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Fully Integrated OTA-C Filter Tunable by Controlled Transconductance Parameter

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Abstract – **This work deals with design of fully integrated 2^{nd}-order tunable filters. These presented filters use transconductance amplifiers as the active components and they are tuned by controlling transconductance parameter of these OTA amplifiers. Cut-off frequency and quality of all the filters can be tuned independently. The introduced filters use voltage-tunable linear transconductor with two cross coupled differential pairs.**

Keywords – **OTA - C filter, g_m - C filter, tunable filter, fully integrated filter**

I. INTRODUCTION

The main advantage of using OTA as active component is that OTA - C filters can be simply tunable by controlling the DC bias voltage or current that changes transconductance parameter of the OTA amplifier. This allows us to tune electronically the filter parameters very simply. This capability is especially important for fully integrated tunable filters. Another advantage is the possibility to fabricate OTA - C filter and digital signal processing circuits on the same semiconductor chip even at digitally oriented technology. Resistor realization is impractical because they take up excessive chip area for resistance values usually called in this filters. OTA - C filters overcome utilization of resistors by circuits that use one or more transconductance amplifiers. This circuit is capable to realize equivalent grounded or floated resistor. Hence OTA - C filters mainly use only transconductance amplifiers and capacitors. Input dynamic range of transconductance amplifiers is mostly limited because of their non-linearity.

Filters described in this paper are supposed to be used in the sigma-delta modulation measuring system for filtering a digitally generated harmonic signal for biasing capacitive sensor. As can be seen in Fig. 1, the harmonic signal generator consists of ROM memory, low-pass sigma-delta first order modulator and analog low-pass filter. Content of ROM memory is a digital pattern of sine wave in 8-bit resolution.

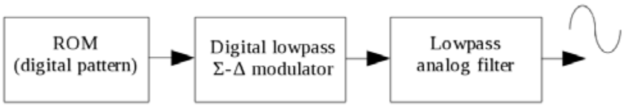

Fig. 1. Block diagram of harmonic signal generator

For measurement of wide range of impedances (mostly capacitances of capacitive sensors) the biasing harmonic input signal at various frequencies must be generated, so tunable low-pass analog filter is needed.

The full system for digital harmonic signal generation is described more deeply in [1], nevertheless, the understanding of the system is not necessary for design and analysis of the presented tunable filters.

As a suitable active device for tunable analog filters the transconductance stage with controlled *gm* parameter seems to be one of the best choices.

II. TRANSCONDUCTANCE AMPLIFIER

Almost linear voltage-controlled CMOS transconductor is described in [2]. This transconductor is based on two differential pairs (M_1,M_4 and M_2,M_3) connected in cross-coupled configuration shown in Fig. 2. Just due the differential connection we are able to reach quite good linearity of the transconductor even with usage of highly non-linear CMOS tranzistors. Transistor M_3 is connected against the transistor M_1, so then the current i_1 is given by difference between transconductance parameters of transistors M_1 and M_3. Relationship between input differential voltage v_d and output current I_{OUT} is given by (1), where k_n is the transconductance parameter and V_A is the bias voltage defined in (2). Transconductance parameter is tunable by varying of the bias voltage V_A and it is obvious that transcondustance of amplifier goes to zero for bias voltage V_A goes to zero. That allows realization of *very small transconductances*, which are important especially for *low frequency filters*.

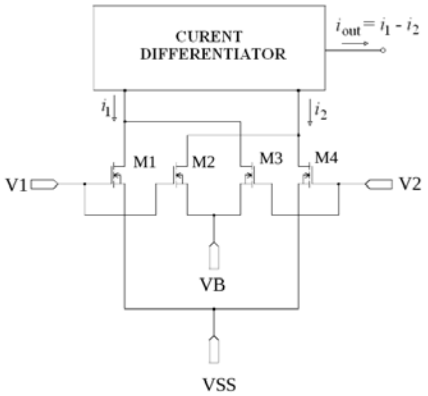

Fig. 2. Cross-coupled differential pair of the OTA stage

Cross-coupled configuration allows realization of transconductance amplifier with nicely linear dependence between the bias voltage V_A and transconductance of the circuit. Linearity dependence is maintained as long as all devices remain in saturation region; this is fulfilled as far as input differential voltage meets the inequality (3) and (4).

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$$I_{OUT} = 2k_n V_A v_d \tag{1}$$

$$V_A = V_B - V_{SS} \tag{2}$$

$$| v_d | < 2 | V_T + V_B | \tag{3}$$

$$| v_d | < 2 | V_{SS} + V_T | \tag{4}$$

If the terminal V_{SS} is grounded, the voltage applied at terminal V_B directly drives transconductance parameter. A suitable low-impedance voltage source for V_B voltage must be used for proper function of transistor M_2 and M_3. The convenient tunable voltage source with low output impedance was designed during this research whose nominal output resistance is less than 40Ω for whole bias range. Simulated result of the transconductance dependence on the controlling voltage V_B is presented in Fig. 3. From the graph is obvious that transconductance of the designed amplifier can be varied by a factor 15.

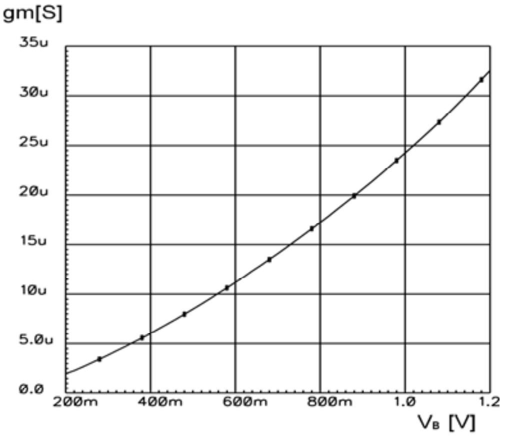

Fig. 3. Transconductance *gm* as a function of V_B voltage

III. OTA-C FILTER STRUCTURE

Two universal structures described in this paper can realize at least two filter functions in dependence on different input and output positions. The third structure can realize only low-pass notch filter. Second order filters have been chosen for the reason of better cut-off frequency tuning and simpler design dependencies. High order filter can be realized utilizing cascade connection of more 2^{nd} order filters. Independency of filter quality during cut-off frequency tuning is also suitable for proper harmonic generator function.

A. Structure 1

The circuit on Fig. 4 can realize low-pass and band-pass filter, Table 1 presents input and output connection for different filter functions. Filter consists of two grounded capacitors and two integrators in a single loop where one ideal integrator consists of g_1 and C_1 and the second lossy integrator consists of g_2, C_2 and g_3 tranconductor, connected as grounded resistor with resistance of $1/g_3$. Equation for filter quality

$$Q = \frac{C_2}{g_3}\sqrt{\frac{g_1 g_2}{C_1 C_2}}\,| \tag{5}$$

and cut-off frequency

$$\omega_0 = \sqrt{\frac{g_1 g_2}{C_1 C_2}} \tag{6}$$

is the same for both filters types. Cut-off frequency can be tuned by transconductance parameter g_1 and g_2. It can be seen that the parameter ω_0 can be varied as much as the transconductance parameter of one transconductor. Parameters Q and ω_0 can be set independently. Tunning of ω_0 without affection of Q is possible when rate $\sqrt{g_1 g_2}/g_3$ stay constant.

TABLE 1: STRUCTURE 1 FILTER TYPE

Filter type	Input	Output
LP	V_{I1}	V_{O2}
BP	V_{I3}	V_{O1}

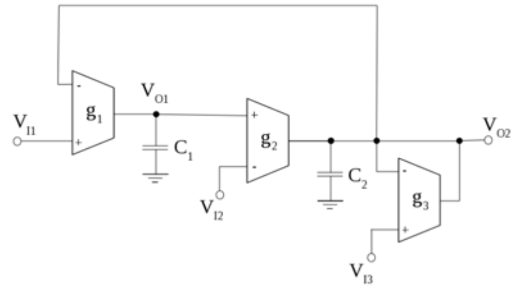

Fig. 4. Configuration of structure 1 filter

Absolute values of capacitors cannot be controlled with any acceptable degree of accuracy. On the other hand the relative ratio between transconductances and especially between capacitances can be controlled much more accurate. Due to that we can exercise good control over the designed Q value but not over ω_0.

B. Structure 2

The circuit on Fig. 5 can realize LP, HP, BP, LPN and HPN filter. Table 2 presents input and output connection for different filter functions. Filter consists of six transconductance amplifiers where two of them are connected as resistor. This circuit can realize low-pass notch filter from V_{O3} when $V_{I1} = V_{I4} = V_{I14}$ meaning that V_{I1} and V_{I4} are connected together and providing input node. Low-pass notch filter is suitable for attenuation of harmonic components near the cut-off frequency.

$$\omega_0 = \sqrt{\frac{g_1 g_2 g_5}{g_6 C_1 C_2}} \tag{7}$$

$$Q = \frac{g_4}{g_3}\sqrt{\frac{g_1 g_5 C_2}{g_2 g_6 C_1}} \tag{8}$$

$$a_2 = \frac{g_5 / g_6}{g_5 / g_6 + g_3 / g_4} \tag{9}$$

Equation for filter quality Q (eq. 8) and cut-off frequency ω_0 (eq. 7) is the same for all filter types. Parameter a_2 (eq. 9) defines ratio ω_0^2 / ω_N^2, where ω_N is angular frequency of zero. Main advantage of this configuration is independent cut-off frequency, quality and ω_N tuning. At the expense of that we must tune six transconductance parameters. For separate tuning of cut-off frequency the two transconductance (g_1 and g_2) must be tuned. Quality is not affected when the g_1/g_2 ration is constant.

TABLE 2: STRUCTURE 2 FILTER TYPE

Filter type	Input	Output
LP	V_{I3}	V_{O1}
HP	V_{I35}	V_{O3}
BP	V_{I3}	V_{O2}
BS	V_{I4}	V_{O3}
LPN	V_{I14}	V_{O3}
HPN	V_{I46}	V_{O3}

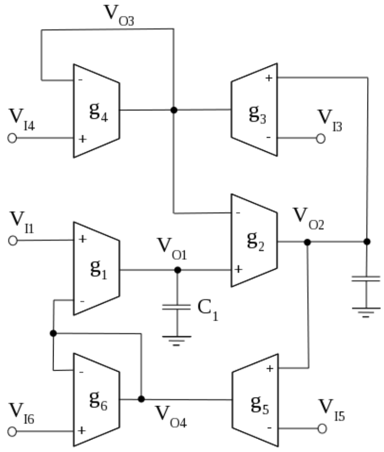

Fig. 5. Configuration of structure 2 filter

B. Structure 3

The circuit from Fig. 6 can realize only low-pass notch filter from input V_I to output V_O. Filter consists from two transconductance amplifier connected as ideal integrator. Capacitor C_2 is connected in feet-back loop. This capacitor is not grounded due to additional parasitic capacitors occurs in circuit. Equations for filter cut-off frequency ω_0 and quality Q is give by (10) and (11). Parameter a_2 (12) defines ratio ω_0^2/ω_N^2, where ω_N is angular frequency of zero. This filter can not be directly use in cascade configuration additional voltage follower must be use in case cascade filter configuration. Parameter a_2 is given by ratio of capacitors and can not be tuned. Independent tuning of filter quality and cut-off frequency is possible in case constant g_1/g_2 ratio.

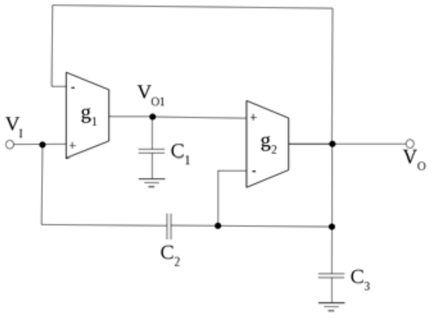

Fig. 6. Configuration of structure 3 filter

$$\omega_0 = \sqrt{\frac{g_1 g_2}{C_1C_2 + C_1C_3}} \tag{10}$$

$$Q = \sqrt{\frac{(C_2 + C_3)g_1}{g_2C_1}} \tag{11}$$

$$a_2 = \frac{C_2}{C_2 + C_3} \tag{12}$$

IV. CONCLUSION

Transconductance amplifier was designed in AMIS CMOS 0.7μm technology and simulated in Cadence design environment. Transconductance parameter can be easy varied by a factor 15 for acceptable DC bias currents. Lowest transconductance that can be realize is about 1μS. Simulated transfer function of the low-pass filter realized by structure 1 is shown in Fig.7. Cut-off frequency was tuned through 1.4 decade from 8.8 kHz to 220 kHz. All transconductance amplifiers have been tuned equally to keep constant quality Q of the filter which was designed as 0.7 for all cut-off frequencies.

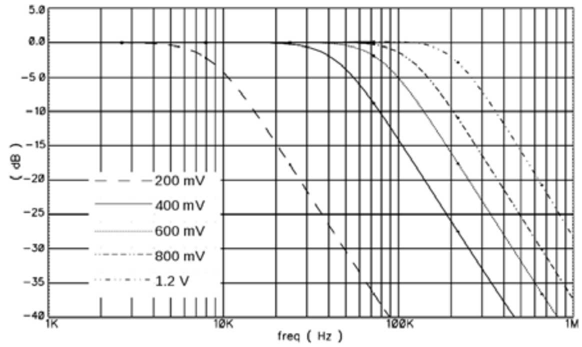

Fig. 7. Transfer function of low-pass filter realized by structure 1 parameterized by control voltage VB

The pre-study work of OTA-C structures can simplify design of other tunable analog circuits. Realization of OTA-C filters with current conveyors CCII+ used as active component will be studied in future work.

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