low voltage applications. The filter architecture is based on transconductance amplifiers, implemented with strictly positive second generation current conveyors. The combination of current conveyors with passive resistors leads to remarkable performances in terms of linearity, current consumption and operating frequency. The differential OTA allows the operation with asymmetrical supply voltages, a stringent requirement in modern signal processing circuitry. The functionality of the proposed circuits is demonstrated through Spice simulations.

1. Introduction

A key component of modern wireless communication systems is the analog channel-band select filter. The requirements for this filter include the high operating frequency, usually in the tens of MHz range, narrow bandwidth, good linearity, low noise and low consumption. Several implementation techniques have been described in the literature [4]. Among these the most important ones are based on OTA-C structures. The main drawback of the OTA-C design is the limited range for the transconductance parameter, the low to medium linearity along with a relatively large consumption [5].

A solution, that could potentially alleviate these problems, is a filter architecture built around current mode signal processing elements. The most often used versatile current mode circuits are the second generation current conveyors (CCII). Current conveyors, connected in fully differential networks, combined with inherently linear passive resistors and a strict common mode voltage control, allow the implementation of linear, high frequency voltage mode filters with reasonably low consumption [3].

The following paragraphs show a possible high frequency low pass filter implementation. The performances of the filter have been demonstrated through Spice simulations.

2. The fully balanced OTA and a typical filter application

Current conveyors play the same role in current mode signal processing as the opamps in voltage mode circuits. Their versatility lies in the configuration of the input and output
terminals. A classical method to build a transconductance amplifier with a CCII cell is to use the Y terminal as a voltage input [5]. The input voltage is then copied to the X terminal. The voltage $V_X$ determines a current through a resistor connected between the X terminal and the ground. This current is then copied to the Z terminal, used as current output. The overall transconductance of the circuit will be equal to the reciprocal of the passive resistance. The major drawback of this circuit is that it either requires symmetrical supply voltages or a redefinition of the reference potential. Additionally, since the Z terminal has high output impedance, its DC voltage cannot be determined precisely without a dedicated common mode feedback circuit, which, in turn, needs a fully differential structure.

The fully differential OTA is more difficult to obtain and requires a combination between two CCII cells and possibly an output stage that allows large output impedances and a common mode control. The differential structure can be derived from a current conveyor by doubling all the elements and feeding the current outputs to a cascode output stage. The block diagram of the resulting transconductance amplifier is given in Fig.1.

![Block diagram of the OTA built with positive CCII-s](image)

**Fig.1. The block diagram of the OTA built with positive CCII-s**

In the ideal case the equivalent transconductance $G_m$ is $1/R$. Real current conveyors exhibit a non-zero parasitic resistances of the X terminal which must be added twice to the passive resistance $R$ when calculating the transconductance [3]. As an example, the class AB current conveyor, built around a translinear input stage, has an $R_X$ in the range of $1k\Omega$ [5]. This limits the highest possible transconductance to around $500\mu S$, achieved without the resistance $R$.

The solution that reduces the relatively high parasitic resistance is to use negative feedback. There are various low input resistance conveyor implementations proposed in the literature. These are mainly using a differential amplifier on the negative feedback path [1][2][3]. The conveyor used to design the filter presented in this paper has been introduced and described by Liu in [3]. The block diagram and the transistor level implementation of Liu's current conveyor is presented in Fig.2.

![Liu's current conveyor: a). block diagram and b). transistor level implementation](image)

**Fig.2. Liu's current conveyor: a). block diagram and b). transistor level implementation**
Liu's CCII is essentially an unbuffered opamp with Miller compensation, whose second gain stage is replicated for copying the X terminal current to the Z output. The opamp is connected in a simple unity gain voltage follower configuration. A special care must be taken of the opamp stability through an adequate compensation. The lead-lag type of compensation, implemented with the resistor $R_C$ and the capacitor $C_C$, yields good results in insuring the stability and in extending the range of the conveyor operating frequencies [5].

With a careful design and the minimization of the critical transistor geometries the range of the OTA operating frequencies can be extended above 100MHz. The voltage at the X terminal closely follows the voltage at the Y terminal. An eventual offset is not critical due to the differential circuit structure. The typical voltage follower bandwidth exceeds 200MHz. Similarly, the bandwidth of the current follower is larger than 200MHz. The typical voltage and current follower characteristics of the conveyor are shown in Fig.3.

![Fig. 3. Voltage (a) and current (b) transfer functions of Liu's current conveyor](image)

In order to fully characterize the frequency response of the circuit one must also consider the variation of the X terminal parasitic impedance with frequency. At higher frequencies $Z_X$ tends to be inductive, its value becoming larger above approximately 10MHz. This variation, shown in Fig.4.a, must also be considered when accounting for the parasitic resistances in the expression of the transconductance.

![Fig. 4. Variation of $R_X$ with frequency (a) and with the X terminal voltage (b)](image)

Another important measure of the OTA performance is its linearity. The main source of distortion is $R_X$. The signal current flowing through the X terminal exhibits a parabolic dependence on the $v_X$ voltage according to the equation (1) (Fig.4.b).

$$i_x = 2A\sqrt{\beta_f I_B \cdot v_x - \beta_f A^2 v_x^2},$$  \hspace{1cm} (1)
where $A$ is the gain of the differential amplifier, $I_B$ is the bias current of the $X$ input stage and $\beta_p$ is the intrinsic transconductance of the p-channel input transistor.

It can be seen that the circuit introduces a significant second order harmonic into the output current. The second order distortion is typical for class-A current conveyors. The distortion can be reduced by decreasing the overall value of $R_X$ [5].

The resulting schematic of the fully differential OTA is presented in Fig.5 [1].

![Fig. 5. The schematic of the fully differential OTA](image)

The $V_{biasn}$, $V_{casn}$ and $V_{casp}$ voltages are provided by a bias circuit that is common to all the OTA cells within the filter. The purpose of the common mode feedback circuit is to set the DC voltages at the OTA outputs and implicitly control the bias point of the transistors in the cascode output stage. Its operation is based on calculating the average of the voltages at $Z_p$ and $Z_m$ and providing a correction voltage to the gates of the NMOS transistors after a comparison with a reference. The feedback loop regulates the bias current of the output stage so that the DC voltage across the single ended output resistance equals the reference voltage.

3. Experimental results

The OTA in Fig.5 can be used to implement any type of filter designed with OTA-C techniques. The applications presented as example in this paper is a 5th order low pass filter simulating the signal flow graph shown in Fig.6 and the state variables of a passive LC prototype [6].

![Fig. 6. The signal flow graph of a 5th order generalized filter](image)

The schematic of the resulting leap-frog filter structure is presented in Fig.6 [4].
The simulated filter has been designed for a 10MHz corner frequency along with a 0.25 dB ripple Chebyshev approximation [7]. All the transconductances have been chosen equal to 200µS according to the 5kΩ termination resistances of the passive prototype. Fig.8 gives magnitude response of the filter.

It can be seen that the magnitude response suffers distortion due to the inherent parasitic capacitances and X terminal input resistances of the CCII cells. The finite output resistance of the OTA also contributes to the distortion of the magnitude response. The simulated corner frequency is approximately 9MHz while the pass-band ripple reaches 0.45dB.
Fig. 9 shows the simulated time domain output signal for a 1V peak-to-peak differential, 500kHz sine wave applied to the input of the filter.

With the 1V peak-to-peak differential input voltage the filter achieves a THD equal to 0.23% or -53dB when considering 10 harmonics of the output signal, all placed in the filter pass-band. The simulated harmonics are summarized in Tab.1. The circuit consumes 6mA from a single 3V supply.

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<th>Tab. 1. Results of the Fourier analysis on the output signal</th>
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4. Conclusions

This paper described a highly linear OTA-C low pass filter, intended for high frequency applications. The transconductance amplifier has been built around two second generation current conveyors and a passive resistor which sets the value of the transconductance parameter. The main advantages of the current mode approach is the high linearity obtained without a significant increase of the current consumption and the high operating frequencies. Furthermore, the filter retains all the advantages of the differential processing, namely low common mode noise, improved linearity and larger signal swings.

References

[7]. A. Williams, Electronic filter design handbook, McGraw-Hill, 1981