Lam King Sum Sam (20423789)
Tse Ming Fung Alfred (20756435)

EESM 5120 Advanced Analog Integrated-Circuit Design and Analysis

Final Project – Filter Design

1. Summary

In this project, an active filter is designed for use as an IF channel-select filter in a direction-conversion ultra-wideband (UWB) receiver. A continuous-time filter is designed and simulated to satisfy the specifications. A table summary of the active filter performance is shown in table 1.

	Specifications	Calculation	Simulation
Characteristic	Low-pass	Low-pass	Low-pass
Passband Gain	0-10 dB	4.59 dB	4.537058 dB
Passband Ripple	<= 1 dB	0.1 dB	0.100315 dB
Lower -3 dB Frequency	5KHz < f_{lo} < 2 MHz	1002.5 KHz	949.5249 KHz
Upper -3 dB Frequency	253 MHz < f_{up} < 264 MHz	258.5 MHz	258.4173 MHz
Lower Corner Channel Attenuation	>15 dBc @ dc	>15 dBc @ dc	>15 dBc @ dc
Adjacent Channel Attenuation	>12 dBc @ 500MHz	-25 dB @ 500 MHz	-29.67 dB @ 500 MHz
Alternating Channel Attenuation	>30 dBc @ 792MHz	-42 dB @ 792 MHz	-46.70 dB @ 792 MHz
Source Resistor	1 KΩ	1 KΩ	1 KΩ
Load Resistor	200 Ω	200 Ω	200 Ω

Table 1: Calculation and Simulation Results

2. Design Choice

To cope with the project specifications, type I Chebyshev filter and Gm-C continuous-time filter approach is selected for the passive and active filter design.

Chebyshev filter is chosen as the passive filter due to its high-Q with high attenuation for a given order comparing with Butterworth and Bessel filter. In addition, type I of Chebyshev filter is chosen as of larger margins for passband ripple.

Gm-C continuous-time filter is chosen for the active filter design due to its high operation frequency which exceeds 100MHz. On the other hand, Switched-Capacitor filter is limited to low-frequency operation which is below 10MHz due to high required sampling frequency. Considering the high frequency operation specified by the project goal, Gm-C continuous-time filter is selected.

The entire Gm cell active filter schematic diagram is shown in figure 1, it consists of three stages, namely high-pass filter stage, low-pass filter stage as well as gain stage. The high-pass filter stage is responsible for filtering out low frequency while allowing high frequency to pass. The low-pass filter stage is responsible for filtering out high frequency while allowing low frequency to pass. The gain-stage is responsible for boosting gain so that the passband gain could satisfy the project requirement.

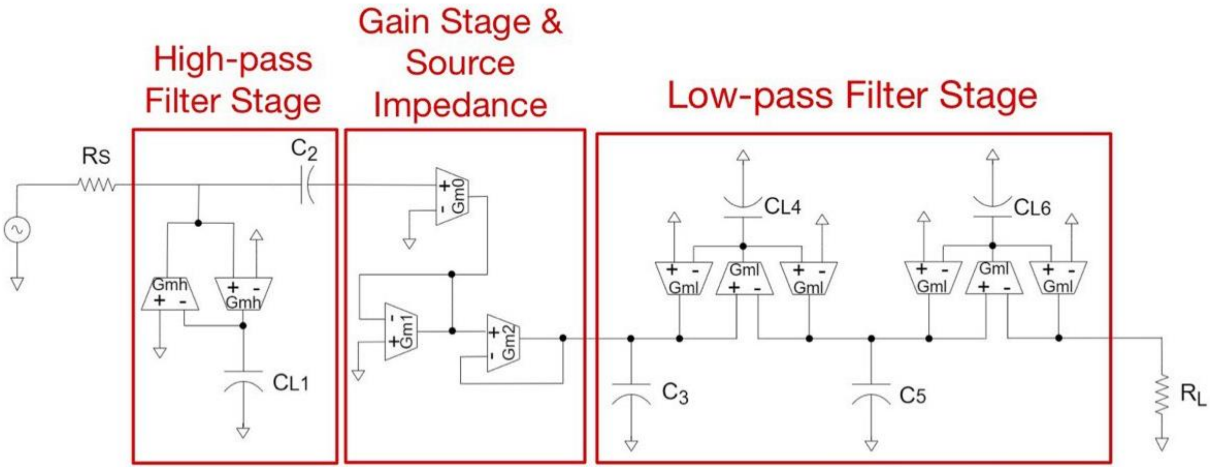

Figure 1 Schematic of a Gm cell active filter

3. Design Procedure

The design procedure is separated into 3 stages, namely high-pass filter stage, low-pass stage as well as gain stage. Design procedure will be explained separately in the below sections. In the design calculation for all three stages, we have made the following assumptions:

***Assumptions*:**

1. $\textit{Taking } f_{lo} = \frac{5K + 2M}{2} = 1002.5\ KHz$
2. $\textit{Taking } f_{up} = \frac{253M + 264M}{2} = 258.5\ MHz$
3. $\textit{Taking } R_s = 1K\Omega\ \&\ R_L = 200\Omega$

A. High-pass filter stage

In high-pass stage, the number of order $= 2$
From the table of 0.1 *dB Chebyshev LC element parameters,*
$C_1 = 0.1841\ F\ \&\ L_2 = 7.4257\ H$
The passive filter model is shown in figure 2.

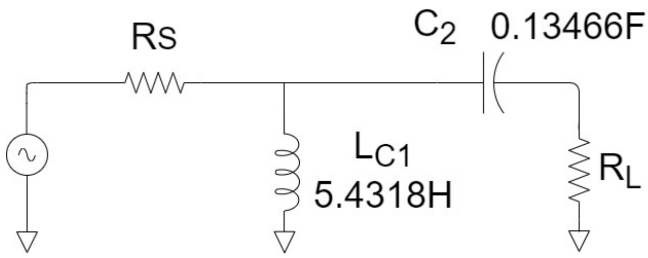

Figure 2 Passive high-pass filter model

To convert a low-pass into a high-pass filter, C_1 & L_2 *is taking reciprocal to form* L_{C1} & C_2.

$$L_{C1} = \frac{1}{C_1} = \frac{1}{0.1841} = 5.4318\ H$$

$$C_2 = \frac{1}{L_2} = \frac{1}{7.4257} = 0.13466\ F$$

To scale the components,

$$L_{f1} = \frac{L_{C1}R_L}{2\pi f_{lo}} = \frac{5.4318 \times 200}{2\pi(1002.5K)} = 172.47\ uH$$

$$C_{f2} = \frac{C_2}{2\pi f_{lo}R_L} = \frac{0.13466}{2\pi(1002.5K)(200)} \approx 106.9\ pF$$

The final passive filter is shown in figure 3.

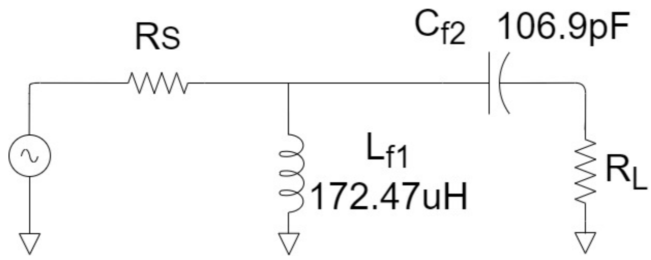

Figure 3 Final passive high-pass filter

To convert passive into active filter, transformation from inductor into Gm cell is needed.
Taking $gm_h = 100\ uS$,

$$C_{Lf1} = L_{f1} \times {gm_h}^2 = (172.47u)(100u)^2 = 1.7247\ pF$$

The active high-pass filter stage is shown in figure 3.

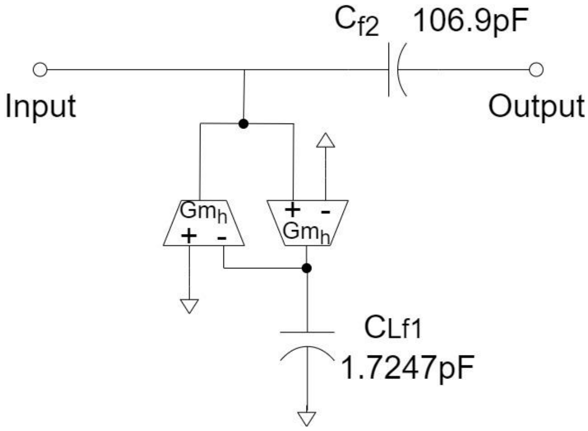

Figure 4 Active high-pass filter stage

B. Low-pass filter stage

In low-pass stage,

$$\because \frac{792M}{258.5M} \approx 3 \ \& \ \frac{500M}{258.5M} \approx 2$$

By looking up the attenuation characteristic curve of 0.1 *dB ripple Chebyshev filter, the order* $\geqslant 3$.

$\therefore$ *To give a larger margin for passband ripple and attenuation, we set* $n = 4$.

According to characteristic curve,

adjacent channel attenuation $\approx -25\ dB$ @ $500\ MHz$

alternating channe attenuation $\approx -42\ dB$ @ $792\ MHz$

By looking up the table of 0.1 *dB ripple Chebyshev LC element parameters,*

$Rs = 5,\ C_3 = 0.1745\ F,\ L_4 = 7.6072\ H,\ C_5 = 0.367\ F,\ L_6 = 7.6143\ H$

The passive filter model is shown in figure 5.

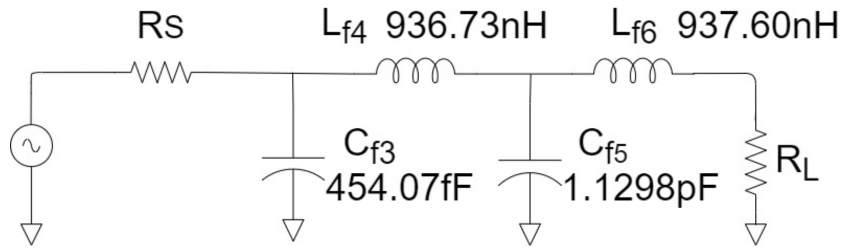

Figure 5 Passive low-pass filter model

To scale the components,

$$C_{f3} = \frac{C_3}{2\pi f_{up} R_L} = \frac{0.1745}{2\pi(258.5M)(200)} = 454.07\ fF$$

$$L_{f4} = \frac{L_4 R_L}{2\pi f_{up}} = \frac{7.6072 \times 200}{2\pi(258.5M)} = 936.73\ nH$$

$$C_{f5} = \frac{C_5}{2\pi f_{up} R_L} = \frac{0.367}{2\pi(258.5M)(200)} = 1.1298\ pF$$

$$L_{f6} = \frac{L_6 R_L}{2\pi f_{up}} = \frac{7.6143 \times 200}{2\pi(258.5M)} = 937.60\ nH$$

The final passive filter is shown in figure 6.

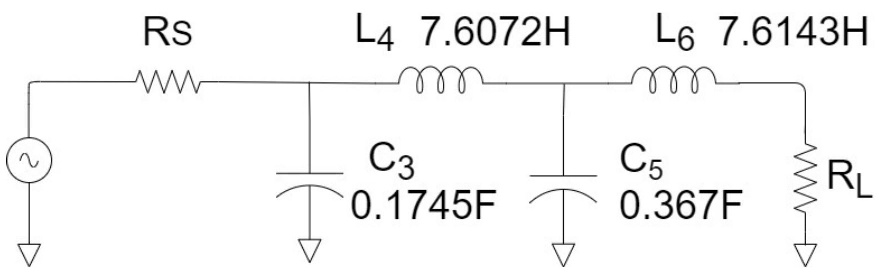

Figure 6 Final passive low-pass filter

$To\ convert\ passive\ into\ active\ filter,\ transformation\ from\ inductor\ into\ Gm\ cell\ is\ needed.$
$taking\ gm_L = 200\ uS,$
$C_{Lf4} = L_{f6} \times {gm_L}^2 = (936.73n)(200u)^2 = 37.469\ fF$
$C_{Lf6} = L_{f6} \times {gm_L}^2 = (937.60n)(200u)^2 = 37.504\ fF$
$The\ active\ low\text{-}pass\ filter\ stage\ is\ shown\ in\ figure\ 7.$

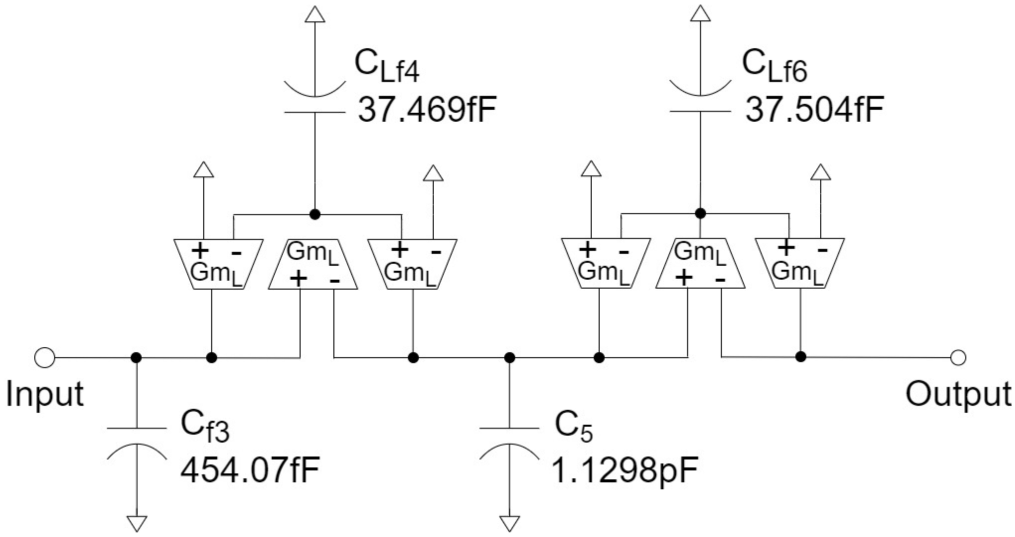

Figure 7 Active low-pass filter stage

C. Gain stage and source impedance

$As\ the\ gain\ of\ passive\ filter\ \approx\ -15\ dB\ \ after\ simulation,$
$in\ order\ to\ cope\ with\ the\ project\ specification,\ we\ set\ the\ gain\ provided\ by\ gain\ stage = 20\ dB.$
$Taking\ gm_0 = 2\ mS\ \&\ gm_1 = 200\ uS,$

$$A = \frac{gm_0}{gm_1} = \frac{2m}{200u} = 10 = 20\ dB$$

$In\ this\ way,\ the\ estimated\ passband\ gain = (20 - 15)\ dB = 5\ dB$
$To\ emulate\ the\ source\ resistance,$

$$gm_2 = \frac{1}{1\ K\Omega} = 1\ mS$$

$The\ gain\ stage\ and\ source\ resistance\ is\ shown\ in\ figure\ 8.$

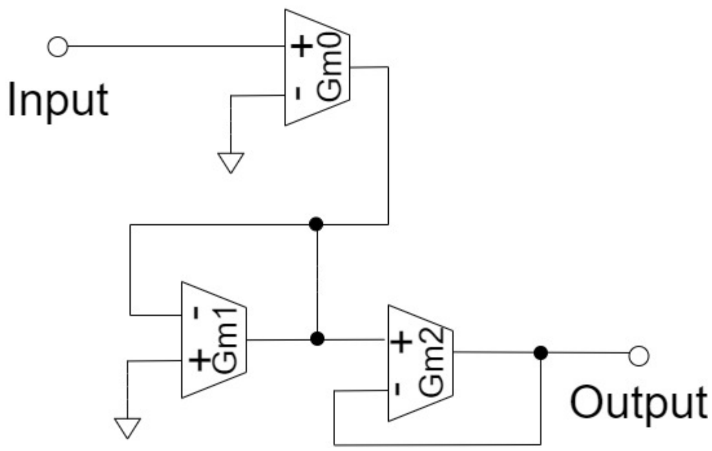

Figure 8 Gain stage and source resistance

4. Simulation Results

The passive filter's AC frequency response is shown below in Figure 9. Figure 10 shows the detail of the detail of the pass band. The passive filter simulation result is used to calculate the gain compensation in the gain stage and to investigate the effect of the passive-to-active filter transformation.

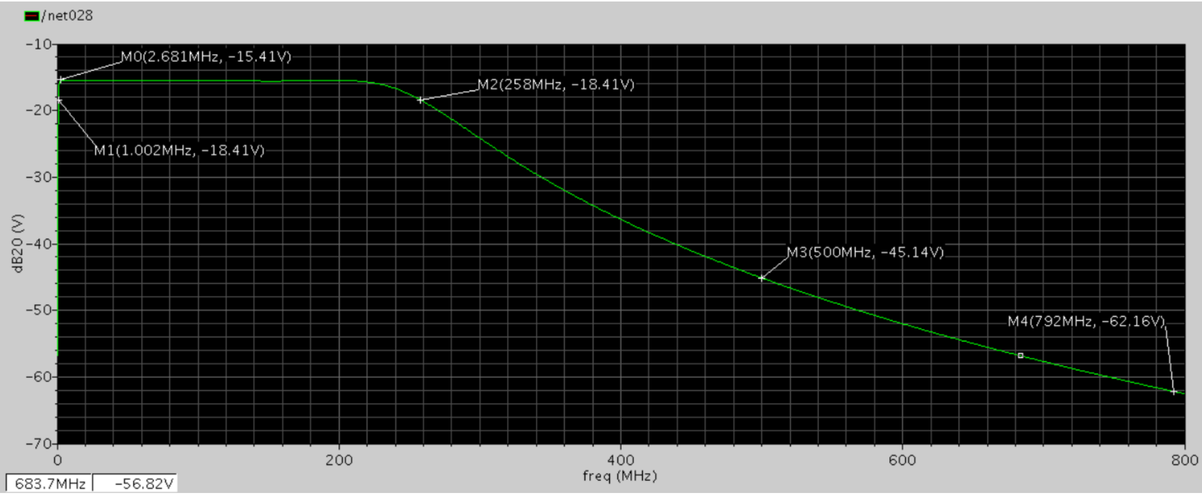

Figure 9 AC response of Passive filter

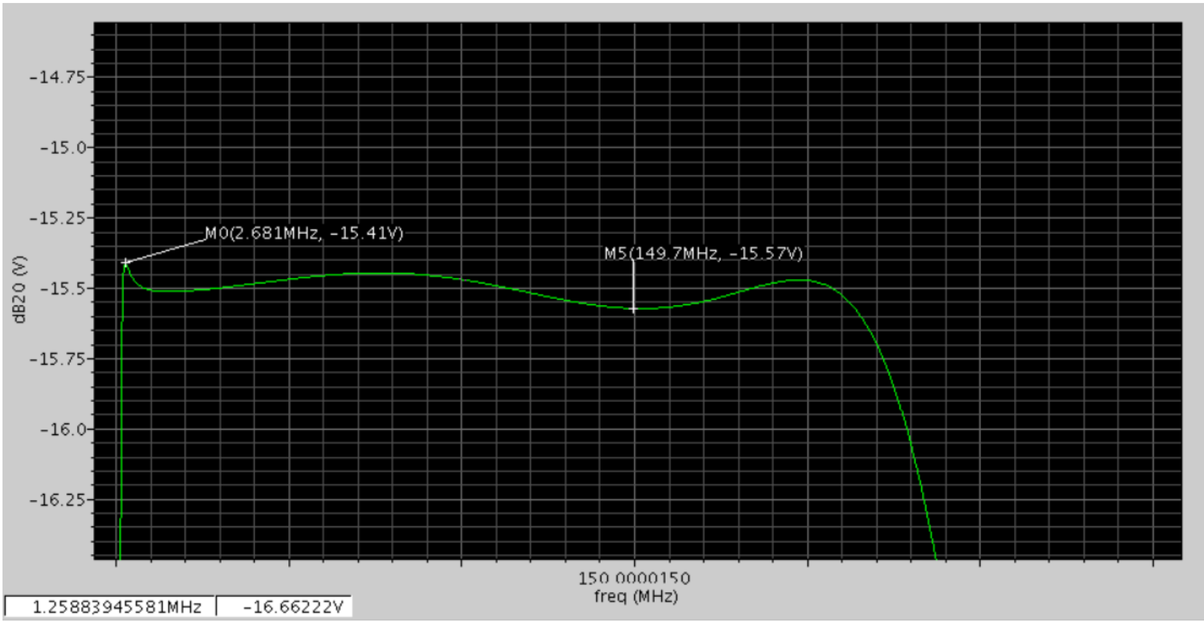

Figure 10 Detailed passband AC response of Passive filter

The complete filter's AC frequency response is shown below in Figure 11. Figure 12 shows the detail of the pass band. Lower –3dB frequency is 949.5249kHz; Upper 3dB frequency is 258.4173MHz. For channel attenuations, at 500MHz the filter has ~29.67dB attenuation; while at 792MHz it has ~46.70dB attenuation.

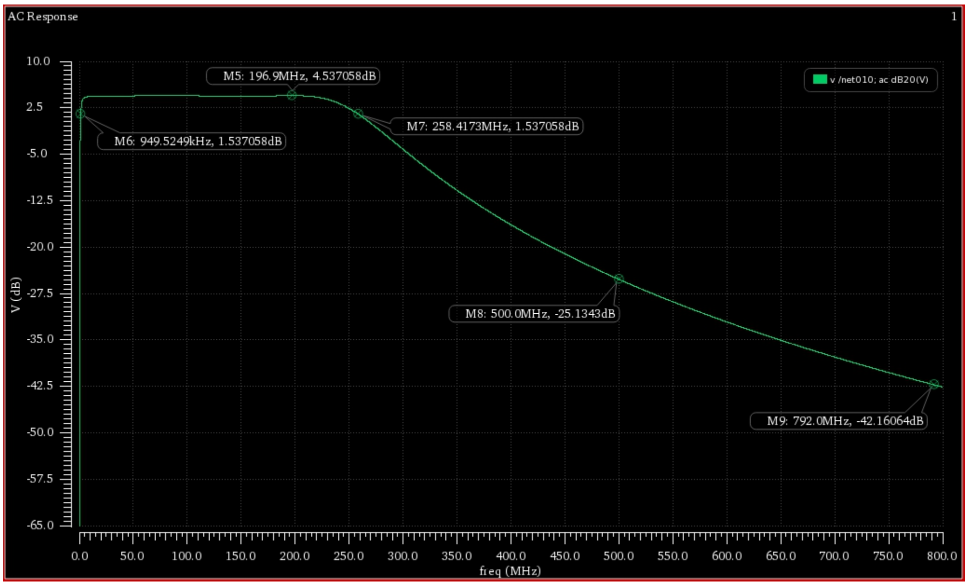

Figure 11 AC response of Gm-C filter

For passband response below shows a ~0.1dB ripple, which meets the requirement.

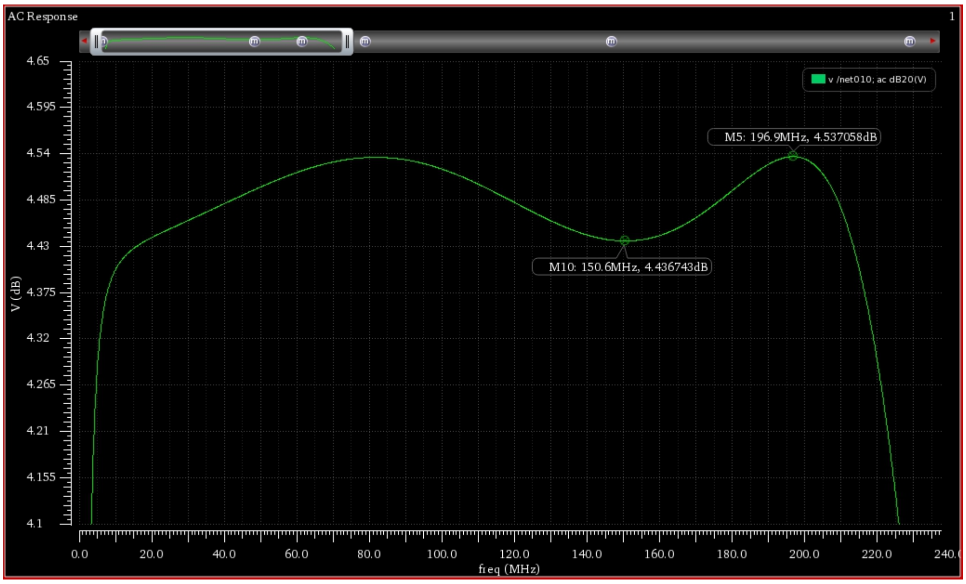

Figure 12 Detailed passband AC response of Gm-C filter

5. Results Comparison

A. Passband gain

The passband gain of Gm-C filter in simulation is slightly lower than the calculation result. This is due to the loading effect which might degrade the gain. In addition, the insertion of gain stage to the active filter might also cause a decrease of the passband gain. Therefore, the gain compensation might not be exactly same as the calculation result.

B. Passband ripple

The passband ripple of Gm-C filter in simulation is close to the calculation result. However, in passive filter simulation, the ripple is slightly larger than Gm-C filter. The passband ripple simulation results in passive and Gm-C filter are good enough to satisfy the project requirement.

C. -3 dB Frequency

The upper and lower -3 dB frequencies of Gm-C filter in simulation are lower than the calculated values. However, the upper -3 dB frequency in the passive filter simulation is 1002 KHz which is closer to the calculation results; the lower frequency in the passive filter simulation is 258 MHz which is worse than the simulation results. Such response is due to replacement of inductors by Gm cells in the transformation from passive to active filter. As inductor is frequency dependent component, the inductor impedance is directly proportional to frequency. Therefore, the existence of inductor in passive filter can improve the performance at low frequency while degrade the performance at high frequency.

D. Attenuation

The lower corner, adjacent and alternating channel attenuation of Gm-C filter in simulation are close to the calculation results. Although the choices of filter order and attenuation are based on observing the characteristic curve of Chebyshev filter which are estimated values, the simulation results are good enough to satisfy the specifications.

6. Discussion

A. Non-ideality

To model non-ideality and finite output resistance, PVCCS component in parallel with a 100MΩ resistor is used for modeling non-ideal Gm cell (See Figure 12):

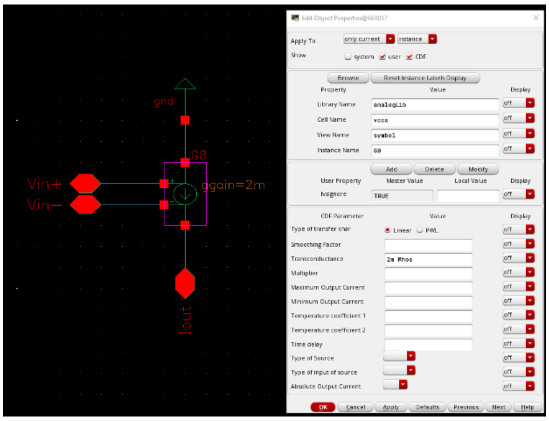

Figure 13 An ideal Gm cell

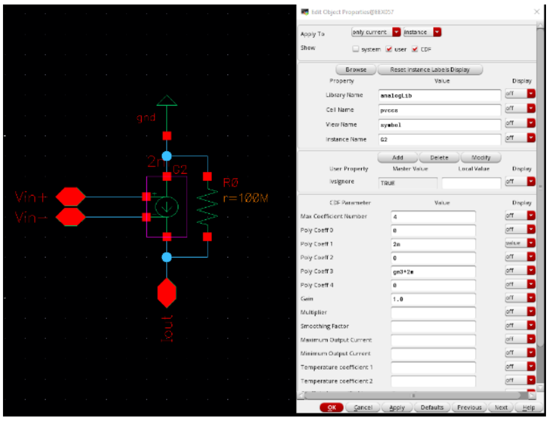

Figure 14 A non-ideal Gm cell

Ideally,

$$y(t) = \alpha_1 x(t), \text{ where } \alpha_1 \text{ is gm of the cell}$$

Modeling non-ideality in practice we apply the following polynomial,

$$y(t) = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

For PVCCS cell, even order harmonics can be cancelled by employing differential topologies. So, α_0 (coefficient 0, c0) and α_2 (coefficient 2, c2) are set as zero. Design variable gm3 is defined for response analysis. Such gm3 is the ratio of coefficient 1, c1 and coefficient 3, c3:

$$gm3 = \frac{c3}{c1}$$

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Periodic Steady State (PSS) analysis shows the harmonic distortion for c3=0 (green) and for c3/c1=0.3 (magenta):

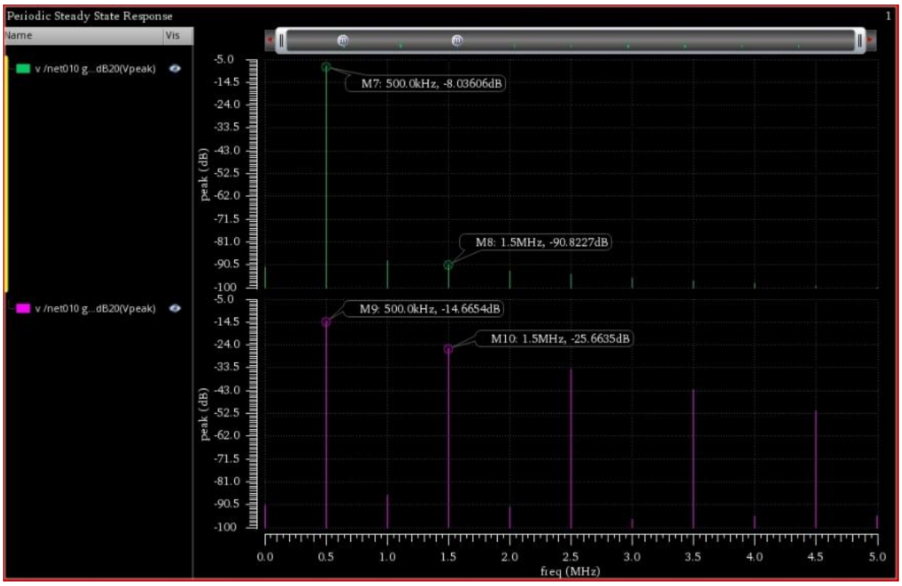


Figure 15 Harmonic Distortion of the filter output

Parametric analysis of `gm3` against distortion attenuation (converted from dB to %) is plotted as below:

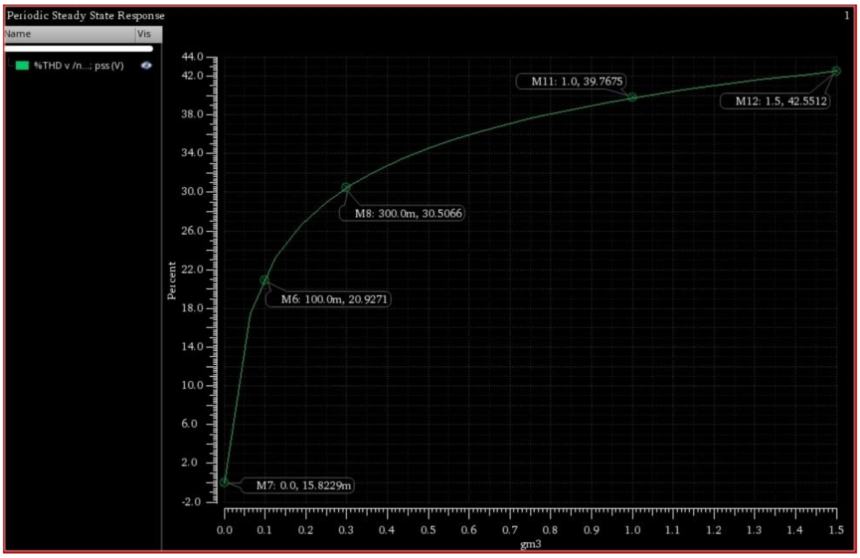
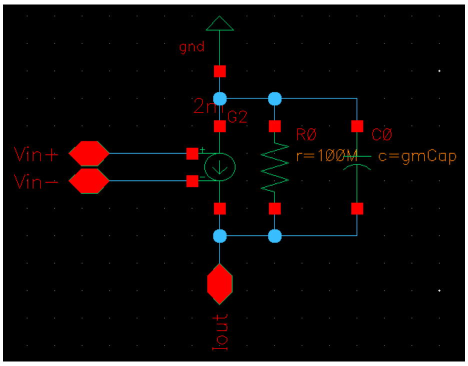


Figure 16 c3/c1 ratio VS THD (in %)

It can be observed that the total harmonic distortion increases as c3/c1 increases. The distortion is comparatively more sensitive when c3 is small (Gm cells are closer to ideal) to when c3 is large. This project does not include any requirement associate with maximum allowable harmonic distortion at the output. But to keep total harmonic distortion as small as -40dB (<1%), according to Figure 14, c3/c1 ratio is required to be very small (~1/100). However, the distortion % saturates as c3 gets larger than 1.5 times of c1.

B. Finite Bandwidth

The finite bandwidth in Gm cells is modeled by paralleling a capacitor with the PVCCS component as below. The effect of filter bandwidth and ripple due to different capacitances, `gmCap`, is conducted by plotting the AC responses at `gmCap` from 0fF to 50fF.



The AC responses are shown below:

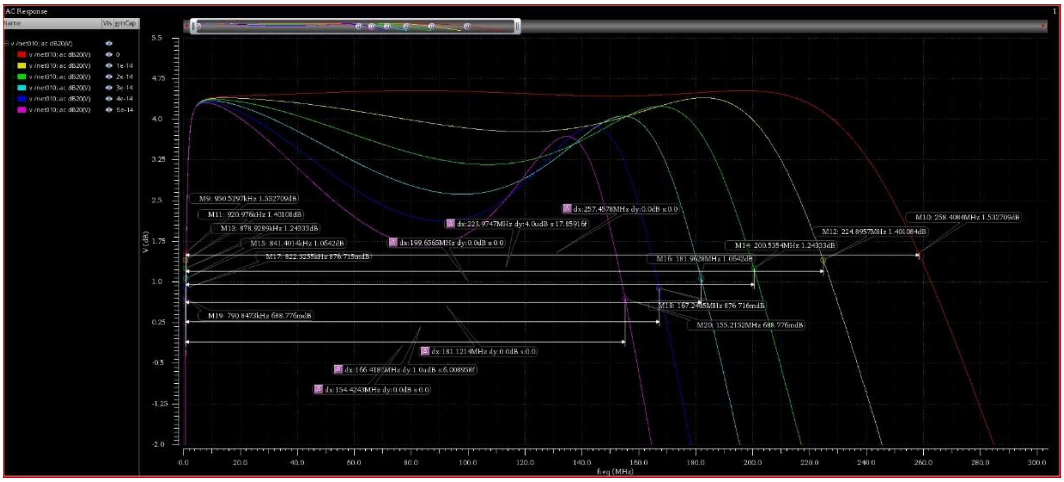


Figure 17 Bandwidth measurement at different `gmCap`

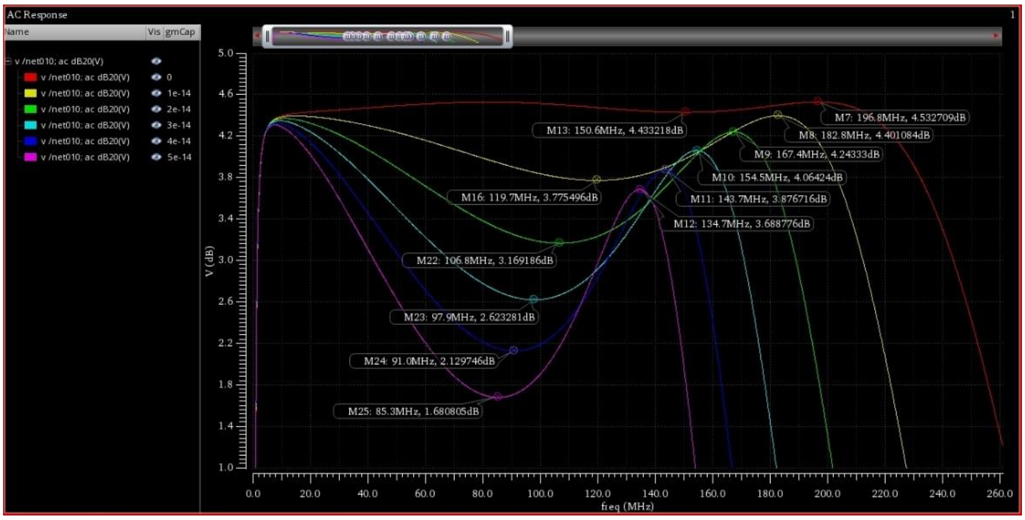


Figure 18 Ripple measurement at different `gmCap`

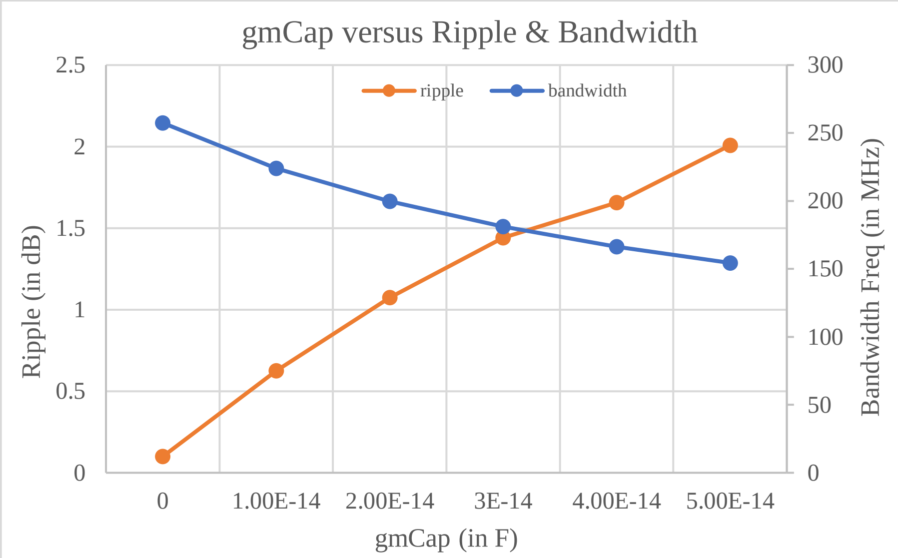


Figure 19 `gmCap` versus Ripple and Bandwidth

Based on the ripple and bandwidth measurements, the result is plotted as above. `gmCap` is 0 indicates the ideal Gm cell case. As the capacitance increases, the bandwidth decreases almost linearly while ripple of the pass band became worse (bigger ripple) in dB, which worsen close to a logarithmical rate. Based on this result, we can limit the transistor level performance. For example, the ripple requirement is less than 1dB, so the capacitance at the output node of the Gm cell should be limited below ~19fF.

7. Problems encountered and solutions

To model non-ideal Gm cell, PVCCS components are used to apply a non-linear polynomial to each Gm cell. When the AC response is analysis by Virtuoso by sweeping gm3, we observed that the plot is always the same at different gm3s. Later after some research and consult with TA, we realize that AC simulation linearizes small-signal analysis, so PSS analysis should be used, which takes large signal analysis into consideration, and total harmonic distortion should be analyzed.

8. Conclusion

Gm-C continuous time filter is selected in this final project as an IF channel-select filter in a direction conversion ultra-sideband (UWB) receiver. It consists of a high-pass filter, a gain stage, and a low-pass filter. From this project, we have learnt how to design a basic filter and optimize and transform the parameters of passive and active filters. Additionally, we have a glimpse of different attributes of a non-ideal Gm cells affect the filter performances.

Further work is also needed to improve the design:

Transistor level design: Transistor level amplifier, instead of Gm cell model, should be used to reflect the real influence by the parasitic capacitance. Pass band ripple and bandwidth will be further degraded so we might need more margin leaving while putting in the ideal Gm cell.

Noise analysis: Noise we not taken in consideration. Further modeling or noise injection technique can be applied to the Gm cells for analysis.

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Automatic tuning: The bandwidth center frequency of a Gm-C filter can vary a lot due to process variation and parasitic capacitance. The master-slave controlling automatic tuning circuit approach can be applied. The master filter refers to the one in the automatic tuning loops, while the slave filter refers to the main filter. The idea assumes that both the master and slave filters match. Therefore, using the same control voltage that control the master filter to control the slave filters, both filters should show the same characteristics.

9. Individual contribution

Name	Tasks	Contribution
Lam King Sum Sam	Passive and ideal active filter design calculation and simulation, Design choice and procedure write up	50%
Tse Ming Fung Alfred	Non-ideality simulation and analysis, Problems encountered and solutions; Conclusion write up	50%

Reference

[1] Howard Luong, EESM5120 Lecture Notes, Advanced Amplifier Design Techniques

[2] Razavi, B., 2016. Design of analog CMOS integrated circuits Second., New York, NY: McGraw-Hill Education

Appendix

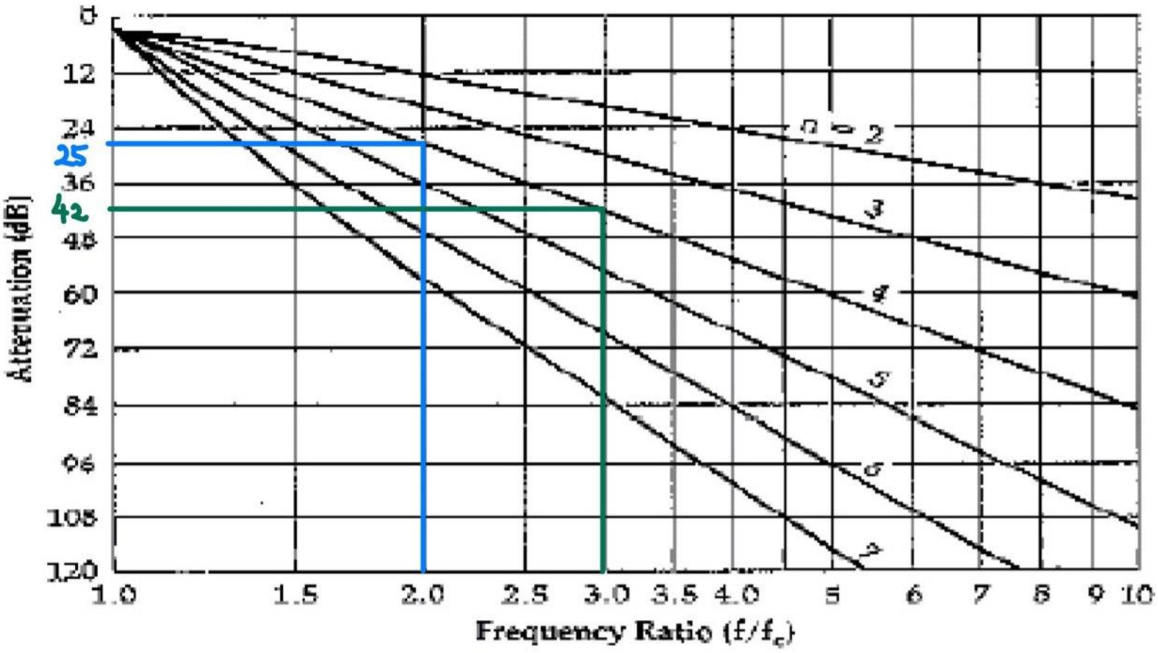
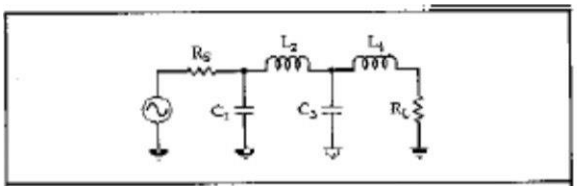


Figure 20 Characteristic curve of 0.1 dB ripple Chebyshev filter



n	R_S/R_L	C_1	L_2	C_3	L_4
2	1.355	1.209	1.638		
	1.429	0.977	1.982		
	1.667	0.733	2.489		
	2.000	0.560	3.054		
	2.500	0.417	3.827		
	3.333	0.293	5.050		
	5.000	0.184	7.426		
	10.000	0.087	14.433		
	∞	1.391	0.819		
3	1.000	1.433	1.594	1.433	
	0.900	1.426	1.494	1.622	
	0.800	1.451	1.356	1.871	
	0.700	1.521	1.193	2.190	
	0.600	1.648	1.017	2.603	
	0.500	1.853	0.838	3.159	
	0.400	2.186	0.660	3.968	
	0.300	2.763	0.486	5.279	
	0.200	3.942	0.317	7.850	
	0.100	7.512	0.155	15.466	
	∞	1.513	1.510	0.716	
4	1.355	0.992	2.148	1.585	1.341
	1.429	0.779	2.348	1.429	1.700
	1.667	0.576	2.730	1.185	2.243
	2.000	0.440	3.227	0.967	2.856
	2.500	0.329	3.961	0.760	3.698
	3.333	0.233	5.178	0.560	5.030
	5.000	0.148	7.607	0.367	7.614
	10.000	0.070	14.887	0.180	15.230
	∞	1.511	1.768	1.455	0.673
n	R_L/R_S	L_1	C_2	L_3	C_4

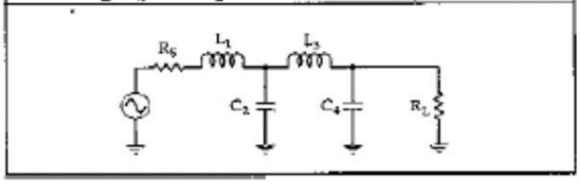


Figure 21 0.1 dB ripple Chebyshev LC element parameters table

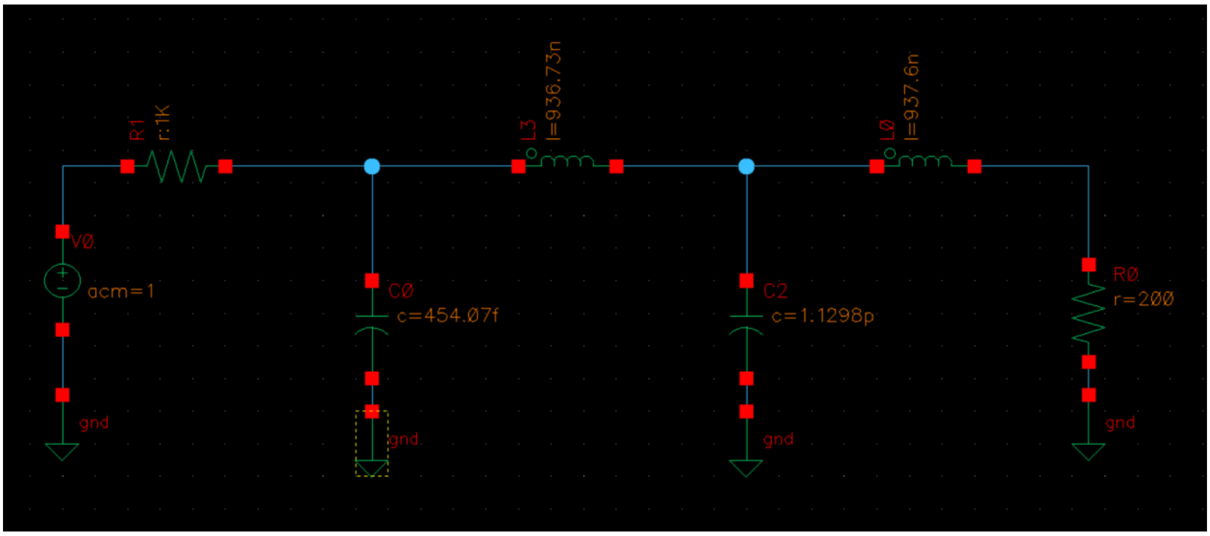


Figure 22 Passive filter schematics

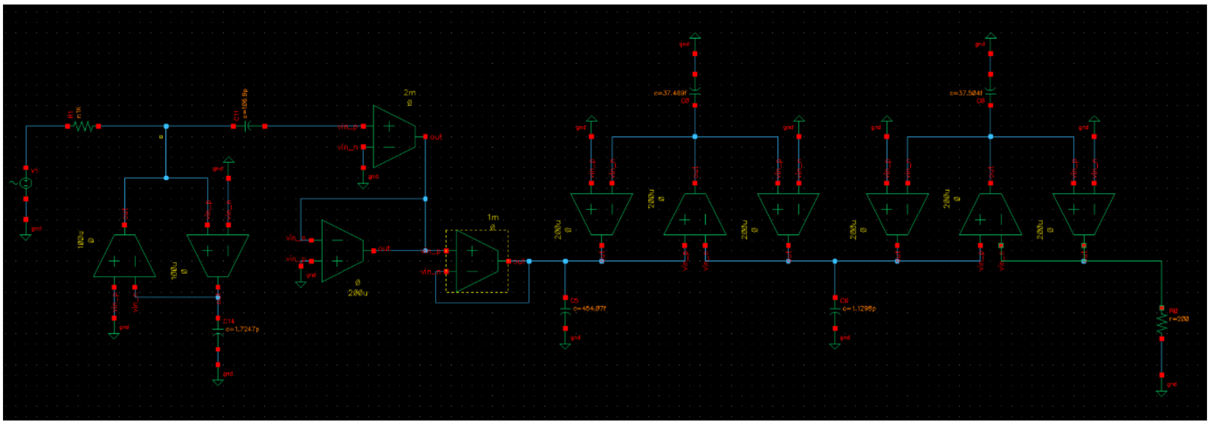


Figure 23 Gm-C filter schematic

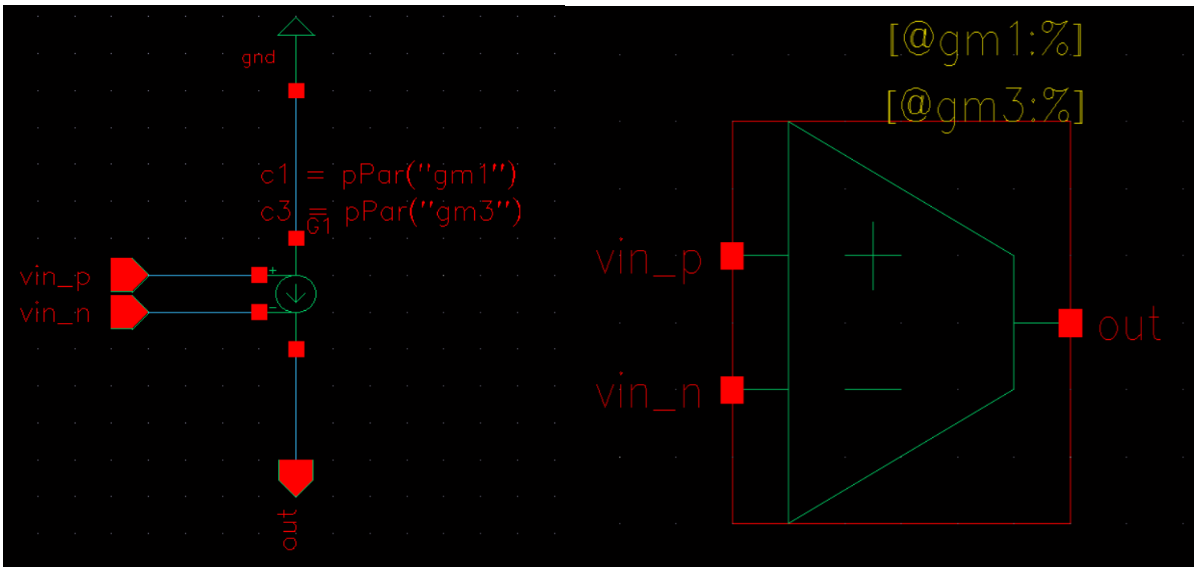


Figure 24 Schematic and symbol of a Gm cell