Current-Mode Video Filters Employing Commercial Active Elements

Dalibor Biolek *dalibor.biolek@unob.cz*
Zdeněk Kolka *kolka@feec.vutbr.cz*
Viera Biolková *biolkova@feec.vutbr.cz*
Mahmoud Shaktour *shaktour@feec.vutbr.cz*

Dept. of Electrical Engineering, FVT UO Brno, Czech Republic
Institute of Microelectronics and Radioelectronics, FEEC BUT, Brno, Czech Republic

A method for the synthesis of floating inductors with the utilization of commercial positive current conveyors, serving as single-input single output OTAs, is presented. These blocks are then employed for the implementation of active filters which simulate the passive low-sensitivity ladder structures. The principle is verified on the example of a 5^{th} - order lowpass filter according to the Feistel-Unbehauen approximation with extremely flat group delay frequency response.

I. Introduction

Today's telecommunication applications lead to the requirements for signal filtering in various frequency bands. These demands are often resolved by a proper combination of analog and digital methods. Particularly extreme requirements are imposed on the analog filters used in the chain of encoding and decoding processes of digital TV signals. Detailed specifications are described in the ITU-R BT.601-6 recommendation „Studio encoding parameters of digital television for standard 4:3 and wide-screen 16:9 aspect ratios“ [1]. For example, the template for the lowpass filter for luminance, RGB or 4:4:4 colour-difference signals prescribes a passband of up to 5.75MHz with a passband ripple of less than 0.1dB, and attenuations of at least 12dB and 40dB at frequencies of 6.75MHz and 8MHz. However, the required maximum change of group delay in the passband is up to 6ns. The above specifications impose excessive requirements on the sharpness of the gain response as well as on the flatness of the group delay response. Actually a minimization of the filter order should be accomplished via selecting a proper approximation, e.g. the Feistel-Unbehauen approximation, which is the well-known Bessel approximation combined with transfer zeros [2]. A high precision of filter parameters in their lot manufacture is another requirement which leads to the design of filter structures with low-sensitivities to manufacturing tolerances and parasitic influences in the frequency band of units of MHz and higher.

The leading manufacturers of video filters concentrate on the design of unified filters of lower orders, usually 4^{th}-7^{th} order, with possibility of their cascade or another arrangement into more complicated units which are able to cover a wider application area [3]. The rather low order is accomplished by selecting such an approximation of frequency response which is not optimal with respect to the group delay. The Butterworth approximation is normally used in most cases. The group delay should be equalized post facto via allpass sections. Some space for a certain improvement appears here: low-order filtering blocks would be designed on the basis of another approximation, which would significantly improve the group delay response, simultaneously preserving the attenuation requirements. Low sensitivities can be achieved by LC ladder simulation. Current-mode filter design provides the necessary linearity and speed in the given frequency region.

A number of papers deal with the synthesis of active filters which simulate low-sensitive passive ladder structures [4-16]. LC ladder simulations by Signal-Flow-Graphs (SFG) [5, 6] and by Element Substitution [7, 8] belong to well-known methods. The initially used conventional operational amplifiers (OpAmps) [5] are substituted by other active elements with more progressive features, e.g. by current-feedback amplifiers (CFAs) [9], operational transconductance amplifiers (OTAs) [10, 11, 12], positive second-generation current conveyors (CCII+s) [12], current differencing buffered amplifiers (CDBAs) [13], current differencing transconductance amplifiers (CDTAs) [14, 15] or current mirror arrays [16].

This paper deals with LC ladder simulation on the principle of inductor replacement by synthetic inductor. Various active elements are today available in the market. Their bandwidth, slew rate and other parameters predestine these elements for the processing of communication signals including video signals, for HDTV equipment, etc. Simpler filtering blocks for video signal processing can be effectively implemented by means of these elements. In the paper, the floating inductor is synthesized via the so-called „super-transistor“ (S-T), which is commercially available in several versions, e.g. OPA615, SHC615, OPA860, and OPA861 [17].

II. Commercial active elements for filter implementation

The OTAs belong to the most popular active components for LC ladder simulation [12], see Fig. 1 a). Several circuits are used for simulating the floating inductor. The most economical one consists of a pair of OTAs and one grounded capacitor, one of them having a single-input and a differential output, the other a differential input and a single output. An interesting commercial element which would be optimal for such implementation was MAX 435 by MAXIM corporation [18]. However, its manufacturing was terminated. The well-known OTA LM13700 by National Semiconductor [19] has a differential input and a single output. However, its bandwidth (2MHz) is too low for video signal processing.

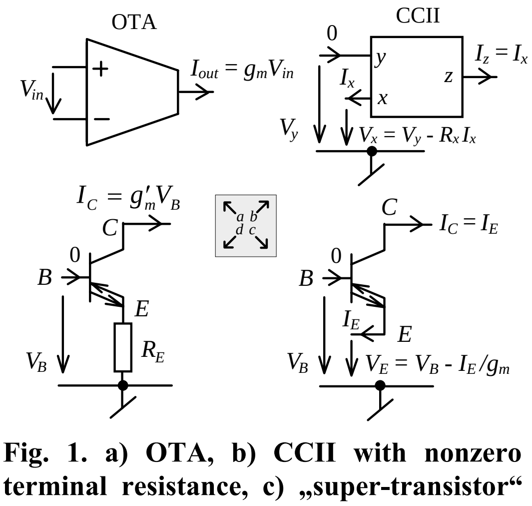

Fig. 1. a) OTA, b) CCII with nonzero *x*-terminal resistance, c) „super-transistor“ as CCII, d) „super-transistor“ with a degeneration R_E resistance as single-input single-output OTA.

It is well known that OTA can be implemented by the CCII: the high-impedance *y* terminal is used for voltage excitation. The low-impedance *x* terminal is grounded. The current, flowing through the *x* terminal into the ground, is equal to the input voltage divided by the internal resistance R_x of the *x* terminal. This current is copied by an internal current mirror onto the *z* terminal. Such a circuit then acts as the single-input single-output OTA with transconductance $g_m = 1/R_x$. When utilizing the current-controlled CCII (CCCII) [20], the transconductance can be controlled electronically by an external quiescent current.

The so-called “diamond transistor” OPA660 [17] by Burr Brown/Texas Instruments belongs to the well-known commercial CCCIIs. However, today it is an obsolete product. Its analogy is available in the form of perspective circuits OPA615, SHC615, OPA860, and OPA861 from the above company. All of them contain the S-T, or – in other words – the CCCII whose intrinsic R_x resistance is adjustable by an external current. In addition, OPA860 contains a very fast and independently utilized voltage buffer, whereas OPA615 and SHC615 include a fast comparator in the form of differential input single output OTA with extremely high transconductance. The “super-transistors” also have comparatively high transconductances (up to 100 mA/V) and their characteristic $I_{out} = f(V_{in})$ is rather nonlinear; thus the linear operation region is within the V_{in} range of tens of milivolts. This drawback, which prevents this element from being used directly for filters with a large dynamic range, can be suppressed by the so-called degeneration resistance R_E in series with the emitter (see Fig. 1 d). The negative feedback will cause a decrease in the original transconductance g_m to the value

$$g'_m = \frac{g_m}{1+g_m R_E} \approx \frac{1}{R_E} \text{ for } g_m >> \frac{1}{R_E}, \qquad (1)$$

and, in addition, a considerable linearization of the OTA and an increased swing of the input voltage.

The S-T drawback consists in the fact that it can be used only as single-input single-output OTA whereas the differential variants are more suitable for economical implementation of floating inductors. That is why more active elements must be used in a concrete filter than in the case of differential types of OTA, e.g. MAX435. The internal OTA in OPA615 and SHC615 has a differential input, but it cannot be used for linear applications because of its strongly nonlinear characteristic $I_{out} = f(V_{in})$. In addition, unlike with the S-T, a simple linearization technique does not exist here.

Concrete experiments lead to the observation that the OPA860 is a useful element for active filters for the frequency range of units and tens of megahertz. A detailed description of the OPA860 parameters is given in [21]. A method for the simulation of floating inductor by S-T and voltage buffer is described below. Some parameters of 5th order video filter with an extremely flat group delay, which has been constructed on the basis of such synthetic inductors, are demonstrated.

III. Floating inductor replacement via "super-transistors"

The proposed circuit for inductance simulation with three S-T and one voltage buffer is given in Fig. 2. The schematic symbol of S-T also includes a possible degeneration resistor R_E for modifying the transconductance according to Eq. (1).

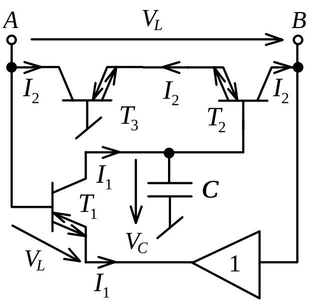

Fig. 2. Simulation of floating inductor.

T_1 together with the voltage buffer acts as differential input OTA. Its output current I_1 is directly proportional to the transconductance g_{m1} of S-T No. 1:

$$I_1 = g_{m1} V_L \, .$$

This current flows through the capacitor C and causes the voltage drop

$$V_C = \frac{I_1}{sC} = \frac{g_{m1}}{sC} V_L \, .$$

Taking S-T with transconductance g_m as an ideal current conveyor CCII with a parasitic resistance $R_x = 1/g_m$ connected to its x terminal (i.e. to the emitter of S-T), then S-T No. 2 and 3 with interconnected emitters in Fig. 2, each with transconductances g_{m2} and g_{m3}, can be modeled as a connection of the ideal CCII (in place of T_3) and T_2 with its emitter connected to the parasitic resistance

$$R_x = \frac{1}{g_{m2}} + \frac{1}{g_{m3}} \cdot$$

The ideal T_3 provides zero voltage at its emitter and the current of T_2 is thus controlled only by the voltage across the capacitor. Its value is as follows:

$$I_2 = \frac{V_C}{R_x} = \frac{g_{m1}}{sCR_x} V_L \, .$$

T_3 accomplishes the inversion of this current regardless of the real value of g_{m3}. That is why the circuit in Fig. 2 represents the lossless floating inductor with the inductance

$$L = C\frac{R_x}{g_{m1}} = \frac{C}{g_{m1}}\left(\frac{1}{g_{m2}} + \frac{1}{g_{m3}}\right). \qquad (2)$$

A practical utilization of the proposed circuit has been verified on the example of 5th - order LC ladder video filter. All inductors of this filter were replaced by the synthetic inductors from Fig. 2. The frequency responses of the resulting active filter were measured and compared with the theoretical responses of passive LC prototype. These experiments are described in Section V. This is preceded by an analysis of real influences of circuit components on the small-signal behavior of the filter as given in Section IV.

IV. Real properties of synthetic inductor

The synthetic inductor in Fig. 2 is a two-terminal device whose small-signal frequency-dependent behavior is affected by a number of factors, particularly by:

- Input resistance R_B and input capacitance C_B of terminal B (base) of S-T.
- Input resistance R_C and input capacitance C_C of terminal C (collector) of S-T.
- Transconductance of S-T, which can be modeled by a resistor R_x in series with the E terminal (emitter). The resistor R_x can also include the external degeneration resistor.
- Input resistance R_{buf} and input capacitance C_{buf} of the voltage buffer.
- Output resistance R_{Obuf} of the voltage buffer.

Assume that both building blocks of the synthetic inductor, i.e. S-T and buffer, are designed with the bandwidth required for the given application. Other real phenomena, e.g. frequency dependence of the buffer gain, parasitic inductance of the E-terminal of S-T, and others which affect the inductor parameters at relatively high frequencies, will not be included in the analysis.

The following parameters are mentioned in [21] for the OPA860 integrated circuit:

$$R_B = 455\text{k}\Omega,\ C_B = 2.1\text{pF},\quad R_C = 54\text{k}\Omega,\ C_C = 2\text{pF},\quad R_{buf} = 1\text{M}\Omega,\ C_{buf} = 2.1\text{pF},\ R_{Obuf} = 1.4\Omega. \tag{3}$$

An analysis of circuit in Fig. 2 discloses the following consequences of the action of parasitic elements (3) for the model of synthetic inductor:

Parasitic shunt resistance R_{A0} and capacitance C_{A0} act across the A terminal and the ground. R_{A0} or C_{A0} is given by a parallel combination of the resistance R_C or capacitance C_C of S-T No. 3 and the resistance R_B or capacitance C_B of S-T No. 1:

$$R_{A0} = R_{C1}\ \&\ R_{B1} \approx 48.3\text{k}\Omega,\ C_{A0} = C_{C3} + C_{B1} \approx 4.1\text{pF}.$$

Accordingly, the parasitic shunt resistance R_{B0} and capacitance C_{B0} act across the B terminal and the ground, where

$$R_{B0} = R_{C2}\ \&\ R_{buf} \approx 51.2\text{k}\Omega,\ C_{B0} = C_{C2} + C_{buf} \approx 4.1\text{pF}.$$

The parasitic capacitances should be taken into account when designing the working capacitances of the LC ladder filter, which are connected to them in parallel. The parasitic resistances introduce additional losses into the circuit with possible degradation of the frequency response.

When designing the capacitance C inside the synthetic inductor, one should take into account the additional parasitic elements which are connected in parallel to this capacitor:

$$C_{cap} = C_{C1} + C_{B2} \approx 4.1\text{pF},\ R_{cap} = R_{C1}\&R_{B2} \approx 48.3\text{k}\Omega.$$

Then the working capacitance should be decreased by C_{cap}. A symbolic analysis of the circuit in Fig. 2 leads to the formula for the impedance between terminals A and B:

$$Z_{AB} = \frac{R_{x1}(R_{x2}+R_{x3})}{R_{cap}} + sR_{x1}(R_{x2}+R_{x3})(C+C_{cap})\,. \tag{4}$$

Note that due to the finite parasitic resistance R_{cap}, the synthetic inductor has a lossy resistance R_s

$$R_s = \frac{R_{x1}(R_{x2}+R_{x3})}{R_{cap}}\,. \tag{5}$$

A comparison of the second component on the right side of Eq. (4) and Eq. (5) confirms the conclusion that the value of the simulated inductance is modified by the capacitance C_{cap}, which is added to the working capacitance C.

The influence of the nonzero output resistance of the voltage buffer is the last effect examined. This resistance should be added to the resistance R_{x1} of S-T No. 1 in equations (4) and (5).

The above real properties are summarized in the model of the inductor in Fig. 3.

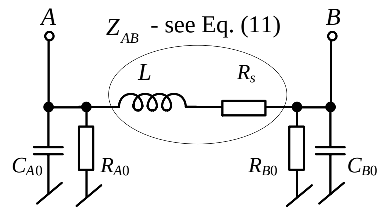

Fig. 3. Model of the synthetic inductor in Fig. 2, with the real effects considered.

V. Utilizing synthetic inductors for LC ladder simulation

Consider the realization of a lowpass LC ladder in Fig. 4. This filter has been designed on the basis of the following specification:

DC gain 0dB, cutoff frequency 5MHz, passband ripple 1dB, attenuation at least 50dB for frequencies above 27MHz, group delay ripple up to 3.58MHz less than 10 ns. This specification corresponds to the parameters of commercial video filter FMS6400-1 by Fairchild Semiconductor [22].

The LC ladder has been designed according to the Feistel-Unbehauen approximation, that is to say with the group delay response being maximally flat within the filter passband.

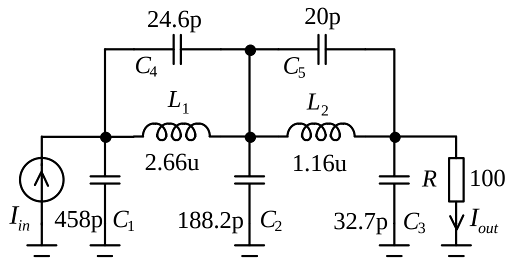

Fig. 4. 5MHz LC ladder.

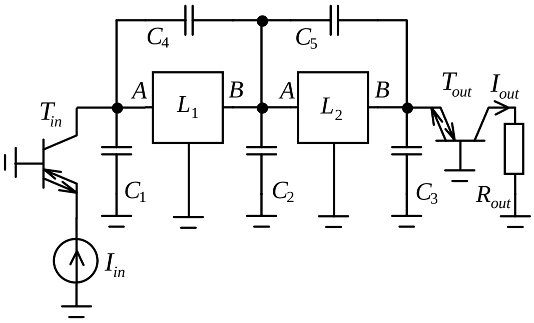

Fig. 5. Active implementation of the filter from Fig. 4. Blocks „L_1“ and „L_2“ are synthetic inductors from Fig. 2.

The active simulation of the filter from Fig. 4 by means of "super-transistors" is given in Fig. 5. T_{in} is designed with a high transconductance in order to provide low driving point impedance for the current source I_{in}. On the contrary, the transconductance of T_{out} is lowered by a degeneration emitter resistor because T_{out} should act as a 100Ω load for the capacitor C_3. Simultaneously this transistor provides an output current into a general load R_{out}.

All the transconductors in the filter were implemented by the OPA860 integrated circuits. The S-T internal transconductance is set by an outside resistor R_Q, which is connected between the „IQ Adjust“ terminal and the negative supply voltage [22]. For the zero value of R_Q, the quiescent current is limited by an internal resistor, and the corresponding maximum g_m is approximately 95mA/V. This setting has been used for testing the filter. According to the datasheet recommendation, 100-Ohm series resistors were added to the base terminals of each S-T. "Super-transistors" were also complemented with 100-Ohm degeneration emitter resistors, excepting T_{in} and T_{out}. For T_{in}, the emitter resistor was omitted in order to set g_m = 95mA/V. Then the input resistance of the filter is only 10.5 Ohms. The degeneration resistance for T_{out} is designed to be 89.5 Ohms. Taking into account the internal T_{out} transconductance, the total load resistance for C_3 is 100Ω.

The synthetic inductors in Fig. 2 were designed with 100-Ohm degeneration resistors for transistors T_1 and T_2. The influence of the output resistance of the voltage buffer was neglected. The internal capacitors for inductors L_1 a L_2 were designed from Eq. (6) to be 199pF and 87pF, respectively. After subtracting the value of parasitic capacitance C_{cap} = 4.1pF, the final values of working capacitances in the synthetic inductors are 195pF and 83pF. The capacitances C_1, C_2, and C_3 of the LC ladder in Fig. 5 were decreased by the parasitic capacitances C_{A0}, C_{B0}, and collector capacitance of T_{in}, specifically to values 452pF, 180pF, and 29pF.

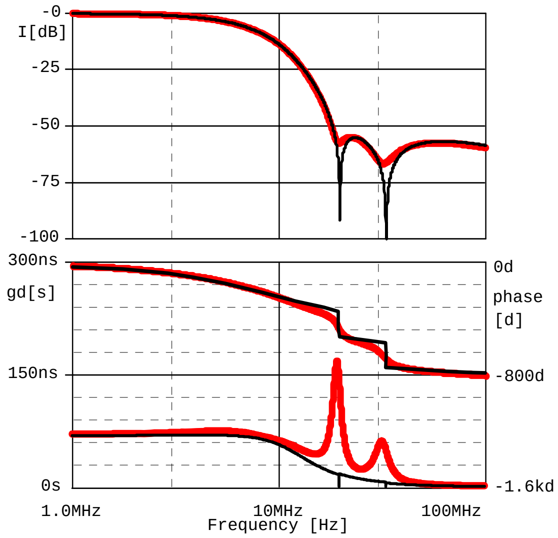

Fig. 6. Frequency responses of the active filter from Fig. 5:— ideal filter,
▬ filter employing OPA860.

In Fig. 6, the frequency responses of active filter are compared with the ideal characteristics of LC ladder, analyzed in PSpice. The amplitude frequency responses are in a good conformity. The plain stopband rejections are due to the finite values of quality factors of synthetic inductors (see Eq. 11). From the same reason, the phase response at these frequencies does not embody jump changes but its slope is adequately increased. That is why the group delay response shows significant peaks near the frequencies of transfer zeros. Fortunately, they occur in the filter stopband. The passband group delay is 68ns with a ripple of only 4ns.

VI. Conclusions

The synthetic floating inductor, employing three current controlled - current conveyors CCCII+, one grounded capacitor, and one voltage buffer is proposed. This building block can be implemented in active filters via commercial active elements which are optimized for fast processing of video signals. It is shown that real parameters of active elements cause several effects in target applications, namely the active simulation of LC ladder. Most of them can be compensated by a careful design of the passive part of the filter. The experiments described demonstrate the availability of proposed synthetic inductor with commercial OTAs in the frequency range of tens to hundreds of megahertz.

Acknowledgment

This work was supported by the GACR under grants No. 102/08/0784, 102/08/0851, and by research programmes MSM 0021630503, MSM 0021630513, and MO FVT0000403.

References

[1] Recommendation ITU-R BT.601-6 "Studio encoding parameters of digital television for standard 4:3 and wide-screen 16:9 aspect ratios". Int. Telecomm. Union/ITU, January 1, 2007.

[2] K. H. Feistel, R. Unbehauen, "Tiefpässe mit Tschebyscheff-Charakter der Betriebsdämpfung im Sperrbereich und maximal geebneter Laufzeit," *Frequenz*, vol. 19, pp. 265-282, 1965.

[3] www.fairchildsemi.com

[4] R. Schaumann, Ghausi, M. S., Laker, K. R., "Design of analog filters," Prentice Hall, 1990.

[5] P. O. Brackett, Sedra, A. S., "Direct SFG simulation of LC ladder networks with applications to active filter design," *IEEE Trans. Circuits Syst.*, vol. CAS-23, pp. 61-67, February 1976.

[6] K. Martin, A. S. Sedra, "Design of Signal-Flow-Graph (SFG) active filters," *IEEE Trans. Circuits Syst.*, vol. CAS-25, pp. 185-195, April 1978.

[7] K. Martin, A. S. Sedra, "Optimum design of active filters using the generalized immitance converters," *IEEE Trans. Circuits Syst.*, vol. CAS-24, pp. 495-503, September 1977.

[8] L. T. Bruton, "Multiple amplifier RC-active filter design with emphasis on GIC realizations," *IEEE Trans. Circuits Syst.*, vol. CAS-25, pp. 830-845, October 1978.

[9] T. S. Rathore, U. P. Khot, "CFA-based grounded-capacitor operational simulation of ladder filters," *Int. J. Circ. Theor. Appl.* (2007), published online on www.interscience.wiley.com.

[10] M. A. Tan, R. Schaumann, "Simulating general parameter LC-ladder filters for monolithic realizations with only transconductance elements and grounded capacitors," *IEEE Trans. Circuits Syst. I*, vol. CAS-36 (2), pp. 299-307, 1989.

[11] J. Ramirez-Angulo, E. Sanchez-Sinencio, "High frequency compensated CM ladder filters using multiple output OTAs," *IEEE Trans. Circuits Syst. II*, vol. CAS-41 (9), pp. 581-586, 1994.

[12] C. Toumazou, F. J. Lidgey, D. G. Haigh, "Analogue IC design: The current-mode approach," IEE Circuits and Systems Series 2, Peter Peregrinus Ltd., 1993.

[13] W. Tangsrirat, N. Fujii, W. Surakampontorn, "Current-mode leapfrog ladder filters using CDBAs," *IEEE Int. Symp. on CAS*, vol. 5, Ladkrabang, Bangkok, V-57-V-60, May 2002.

[14] D. Biolek, V. Biolkova, "SFG simulation of general ladder filter using CDBAs," *IEEE European Conf. ECCTD03*, Krakow, Poland, vol. 1, pp. 385-388, August 2003.

[15] H. Kuntman, A. Uygur, "Seventh-order elliptic video filter with 0.1 dB pass band ripple employing CMOS CDTAs," *AEU – Int. J. of Electronics and Communications*, Vol. 61, Issue 5, pp. 320-328, May 2007.

[16] G. Souliotis, I. Haritansis, "Current-mode filters based on current mirror arrays," *Int. J. Circ. Theor. Appl.* (2008), published online on www.interscience.wiley.com.

[17] www.ti.com

[18] MAX435/436 Wideband Transconductance Amplifiers. Datasheet, 19-0042, Rev. 1, 4/93. Maxim Integrated Products.

[19] LM13700 Dual Operational Transconductance Amplifiers with Linearizing Diodes and Buffers. Datasheet, June 2004, National Semiconductor.

[20] A. Fabre, O. Saaid, F. Wiest, C. Boucheron, "Current-controlled bandpass filter based on translinear conveyor," *Electron. Lett.*, vol. 31, no. 20, 1995, pp. 1727-1728.

[21] OP860. Wide Bandwidth Operational Transconductance Amplifier (OTA) and Buffer. Datasheet, Texas Instruments, SBOS331B, June 2006.

[22] FMS6400-1 Dual Channel Video Drivers with Integrated Filters and Composite Video Summer. Datasheet, Fairchild Semiconductor, June 2005.