A Continuous-time Low-pass Filter for UHF RFID

ELEC 5040 - Final Project

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Part A. Project Summary

Parameters	RFID Specifications	Simulated Value
Characteristic	Low-pass	Low-pass
Passband Gain	4 – 30 dB	10.2 - 20.2 dB
Passband Ripple	≤ 1 dB	0.1 dB
Clock Frequency f_s	≤ 200 MHz	200 MHz
Lower -3dB Frequency	8 KHz	34.44 KHz
Upper -3dB Frequency f_{up}	50 KHz – 1.28 MHz (in 4 steps)	77.19 KHz
Lower Corner Channel Attenuation	> 20 dBc @ dc	35.70 dBc
Adjacent Channel Attenuation	> 30 dBc @ 2 * f_{up}	50.14 dBc
Alternating Channel Attenuation	> 50 dBc @ 3 * f_{up}	63.63 dBc
Source Resistor	10 KW	10 KW
Load Resistor	2 KW	2 KW

Table 1. Specifications comparison of the target and simulated value

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Part B. Introduction

1. Overview

In this design, we designed a continuous-time filter for UHF RFID application. The whole circuits consist of 3 parts: 1st stage is a gain stage, 2nd stage is negative feedback to emulate the source resistance, 3rd stage is the Chebyshev type I filter stage. We have verified the results through, HSPICE, MATLAB & SIMULINK [1], and Cadence. Both the behavioral-level design and transistor design, with a low power 80dB differential amplifier are simulated to achieve the UHF RFID application.

2. Design methodology

In the first step, we regard the low-pass UHF RFID as a band pass filter. With the given parameters specified in the specification table. We can find the element values of the passive low pass filter prototype listed in the table. Next, we transform the low-pass filter to band-pass filter. Then the passive filter is converted to active filter by replacing series and parallel inductors with corresponding gyrator, which is to get the active band-pass filter. For the active band-pass filter, the first stage a gain stage, which is used to reduce the high frequency noises. We, then, implement the Gm-C band-pass filter by replacing the ideal Gm-C cell with low power differential amplifier, which provides a sufficient large gain of 80dB.

3. Design Process

(a) Filter type choice

To achieve the low-pass filter specified by table 1, firstly we regard the problem as a band-pass filter design, the lower and upper 3dB frequency are defined above. The first step for the band-pass filter design is to choose the filter type and order by referring to the attenuation curves. The pass-band ripple is less than 1 dB, we choose Chebyshev Type-I attenuation curves (0.1dB) with design margin.

For Chebyshev type I, we set lower cutoff frequency as 8kHz and upper cutoff frequency as 75kHz. The sampling frequency is set to 1MHz. And the order calculated by MATLAB is 6. The code is shown below:

```
% Chebyshev type I filter simulation
fs = 1E8
fu = 75E3;
fl = 8E3;
wp = fu - fl;
ws1 = wp + 2*fl;
ws2 = wp + 2*fu;
ws3 = wp + 4*fu;
n1 = cheb1ord(wp*2/fs,ws1*2/fs,0.5,20)
n2 = cheb1ord(wp*2/fs,ws2*2/fs,0.5,30)
n3 = cheb1ord(wp*2/fs,ws3*2/fs,0.5,50)
```

Code 1: Chebyshev Type I filter order function in MATLAB

Therefore, we get the simulation result from MATLAB for our design:

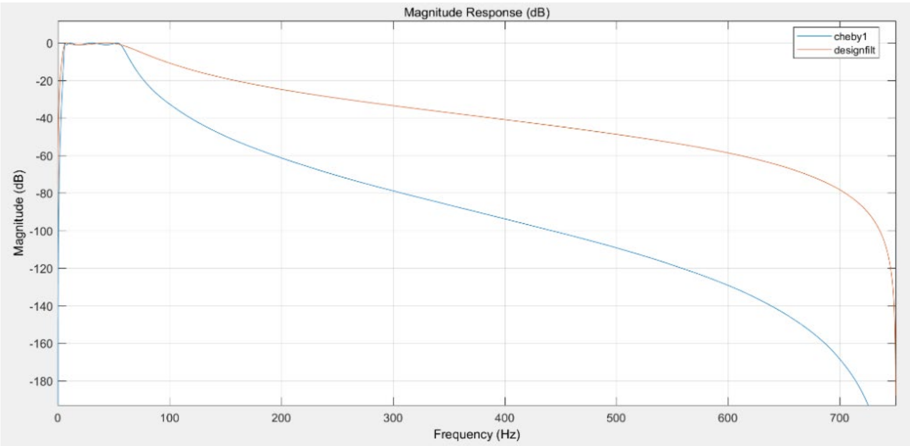


Figure 1: Simulation result of Chebyshev Type I filter and designed filter

Transfer Function analysis:
As the filter is a response depends on input frequency of the signal. It can be analysis by frequency domain (s-domain in continuous time space and z-domain in discrete time space). In last section, the fundamental parameters of the selected Chebyshev filter were already calculated so the transfer function can be formulated and verify whether it can fulfil the requirement. In Figure 2, we can see the center frequency is 41.5kHz and passband ripple is within 1dB.

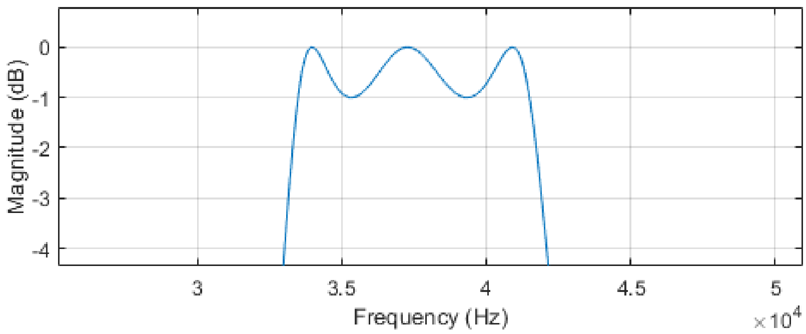


Figure 2: Simulation result of Chebyshev Type I filter form transfer function

As the limitations of MATLAB [1], indicating this filter in transfer function may cause numerical error. We chose second order sections matrix (SOS) to verify this filter. The sos matrix is calculated as:

$$sos = \begin{bmatrix} 0 & 0 & 0 & 1 & -2 & 1 \\ 1 & 0 & -1 & 1 & -2 & 1 \\ 1 & -2 & 1 & 1 & -2 & 1 \end{bmatrix}$$

Also, the designed filter is stable.

(b) Passive filter design

As the order is 6 and $R_S/R_L = 5$, referring to the attenuation curves (left), we can get the prototype design shown Figure 3. The values of capacitors and inductances are summarized in table 2.

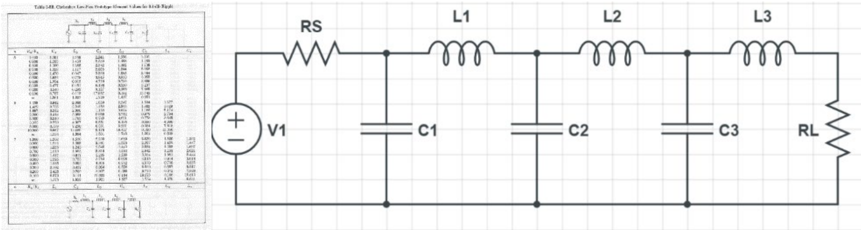


Figure 3: Chebyshev Type I filter with ideal components

Parameter	value
Rs	5 W
RL	1 W
C1	0.139F
L1	7.250H
C2	0.361F
L2	9.261H
C3	0.384F
L3	7.618H

Table 2. Parameters for Chebyshev Type I filters

Then, the following transformation and scaling are performed (low-pass to band-pass transform):

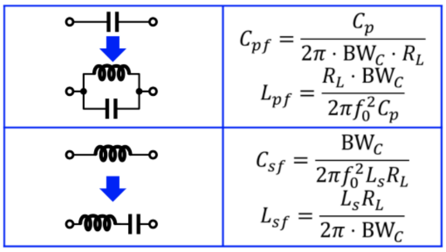
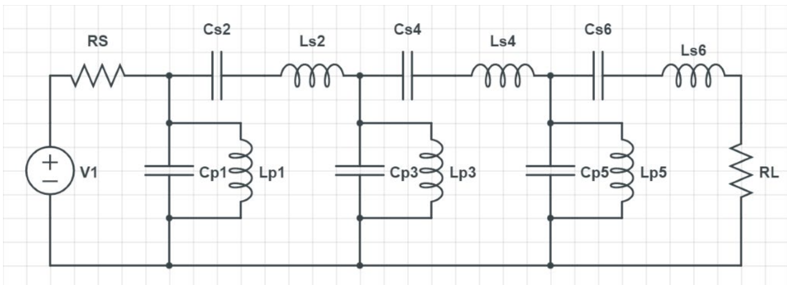


Figure 4: equivalent circuit of non-ideal capacitor and inductor

The equivalent circuits are shown below, and parameters are summarized in table 3:



Parameter	Value	Parameter	Value
Cp1	165pF	Lp1	89.1mH
Cs2	427pF	Ls2	34.4mH
Cp3	428.8pF	Lp3	34.3mH
Cs4	334pF	Ls4	44mH
Cp5	456.1pF	Lp5	32.2mH
Cs6	406.4pF	Ls6	36.6mH
RS	10 kW	RL	2 kW

Figure 5: Chebyshev Type I filter with non-ideal components

After the transformation, a Simulink (MATLAB) Sims cape circuit was built to verify the design is stick to our assumptions.

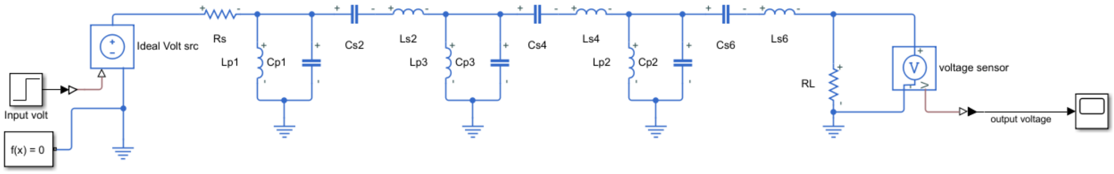


Figure 6: Chebyshev Type I filter with non-ideal components

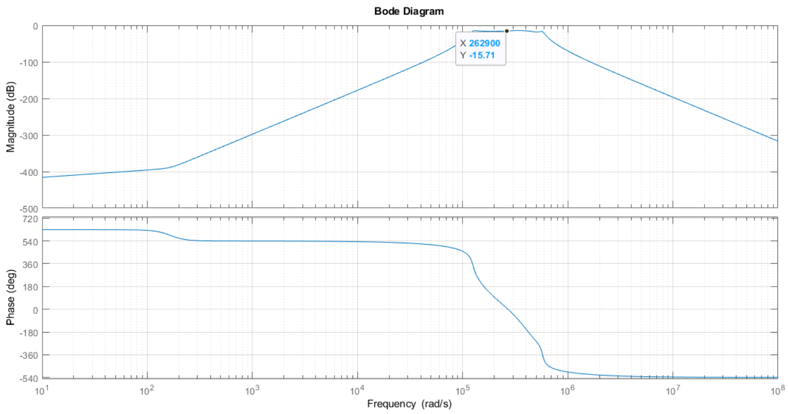


Figure 7: Simulation result of Chebyshev Type I filter in SIMULINK

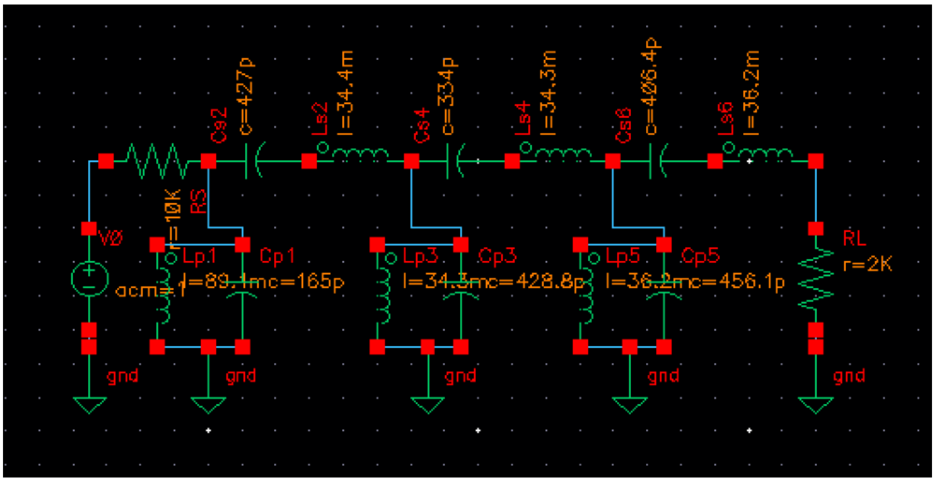


Figure 8: Simulation Chebyshev Type I filter circuit in Cadence

In the next step, we convert the passive filter to active filter with ideal Gm-C cell, the gain stage implements gm1/gm2 = 20mS/2mS = 10 = 20 dB to leave some design margin. The schematic view of Gm-C filter in Cadence is shown below. To implement the ideal Gm-C cell, we use a voltage-control current source with finite bandwidth and output impedance and limited linearity to model the transconductance amplifiers. The figure of the ideal Gm-C cell is shown in figure below.

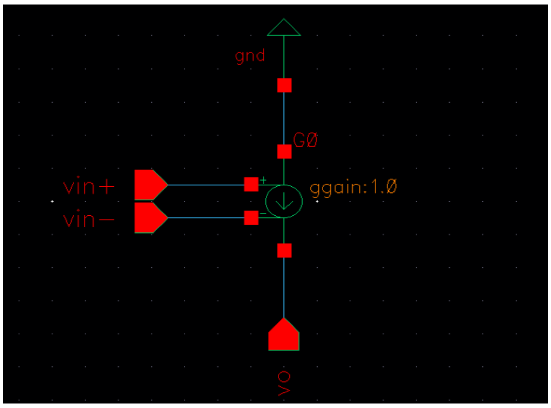


Figure 9: Circuit of ideal Gm cell

Then, we replace the series and parallel inductors with corresponding Gm-C cells and implement the gain stage by 3 more cells (two for boosting the gain and one for emulating the input resistance). As every two order L-C requires five Gm cells and our design is a 6[th] order Chebyshev Type I filter, we need totally 18 Gm cells for the implementation and the circuit of the filter is shown below.

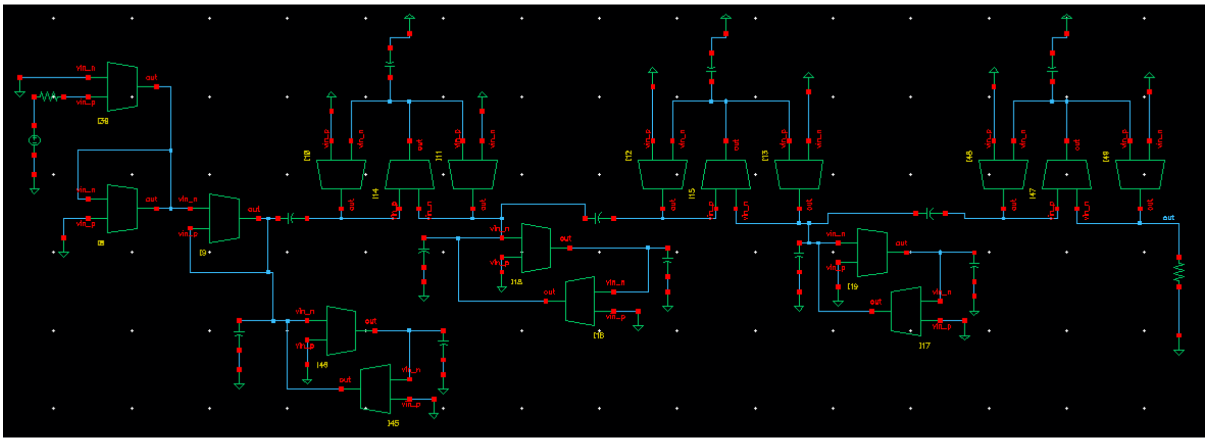


Figure 10: Simulation Chebyshev Type I filter with Gm Cell circuit in Cadence

(c) Simulation results

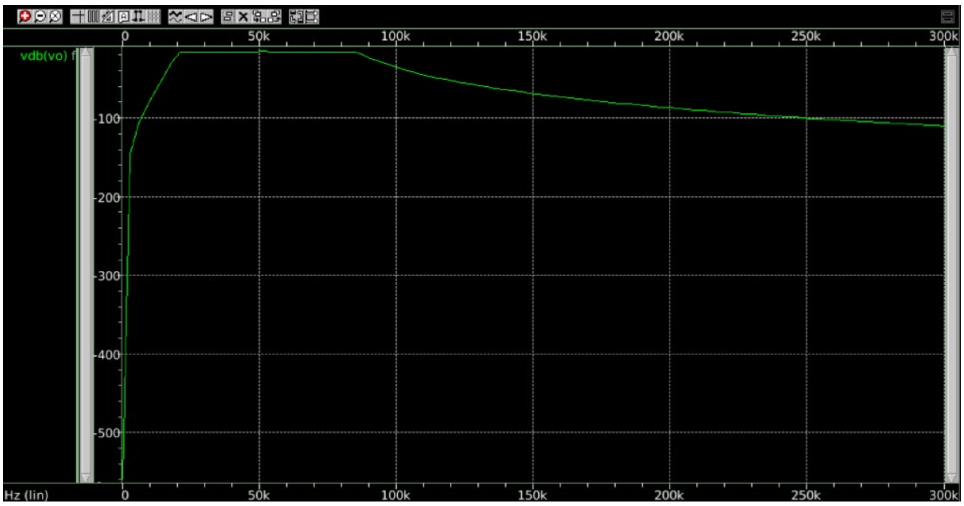


Figure 11. HSPICE results of Chebyshev type I filter (passive filter)

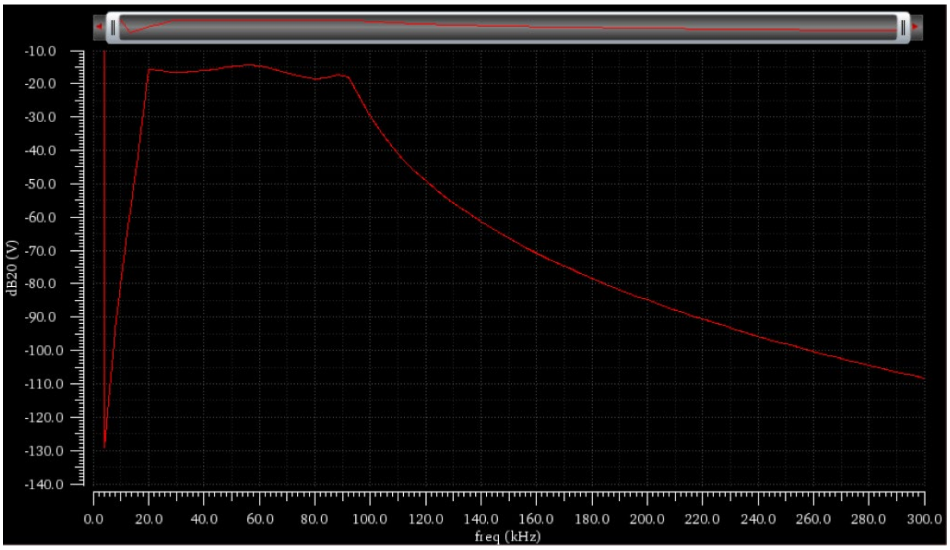


Figure 12. Cadence results of Chebyshev type I filter (passive filter)

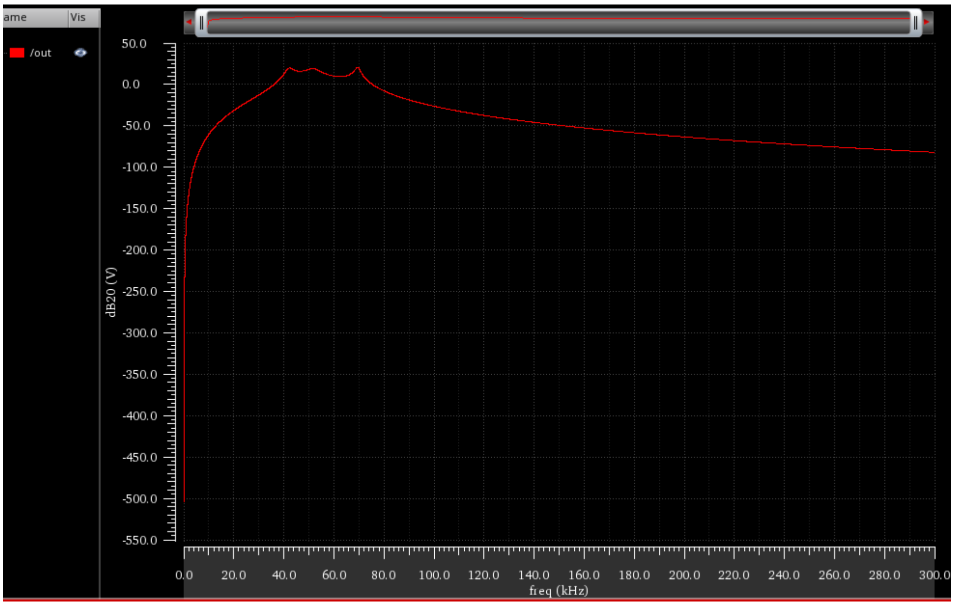


Figure 13. Cadence results of Gm-C filter (active filter)

(d) Comparison of calculated and simulated results

Below is a table for the comparison of results. Generally, the simulation shows that our design can meet the requirements of the project. Though, there are some flaws in terms of the implementation by OTAs and we will discuss them in the next section.

Parameters	**RFID Specifications**	**Calculated Value (theoretical equations and MATLAB simulations)**	**Simulated Value (Cadence)**
Characteristic	Low-pass	Low-pass	Low-pass
Passband Gain	4 – 30 dB	20 dB	10.2 - 20.2 dB

Passband Ripple	≤ 1 dB	1 dB	0.1 dB
Clock Frequency fs	≤ 200 MHz	N/A	N/A
Lower -3dB Frequency	8 KHz	33.19 KHz	34.44 KHz
Upper -3dB Frequency fup	50 KHz – 1.28 MHz (in 4 steps)	41.92 KHz	77.19 KHz
Lower Corner Channel Attenuation	> 20 dBc @ dc	225 dBc	35.70 dBc
Adjacent Channel Attenuation	> 30 dBc @ 2 * fup	43.3 dBc	50.14 dBc
Alternating Channel Attenuation	> 50 dBc @ 3 * fup	93.7 dBc	63.63 dBc
Source Resistor	10 K W	10 K W	10 K W
Load Resistor	2 K W	2 K W	2 K W

Table 3. Comparison of calculated and simulated results

4. Advanced Filter Design and Performance with Non-idealities and Actual Amplifier

(a) Effects of non-idealities

Non-ideal components always exist. Non-ideal inductor (capacitor) is limited in operation region so that it has capacitance (inductance) behaviors. In figure 4, non-inductor is transformed as a capacitor-series-inductor and the non-capacitor is transformed as inductor-parallel-capacitor where these equivalent circuits contain ideal inductors and capacitors.
As Gm cell (as equivalent inductors and capacitors) made with MOSFET. In other word, Gm cells contain the disadvantage of MOS devices, including limited operated frequency and region, linearity, active power consumption. During the implementation process, we are not only considering the filter circuit but also considering the effects of Gm cell.

(b) Design and simulation with the actual amplifier from the midterm project at the transistor level

We implement the operational amplifier designed in the midterm project in Cadence. The basic parameters of the amplifier are as follows. The differential amplifier is transformed into a single output OTA by removing one of its load capacitors and make it a current output. We can directly measure the output by the drain current of M10.

Supply Voltage	**+/- 1.0 V**	**Output Resistor**	4.75M W
Low-frequency Gain A_0	80 dB	**Unity-Gain Frequency f_0**	600 MHz

Table 4. Parameters of OTA

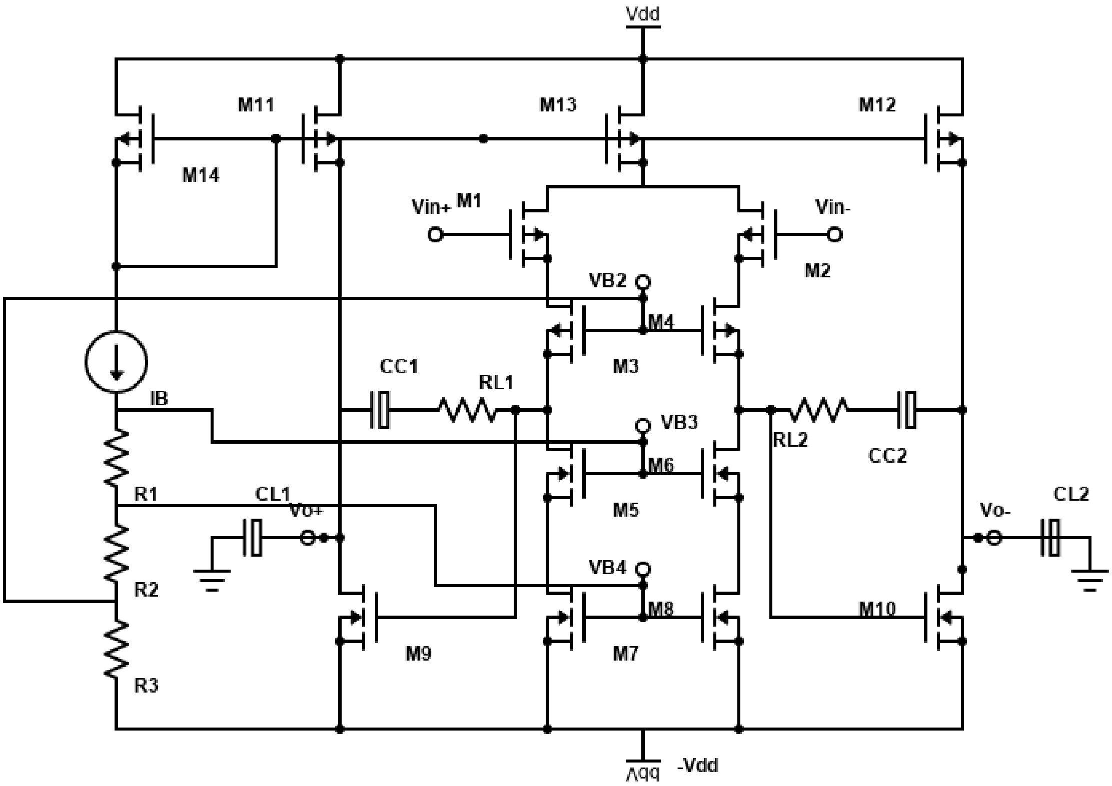


Figure 14. Circuit of 80-dB 2-stage Opamp designed previously

In order to implement the lowpass filter by the OTA mentioned above, we need altogether 18 Gm Cells which make up of four stages. As we replace the inductors by gyrators, the corresponding capacitors are calculated by the following equation and their values are shown in the table below.

$$C = (g_m)^2 \times I$$

Parameter	**value**	**Parameter**	**value**
Cpp1	423.4nF	Css2	163.5nF
Cpp3	163nF	Css4	209.1nF
Cpp5	153nF	Css6	172nF

Table 5. capacitance of gyrators

With all the required parameters calculated, we implement the filter in Cadence and the circuit is shown in the below figure. The three cells are the first stage which is used to increase the gain and emulate the large input resistor. The first 3 arrays are the 6th order Chebyshev bandpass filter consist of OTAs. The input is an AC source with amplitude of 1 and we check its behaviour by sweeping from 0k to 300k frequency.

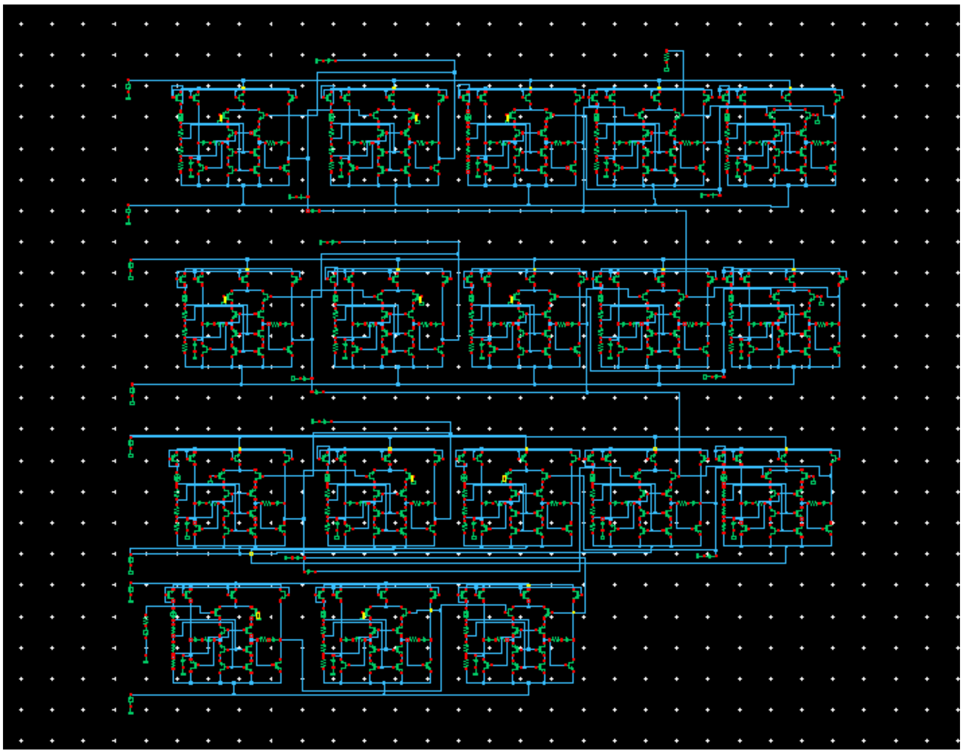


Figure 15. Circuit of a Gm Cell

(c) Problems encountered and solutions

The frequency of the circuit is shown below. We can see that it is distinct from the simulation made based on passive components or ideal Gm-cells. By checking the simulation log from Analog Environment, we know that there's no error in our circuit implementation, can the possible causes or some non-ideal factors that lead to this result are discussed below.

First of all, it is hard to accurately calculate the gm value for our amplifier. To obtain the transconductance (Gm value), we first apply the equation:

$$G_m = \frac{\Delta I_{out}}{\Delta V_{in}}$$

To do that, we remove the loading first and plot the ac current in the final stage via AC simulation. The measured result of Gm-cell 's transconductance by both equations are shown below, with a gm of around 200ms, and it is not an expected value.

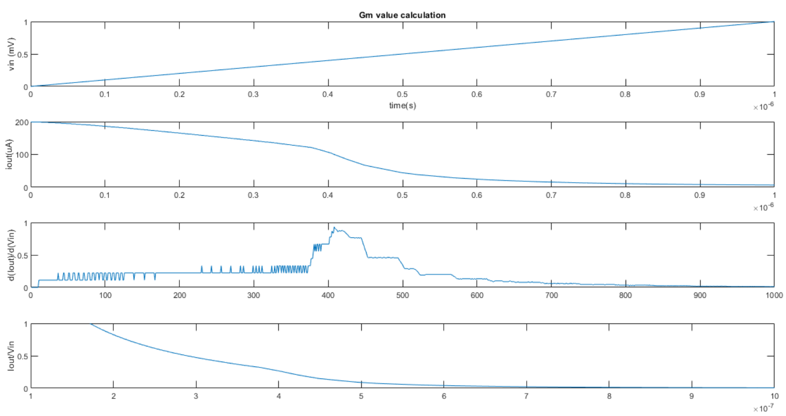


Figure 17. Gm value measurement

Then we apply the below equation by small signal model calculation. We replace the load capacitor by a voltage source and measure the output current. The final output resistance is 4.57M ohm and the gm is 2.18ms. It is clearly not the same as the above calculated gm and that makes our simulation tough.

$$G_m = \frac{A_v}{r_o}$$

Besides, some non-ideal factors decrease the accuracy. For example, the gm of the first stage should be large the boost the gain, but in our implementation, even though we increase it by reducing the output resistor, we are not sure is the gm ratio is large enough. Moreover, the loading effect and some other phenomenon of the active devices may affect the outcome.

5. Conclusion

(a) Summary of your design and what you have learned from the project

Through the whole project, we learned how to design a pass-band filter for UHF RFID application, implemented the behavior level in MATLAB and verification by circuits. Also, we checked the results of filter design in transistor level. Most requirements are met by fine-tuning the corresponding influence factors. The pass-band gain is about 20dB by tuning the transconductance of the amplifier in the first gain stage, the passband gain and attenuation at different frequency are achieved by choosing the best order of Chebyshev Type I filter.

We, now, have a comprehensive understanding on the design process of analog pass-band filter design and the influence factors on specific parameters. All these tools, including MATLAB & SIMULINK, HSPICE and cadence are robust for both transistor level circuits design and verification. What is most important is that the engineers should have the whole design blueprint in our mind first before delving into simulation, which will make the designer approach the target parameters easier with the simulation results.

(b) Possible improvement

Throughout the project, the simulation results are satisfying for the parts of passive components and ideal Gm-Cells. The frequency response corresponds with the prototype we generated from MATLAB. However, when we replace the Gm-Cells with the OTAs, the simulation result is not as expected. We think that the major improvement should be optimizing the actual-filter design and make its behavior similar to the predictions. To do that, we need to get more familiar with the attributes and non-idealities of the active devices and how to compensate them in the design.

Moreover, we also identify some other possible improvements of our lowpass filter and below is a summary of them.

- Passband Frequency and ripple
  - As Elliptic and Chebyshev filter have constant ripple, it has the potential to implement a filter by While Bessel or Butterworth filter.
- Gm Cell
  - As Gm cell is an active device, power consumption in operation is important. A low transconductance is ideal to reduce power consumption.

Part C. Individual Contribution:

Runzhou	MALTAB simulation, calculations, Cadence circuit implementation
Zachary	Cadence circuit, Gm-Cell implementation
Jonathan	MALTAB &Simulink simulation, Gm-Cell implementation

Part D. References:

[1] CHEBYSHEV TYPE I FILTER DESIGN - MATLAB CHEBY1
In-text: (Chebyshev Type I filter design - MATLAB cheby1, 2020)
Your Bibliography: Mathworks.com. 2020. Chebyshev Type I Filter Design - MATLAB Cheby1. [online] Available at: <https://www.mathworks.com/help/signal/ref/cheby1.html> [Accessed 21 December 2020].

[2] R. Martin, “Use Of Matlab In Design and Analysis Of Analog Bandpass Filters To Meet Particular Specifications,” ASEE PEER Document Repository, 10-Mar-2015. [Online]. Available: https://peer.asee.org/use-of-matlab-in-design-and-analysis-of-analog-bandpass-filters-to-meet-particular-specifications. [Accessed: 21-Dec-2020].

[3] Razavi, Behzad. “Design of Analog CMOS Integrated Circuits”, McGraw-Hill Education, (2017).