# OPTIMIZATION OF LADDER FILTERS WITH GmC SIMULATION OF FLOATING INDUCTORS

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ABSTRACT:

A method of designing active filters from LC ladders is proposed in the paper, where the floating inductors are simulated by Operational Transconductance Amplifiers (OTAs). The problem of optimizing the dynamic range is described from the point of view of voltage and current limitations of the OTAs. The method is illustrated on the example of a video filter with extreme requirements on the group delay response.

**Keywords:** Ladder filter, OTA, current mode, optimization

## 1 INTRODUCTION

Replacement of conventional inductors by synthetic ones in passive LC ladder filters belongs to well-known methods of high-order low-sensitivity filter design. An efficient way of simulating the floating inductor consists in replacing the inductor by three OTAs (Operational Transconductance Amplifier) and one grounded capacitor [1]. However, the common drawback of OTAs is the low-level input voltage providing the linear mode of the amplifier. This can be in conflict with the requirements for a large dynamic range of signals being processed. When the filter is designed for the current-mode, the current limitations of the active elements should also be carefully monitored.

MAX435 is a commercial OTA [2], which appears to be an optimal circuit element for such designs. Its differential input and output can be utilized for the simplification of the well-known circuitry for simulating the floating inductor [1]. The transconductance of MAX435 is adjusted by an external two-terminal device. In the case of linear resistor, OTA has an extremely linear I&V characteristic. The limitations of the output current can be precisely set by another external resistor.

Using the concrete example of 5th-order video filter, a method for designing and optimizing such a circuit is described in this paper. The commercial MAX435 is used in the subcircuits of synthetic inductances. The procedure described can be applied to an arbitrary type of OTA.

## 2 MAX435 - A COMMERCIAL OTA

MAX435 is an OTA with 275MHz bandwidth and 850V/us slew rate. Its recommended symmetrical power supply is +-5V. The transconductance $g_m$ is set within a wide range by means of auxiliary $R_t$ resistor [2]. The recommended maximum current through $R_t$ as well as the output current are 10mA. A concrete saturation level $I_{max}$ can be adjusted by $R_{set}$ resistance approximately from 3mA up. $R_{set}$ = 5.9kΩ corresponds to a current of 10mA. The maximum recommended differential voltage is 2.5V.

## 3 SYNTHETIC INDUCTOR BASED ON MAX435

Fig. 1 shows a synthetic floating inductor which employs a pair of differential-input differential-output OTAs. It is a generalization of the circuit from [1], where three single-output OTAs are used for inductor replacement. The signal flow graphs attached describe the process of transforming voltage $V_1$ into current $I_1$ of OTA No. 1, transforming current $I_1$ into voltage across the capacitor, and transforming capacitor voltage into current $I_2$.

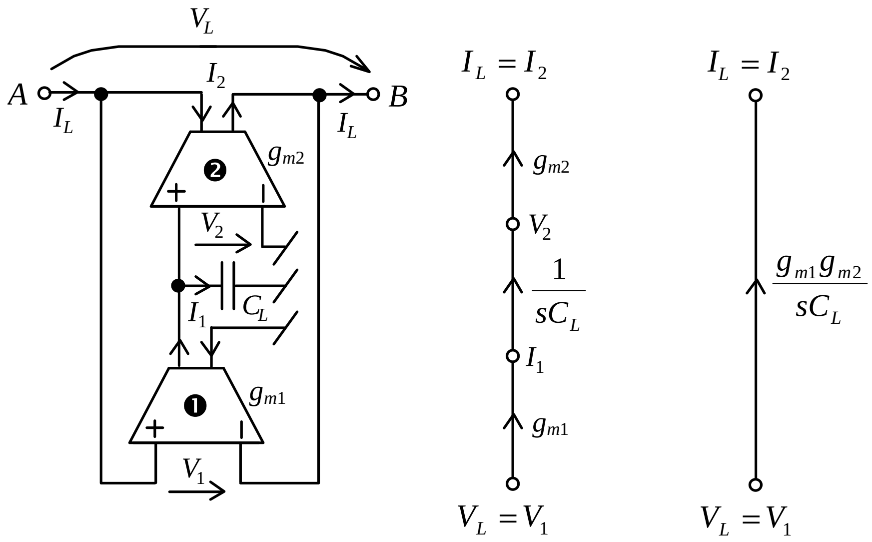


**Fig. 1:** Synthetic inductor and the corresponding signal flow graphs.

It follows from the last graph that the circuit implements a lossless floating inductor with the inductance

$$L = \frac{C_L}{g_{m1}g_{m2}}. \tag{1}$$

There are two degrees of freedom when designing the transconductances $g_{m1}$ and $g_{m2}$ and the capacitance $C_L$ from the desired inductance value. They can be used for dynamic range optimization. The following rule results from (1):

The inductor is preliminarily designed with the parameters $g_{m1}$, $g_{m2}$, and $C_L$. These parameters will be modified according to the rule

$$C_L' = a_0 C_L,\ g_{m1}' = a_1 g_{m1},\ g_{m2}' = a_2 g_{m2}, \tag{2}$$

where $a_0$, $a_1$, and $a_2$ are real positive numbers, fulfilling the equality

$$a_0 = a_1 a_2. \tag{3}$$

Then the resulting inductance is not changed due to this modification. However, current $I_1$ will be $a_1$ times greater and voltage $V_2$ will be $a_1/a_0$ times greater than before the modification of the parameters.

This rule will be used for the dynamic range optimization of target application, i.e. the active filter which simulates the LC ladder.

The following equality also results from the graph in Fig. 1:

$$\frac{V_2}{V_1} = \frac{g_{m1}}{g_{m2}} \frac{I_2}{I_1} . \tag{4}$$

The purpose of optimizing the upper limit of the dynamic range is to equalize the voltage and current levels inside the synthetic inductors, thus $V_1 = V_2$ and $I_1 = I_2$. Eq. (4) shows that a complete equalization is enabled only when both transconductances are equal.

## 4 LC LADDER SIMULATION

Fig. 2 (a) shows the schematic of a lowpass LC ladder filter which has been designed according to Bessel approximation on the basis of the following specifications:

DC gain 0dB, 3-dB cutoff frequency 5MHz, attenuation at least 50dB for frequencies above 27MHz, maximally flat group delay. This specification is derived from the parameters of commercial video filter FMS6400-1 by Fairchild Semiconductor [3].

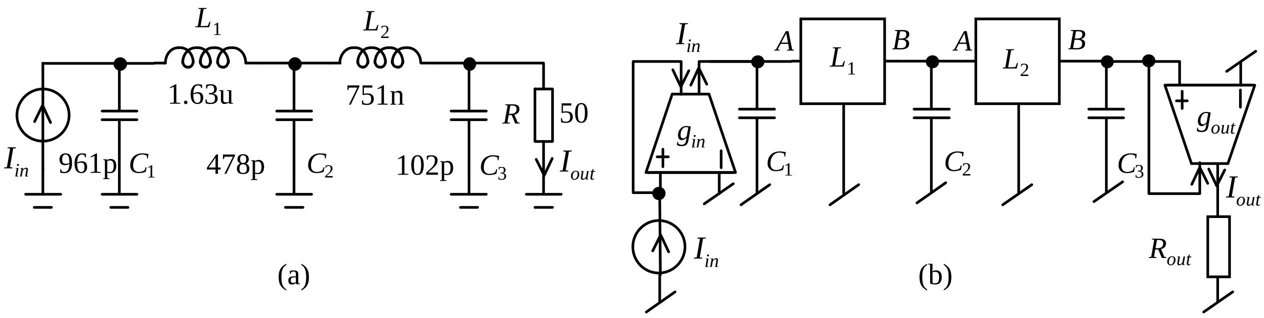


**Fig. 2:** (a) 5MHz lowpass ladder, (b) active ladder simulation by means of synthetic inductors and OTAs.

An active realization of the LC ladder is shown in Fig. 2 (b). Blocks "$L_1$" and "$L_2$" are the synthetic inductors from Fig. 1. OTA with transconductance $g_{in}$ serves as a current-controlled current source, providing low driving point impedance $R_{in} = 1/g_{in}$ for the input current source. OTA with transconductance $g_{out} = 1/R$ =20mS delivers current $I_{out}$ into an independent load $R_{out}$.

Let us design the active filter from Fig. 2 (b) for a maximum driving current value of 10mA.

The results of PSpice AC analysis of the passive LC ladder from Fig. 3(a) are shown in Fig. 3. The analysis was performed on the assumption of the attribute AC=10mA of the current source $I_{in}$. Those curves are depicted which are important for studying the filter dynamic range, i.e. the output voltage across $R$ (i.e. the input voltage of the terminating OTA), the output current through $R$ (i.e. the output current of the terminating OTA), the voltages across $L_1$ and $L_2$ (i.e. the input voltages of OTA No. 1 in the synthetic inductors from Fig. 1), and the currents through $L_1$ and $L_2$ (i.e. the output currents of OTA No. 2 in the synthetic inductors from Fig. 1). The curves are determined by the parameters of filter elements and they can be influenced only via choosing another realization structure, another approximation of frequency response or another impedance level. The Bessel approximation used here guarantees a maximally flat group delay response.

Fig. 3 shows that both the synthetic inductors and the terminating OTAs should be designed for a maximum current of 10mA. It is fulfilled for MAX435 when adjusting $R_{set}$ = 5.9kΩ. The input voltage of the end OTA is maximum (1V) for low frequencies. The required $g_m$ value of this OTA is $1/R$ = 20mA/V and it can be set via $R_t$ = 200Ω [2]. This amplifier will operate in the linear regime till its full current excitation.

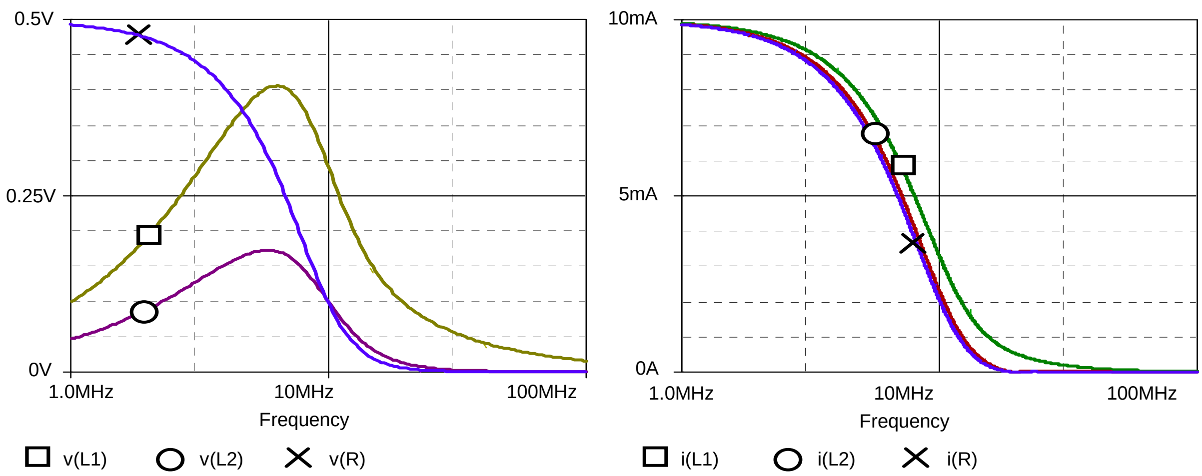


**Fig. 3:** Results of the AC analysis of LC ladder from Fig. 2 (a) for $I_{in}$ = 10mA.

The front-end OTA, excited by the current source $I_{in}$, will be designed with $g_{in}$ = 100mA/V or $R_t$ = 40Ω in order to provide low driving point impedance $R_{in} = 1/g_{in}$ = 10Ω. The maximum value of the input voltage will be 100mV for full current excitation of the filter input.

The curves V(L1), V(L2), I(L1), and I(L2) can be used for designing the synthetic inductors. The voltage across L1 (L2) takes its maximum value 408mV (173mV) at a frequency of 6.31MHz (5.75MHz). As stated before, the currents are maximum, i.e. 10mA at a frequency of 0 Hz.

In the first step, a preliminary design of the synthetic inductors according to Eq. (1) will be performed. The initial capacitance in both inductors will be set to 100pF. For equal values of $g_{m1}$ and $g_{m2}$, Eq. (1) leads to the results in Tab. 1, column ①.

**Tab. 1:** Parameters of elements of the synthetic inductors before and after optimization.

| | | ① before optimization | ② after optimization |
|---|---|---|---|
| $L_1$ | $g_{m1}$ [mA/V] | 7.833 | 24.505 |
| | $g_{m2}$ [mA/V] | 7.833 | 24.505 |
| | $R_{t1}$ [Ω] | 511 | 163 |
| | $R_{t2}$ [Ω] | 511 | 163 |
| | $C_L$ [pF] | 100 | 979 |
| $L_2$ | $g_{m1}$ [mA/V] | 11.539 | 57.902 |
| | $g_{m2}$ [mA/V] | 11.539 | 57.902 |
| | $R_{t1}$ [Ω] | 347 | 69 |
| | $R_{t2}$ [Ω] | 347 | 69 |
| | $C_L$ [pF] | 100 | 2518 |

The Signal-Flow-Graph from Fig. 1 describes relations among the internal variables of the synthetic inductor, particularly between the inductor terminal voltage, the output current of OTA No. 1, the input voltage of OTA No. 2, and the inductor terminal current. These relations can be pre-set in the Probe postprocessor of PSpice simulator [4]. The results are shown in Fig. 4 (a). The left-side part contains the curves of OTA input voltages, the right-side shows the curves of OTA output currents.

The maximum values of voltages and currents from Fig. 4 are given in Table 2, column ①. Note that the input voltages of OTA No. 2 are too high whereas the output currents of OTA No. 1 do not reach their permitted maxima for either inductor. In addition, the following equality is true:

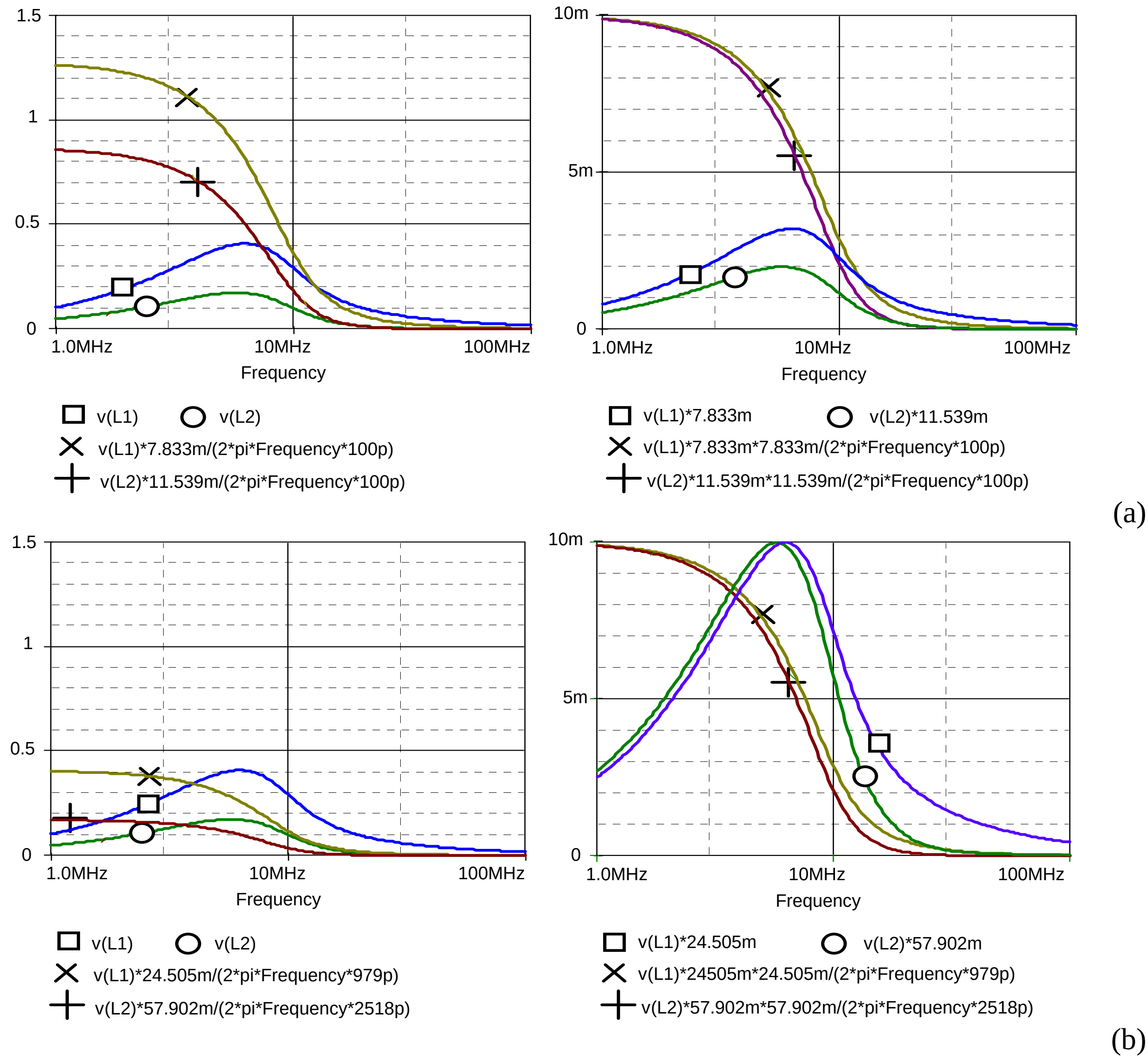


**Fig. 4:** PSpice analysis of internal relations of synthetic inductors by means of dependences described by Signal-Flow-Graphs from Fig. 1, (a) before, (b) after optimizing the upper limit of the dynamic range.

**Tab. 2:** Maximum values of inductor voltages and currents before and after optimization.

| | | ① before optimization | ② after optimization |
|---|---|---|---|
| $L_1$ | $V_{1\max}$ [V] | 0.4082 | 0.4082 |
| | $V_{2\max}$ [V] | 1.277 | 0.4082 |
| | $I_{1\max}$ [mA] | 3.197 | 10.003 |
| | $I_{2\max}$ [mA] | 10 | 10 |
| $L_2$ | $V_{1\max}$ [V] | 0.1727 | 0.1727 |
| | $V_{2\max}$ [V] | 0.8666 | 0.1727 |
| | $I_{1\max}$ [mA] | 1.992 | 9.998 |
| | $I_{2\max}$ [mA] | 10 | 10 |

$$\frac{V_{2\max}}{V_{1\max}} = \frac{I_{2\max}}{I_{1\max}}, \qquad (5)$$

which is in conformity with Eq. (4). These ratios are 3.128 for inductor No. 1 and 5.018 for inductor No. 2.

Applying the rule from Section 3 and the corresponding equations (2) and (3), we conclude that the upper limits of the dynamic ranges of voltages and currents in the inductors can be equalized if both transconductances are multiplied by ratio (5) and the capacitance is simultaneously multiplied by the square of this ratio. After this optimization, the parameters of the elements are as shown in Table 1, column ②. The corresponding frequency responses are given in Fig. 4 (b) and the maximum values of voltages and currents can be found in column ② of Table 2.

Frequency responses of the optimized active filter, simulated in PSpice simultaneously with the frequency responses of ideal LC ladder, are shown in Fig. 5. Note that the group delay is more sensitive to real properties of the amplifiers than the gain response. The analysis found that low output impedance of MAX435, namely 3.5kΩ, is a dominant factor which imports losses to the ladder structure. Nevertheless, the group delay ripple is less than is specified for similar commercial video filter FMS6400-1 [3].

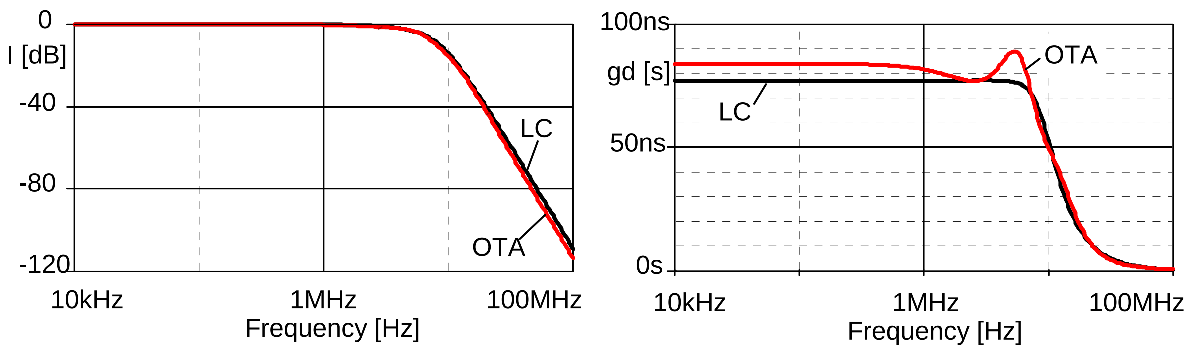


**Fig. 5:** Frequency responses of ideal LC ladder (LC) and optimized active filter (OTA).

## 5 CONCLUSIONS

A circuitry simulating the lossless floating inductor, employing a pair of differential-input differential-output OTAs is proposed in the paper. A method of optimizing the upper limit of the dynamic range of OTA input voltages and output currents is described. This method is demonstrated on the example of $5^{th}$-order video filter which uses the commercial OTAs MAX435. The results of PSpice analyses are in accordance with the design assumptions.

## 6 ACKNOWLEDGMENT

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## 7 REFERENCES

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