

Pseudo-Differential Filter Design Using Novel Adjustable Floating Inductance Simulator with Electronically Controllable Current Conveyors

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Abstract—This paper presents new floating inductance simulator based on three electronically controllable current conveyors (ECCIs) and differential voltage buffer (DVB). The inductance simulator offers simple electronic control of inductance value as well as simple control of losses by change of parameters of active elements. Based on this floating inductance simulator, example of reconnection-less reconfigurable pseudo-differential first-order filter, allowing change of transfer function between high-pass and inverting all-pass response, is discussed and studied. Moreover, the proposed structure can be easily extended to a pseudo-differential second-order band-pass filter. Behaviour of presented solutions is verified by PSpice simulations and also experimentally in frequency band up to 10 MHz. Obtained results confirmed expected features.

Index Terms—Differential active filter; differential mode; pseudo-differential-mode; electronic control; inductance simulator; reconfigurability.

I. INTRODUCTION

In general, fully-differential (symmetrical) circuits have many applications due to specific features they offer, i.e. attenuation of common-mode noise as well as better rejection of signals incoming from power supply sources and possibly also better dynamics in comparison to single-ended circuitries [1]–[4]. However, increased complexity of circuitry is cost for these benefits. Electronic controllability of parameters of analogue and mixed-mode circuits is useful in single-ended as well as in case of differential-mode operation. Therefore, circuit solutions allowing these features are subjects of interest of many researchers [4]. Digital control of important parameters of the differential-

filter was also investigated in the past [5].

Division of differential systems (for example see [1]–[8]) to truly-differential and so-called pseudo-differential-mode of operation, is perfectly explained in [8] which brings new insight into this research topic. Note that complexity of pseudo-differential-mode circuits is significantly reduced in comparison to fully-differential-mode solutions due to partially grounded subparts of differential systems, i.e. input and output ports are differential whereas their inner circuitry consists of grounded (analog ground) passive components and terminals. Many from previously reported pseudo-differential circuit solutions were focused on biquadratic (second-order) active filters, [6]–[9] for instance. Electronic controllability [6] as well as multi-functionality (providing several transfer responses) [7] were also studied in the past.

In this paper we are introducing a novel solution of floating inductance simulator allowing features not reported in previous works. These features are beneficial especially in electronic reconfiguration of transfer function and electronic control of pseudo-differential-mode filter parameters. Here proposed filtering applications can be divided to two groups: (i) first-order reconfigurable filter, (ii) second-order band-pass filter. Comparison of selected solutions of first-order active filters in single-ended, fully-differential, or pseudo-differential form [10]–[14] is available in Table I. In general, many of these have multifunctional features, however, features such as reconnection-less reconfigurability (possible to obtain various transfer responses without change of input/output terminal) were studied only in single-ended filtering solutions (see for example [15]). To the best of authors' knowledge, circuits allowing reconfiguration of transfer responses, i.e. certain multi-functionality of the filter between at least two different types of fully-differential or pseudo-differential filters were not reported in the open literature yet. Here presented structure of floating inductance simulator allows such electronic reconfiguration, if its

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implementation is appropriate, as it is shown in this paper.

TABLE I. COMPARISON OF REPORTED PSEUDO/FULLY-DIFFERENTIAL FIRST-ORDER MULTIFUNCTIONAL FILTERS.

Work	No. of pas./act. elements	Available functions	Transfer response configurability
[10]	4-6/1	AP, BR	No
[11]	2-6/1-2	LP, HP, AP	No
[12]	4/1	AP	No
[13]	4/2	AP, LP	No
[14]	1/3	AP	No
Fig. 3	2(6)/1(4)	HP, iAP	Yes

Note: (i) DT – (inverting) direct transfer; (i) AP – (inverting) all-pass; LP – low-pass; (i) HP – (inverting) high-pass; BR – band reject.

II. DESCRIPTION OF FLOATING INDUCTANCE SIMULATOR

Proposed floating inductance simulator shown in Fig. 1 employs three electronically adjustable current conveyors of second generation (ECCII) [16] described by the following inter-terminal transfers: $I_Z = B \cdot I_X$, $V_X = V_Y$, $I_Y = 0$ and one differential voltage buffer (DVB) [16] providing the following operation: $V_+ - V_- = V_{out}$. Note that the current gain B of each ECCII is controllable linearly by DC voltage ($B \cong V_{SET_B}$). Commercially available devices EL2082 and AD830 are examples of previously discussed elements (ECCII, DVB) with well-fitting behaviour up to several tens of MHz. Assuming $R_{x1} = R_{x2} = R_3$ are equal and designated as R_{L_int} , the admittance description (based on method of unknown nodal voltages: $I = Y \times V$) of the circuit in Fig. 1 presents set of equations:

$$\begin{bmatrix} I_{inp1} \\ I_{inp2} \end{bmatrix} = \begin{bmatrix} a^{-1}B_1 & -a^{-1}B_1 \\ -a^{-1}B_2 & a^{-1}B_2 \end{bmatrix} \begin{bmatrix} V_{inp1} \\ V_{inp2} \end{bmatrix}, \quad (1)$$

where $a = sC_{L_int}R_{L_int}^2 + (2 - B_3)R_{L_int}$.

Then, assuming $B_1 = B_2 = B_{1,2}$, impedance of equivalent inductance emulator has the following theoretical form

$$\begin{aligned} L_{eq}(s) &= sL_{eq_int} + R_{s_int} = \\ &= \frac{sC_{L_int}R_{L_int}^2}{B_{1,2}} + \frac{(2 - B_3)R_{L_int}}{B_{1,2}}, \end{aligned} \quad (2)$$

where C_{L_int} and R_{L_int} are passive elements of the inductance simulator and it is clear that the proposed circuit behaves as lossy inductance. However, the lossy part R_{s_int} in (1) can be easily eliminated by selecting current gain B_3 (ECCII₃) equal to 2, losses are negative for $B_3 > 2$. Nevertheless, lossy part of the proposed inductance simulator can be also beneficial for application as introduced later. Moreover, it is obvious that value of L_{eq_int} can be controlled electronically by B_1 and B_2 .

Proposed inductance simulator in Fig. 1 was designed for further implementations with the following values of internal elements: $R_{L_int} = 560 \Omega$, $C_{L_int} = 470 \text{ pF}$ as a particular example. The PSpice simulation results of the inductance simulator in grounded form are shown in Fig. 2. Inductance value L_{eq} was changed from $2.63 \mu\text{H}$ to $0.13 \mu\text{H}$ by $V_{SET_B1,2}$ between 0.1 and 2 V, i.e. gains B_1 and B_2 are between 0.1 and 2.

III. INDUCTANCE SIMULATOR IMPLEMENTATION IN PSEUDO-DIFFERENTIAL FILTERING APPLICATIONS

Benefits of the proposed solution were verified in several filtering applications shown in the following sections. Inductance simulator is used as floating element in RL or RLC ladder structures. Theoretical expectations are supported by simulation results and also by laboratory experiments.

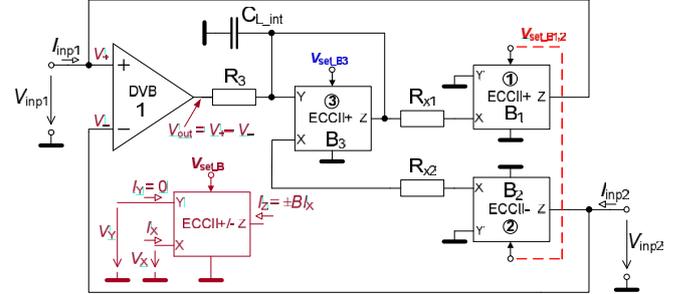


Fig. 1. Proposed floating inductance simulator based on ECCII and DVB including description of behaviour of active elements (brown colour).

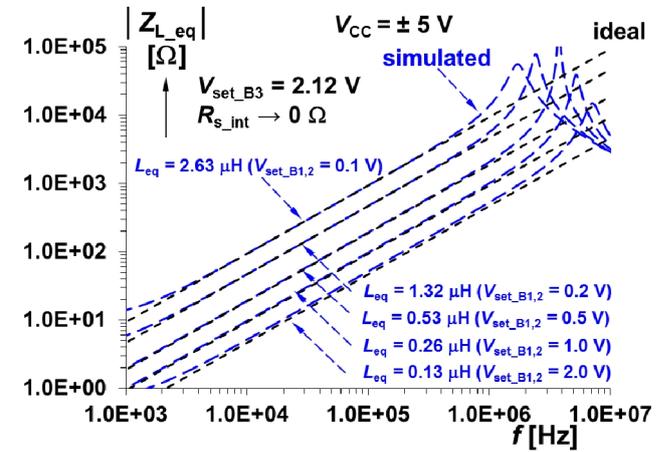


Fig. 2. Simulation results of impedance characteristics (magnitude) of proposed inductance simulator (Fig. 1) in lossless mode while tuning $B_{1,2}$.

A. Reconfigurable First-Order High-Pass/Inverting All-Pass Filter

Proposed circuit in Fig. 3 has a pseudo-differential configuration, which, in accordance with [8], means that it has differential input/output terminals, but inner circuit itself is not fully symmetrical. Special features of the introduced inductance simulator in Fig. 1 are very useful for reconnection-less reconfigurability of transfer function in pseudo-differential first-order high-pass/inverting all-pass (HP/iAP) filter. These features are not available if any standard solution of simulator of lossless inductance is employed as L_{eq} in structure shown in Fig. 3.

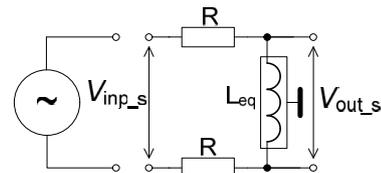


Fig. 3. Implementation of the floating inductance simulator in pseudo-differential-mode reconfigurable first-order HP/iAP filter (V_{inp/out_s} – symmetrical input/output voltage).

Differential-mode transfer function (full description) (1)

applied) of the circuit in Fig. 3 has symbolical form

$$K_{HP_iAP}(s) = \frac{V_{out_s}}{V_{inp_s}} = \frac{2 \left(s + \frac{2 - B_3}{C_{L_int} R_{L_int}} \right)}{s + \frac{R_{L_int} (2 - B_3) + R (B_1 + B_2)}{C_{L_int} R_{L_int}^2}} \quad (3)$$

Transfer function (3) offers high-pass (HP) response, if $B_3 = 2$

$$K_{HP}(s) = 2 \frac{s}{s + \frac{R (B_1 + B_2)}{C_{L_int} R_{L_int}^2}}, \quad (4)$$

where cut-off (pole) frequency is defined by

$$\omega_{p1} = \frac{R (B_1 + B_2)}{R_{L_int}^2 C_{L_int}}. \quad (5)$$

The easiest example of inverting all-pass (iAP) response is available for $R = R_{L_int}$, $B_1 = B_2 = B_{1,2} = 1$, $B_3 = 3$, from (3) we obtained simplified form of transfer

$$K_{iAP}(s) = 2 \frac{s - 1/(C_{L_int} R)}{s + 1/(C_{L_int} R)}. \quad (6)$$

The following relation must be valid for B_3 if iAP response is requested

$$B_3 = 2 + \frac{B_1 + B_2}{2}. \quad (7)$$

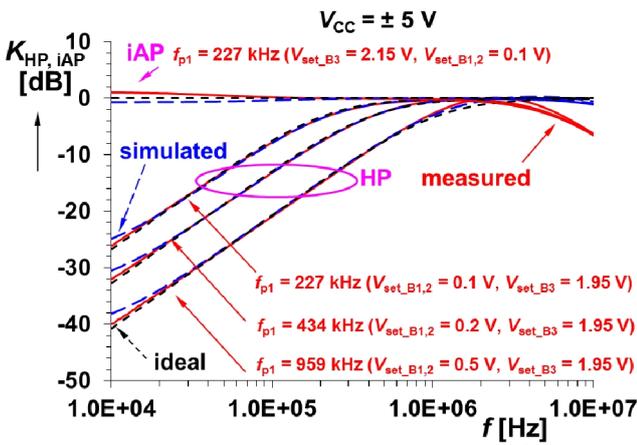


Fig. 4. Magnitude responses of the pseudo-differential-mode reconfigurable HP/iAP filter reconfigured by control of V_{set_B3} and several examples of tuning of the cut-off frequency of HP response by $V_{set_B1,2}$.

Both pole/zero frequency has simple form $\omega_{p1} = 1/RC_{L_int}$. Also note that pole frequency can be controlled electronically by $V_{set_B1,2}$ and type of transfer function is reconfigured by loss part of inductor simulator (B_3 gain). Figure 4 includes comparison of experimental and simulated

results of the filter from Fig. 3, when working resistor was set $R = 1 \text{ k}\Omega$. Resulting traces were obtained for ideal cut-off frequency equal to 216 kHz (simulated 226 kHz, measured 227 kHz) obtained by $V_{set_B1,2} = 0.1 \text{ V}$, $V_{set_B3} = 1.95 \text{ V}$ (HP response) or 2.15 V in case of iAP response ((7) for B_3). The example of ω_{p1} tuning in case of the HP response by control of $B_{1,2}$ can be observed also in Fig. 4. In measurements the change of $V_{set_B1,2}$ between 0.1 and 0.5 V ensures adjustment of f_{p1} from 227 kHz to 959 kHz, respectively.

B. Pseudo-Differential-Mode Second-Order Band-Pass Filter

This application is easily available by adding a capacitance between output terminals as shown in Fig. 5. Transfer function of ideal RLC ladder structure employing lossless L_{eq} considered in fully-differential form (1) is defined as

$$K_{BP}(s) = \frac{s \frac{1}{RC}}{s^2 + \frac{1}{2RC} s + \frac{1}{L_{eq} C}}. \quad (8)$$

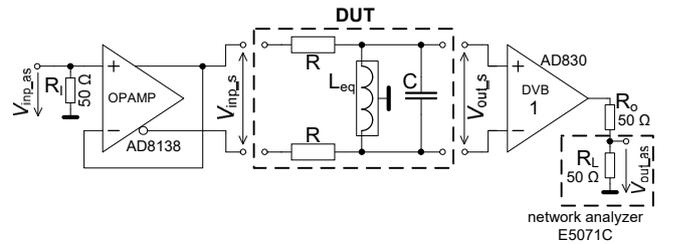


Fig. 5. Implementation of the inductance simulator in second-order RLC ladder differential band-pass filter. Schematic includes experimental setup (V_{inp/out_as} – asymmetrical voltage; V_{inp/out_s} – symmetrical voltage).

Considering the implementation of lossless L_{eq_int} (i.e. $B_3 = 2$), transfer function (8) changes to

$$K_{BP}(s) = \frac{s \frac{1}{RC}}{s^2 + s \frac{1}{2RC} + \frac{B_1 + B_2}{2R_{L_int}^2 C_{L_int} C}}, \quad (9)$$

where center (pole) frequency and quality factor have the following expressions:

$$\omega_{p2} = \frac{1}{R_{L_int}} \sqrt{\frac{B_1 + B_2}{2C_{L_int} C}} \Rightarrow \omega_{p2}|_{B_1=B_2=B_{1,2}} = \frac{1}{R_{L_int}} \sqrt{\frac{B_{1,2}}{C_{L_int} C}}, \quad (10)$$

$$Q = \frac{2R}{R_{L_int}} \sqrt{\frac{(B_1 + B_2)C}{2C_{L_int}}} \Rightarrow Q|_{B_1=B_2=B_{1,2}} = \frac{2R}{R_{L_int}} \sqrt{\frac{B_{1,2}C}{C_{L_int}}}. \quad (11)$$

Note that this second-order BP filter allows tuning of the pole frequency with theoretically no effect on bandwidth, because $BW [\text{Hz}] = 1/(4\pi RC)$, and also change of quality

factor without change of gain during the tuning process. Note that both filters (Fig. 3 and Fig. 5) have +6 dB pass-band gain (see const. 2 in (3) and (9)). However, experimental setup (output divider R_O and R_L of network analyser) performs division by 2, therefore, ideal pass-band gain of the whole system is 0 dB.

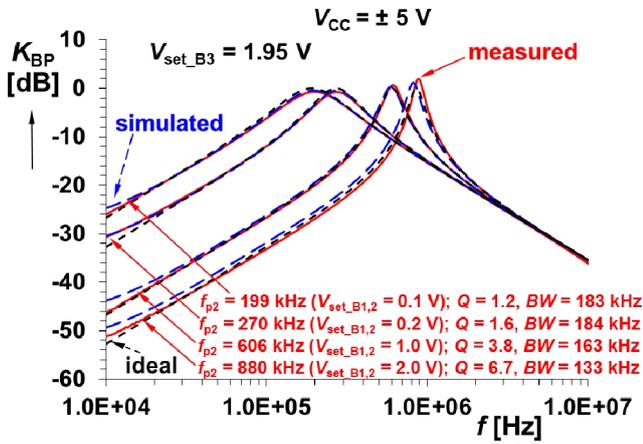


Fig. 6. Magnitude responses of the differential-mode second-order BP filter during tuning of the center frequency.

Comparison of experimental results, simulations, and theoretical traces of magnitude and phase responses for the pseudo-differential-mode BP filter is given in Fig. 6. Passive component values and active parameters were set as follows: $R_{L_int} = 560 \Omega$, $C_{L_int} = C = 470$ pF, $R = 1$ k Ω , $B_3 = 0$ and $B_1 = B_2 = B_{1,2} = 1$ ($V_{set_B1,2} = 1$ V). Theoretical, experimentally tested, and simulated BP achieved $f_{p2} = \{605, 606, \text{ and } 596\}$ kHz, with $BW = \{169, 163, \text{ and } 163\}$ kHz and $Q = \{3.6, 3.8, \text{ and } 3.7\}$ respectively. Tuning process (adjustment of $B_{1,2}$) can be also observed in Fig. 6. In measurements, adjusting of $V_{set_B1,2}$ between 0.1 V and 2 V offers range of f_{p2} tuning from 199 kHz to 880 kHz. All details are noted in figures. Presented experimental results in Fig. 4 and Fig. 6 were carried out using vector network analyser E5071C with test setup given in Fig. 5. Figure 7 shows the fabricated prototype including converters from single-ended to differential mode and vice versa serving for performed experimental tests.

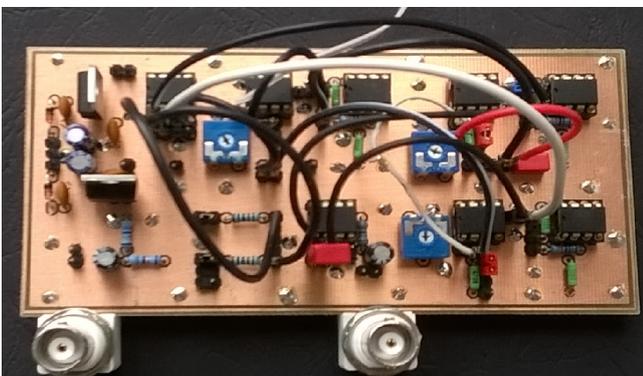


Fig. 7. Fabricated experimental prototype of pseudo-differential filter.

IV. DISCUSSION AND SUMMARIZATION OF RESULTS

Analysis of discussed inductance simulator revealed following advantages: a) possible implementation in differential applications (floating element), b) pseudo-

differential character of circuitry (inner grounded capacitor), c) simple electronic controllability of inductance value and losses including special form of losses (2) that allows interesting applications. Note that these features are not simultaneously available in many standard solutions. The value of designed inductance simulator was tested from 2.63 μ H to 0.13 μ H ($V_{set_B1,2}$ adjusted from 0.1 V up to 2.0 V), i.e. tunability ratio is approximately 1:20.

In accordance to the state-of-the-art discussed in Table I, the first application example of the designed special inductance implementation (reconfigurable first-order filter) represents unique device, because up to now (pseudo)differential-mode reconfigurable filters have not been widely investigated. Operation of the HP/iAP was verified by change of V_{set_B3} from 1.95 V to 2.15 V (HP \rightarrow iAP). Tuning range of the pole frequency yields values from 227 kHz to 959 kHz ($V_{set_B1,2}$ set from 0.1 V to 0.5 V). The second example of application, the pseudo-differential second-order BP was tested in frequency range from 199 kHz to 880 kHz ($V_{set_B1,2}$ set from 0.1 V to 2.0 V) with almost constant bandwidth approximately equal to 165 kHz.

V. CONCLUSIONS

Presented floating inductance simulator was tested in two novel applications namely pseudo-differential-mode reconfigurable first-order HP/iAP filter and second-order BP filter derived from passive prototypes. Due to limitations of commercially available devices used in inductance simulator, targeted frequency range was in hundreds of kHz. Experimental results are in good agreement with simulations and theory. Proposed inductance simulator offers interesting features in given applications and special form of its losses (in lossy mode of operation) brings useful implementations also in pseudo-differential-mode oscillators. Future potential of differential-mode circuits is under great interests of many researchers. Therefore, we expect further development of these circuits especially with reconnection-less reconfigurations.

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