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LABORATORY TASK DEDICATED TO FILTERS WITH SWITCHED CAPACITORS

LABORATORNÍ ÚLOHA ZAMĚŘENÁ NA FILTRY SE SPÍNANÝMI KAPACITORY

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Abstract

This thesis describes the basic principles of circuits based on switched capacitor technology. The advantages of using this technology are described, and the different connection types of switched capacitors are shown. A graphic comparison of the operation of classic analog filters and filters based on switched capacitor technology is also provided. A solution for the implementation of a laboratory board for use in education is offered. The board has been successfully tested, and an example of a laboratory problem solution is given.

Keywords

Analog filter, switched capacitor filters, switched capacitor technology, Op Amp, inverting Op Amp, low-pass filter, high-pass filter, bandpass filter, state variable filter, integrated board, LTC1043, LT1056, approximation types.

Abstrakt

Tato práce popisuje základní principy obvodů založených na technologii spínaných kondenzátorů. Jsou popsány výhody použití této technologie a uvedeny různé typy zapojení spínaných kondenzátorů. Je také uvedeno grafické srovnání činnosti klasických analogových filtrů a filtrů založených na technologii spínaných kondenzátorů. Je nabídnuto řešení pro realizaci laboratorní desky pro použití ve výuce. Deska byla úspěšně otestována a je uveden příklad řešení laboratorního problému.

Klíčová slova

Analogový filtr, spínané kondenzátorové filtry, technologie spínaných kondenzátorů, operační zesilovač, invertující operační zesilovač, dolní propust, horní propust, pásmová propust, stavově proměnný filtr, integrovaná deska, LTC1043, LT1056, aproximační typy.

Rozšířený abstrakt

V současné době je kladen velký důraz na miniaturizaci velikosti desek s plošnými spoji jako celku, a to jak jednotlivých součástek, tak celých elektronických systémů. Tento problém lze vyřešit pomocí technologie spínaných kapacitorů. Tato technologie přináší mnoho výhod, například zmenšení rozměrů součástek při realizaci elektronických filtrů.

Cílem této práce je seznámit se se základními vlastnostmi této technologie pro následný návrh laboratorní úlohy pro účely výuky. Princip technologie spínaných kondenzátorů je ukázán na jednoduchém příkladu nahrazení klasického rezistoru jeho ekvivalentním obvodem se spínaným kondenzátorem. Tento obvod lze realizovat pomocí přesného stavebního bloku LTC1043, který obsahuje dva spínače a může být řízen externím hodinovým signálem.

V této práci bude nejprve nastudována teorie technologie spínacích kondenzátorů. Poté bude uvedeno schéma budoucího laboratorního přípravku, které bylo testováno v simulátoru OrCAD PSpice. Nakonec bude představena realizace budoucí laboratorní přípravku, který byl testován, a byl uveden příklad řešení laboratorní úlohy.

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Brno, May 28, 2023

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SYMBOLS AND ABBREVIATIONS

Abbreviations:

CMOS	Complementary metal–oxide–semiconductor
MOSFET	Metal–oxide–semiconductor field-effect transistor
BUT	Brno University of Technology
KHN	Kerwin-Huelsman-Newcomb (filter)
BNC	Bayonet Neill–Concelman (connector)
PCB	Printed Circuit Board

Symbols:

ω_0	cutoff angular frequency	(s ⁻¹)
n	order of filter	(-)
B_n, H_n, K_n	transfer function of filter	(-)
ε	pulsation index	(-)
C_n	Chebyshev polynomial	(-)
R_n	elliptic rational function	(-)
ξ	selectivity factor	(-)
U	voltage	(V)
I	current	(A)
n_i	zeros at transfer function	(-)
p_i	poles at transfer function	(-)
φ	phase	(°, rad)
Q	quality factor	(-)
f_0	central frequency	(Hz)
K_0	transmission on f_0	(-)
ΔQ	charge	(C/s)
T	period	(s)
R	resistance	(Ω)
C	capacity	(F)
G	gain	(-, dB)

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INTRODUCTION

This bachelor's thesis aims to study the principles of circuit function built on switched capacitor technology.

Nowadays, board manufacturers strive to minimize both specific components and boards in general. Switched capacitor technology solves this problem, as the main advantage of switched capacitor circuits is their compactness compared to conventional high-power resistors, for example.

To achieve these goals, the methods of using this technology were analyzed, followed by simulations of various integrated circuits available on the market using the OrCAD Pspice simulation program.

In this bachelor's thesis, the main principles of operation of circuits using switched capacitors were analyzed, upon which a solution was proposed for the construction of future laboratory tasks. This will allow students to learn all the intricacies of technology based on switched capacitors.

1. FILTERS

Electrical filters are actively used in receiving and transmitting devices for signal processing to extract more useful and necessary parts of the signal or its spectrum. Electrical filters process the signal spectrum to suppress unwanted components that are considered unnecessary in radio engineering and are not used for further signal processing.

1.1 Types of filters

Electrical filters fall into two main categories: passive and active filters. Passive filters consist of passive electrical components such as resistors, capacitors, and inductors. This type of filter does not require a power source to run the circuit, and it does not amplify the output signal. Unlike passive filters, active filters amplify the power of the output signal and also use one or more active components such as transistors or operational amplifiers.

1.1.1 According to the filter type

Filters are divided depending on the frequencies that the filters allow or block. These are low-pass, high-pass, band-pass, and band-stop filters, their characteristics are shown in Figure 1.1.

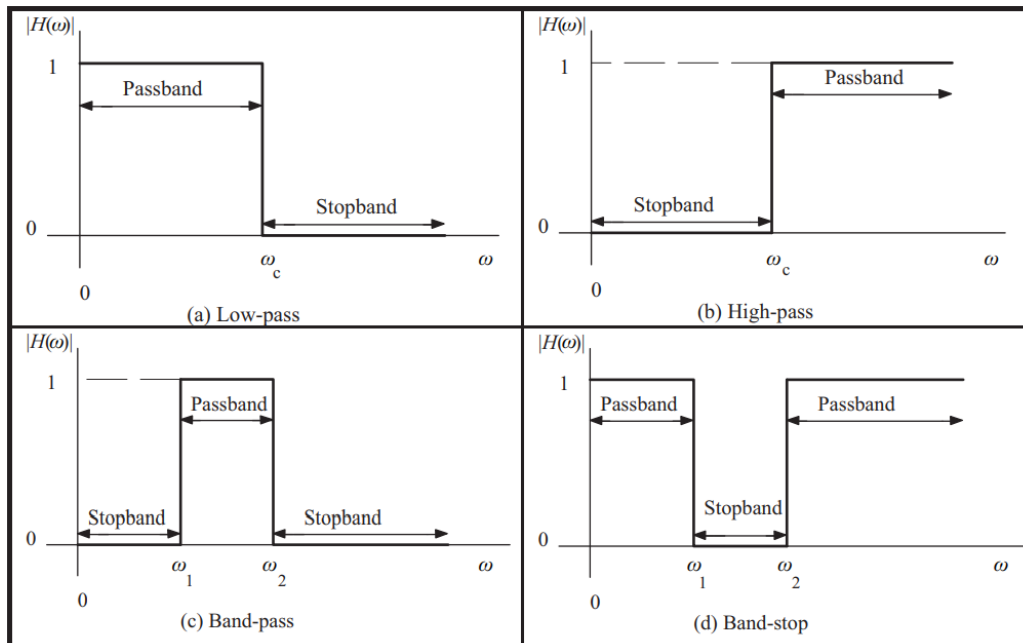


Fig. 1.1 Common type of filters [1]

An ideal low-pass filter shown in Figure 1.1a passes low frequencies up to frequency ω_c , where the filter's characteristic tends to zero and then the filter does not pass any signal with a higher frequency than ω_c [1]. The filter gain in the passband is unity and zero in the stopband.

An ideal high-pass filter is shown in Figure 1.1b. In essence, this is an inversion filter from a low-pass filter, where, on the contrary, frequencies up to frequency ω_c are not passed, and beyond this frequency, the filter is open and passes all frequencies up to infinity. After this frequency, its filter gain is 1.

The bandpass filter suppresses harmonic signal frequencies up to the ω_1 frequency and then passes all signal components until it reaches the ω_2 frequency, where it closes again and does not pass any signal, or: $\omega_1 < \omega < \omega_2$. Figure 1.1c.

A band-stop filter, unlike a band-pass filter, does not pass, but suppresses frequencies in the specified range $\omega_1 < \omega < \omega_2$, where all frequencies between ω_1 and ω_2 are completely suppressed. These filters are often called notch filters. Band-stop filters, which suppress frequencies in the specified range $\omega_1 < \omega < \omega_2$, are often called notch filters. Figure 1.1d.

The ideal filters have been described above, which do not exist in our time. Because the gain characteristics of such filters will not instantly rise from 0 to 1 or fall from 1 to 0. In reality, the transition from the pass part to the suppressed part will take some time. This period of the segment is called the transition band. Figure 1.2. [1]

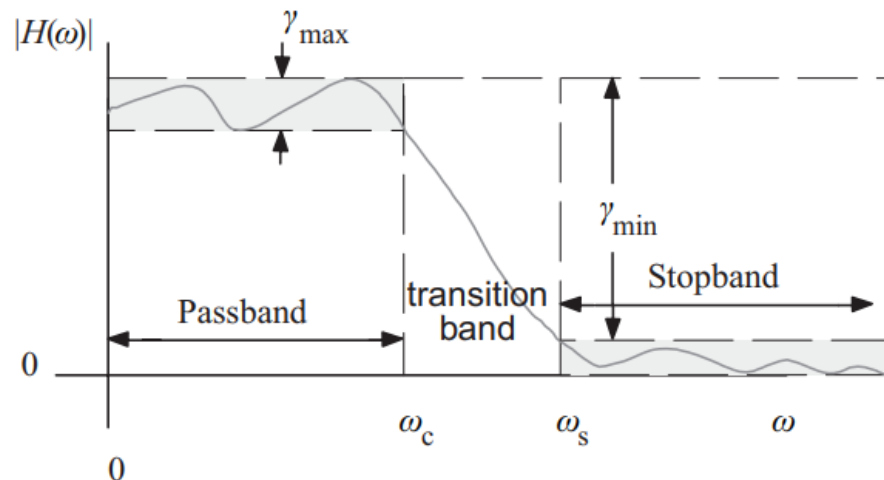


Fig. 1.2 Realistic low-pass filter 0

1.1.2 According to the order of the filter

In a passive filter, the number of reactive elements, such as inductors and capacitors, determines the filter order. The more reactive elements there are in the circuit, the higher

the filter order can be. However, the minimum number of reactive elements must correspond to the filter order. For example, for a 3rd order filter, at least 3 reactive elements must be present in the circuit. By increasing the filter order, we change the slope of the rolloff and increase it by 20 dB/decade. Table 1.1 shows how the filter order affects the amount of rolloff in the amplitude response. The number of zeros and poles of the filter transfer function $H(s)$, which describes the filter's behavioral characteristic, can also determine the filter order.

Table 1.1 Decay slope versus filter order

The order of filter	Rolloff [dB/oct]	Rolloff [dB/dec]
1	-6	-20
2	-12	-40
3	-18	-60
4	-24	-80
5	-30	-100

The order of the filter affects the decay rate after the cutoff frequency. For example, to narrow the transition band and increase the steepness of the slope, we need to increase the filter order (see Figure 1.3). In reality, when implementing a filter, the order of the filter determines the number of reactive components used in the circuit, which can affect the size of the filter, its cost, and the sensitivity of the filter, necessitating fine-tuning.

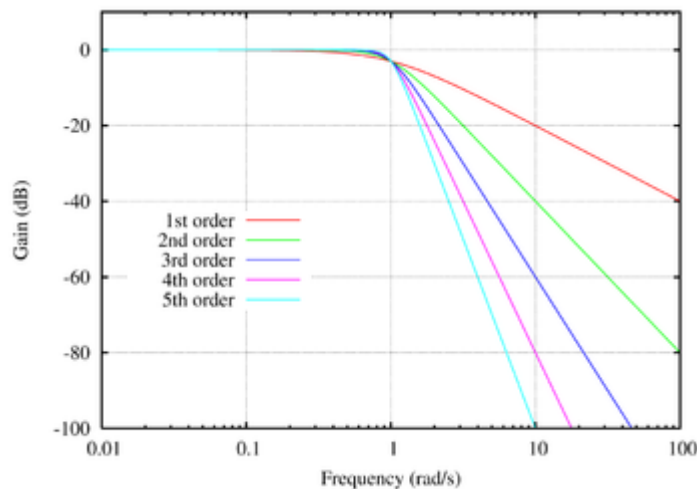


Fig. 1.3 The gain of Butterworth low-pass filters of orders 1 through 5 [2]

It is also worth adding that the cascading arrangement of several filters increases the overall order of the transfer function. Figure 1.4.

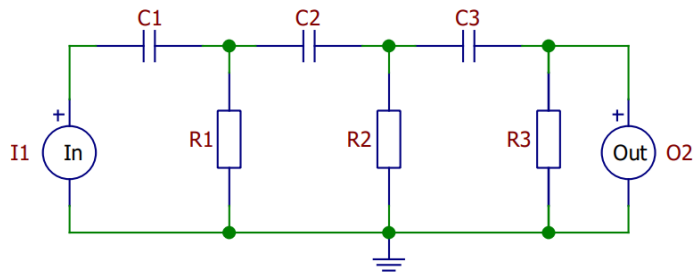


Fig. 1.4 Cascade connection of 3 high-pass filters

1.1.3 Butterworth approximation

The Butterworth filter is designed to have a frequency response that is as smooth as possible at passband frequencies. Such a filter decreases smoothly (unlike the Chebyshev filter) to non-passing frequencies. Figure 1.3 shows a Butterworth low-pass filter, where a first-order filter attenuates at -20 dB/dec, a similar second-order filter attenuates at -40 dB/dec, and so on.

In fact, the Butterworth filter is the only filter that retains the cutoff shape of the frequency response for higher filter orders. In addition, this filter has a more linear phase-frequency response.

The transfer function of a Butterworth filter can be described by the following expression

$$|B_n(\omega)| = \sqrt{1 + \left(\frac{\omega}{\omega_0}\right)^{2n}}, \quad (1.1)$$

where n is filter order and ω_0 is cutoff frequency (-3 dB).

Let's consider a variant of the normalized low-pass filter on Table 1.2. The purpose of normalization is to generalize the characteristics of filters in the further design of different types of filters.

Table 1.2 Normalized Low-Pass Filter Coefficient of Butterworth Approximation

n	b₀	b₁	b₂	b₃	b₄	b₅	b₆	b₇
1	1,000							
2	1,000	1,414						
3	1,000	2,000	2,000					
4	1,000	2,613	3,414	2,613				
5	1,000	3,236	5,236	5,236	3,236			
6	1,000	3,863	7,464	9,142	7,464	3,864		

7	1,000	4,494	10,098	14,592	14,592	10,098	4,494	
8	1,000	5,126	13,137	21,846	25,688	21,846	13,137	5,126

1.1.4 Chebyshev approximation

The Chebyshev filter is used when small ripples are allowed in the passband (for the Chebyshev filter of the first type) or in the stopband (for the Chebyshev filter of the second type). This type of filter also has a steeper frequency response rolloff. The Chebyshev filter is used when it is important to have smoothness and steepness of the frequency response during the transition from the passband to the suppression band. The frequency response of the filter behavior is described by Chebyshev polynomials.

The frequency response of the Chebyshev filter is described by the function

$$|H_n(j\omega)| = \frac{1}{\sqrt{1 + \varepsilon^2 C_n^2\left(\frac{\omega}{\omega_0}\right)}}, \quad (1.2)$$

where ε is pulsation index, ω_0 cutoff frequency, C_n Chebyshev polynomial of the n th order.

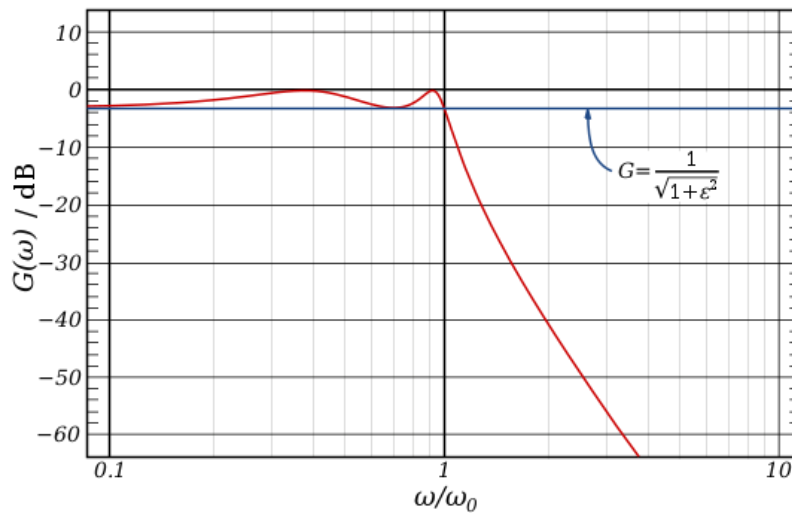


Fig. 1.5 The frequency response of Chebyshev filter (low-pass filter) [2]

Table 1.3 Normalized Low-Pass Filter Coefficient of Chebyshev Approximation (3 dB, $b_n=1$)

n	b ₀	b ₁	b ₂	b ₃	b ₄	b ₅	b ₆	b ₇
1	1,002							
2	0,708	0,645						
3	0,251	0,928	0,597					

4	0,177	0,405	1,169	0,582				
5	0,063	0,408	0,549	1,415	0,574			
6	0,044	0,163	0,699	0,691	1,663	0,517		
7	0,016	0,146	0,300	1,052	0,831	1,912	0,568	
8	0,011	0,056	0,321	0,472	1,467	0,972	2,161	0,567

1.1.5 Inverse Chebyshev approximation

Just as the Chebyshev filter of the first kind has ripple in the passband, the Chebyshev filter of the second kind (also known as the inverse Chebyshev filter [2]) has ripple in the stopband. These filters are used less frequently because they exhibit a less steep roll-off.

The frequency response of the inverse Chebyshev filter is described by the function

$$H_n(j\omega) = \frac{1}{\sqrt{1 + \frac{1}{\epsilon^2 C_n^2\left(\frac{\omega}{\omega_0}\right)}}} \quad (1.3)$$

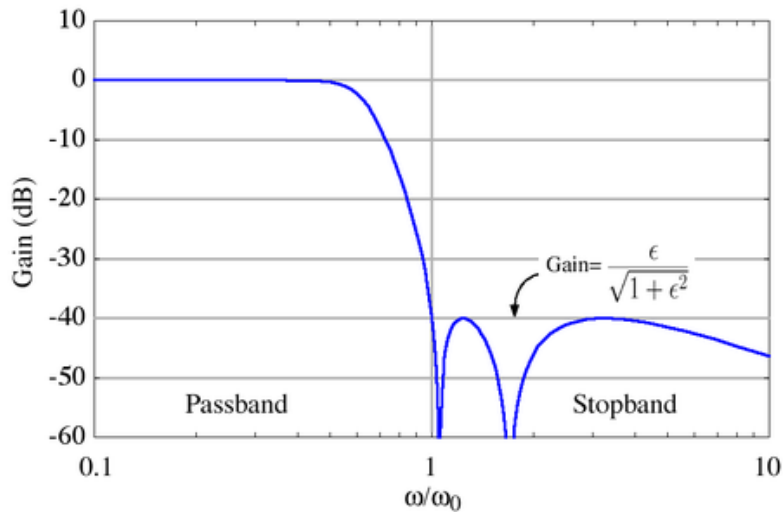


Fig. 1.6 The frequency response of inverse Chebyshev filter (low-pass filter) [2]

1.1.6 Cauer (Elliptic) approximation

The main feature of the Cauer filter is that it exhibits ripple in both the passband and the stopband, which are independent of each other. Additionally, this type of filter has a very steep frequency response slope, allowing for effective separation of frequencies. The Cauer filter can be considered as an implementation of the filters described earlier.

For instance, by eliminating the ripple in the stopband, we obtain the Chebyshev filter. Similarly, removing the ripple in the passband yields the inverse Chebyshev filter. Finally, if there are no ripples in either the passband or the stopband, we obtain the Butterworth filter.

The frequency response of the Cauer filter is described by the function

$$|H_n(j\omega)| = \frac{1}{\sqrt{1 + \varepsilon^2 R_n^2\left(\xi, \frac{\omega}{\omega_0}\right)}}, \quad (1.4)$$

where ε is pulsation index, ω_0 cutoff frequency, R_n is the n th-order elliptic rational function, ξ is the selectivity factor.

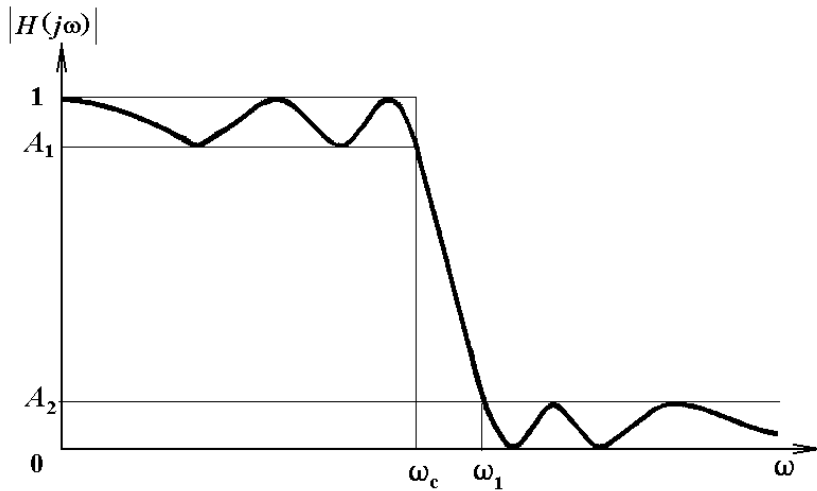


Fig. 1.7 The frequency response of Cauer filter [2]

1.2 Transfer function

The transfer function of filters serves to mathematically describe the behavior of various filters. The main equation of the function has the form

$$H(s) = \frac{U_2(s)}{U_1(s)}, \quad (1.5)$$

where U_1 , U_2 are the input and output voltage images of the filter, s is the Laplace transform operator, $s = \sigma + j\omega$.



Fig. 1.8 Double gate

In essence, the transfer function is the ratio of two polynomials. The roots of the numerator polynomial are called zeros, and the roots of the denominator polynomial are called poles. The arrangement of zeros and poles on the complex plane determines the behavior of the filter, as well as its oscillation stability.

An equation representing the roots and zeros of the transfer function is given

$$H(s) = \frac{U_2(s)}{U_1(s)} = \frac{a_m}{b_n} \cdot \frac{(s-n_1) \cdot \dots \cdot (s-n_i)}{(s-p_1) \cdot \dots \cdot (s-p_i)} \quad (1.6)$$

The complex transfer function has the form

$$H(s) = |H(s)|e^{-j\varphi(\omega)}, \quad (1.7)$$

where the modulus of the transfer function is the amplitude frequency response, and the argument of the function is the phase frequency response.

The general transfer function of the 2nd order filter has the form

$$H(s) = K_0 \frac{s^2 + \frac{\omega_n}{Q_n}s + \omega_n^2}{s^2 + \frac{\omega_p}{Q_p}s + \omega_p^2} = \frac{a_2s^2 + a_1s + a_0}{b_2s^2 + b_1s + b_0}, \quad (1.8)$$

where ω is the cutoff frequency, Q is the quality factor.

The quality factor Q of the filter determines the resonance band and shows how many times the filter energy is greater than the energy loss when the phase changes by 1 rad. The higher the quality factor, the lower the loss, hence the attenuation lasts longer.

1.2.1 Transfer function of the low-pass filter

The low-pass filter passes frequencies up to the resonant frequency, where its frequency response cuts off (in the ideal case) or attenuates (in the real case) with a slope of -40 dB/dec. The coefficients a_2 and a_1 are equal to zero. The transfer function of the low-pass filter is

$$H(s) = K_0 \frac{\omega_p^2}{s^2 + \frac{\omega_p}{Q_p}s + \omega_p^2} = \frac{a_0}{b_2s^2 + b_1s + b_0}. \quad (1.9)$$

1.2.2 Transfer function of the high-pass filter

The high-pass filter has zeros located at the origin, that is, the coefficients a_1, a_0 are zero. The transfer function will then take the form

$$H(s) = K_0 \frac{s^2}{s^2 + \frac{\omega_p}{Q_p}s + \omega_p^2} = \frac{a_2 s^2}{b_2 s^2 + b_1 s + b_0}. \quad (1.10)$$

1.2.3 Transfer function of the bandpass filter

A bandpass filter passes frequencies in a certain limited frequency range. Its transfer function has zero coefficients a_2, a_0 and has the form

$$H(s) = K_0 \frac{\frac{\omega_p}{Q_p} s}{s^2 + \frac{\omega_p}{Q_p}s + \omega_p^2} = \frac{a_1 s}{b_2 s^2 + b_1 s + b_0}. \quad (1.11)$$

1.2.4 Transfer function of the band-stop filter

A band-stop filter, unlike a band-pass filter, delays frequencies in a certain limited frequency zone. Therefore, its transfer function has a zero coefficient only a_1 and has the form (when $\omega_n = \omega_p$)

$$H(s) = K_0 \frac{s^2 + \omega_p^2}{s^2 + \frac{\omega_p}{Q_p}s + \omega_p^2} = \frac{a_2 s^2 + a_0}{b_2 s^2 + b_1 s + b_0}. \quad (1.12)$$

1.3 Switched capacitor technology

1.3.1 History

The history of switched capacitors began in the 19th century when the famous physicist J. C. Maxwell first mentioned them. However, the real discovery of switched capacitors took place a hundred years later by the German-American scientist Gerhard Fettweis [3]. In 1981, during a conference in Chicago, Fettweis drew attention to Backer's 1967 patent, which described circuits consisting of switches, capacitors, and operational amplifiers. Nevertheless, it was Fettweis himself who investigated circuits containing periodically controlled capacitors. In 1963, Fettweis presented his doctoral dissertation on Resonant Transfer Circuits, where circuits were used to achieve break-even transfer of electrical charge between capacitors using a switch and an inductor.

1.3.2 CMOS transistors

Maxwell's principle involves the synchronous switching of a charged capacitor connected in series to a battery. The switching takes place at each period T , causing the polarities

to change. Within one period, the capacitor gets charged from the battery with an electric charge. When the switches are toggled, the capacitor discharges, resulting in an average current of $I = 2CU/T$. This average current value is then passed through a resistor equivalent to $T/2C$ (refer to Figure 1.9).

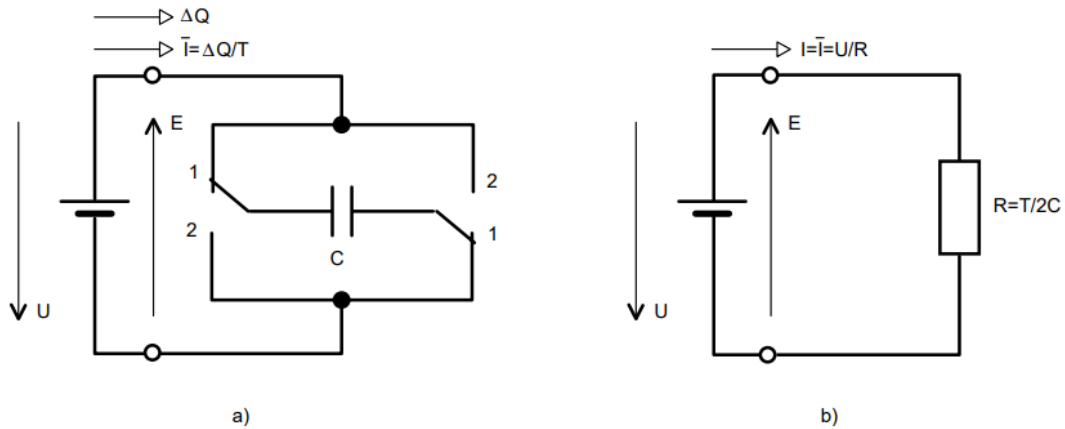


Fig. 1.9 a) Maxwell's principle of switched capacitors, b) Equivalent Circuit [3]

Consider an active RC filter, which is implemented using a switched capacitor filter. The capacitor size is approximately 5 pF, and the resistance of the CMOS transistor is 1 kΩ. The time constant in this case will be equal to 5 ns. The approximate charge time for a capacitor is 7 time constants, so switched capacitors used with CMOS technology can be used at sampling rates up to tens of MHz. If we take into account that the sampling frequency is 100 kHz, then we can replace the 10 MΩ resistor with a 1 pF capacitor. Such a capacitor occupies 500 times less area on the board than the original resistor, which allows for the reduction of the overall dimensions of the board (Figure 1.10).

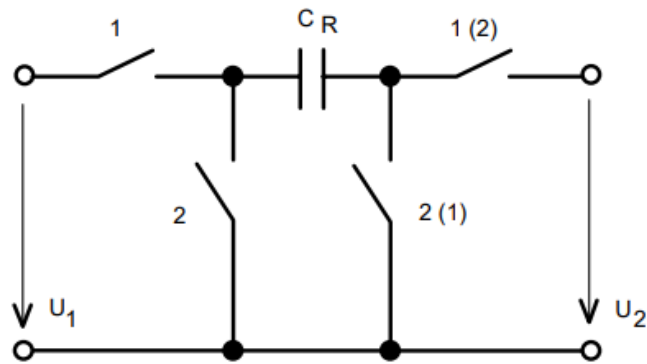


Fig. 1.10 Implementation of RC by Switched Capacitors [3]

1.3.3 Analysis of available integrated circuits

The first and easiest method to implement switched capacitor filters is to replace all the resistors in the original filter with their switching equivalents.

Another possibility of implementing these schemes is with the help of integrated filters with a finely tuned frequency response. Such filters contain switching signal generators but can also be connected to an external generator. Such integrated circuits often contain an operational amplifier that is not connected to the general circuit. The user themselves create and connect a filter using external elements.

The MAX265 and MAX266 integrated circuits contain two second-order filters. Six bits set the ratio of the switching frequency to the sampling frequency. The integrated circuits LTC1059, LTC1060, LTC1061, and LTC1064 contain two integrators with the same time constants. The transfer function and quality factor are adjusted using external resistors and by properly setting the inputs and outputs. They can be used at frequencies ranging from 0.1 Hz to 140 kHz. The maximum sampling frequency is up to 7 MHz. The ratio of the sampling frequency to the switching frequency can be set to either 100:1 or 50:1. [4]

The final way to implement a switched capacitor filter is with the Precision LTC1043 building block, which is shown in Figure 1.11. It contains 4 precise switches and a switchable signal generator. Additionally, a switchable signal generator can be brought from outside and switched with a frequency of up to 5 MHz. With the help of such a block and high-quality components, it is possible to implement various circuits and filters with switched capacitors.

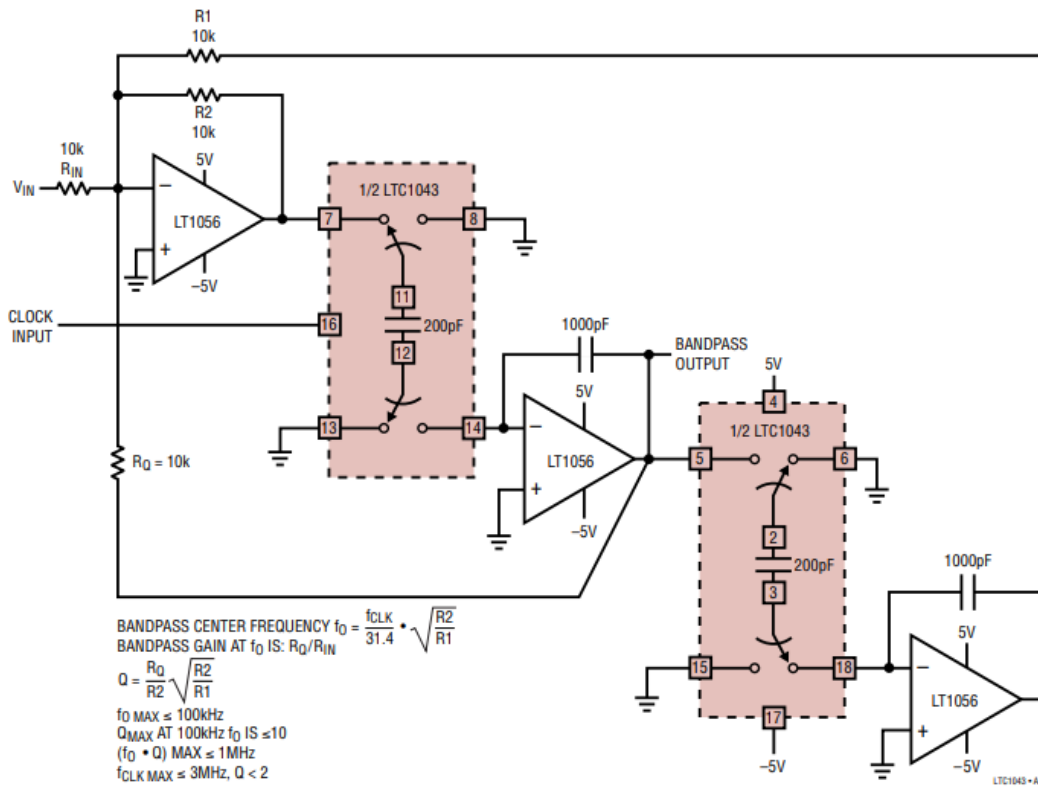


Fig. 1.11 High Frequency Clock Tunable Bandpass Filter by LTC1043 [4]

2. SWITCHED CAPACITOR CIRCUIT IMPLEMENTATION

Over the past decades, most passive and active filters designed with resistors and capacitors have been replaced by a special type of integrated filter called a switched capacitor filter. The reason for this replacement was the large size of the resistors on the board. Switched capacitor filters take up much less space on the board, are more accurate, and are highly tunable, although such circuits require an additional clock signal.

For the implementation of the laboratory stand, an integrated circuit LTC1043 was chosen, which was described earlier.

2.1 Resistance as a Switched Capacitor

Consider a resistance that is a simple resistor, such as a switched capacitor circuit.

The principle is based on the fact that the capacitor is charged and discharged with charge when the switches are open and closed. To control the switches, the circuit needs a generated clock signal. Such circuits are most often implemented using CMOS technology.

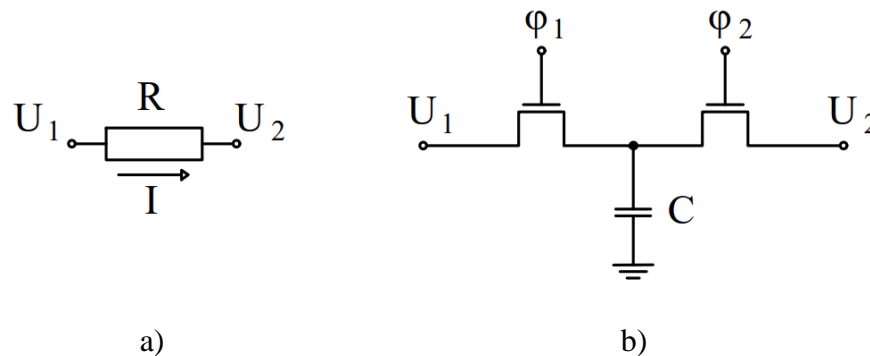


Fig. 2.1 a) Resistor and b) its analogue implemented using a switched capacitor circuit

Figure 2.1a shows a resistor with resistance R and current I , which is equal to

$$I = \frac{U_2 - U_1}{R}. \quad (2.1)$$

Figure 2.1b shows the implementation of the same resistor and its resistance using a switched capacitor coated on two MOS transistors. If the transistors pass and delay the current with a frequency that is sufficiently greater than the frequency of the signal, then a charge equal to

$$Q = C(u_2 - u_1). \quad (2.2)$$

The average current that flows through the capacitor is

$$i(t) = \frac{dQ}{dt} = \frac{\Delta Q}{\Delta t} \approx \frac{C(u_2 - u_1)}{T_{clk}} . \quad (2.3)$$

The equivalent resistance, which is formed by the same current on the capacitor is

$$R_{eq} = \frac{(u_2 - u_1)}{i(t)} = \frac{T_{clk}}{C} = \frac{1}{f_{clk} \cdot C} , \quad (2.4)$$

where f_{clk} is the switching frequency of the transistors.

By adjusting the switching frequency or the value of the capacitor, we can achieve the desired resistor value, which would be too large for the board. For example, with a capacitor volume of 1 pF and a typical switching frequency of an nMOSFET transistor of 100 kHz, the equivalent resistance from (2.4) is 10 MΩ [1][5]. Thus, when using this technology, we can reduce the size of the boards produced many times over.

2.2 Passive Low-Pass Filter Analysis

Consider an example of switched capacitor technology on a simple passive low-pass filter implemented with a resistor and a capacitor. Given a threshold frequency of 1 kHz and a 1 kΩ resistor, the value of the low-pass filter capacitor is

$$C_2 = \frac{1}{2\pi R_1 f_0} = \frac{1}{2\pi \cdot 1 \cdot 10^3 \cdot 1 \cdot 10^3} \cong 160 \text{ nF} . \quad (2.5)$$

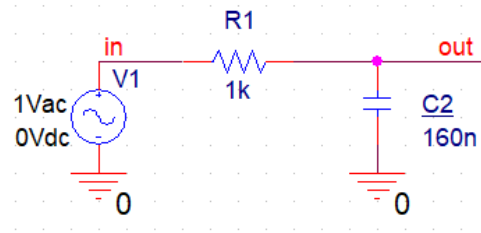


Fig. 2.2 Passive low-pass filter

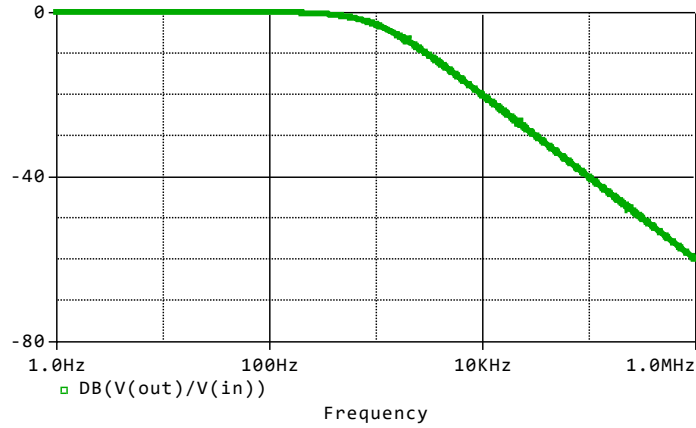


Fig. 2.3 Low-pass filter gain characteristic

The low-pass filter resistor shown in Figure 2.2 has been replaced by the LTC1043 integrated circuit, which contains a dual block for implementing switched capacitor circuits. An external clock signal with a clock frequency of 1 MHz (switching period of 1 μ s) was brought to the switch. With this clock frequency and a 1 k Ω equivalent resistor, the equivalent capacitance of the capacitor from (2.4) is

$$C_{eq} = \frac{1}{f_{clk} \cdot R_{eq}} = \frac{1}{1 \cdot 10^6 \cdot 1 \cdot 10^3} = 1 \text{ nF} . \quad (2.6)$$

The passive low-pass filter was simulated using the OrCAD PSpice design and simulation application. In the standard libraries of this program, the necessary component LTC1043 is available, specifically half of this integrated microcircuit.

The simulation of the passive low-pass filter and its analog based on the LTC1043 integrated microcircuit was performed in the time domain at different frequencies. The readings of the maximum output voltage were taken, from which the gain characteristic was compiled. It is worth noting that the data was collected after a long run of the circuit, as the capacitor needs to overcome a transient phenomenon when the simulation starts and the circuit may resonate at the desired frequencies. This phenomenon was mainly observed at high frequencies. A table of simulation results is provided in Appendix A.1.

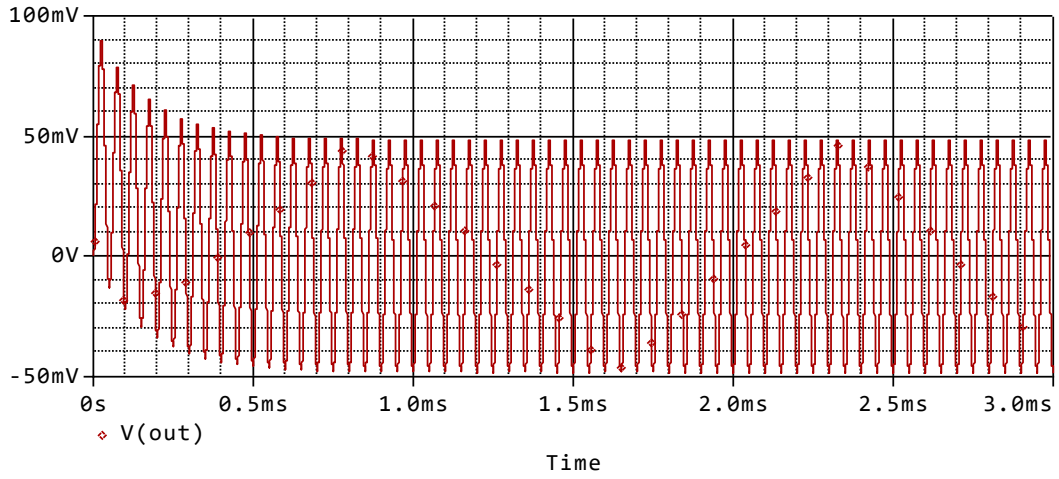


Fig. 2.4 Transient at the beginning of the simulation

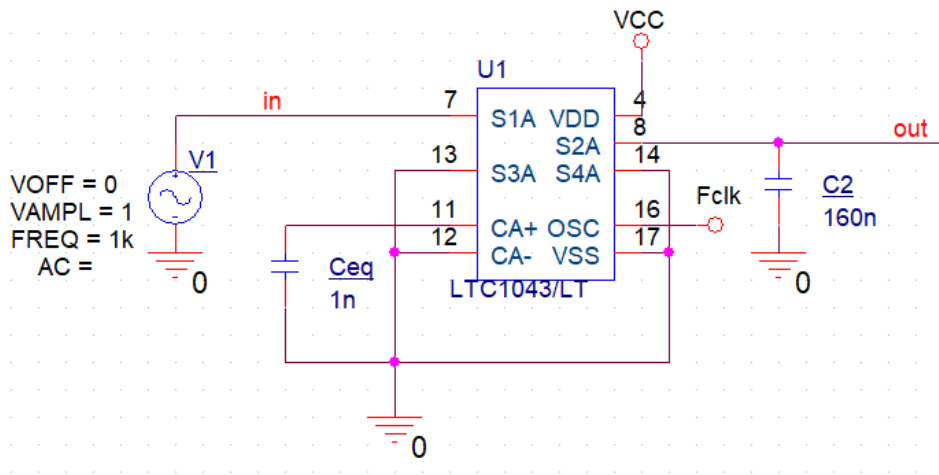


Fig. 2.5 Implementation of a resistor as a switched capacitor based on the integrated circuit LTC 1043

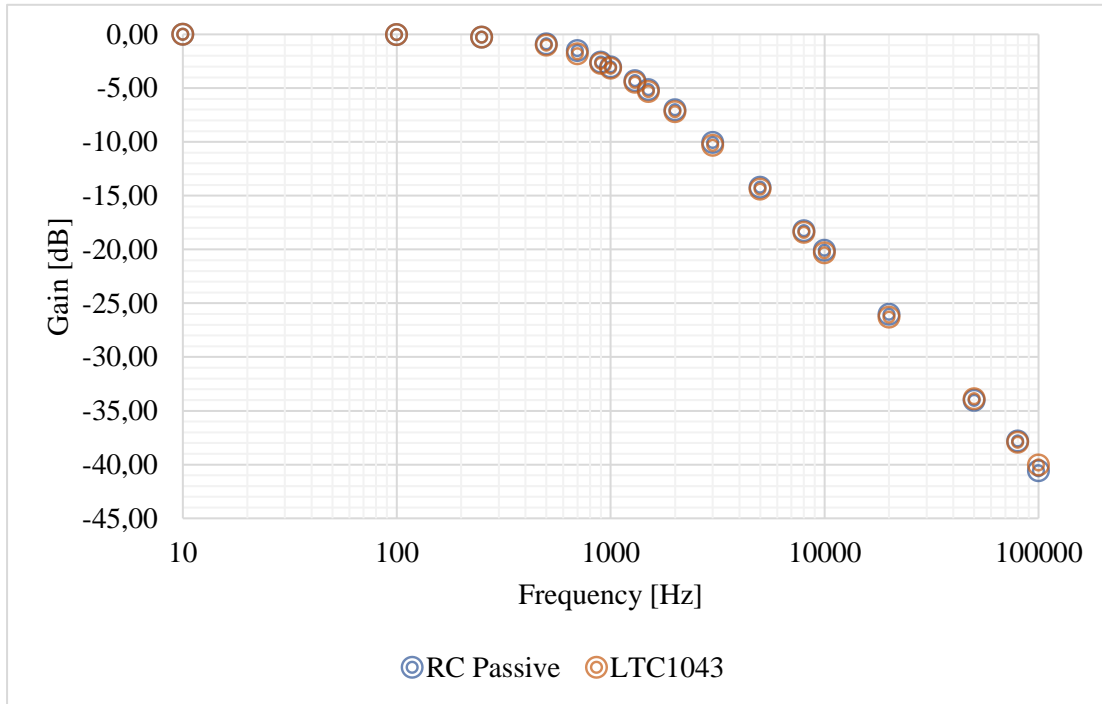


Fig. 2.6 Gain characteristic of a passive filter and a filter implemented using switched capacitors

As we can see from Figure 2.6, the gain characteristics of a simple passive low-pass filter and a filter based on an integrated LTC1043 chip are similar. This similarity indicates that the technology described above successfully copes with the task.

2.3 Active Low-Pass Filter Analysis

In the modern world, passive filters have been replaced by active filters, and in practice, circuits with an inverting amplifier are most common. Consider the operation of an inverting lossy integrator. (Figure 2.7) [6]

The transfer function of an inverting lossy integrator is

$$K(s) = -\frac{K_0}{1+s} \quad (2.7)$$

This filter, shown in the figure 2.7, is a first-order low-pass filter whose cutoff frequency is

$$\omega_c = \frac{1}{R_2 C} \quad (2.8)$$

And its transfer function in the passband is

$$K_0 = \frac{R_2}{R_1} \quad (2.9)$$

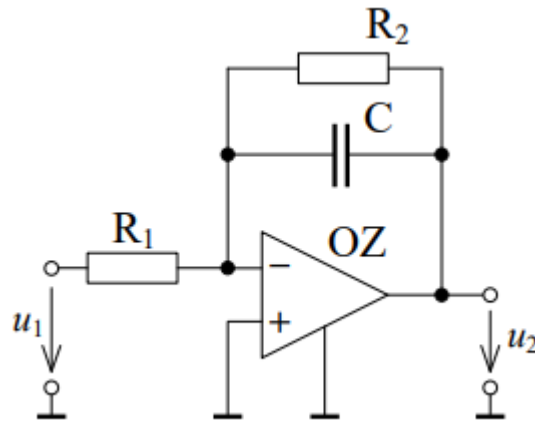


Fig. 2.7 Inverting lossy integrator [6]

With the required cutoff frequency of 1 kHz, as in the passive RC filter, the capacitor C with a value of approximately 160 nF (2.5), and the resistances R_1 and R_2 with a value of 1 k Ω , such a filter will pass low frequencies and not pass high frequencies. The cutoff frequency of -3 dB will be equal to the required frequency of 1 kHz. The gain characteristic of the filter in this case will be the same as that of a passive low-pass filter (Figure 2.3).

Since the purpose of this project is switched capacitor filters, we will replace the resistor R_1 with an integrated circuit LTC1043, where the equivalent capacitance of the capacitor will be the same as when replacing the resistor with a passive low-pass filter, that is, with a value of 1 nF (2.6) (Figure 2.8).

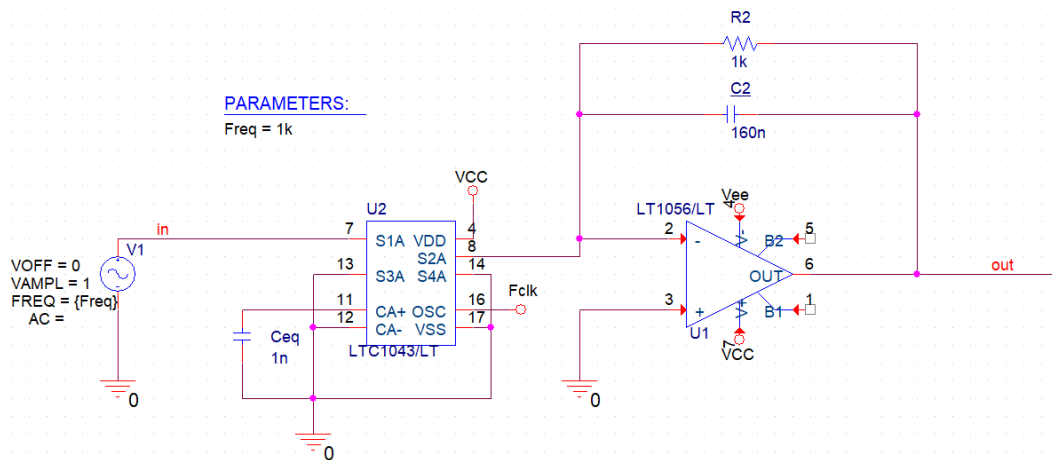


Fig. 2.8 Scheme of connecting of the integrating filter with the block LTC1043

As in the previous case, the simulation was carried out in the time domain at different oscillator frequencies from a frequency of 10 Hz up to 1 MHz.

The measured gain characteristic is shown in Figure 2.9, where one characteristic represents an active low-pass filter with a classical resistor, and the second characteristic represents the same filter but with a switched capacitor resistor.

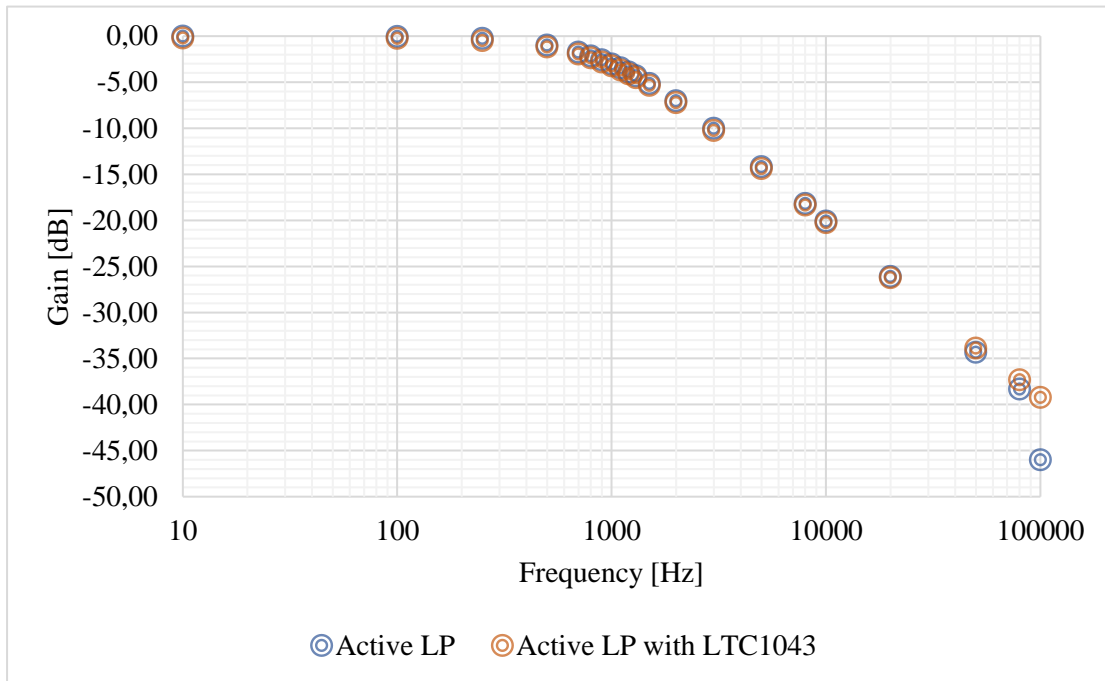


Fig. 2.9 Gain characteristic of an active filter and a filter implemented using switched capacitor

As we can see, the technology implemented on the switched capacitor works flawlessly, and the filter cutoff frequency is still 1 kHz. Of course, resistors with any rating can be replaced in this way. This experiment was carried out only to check the performance of the filter and for clarity. A table of simulation results is given in Appendix A.2.

2.4 Three amplifier state variable filter

The three-amplifier state-variable filter is a multifunctional filter that allows us to implement several different types of filters in one circuit, corresponding to the requested parameters. Of course, this option will increase the number of active elements in the circuit, but thanks to this, we can improve the quality of the filter. [6]

2.4.1 KHN filter

One of the most common filters is the KHN (Kerwin-Huelsman-Newcomb) filter or the state-

variable filter (Figure 2.10). The KHN filter can simultaneously be a low-pass filter, a band-pass filter, and a high-pass filter. This filter belongs to the "biquad" type filters and is a second-order filter. It has increased stability and is easily adjustable [6]. A ready-made variant of the variable state filter can be found in the integrated circuits National (AF100 and AF150) or Burr-Brown (UAF series). The module has built-in operational amplifiers as well as some circuit elements. Resistors R_G , R_Q , and R_F are connected externally, meaning that by changing the resistance values of these resistors, we can achieve the desired filter result [7]. This is where we can introduce a switched capacitor structure to replace the resistors, allowing us to have a customizable compact filter with three different outputs. Despite the large number of components in an integrated circuit, a bandpass filter implemented in this way will have a high quality factor.

The two R_F resistors set the center pass frequency of the band pass filter. Resistors R_Q and R_G determine the quality factor and the coefficient of the amplifier in the passband of the filter.

Equations for calculating filter parameters

$$R_F = \frac{5,03 \cdot 10^7}{f_0} [\Omega] , \quad (2.10)$$

$$R_Q = \frac{10^5}{3,48Q+G-1} [\Omega] , \quad (2.11)$$

$$R_G = \frac{3,16 \cdot 10^4 Q}{G} [\Omega] . \quad (2.12)$$

From Equation 2.10, we see that the center frequency of the bandpass filter is independent of the resistance values R_Q and R_G . Therefore, it is possible to use a variable potentiometer to control the filter's quality factor (and gain), but still use switched capacitor technology to adjust the center frequency of the filter.

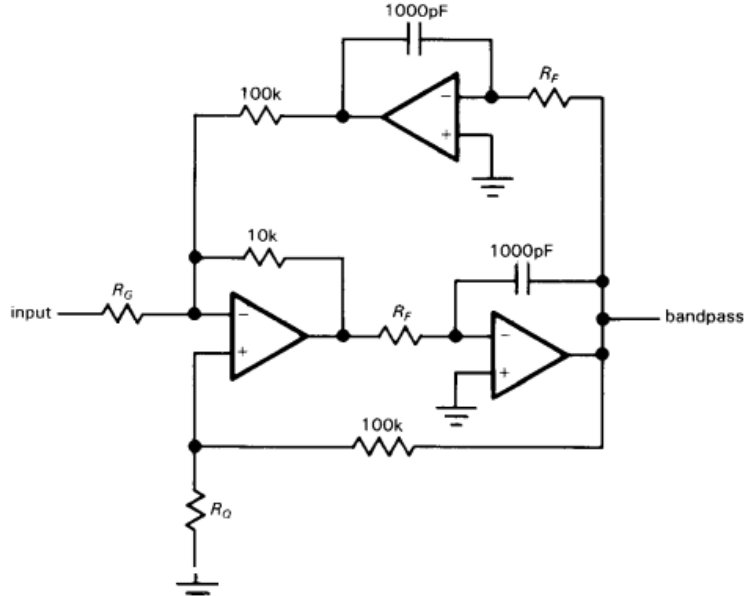


Fig. 2.10 KHN state variable filter [7]

2.4.2 Modified KHN filter

The modified KHN filter is a filter with independently adjustable bandwidth (or Q factor), while maintaining an unchanged gain. This feature presents a significant advantage of such a filter. Its only drawback is the introduction of an additional operational amplifier in the circuit. The quality factor, gain, and center frequency of the filter passband are independent of each other and can be determined using the following equations

$$f_0 = \frac{1}{2\pi R_F C}, \quad (2.13)$$

$$Q = \frac{R_1}{R_Q}, \quad (2.14)$$

$$G = \frac{R_1}{R_G}, \quad (2.15)$$

$$R \approx 10 \text{ k}\Omega \text{ (noncritical, matched)}. \quad (2.16)$$

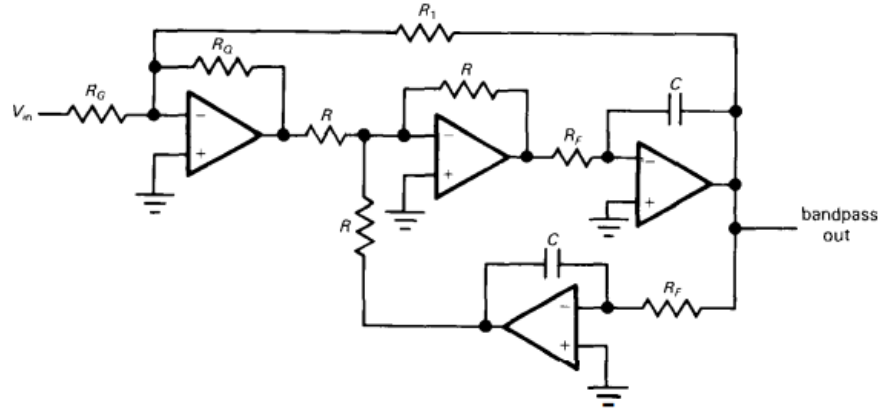


Fig. 2.11 Modified KHN filter [7]

2.4.3 Tow-Thomas filter

This filter consists of three operational amplifiers and allows us to implement a bandpass filter and two low-pass filters, which are rotated by 180 degrees to each other. Negative feedback ensures the stability of the filter. If we assume that the resistors R_5 and R_6 are equal, then

$$K_{LP2}(p) = -K_{LP1}(p) . \quad (2.17)$$

The characteristic angular frequency ω_0 and the quality factor Q of the filter are determined by the expression

$$\omega_0 = \frac{1}{\sqrt{R_2 R_3 C_1 C_2}} , \quad (2.18)$$

$$Q = R_1 \sqrt{\frac{C_1}{R_2 R_3 C_2}} . \quad (2.19)$$

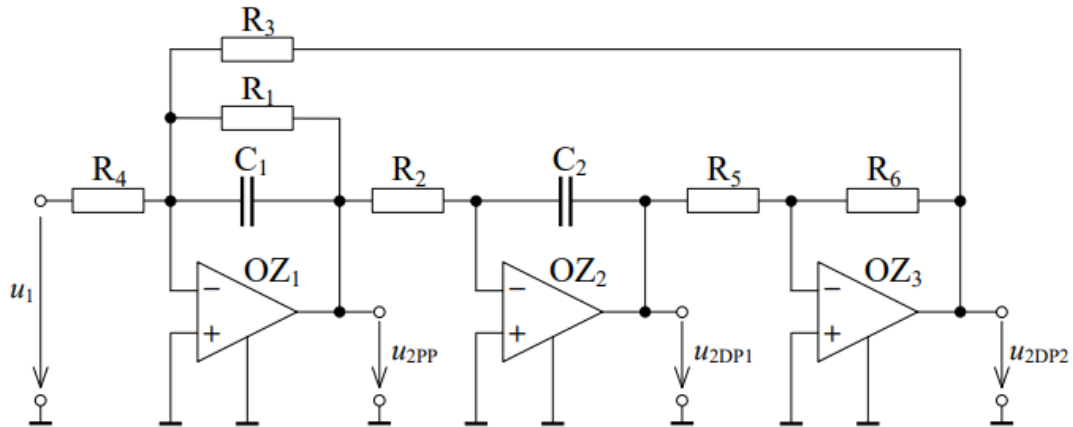


Fig. 2.12 Tow-Thomas filter [6]

2.4.4 Implementation of High Frequency Clock Tunable Bandpass Filter

The High Frequency Clock Tunable Bandpass Filter, developed by Analog Devices, Inc. and described earlier in chapter 1.3.4, was successfully simulated in the OrCAD PSpice design and simulation application. The connection diagram of the device is shown in Figure 1.9. This circuit utilizes two halves of the previously selected LTC1043 switched capacitor integrated circuit. Furthermore, the switches shown in the diagram are connected in different positions.

This circuit belongs to the type of filters described in Chapter 2.4 or, in its own way, a KHN filter, which is capable of producing three different filters: a bandpass filter, a low-pass filter, and a high-pass filter. In fact, in such a circuit, the first operational amplifier functions as an adder, and the subsequent two operational amplifiers act as integrators. The maximum frequency response of such a filter reaches -40 dB/dec or -18 dB/oct.

The bandpass center frequency of the filter is

$$f_0 = \frac{f_{CLK}}{31,4} \cdot \sqrt{\frac{R_2}{R_1}}. \quad (2.20)$$

Bandpass gain at f_0 is

$$G_0 = \frac{R_Q}{R_2}. \quad (2.21)$$

Quality factor Q is

$$Q = \frac{R_Q}{R_2} \cdot \sqrt{\frac{R_2}{R_1}}. \quad (2.22)$$

The maximum bandpass center frequency of the filter is 100 kHz, and the maximum quality factor at this frequency can be 10 [4]. The maximum bandwidth can reach 1 MHz. The maximum switching frequency of the switches can reach 3 MHz (with a quality factor of 2).

If we connect this filter with the parameters given in the catalog data sheet, that is, all resistors have a nominal value of 10 kΩ, and at the same time apply a clock signal of 1 MHz, then from equation 2.11, the band center frequency will be $f_0 = 31.8$ kHz. The DC gain G_0 , calculated with equation 2.12, will be equal to 1 or 0 dB, and the quality factor Q , calculated using equation 2.13, will be equal to 1.

Before simulating this circuit, let's calculate the resistance value we'll get using a 200 pF equivalent capacitance and a 1 MHz clock signal. From equation 2.6, we obtain

$$R_{eq} = \frac{1}{f_{clk} \cdot C_{eq}} = \frac{1}{1 \cdot 10^6 \cdot 200 \cdot 10^{-12}} = 5 \text{ k}\Omega . \quad (2.23)$$

With this resistor value, we should achieve the same frequency response as when using switched capacitors.

First, let's consider a three-state filter connection diagram using conventional resistors, as shown in Figure 2.13. In the circuit, the equivalent resistors R_{eq1} and R_{eq2} have a value of 5 kΩ. At the outputs (out0, out1, and out2), we should observe the characteristics of a high-pass filter, a band-pass filter, and a low-pass filter.

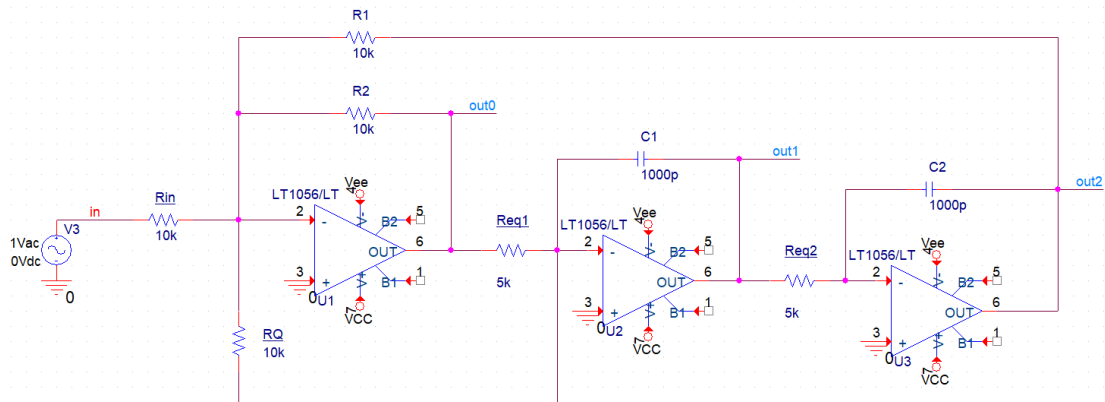


Fig. 2.13 Circuit of three amplifier state variable filter with conventional resistors

An analysis of the AC circuit sweep (frequency response) of the circuit shown in Figure 2.13 is presented in Figure 2.14, where the vertical axis displays the output gain relative to the input in dB, and the horizontal axis displays the frequency in logarithmic scale. In Figure 2.14, the green curve represents the frequency response of the high-pass filter

(out0), the red curve represents the frequency response of the bandpass filter (out1), and the blue curve represents the frequency response of the low-pass filter (out2). Additionally, we observe that the center frequency of all the filters is slightly above 30 kHz (or 31.62 kHz as measured with a cursor), which aligns with the previously calculated values from Equation 2.20, specifically 31.8 kHz.

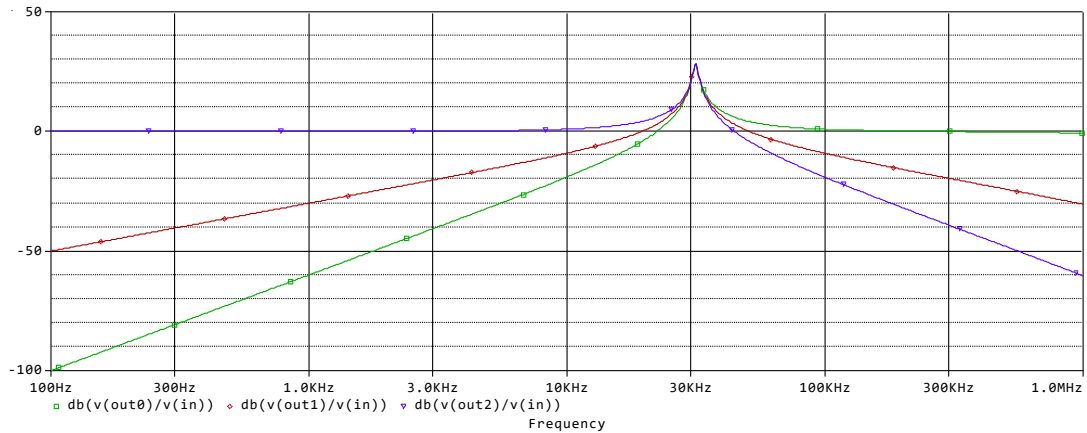


Fig. 2.14 Frequency response of a three-state filter with conventional resistors

In the next step, let's replace the equivalent resistors R_{eq1} and R_{eq2} with equivalent capacitances C_{eq1} and C_{eq2} , using the LTC1043 integrated circuit with switching capacitors as resistors, which we will switch with a 1 MHz clock signal (Figure 2.15).

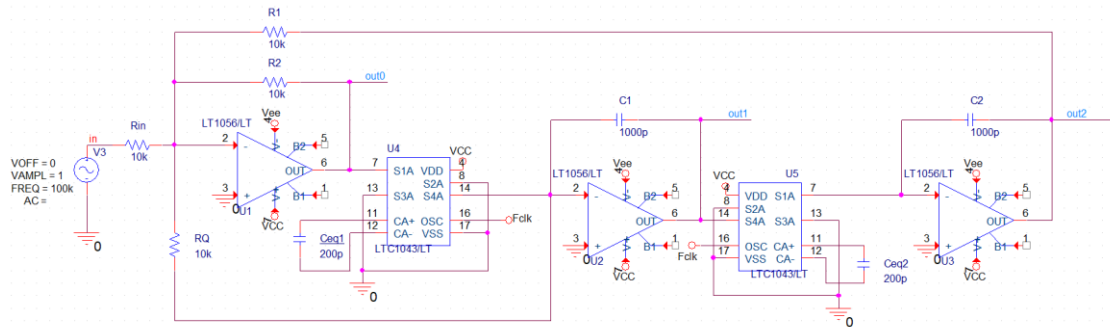


Fig. 2.15 Circuit of three amplifier state variable filter with switching capacitors

As in the low-pass filter analysis described in Chapters 2.2 and 2.3, the simulation was performed in the clock domain at different frequencies. Output voltages were measured from the outputs out0, out1, and out2. It is worth noting that when this circuit is turned on in the clock domain, the capacitor needs some time to charge and overcome the transient

phenomenon. Based on this, the readings were taken after the circuit had been operating for a long period of time.

The frequency response of the filter with a three-amplifier state variable filter is shown in Figure 2.16. It clearly demonstrates the successful operation of the switching capacitor technology. The center frequency of the filter corresponds to the calculated value of 31.8 kHz. With equal resistor values, the quality factor is 1, resulting in a bandwidth of 31.8 kHz for the bandpass filter. The maximum decline in the frequency response matches the specified value of -40 dB/dec. A table of simulation results is provided in Appendix A.3.

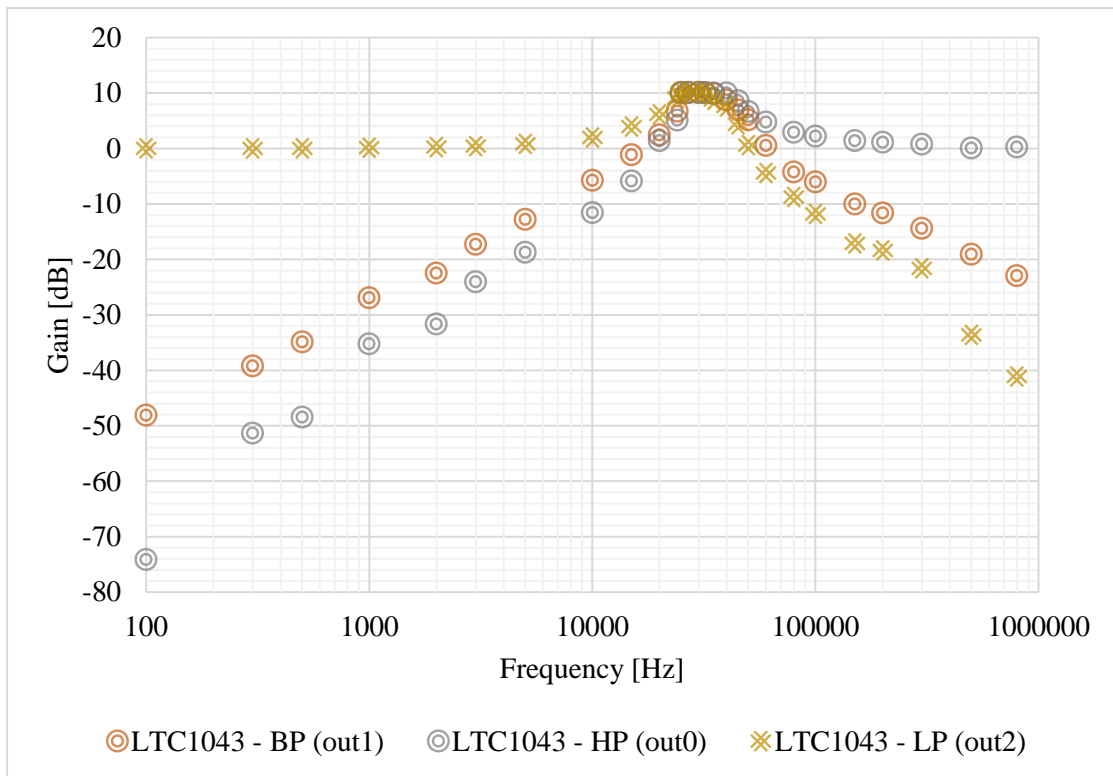


Fig. 2.16 Frequency response of a three-state filter with switching capacitors

If we compare Figures 2.14 and 2.15, then we see that filters using the technology of switching capacitors are not inferior to filters built on classic resistors.

3. LABORATORY BOARD

The purpose of this work was not only to design a theoretical schematic circuit for laboratory work focused on filters with switching capacitors but also to implement the proposed schematic circuit in the form of a laboratory board for future use. The proposed electrical circuit diagram is designed in a way that makes problem-solving easy in case of a possible breakdown.

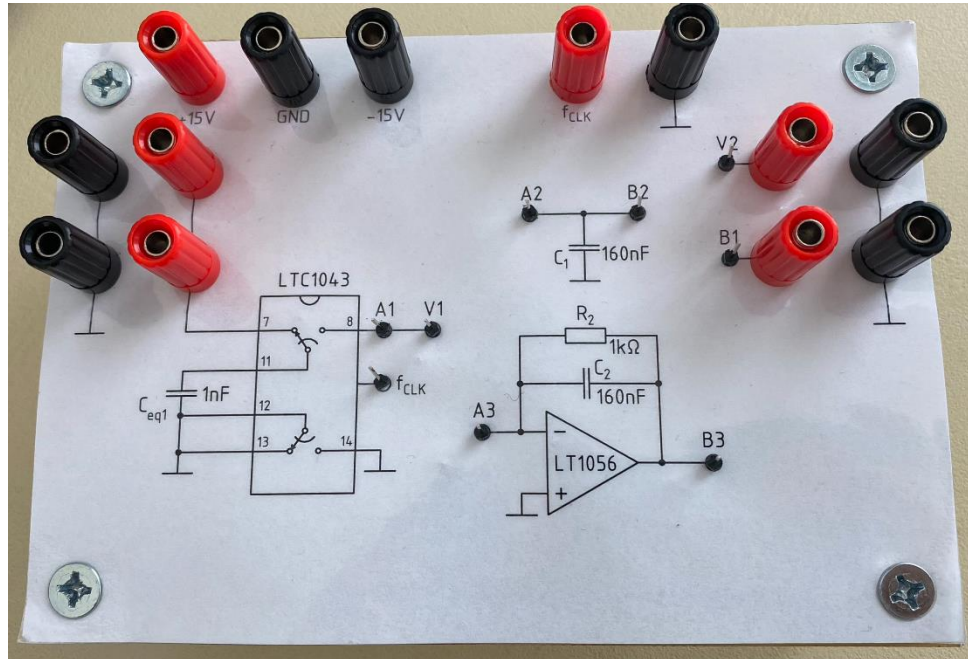


Fig. 3.1 Laboratory board dedicated to filters with switched capacitors

3.1 Description of the laboratory board construction

The laboratory board is realized by using two printed circuit boards. On the upper board, there are insulated connection posts for connecting banana plugs. These posts are used to connect all the necessary equipment, such as an oscilloscope, voltmeter, as well as an input signal generator and a clock signal generator. The whole circuit is powered from a DC power supply with a symmetrical ± 15 V supply. On the top of the PCB, there are also pins for connecting certain electrical circuits, which allow us to connect different circuits for measuring the amplitude and phase characteristics of a specific filter.

The upper part of the PCB is made using double-sided technology, where the two sides of the board are soldered together in the necessary places.

Two Pin-Line Headers lines with 11 pins on each side were used to connect the two PCBs (top and bottom) to each other, which made connecting and debugging the PCBs much easier.

The bottom printed circuit board is designed with single-sided technology, where the top side of the board contains all the components, including the extended Pin-Line Headers, and the bottom side has a layer of copper and soldered contacts of all the components. This board contains an LTC1043 integrated circuit and an LT1056 operational amplifier for implementing an active low-pass filter. Each integrated circuit has its own symmetrical power line. To prevent the DC current from affecting the operation of the integrated circuits, 100 nF limiting capacitors were used for each voltage pole, and these capacitors are placed as close as possible to the integrated circuits.

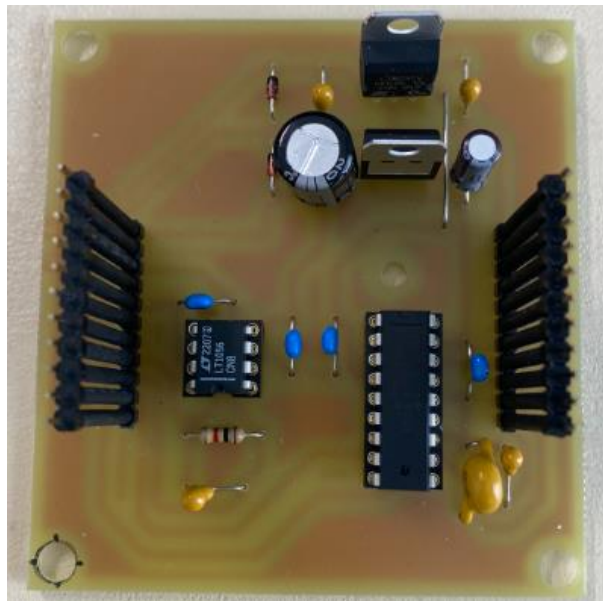


Fig. 3.2 Bottom printed circuit board of the laboratory board

3.2 Powering the laboratory board

As mentioned before, the board is powered by an uninterruptible power supply with a symmetrical ± 15 V supply. This is the first power line used to power the LT1056 operational amplifier. The second power line is needed to supply the LTC1043 integrated circuit, which has a rating of ± 5 V. With the help of the first ± 15 V supply line and two voltage regulators, it is possible to reach the required rating to supply the integrated circuit. For the positive pole, a linear voltage regulator, L7805CV, is used, and for the negative pole, its counterpart, L7905CV, is used.

In addition, two Zener diodes, 1N4148, are present in the power supply circuit to protect against output polarity reversal. The circuit board power supply is shown in Figure 3.3.

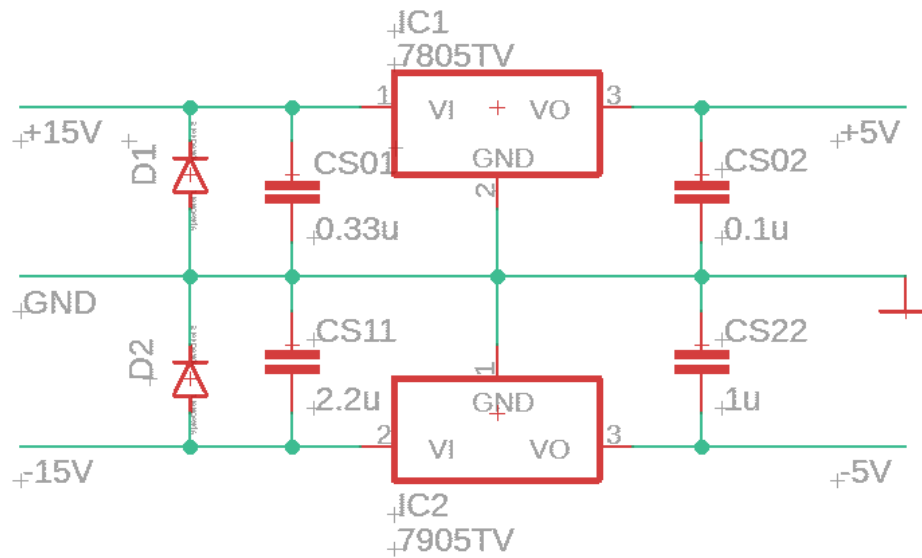


Fig. 3.3 Circuit board power supply

3.3 Passive low-pass filter

The first scheme that can be implemented on this laboratory stand is a passive low-pass filter, or an integrating filter.

When the power supply is connected, it is necessary to connect the clock signal generator. To do this, you must connect the oscillator cables marked f_{clk} and ground to the designated ports of the laboratory board. For proper operation of the integrated circuit, the clock signal must be rectangular with an amplitude of 5 V and a duty cycle of 50 %. The switched capacitor C_{eq1} is rated 1 nF. So, with a certain clock signal, the LTC1043 integrated circuit will represent a resistance in a simple low-pass filter. For the final connection of the integrated filter, you need to connect the pin from the output of integrated circuit A1 to pin A2 of capacitor C_1 . To output the signal to the oscilloscope, it is necessary to connect pin B2 from capacitor C_1 to the output ports of the laboratory board B1.

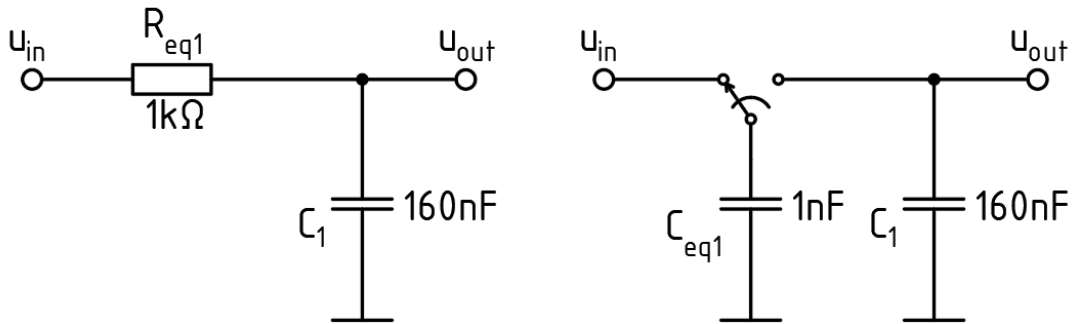


Fig. 3.4 Passive low-pass filter circuit (left) and its equivalent connection on the laboratory board (right)

3.4 Active low-pass filter

In the same way as the passive integrator, the active low-pass filter with the LT1056 operational amplifier is connected. The output pin A1 from the LTC1043 integrated circuit is connected to the inverter input of the operational amplifier on pin A3. The output of the amplifier is connected to pin B3, which is further connected to the output port on pin B1. With this connection we are able to implement an active low pass filter using switched capacitor technology.

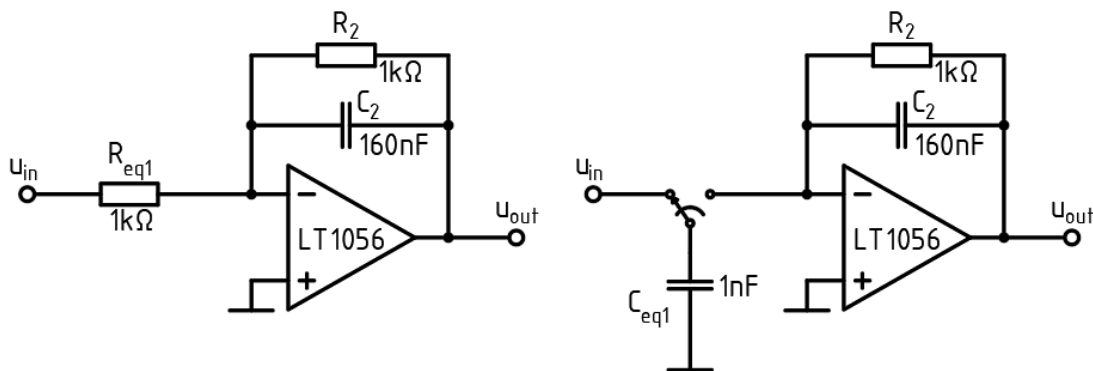


Fig. 3.5 Active low-pass filter circuit (left) and its equivalent connection on the laboratory board (right)

4. LABORATORY TASK

4.1 Objective of the laboratory task

The main objective of this laboratory task is to introduce students to switched capacitor technology for the construction of multi-frequency electrical filters. Through the example of a low-pass filter, students will demonstrate that switched capacitors technology is no worse than traditional passive resistors.

4.2 Working tasks

1. Calculate the clock signal frequency of the LTC1043 integrated circuit to implement passive and active low-pass filters with cut-off frequency $f_0 = 1$ kHz and given an equivalent capacitor $C_{eq1} = 1$ nF, and its equivalent resistance $R_{eq1} = 1$ k Ω . The clock signal must have an amplitude of 5 V and a rectangular waveform. Write down the final clock signal in the protocol.
2. Measure the amplitude and phase frequency response of a passive low-pass filter using an LTC1043 integrated circuit with a switchable capacitor as the required resistance. Display the phase frequency response of the filter in XY form at the cutoff frequency.
3. Measure the amplitude and phase frequency response of an active low-pass filter with an operating amplifier using an LTC1043 integrated circuit with a switchable capacitor as the required component. Display the phase frequency response of the filter in XY form at the cutoff frequency.
4. Show the effect of changing the frequency of the clock signal on the parameters of the proposed filters, that is, on the cutoff frequency of the filter.

4.3 Process of execution

To measure the frequency characteristics of the module and the phase it is necessary to initially calculate the clock signal frequency for the switching of the LTC1043 integrated circuit with a capacitor.

With a desired cutoff frequency of 1 kHz and a given capacitor $C1 = 160$ nF, the value of the equivalent resistor R_{eq1} would have to be about 1 k Ω (exactly 995 Ω). To calculate the clock frequency, we start from the equation

$$C_{eq1} = \frac{1}{f_{clk} \cdot R_{eq1}}. \quad (4.1)$$

Therefore, the clock frequency for the capacitor switching by the LTC1043 integrated circuit must be

$$f_{clk} = \frac{1}{R_{eq1} \cdot C_{eq1}}. \quad (4.2)$$

Connect a clock signal generator to the laboratory stand with the calculated clock signal value. The signal amplitude must be 5 V, and it should have a rectangular waveform. The board is powered by an uninterruptible power supply with symmetrical ± 15 V supply. We connect one oscilloscope channel and a generator of alternating current to the input of the board. Recommended values for the input signal are an amplitude of 1 V and a sinusoidal shape. Additionally, we connect the second oscilloscope channel to the output to measure the changes at the output.

To display the clock signal, use the f_{clk} pin, which should be connected to output pin B1 with a wire.

To connect the passive low-pass filter circuit, it is necessary to connect pins A1 and A2. To display the output signal, you need to connect pins B2 and B1. In the case of the active low-pass filter connection, pins A1 and A3 must be connected. To display the signal on the second channel of the oscilloscope, connect pins B3 and B1.

4.4 Example of a completed laboratory task

4.4.1 Calculation of the clock signal for the switched capacitor filter

Calculation of the clock frequency for switching a capacitor with given parameters ($f_0 = 1$ kHz, $R_{eq1} = 1$ k Ω , $C_{eq1} = 1$ nF, $C_1 = 160$ nF)

$$f_{clk} = \frac{1}{R_{eq1} \cdot C_{eq1}} = \frac{1}{1 \cdot 10^3 \cdot 1 \cdot 10^{-9}} = 1 \text{ MHz} . \quad (4.3)$$

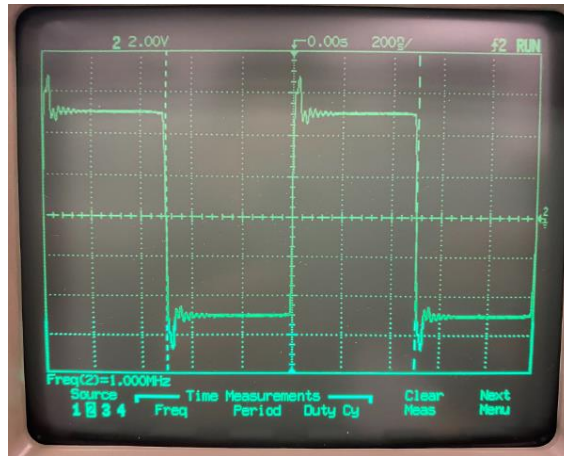


Fig. 4.1 Clock frequency waveform

4.4.2 Measuring the frequency response of the module and the phase of the passive filter

Table 4.1 Measuring the amplitude-frequency response of a passive low-pass filter

Passive LP					
f [Hz]	Vout [V]	Vout [dB]	f [Hz]	Vout [V]	Vout [dB]
10	1,0155	0,13	1100	0,6640	-3,56
100	1,0080	0,07	1150	0,6560	-3,66
250	0,9845	-0,14	1200	0,6485	-3,76
500	0,9140	-0,78	1300	0,6330	-3,97
700	0,8360	-1,56	1500	0,5780	-4,76
800	0,7890	-2,06	1900	0,4810	-6,36
850	0,7735	-2,23	2000	0,4590	-6,76
900	0,7500	-2,50	3000	0,3435	-9,28
925	0,7445	-2,56	5000	0,2250	-12,96
950	0,7420	-2,59	8000	0,1560	-16,14
975	0,7185	-2,87	10000	0,1310	-17,65
1000	0,7110	-2,96	20000	0,0820	-21,72
1025	0,7030	-3,06	50000	0,0305	-30,31
1050	0,6955	-3,15	80000	0,0060	-44,44
1075	0,6875	-3,25	100000	0,0035	-49,12

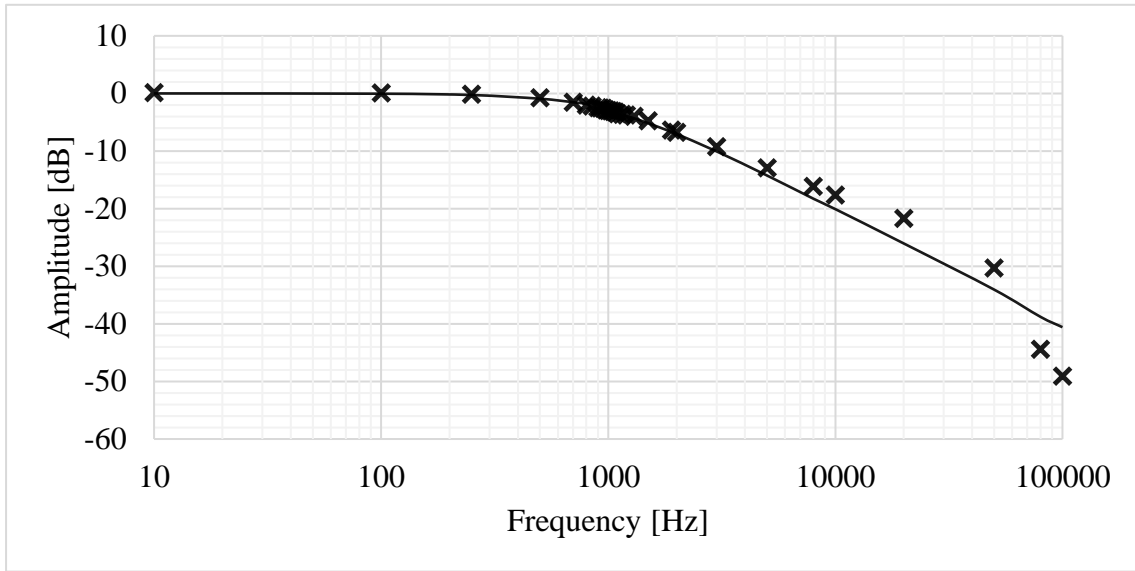


Fig. 4.2 Amplitude-frequency response of a passive low-pass filter

Table 4.2 Measurement of phase-frequency response of a passive low-pass filter

Passive LP			
f [Hz]	V1 [V]	V2 [V]	ϕ [°]
100	0,160	1,075	-8,56
200	0,255	1,075	-13,72
500	0,545	1,075	-30,46
800	0,695	1,075	-40,28
1000	0,800	1,075	-48,09
1200	0,850	1,075	-52,25
1500	0,905	1,075	-57,34
1800	0,935	1,075	-60,43
2000	0,960	1,075	-63,26
3000	1,015	1,075	-70,77
4000	1,035	1,075	-74,32
5000	1,050	1,075	-77,62
10000	1,065	1,075	-82,18

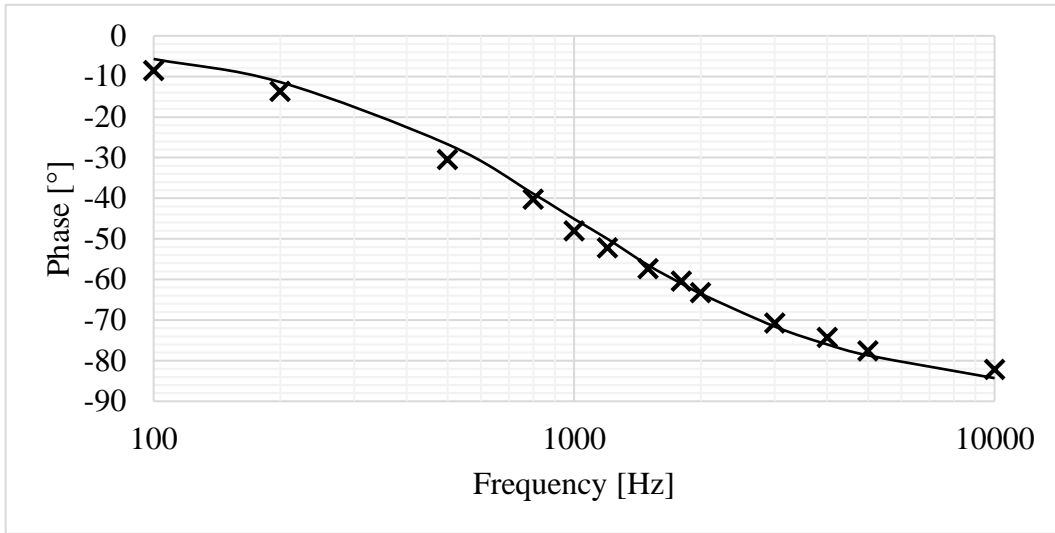


Fig. 4.3 Phase-frequency response of a passive low-pass filter

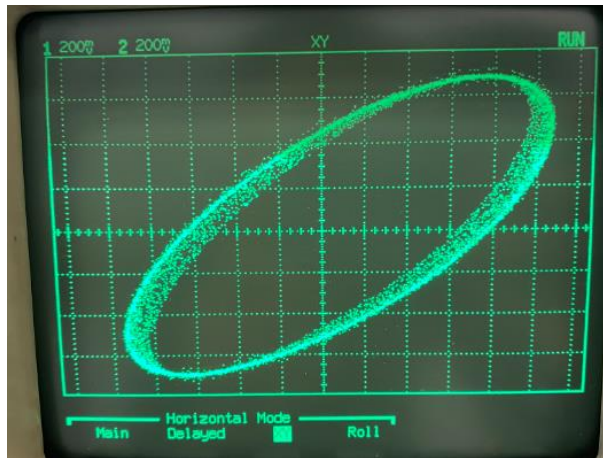


Fig. 4.4 Phase-frequency response of a passive low-pass filter in XY form (input frequency 1 kHz)

4.4.3 Measuring the frequency response of the module and the phase of the active filter

Table 4.3 Measuring the amplitude-frequency response of an active low-pass filter

Active LP					
f [Hz]	Vout [V]	Vout [dB]	f [Hz]	Vout [V]	Vout [dB]
10	2,0000	6,02	1100	1,2810	2,15

100	1,8440	5,32	1150	1,2660	2,05
250	1,7890	5,05	1200	1,2340	1,83
500	1,6560	4,38	1300	1,1720	1,38
700	1,5470	3,79	1500	1,0780	0,65
800	1,4840	3,43	1900	0,9060	-0,86
850	1,4530	3,25	2000	0,8900	-1,01
900	1,4220	3,06	3000	0,6400	-3,88
925	1,3910	2,87	5000	0,4370	-7,19
950	1,3590	2,66	8000	0,2960	-10,57
975	1,3440	2,57	10000	0,2340	-12,62
1000	1,3280	2,46	20000	0,1680	-15,49
1025	1,3120	2,36	50000	0,0620	-24,15
1050	1,2970	2,26	80000	0,0180	-34,89
1075	1,2970	2,26	100000	0,0110	-39,17

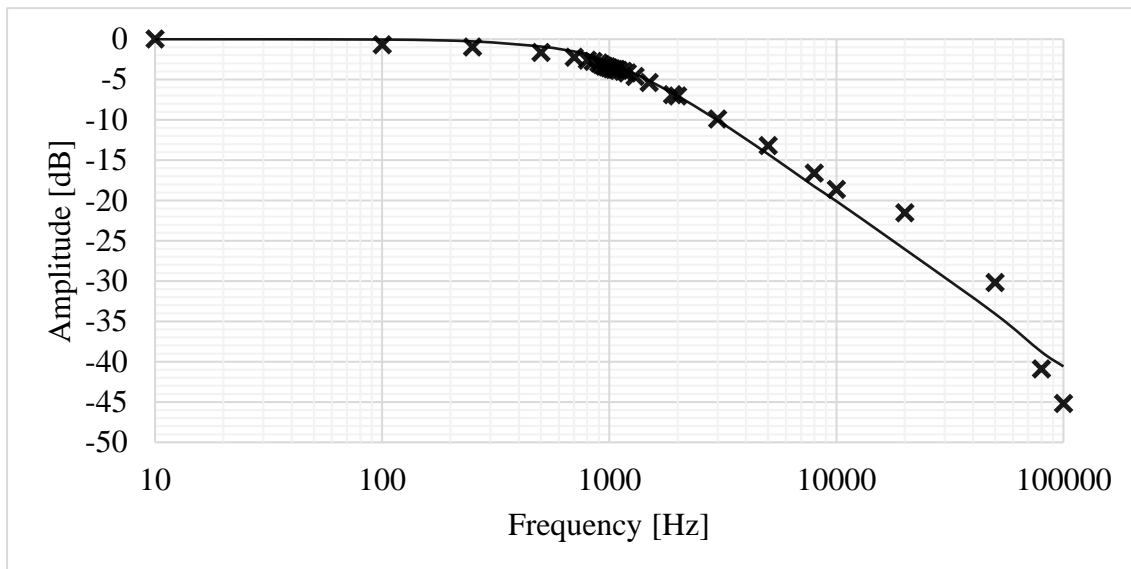


Fig. 4.5 Amplitude-frequency response of an active low-pass filter

Table 4.4 Measurement of phase-frequency response of an active low-pass filter

Active LP			
f [Hz]	V1 [V]	V2 [V]	ϕ [°]
100	0,1450	1,0750	-7,75
200	0,2250	1,0750	-12,08
500	0,4750	1,0750	-26,22
800	0,6500	1,0750	-37,20

1000	0,7350	1,0750	-43,14
1200	0,8050	1,0750	-48,49
1500	0,8700	1,0750	-54,03
1800	0,9100	1,0750	-57,83
2000	0,9350	1,0750	-60,43
3000	1,0000	1,0750	-68,47
4000	1,0300	1,0750	-73,36
5000	1,0400	1,0750	-75,34
10000	1,0610	1,0750	-80,74

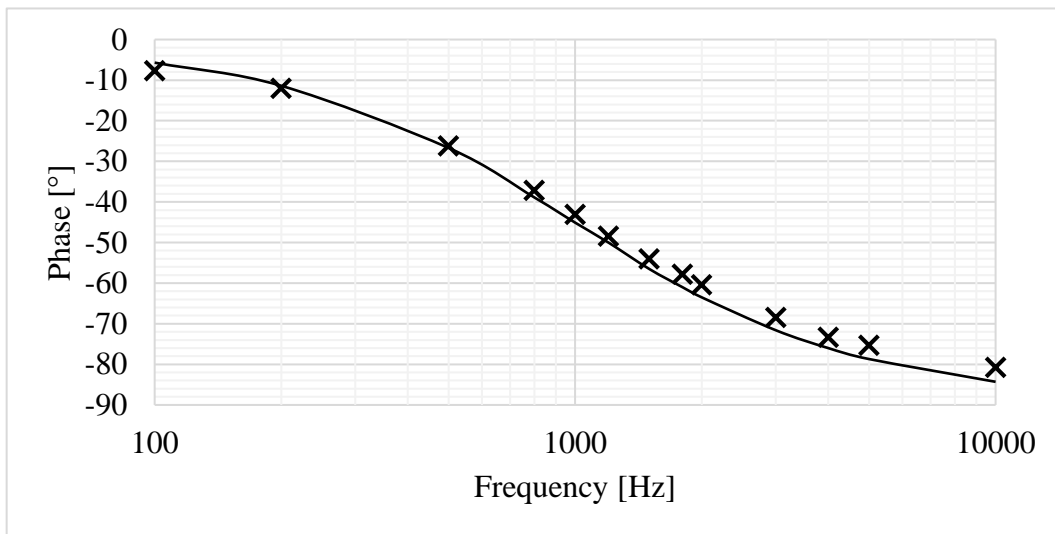


Fig. 4.6 Phase-frequency response of an active low-pass filter

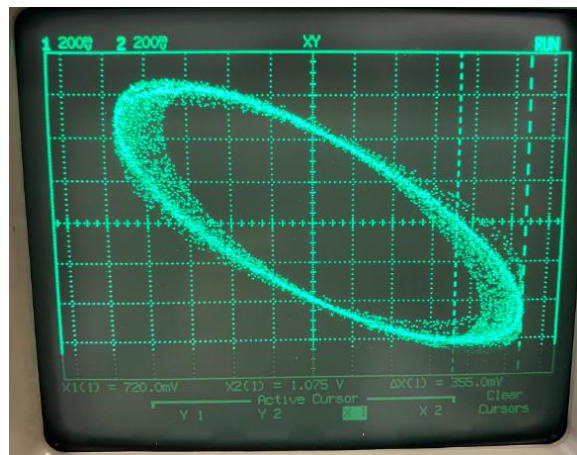


Fig. 4.7 Phase-frequency response of an active low-pass filter in XY form (input frequency 1 kHz)

4.4.4 The effect of changing the switching frequency on the shift of the cut-off frequency

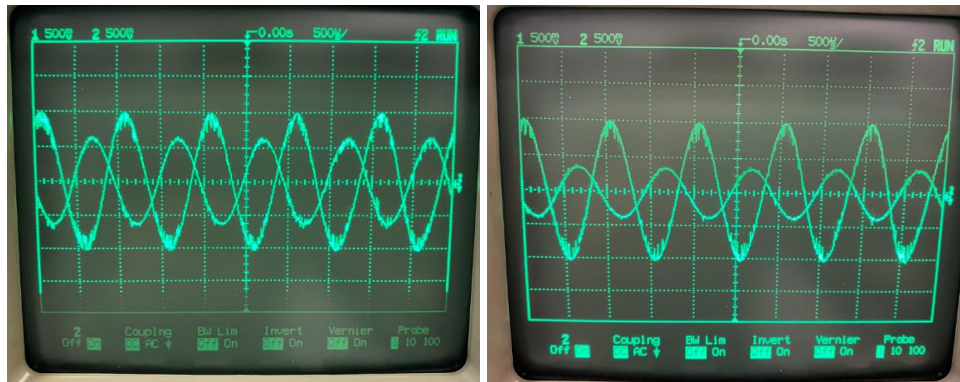


Fig. 4.8 Changing the switching frequency, the input frequency is 1 kHz:
a) Progress of the input and output signal at a switching frequency of 1 MHz, b) Progress of the input and output signal at a switching frequency of 500 kHz

4.4.5 Conclusion of the laboratory task

To measure the frequency characteristics of the module and the phase, the clock signal frequency for switching the LTC1043 integrated circuit with a capacitor was initially calculated. With these component parameters and a calculated clock signal of 1 MHz, such a filter has a cutoff frequency of 1 kHz.

According to the measured values plotted on the graphs, the clock frequency of the signal is calculated correctly.

The frequency characteristics of the modulus and phase of passive and active low-pass filters are similar and also correspond to the filtering theory. When measuring the phase frequency response, both filters change their phase value from 0° to -90° , and at the cutoff frequency, the phase reading is -45° , indicating that the switchable capacitor-based filter technology is not inferior to classical analog filters.

It was also shown in the practical example that the switching capacitor clock signal frequency is inversely proportional to the manufactured equivalent resistance because by changing the clock signal from 1 MHz to 500 kHz, the amplitude of the output signal decreased almost twice.

5. CONCLUSION

In this bachelor's thesis, the technology of switched capacitor filters was analyzed. Calculations have shown that the use of this technology reduces the overall dimensions of the board many times.

To realize the laboratory board, the basics of signal filtering were studied, and the basic principles were analyzed. Various types of approximations of such filters were also studied. Then the switched capacitor technology itself was directly studied, in which CMOS switching technology was used. To implement this circuit, an analysis of the integrated circuit boards available on the market was performed to find an elegant and cost-effective solution. It was decided to use the LTC1043 integrated circuit as it allows us to achieve this goal. As it turned out, the LTC1043 block includes the ability to use two switching capacitors at once, which helps us expand our capabilities when offering a solution.

The simulation in the OrCAD PSpice simulation program clearly showed us that the switching capacitor technology is in no way inferior to the classical RC filters. An integral part of the simulation was an operational amplifier LT1056, which helped us to build the intended circuits, for example, an active integrating filter.

Of course, filters built with switched capacitors have their disadvantages. One of them is that we have to use a clock signal, which unfortunately is limited. Thus, this technology is not really suitable for the implementation of high-pass filters. The next disadvantage is that the capacitance values of the capacitors used during operation cannot be exact. For this, it is necessary to calibrate the device before using it.

The proposed laboratory stand was implemented with two circuit boards using the LTC1043 precision building block and one LT1056 operational amplifier. On this laboratory stand, students will be able to familiarize themselves with the technology employed in switching capacitors, particularly the passive and active low-pass filters. The laboratory work is designed in such a way that students will be able to complete all tasks within the allocated time. Based on the measurements conducted during the laboratory task, students will discover one of the main advantages of switching capacitor technology: the filter constructed using this technology can be adjusted by modifying the clock frequency of the switching capacitor.

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Appendix A - Measured values

A.1 Table of gain characteristic of a passive filter and a filter implemented using switched capacitors

Freq [Hz]	RC Passive		LTC1043	
	V _{out} [V]	V _{out} [dB]	V _{out} [V]	V _{out} [dB]
10	1,0000	0,00	0,9999	0,00
100	0,9950	-0,04	0,9947	-0,05
250	0,9690	-0,27	0,9681	-0,28
500	0,9000	-0,92	0,8882	-1,03
700	0,8390	-1,52	0,8099	-1,83
800	0,8100	-1,83	0,7700	-2,27
850	0,7600	-2,38	0,7510	-2,49
900	0,7410	-2,60	0,7320	-2,71
925	0,7320	-2,71	0,7224	-2,82
950	0,7230	-2,82	0,7130	-2,94
975	0,7140	-2,93	0,7042	-3,05
1 000	0,7050	-3,04	0,6952	-3,16
1 025	0,6960	-3,15	0,6862	-3,27
1 050	0,6870	-3,26	0,6770	-3,39
1 075	0,6790	-3,36	0,6687	-3,50
1 100	0,6710	-3,47	0,6600	-3,61
1 150	0,6540	-3,69	0,6437	-3,83
1 200	0,6380	-3,90	0,6276	-4,05
1 300	0,6080	-4,32	0,5970	-4,48
1 500	0,5520	-5,16	0,5418	-5,32
1 900	0,4630	-6,69	0,4537	-6,86
2 000	0,4450	-7,03	0,4355	-7,22
3 000	0,3140	-10,06	0,3038	-10,35
5 000	0,1940	-14,24	0,1900	-14,42
8 000	0,1220	-18,27	0,1200	-18,42
10 000	0,0990	-20,09	0,0963	-20,32
20 000	0,0499	-26,04	0,0484	-26,30

50 000	0,0198	-34,06	0,0202	-33,90
80 000	0,0128	-37,83	0,0127	-37,96
100 000	0,0093	-40,58	0,0099	-40,05

A.2 Table of gain characteristic of an active filter and a filter implemented using switched capacitors

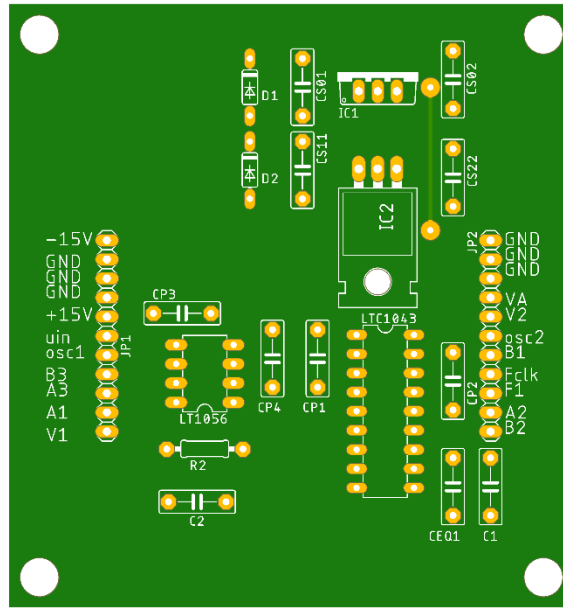
Freq [Hz]	Active LP		LTC1043	
	Vout [V]	Vout [dB]	Vout [V]	Vout [dB]
10	1,0000	0,00	0,9752	-0,22
100	0,9953	-0,04	0,9698	-0,27
250	0,9701	-0,26	0,9455	-0,49
500	0,8937	-0,98	0,8713	-1,20
700	0,8180	-1,74	0,7976	-1,96
800	0,7795	-2,16	0,7599	-2,38
850	0,7605	-2,38	0,7415	-2,60
900	0,7417	-2,60	0,7233	-2,81
950	0,7234	-2,81	0,6989	-3,11
1 000	0,7054	-3,03	0,6878	-3,25
1 050	0,6879	-3,25	0,6709	-3,47
1 100	0,6709	-3,47	0,6543	-3,68
1 150	0,6544	-3,68	0,6383	-3,90
1 200	0,6384	-3,90	0,6226	-4,12
1 300	0,6079	-4,32	0,5929	-4,54
1 500	0,5529	-5,15	0,5393	-5,36
2 000	0,4455	-7,02	0,4347	-7,24
3 000	0,3149	-10,04	0,3074	-10,25
5 000	0,1952	-14,19	0,1908	-14,39
8 000	0,1234	-18,17	0,1208	-18,36
10 000	0,0989	-20,10	0,0969	-20,27
20 000	0,0496	-26,09	0,0488	-26,23
50 000	0,0192	-34,33	0,0202	-33,89
80 000	0,0121	-38,34	0,0136	-37,33
100 000	0,0050	-46,02	0,0109	-39,25

A.3 Table of gain characteristic of three amplifier state variable filter with switched capacitors

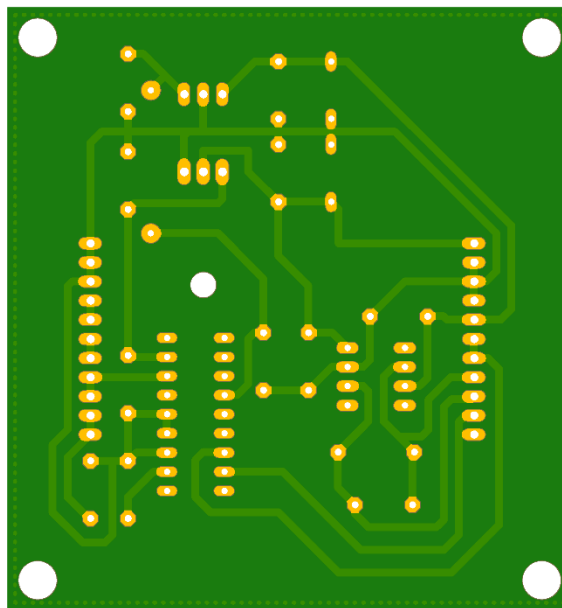
Freq [Hz]	LTC1043 - BP (out1)		LTC1043 - HP (out0)		LTC1043 - LP (out2)	
	Vout [V]	Vout [dB]	Vout [V]	Vout [dB]	Vout [V]	Vout [dB]
100	0,00393	-48,1121	0,00020	-74,1549	1,00063	0,0055
300	0,01092	-39,2355	0,00271	-51,3461	1,00343	0,0297
500	0,01804	-34,8777	0,00377	-48,4805	1,00169	0,0147
1 000	0,04510	-26,9167	0,01722	-35,2793	1,01377	0,1188
2 000	0,07514	-22,4830	0,02602	-31,6950	1,02913	0,2494
3 000	0,13615	-17,3197	0,06287	-24,0311	1,04870	0,4130
5 000	0,22906	-12,8011	0,11538	-18,7576	1,09515	0,7895
10 000	0,51524	-5,7598	0,26395	-11,5696	1,25339	1,9617
15 000	0,87874	-1,1228	0,50868	-5,8712	1,57449	3,9428
20 000	1,32041	2,4142	1,17717	1,4168	2,01946	6,1047
24 000	2,16922	6,7261	1,79029	5,0585	2,83470	9,0501
25 000	3,19410	10,0870	3,16355	10,0035	3,19404	10,0868
27 000	3,19409	10,0869	3,17718	10,0408	3,19401	10,0867
30 000	3,19391	10,0865	3,18007	10,0487	3,18576	10,0643
32 000	3,18712	10,0680	3,17982	10,0481	3,15344	9,9757
35 000	3,11634	9,8729	3,16856	10,0172	2,72435	8,7053
40 000	2,72290	8,7006	3,15847	9,9895	2,38878	7,5635
45 000	2,21690	6,9149	2,69035	8,5962	1,65211	4,3608
50 000	1,80800	5,1440	2,14236	6,6178	1,06621	0,5569
60 000	1,06459	0,5436	1,72761	4,7489	0,59870	-4,4559
80 000	0,61419	-4,2339	1,39690	2,9033	0,36583	-8,7345
100 000	0,49774	-6,0599	1,28547	2,1812	0,25686	-11,8061
150 000	0,31480	-10,0393	1,17204	1,3788	0,13917	-17,1289
200 000	0,26217	-11,6285	1,13780	1,1213	0,12057	-18,3751
300 000	0,19064	-14,3959	1,08897	0,7403	0,08286	-21,6334
500 000	0,11083	-19,1072	1,00459	0,0398	0,02077	-33,6492
800 000	0,07109	-22,9638	1,02536	0,2175	0,00878	-41,1301

Appendix B - Small printed circuit board

B.1 Component assembly plan for the top side of the small circuit board

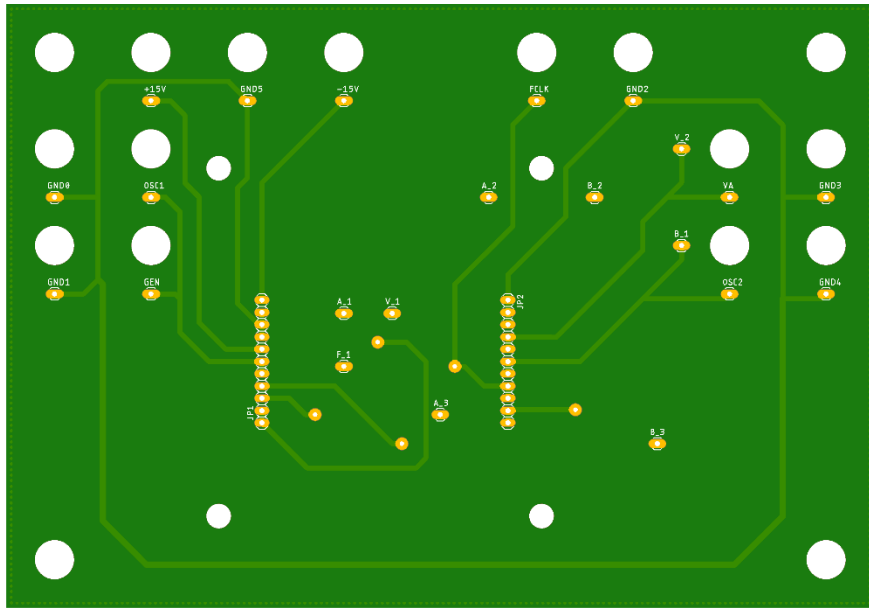


B.2 Component assembly plan for the underside of the small circuit board

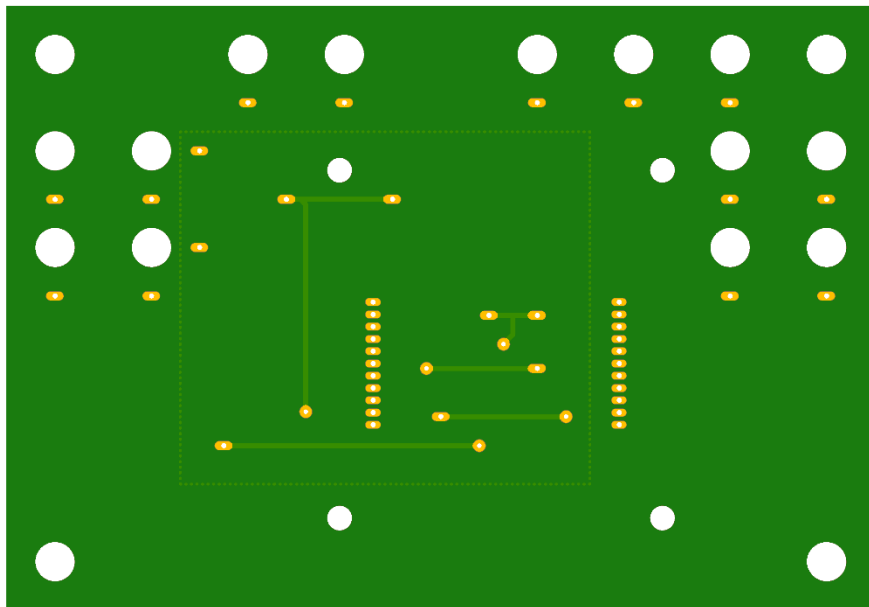


Appendix C - Large printed circuit board

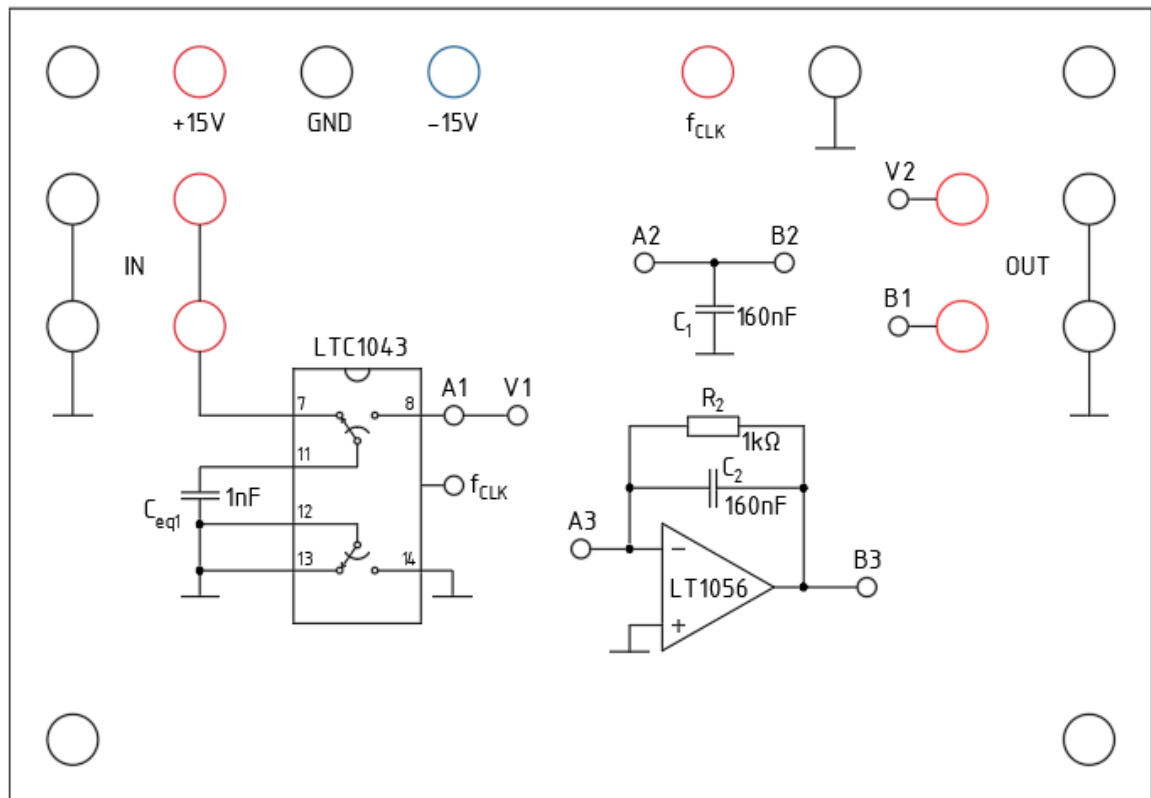
C.1 Component assembly plan for the top side of the large circuit board



C.2 Component assembly plan for the underside of the large circuit board

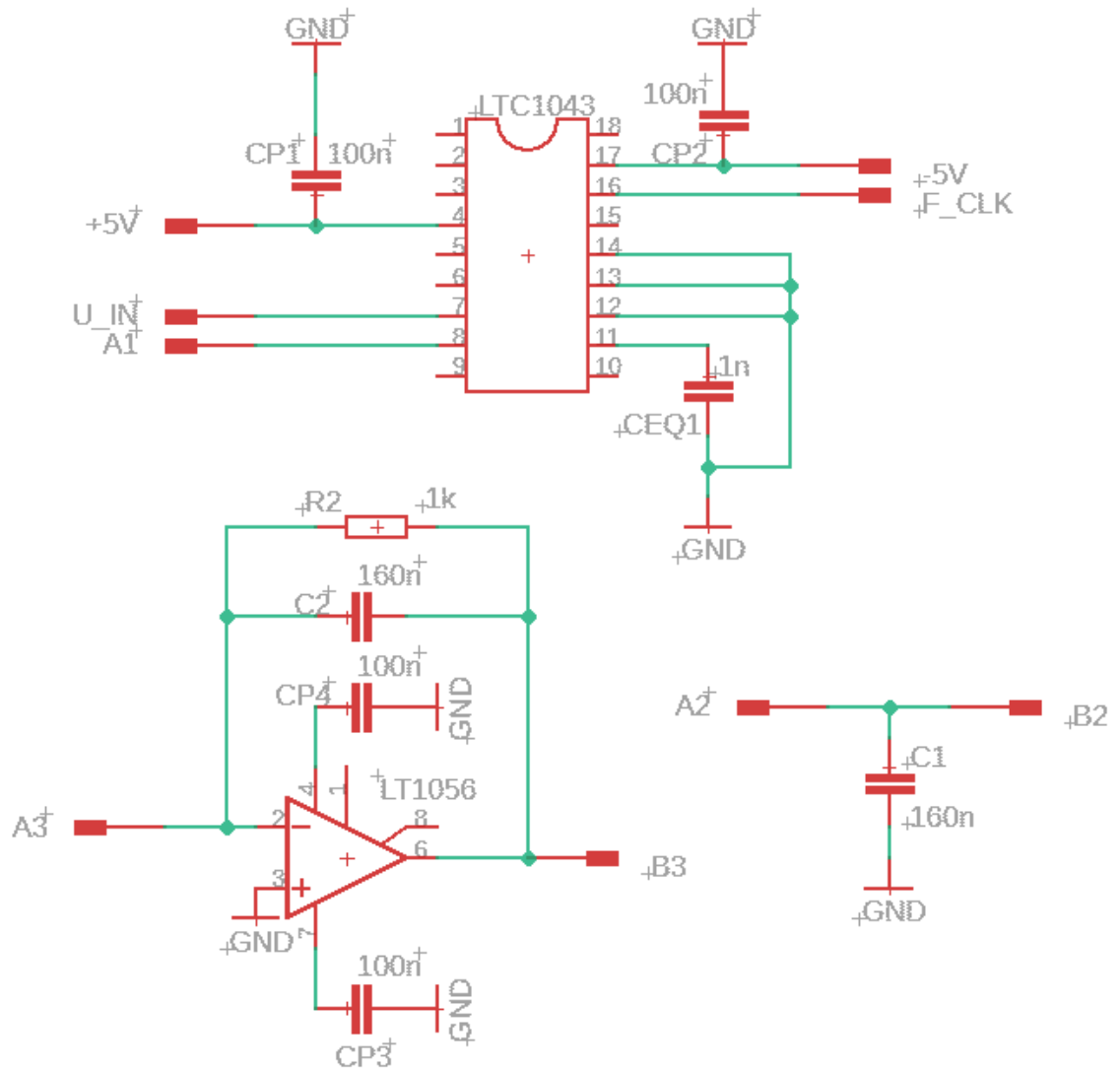


C.3 Front side of the laboratory stand

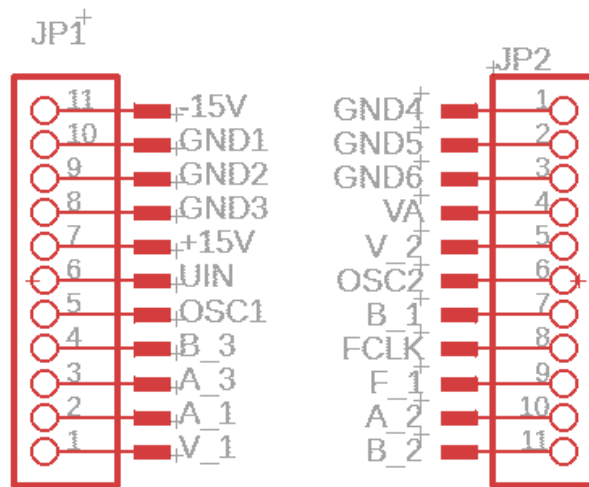


Appendix D - Wiring diagrams of the laboratory board

D.1 Wiring diagrams of the laboratory board of small board



D.2 Pin-Line Headers pinout



D.3 Circuit board power supply

