EC 447 ACTIVE FILTERS
COURSE PROJECT REPORT

REALIZATION OF 4TH ORDER LOW PASS FILTER USING Gm - C

Submitted by

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VII semester B.Tech ECE

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November 2022

- **AIM**

Design a Transconductance-C (Gm-C) low pass filter in 0.35 μm CMOS technology node from TSMC using LTSpice circuit simulator (or any other suitable circuit simulator) for the specifications mentioned.

- **BROAD EXPECTATIONS:**

Realizing an ideal Gm-C Filters

1. a) Ideal Filer using RLC circuit which meets the specifications

   b) Ideal Gm-C filter for the specifications using macromodel for the Gm.

2. Designing the transconductor in 0.35 μm CMOS technology node from TSMC and validating its use as a Gm-C integrator.

The capacitor calculated to be used in the first node of the filter may be used as the integrating capacitor for testing the Gm-C integrator.

3. Realize the transistor level Gm-C filter for the given specification.

- **COMMON SPECIFICATIONS:**
  1. Fourth order Maximally flat response
  2. Power supply 3.3 V
  3. Use length of 0.5 μm for all transistors
  4. Use even number of fingers for the transistors.

- **TRANSCONDUCTOR SPECIFICATIONS:**

1. Gm	= 1 mS
2. Gate overdrive for input transistors	= 200 mV
3. Input/output common-mode voltage	= 1.65 V

- **FILTER SPECIFICATIONS:**

1. Attenuation at pass band edge	= 2 dB
2. Band-edge	= 110 MHz

- **METHODOLOGY:**

a. Ideal filter realization using RLC which meet the specifications.

I. Initially fourth order prototype Butterworth filter is designed and verified using LT Spice.

<u>Design:</u>

a. Ideal Filter using RLC circuit.

Given: pass band attenuation = 2 dB
Band edge = 110 MHz
order, n = 4.

$\omega_{p,mf} = 110M \times 2\pi$, pass band edge for maximally flat response
=

$\omega_{p,b}$ → pass band edge for butterworth filter.

→ Finding the value of ϵ

$$-20\log|T_n(j\omega)| = 2$$

$$\Rightarrow -20\log\left(\frac{1}{\sqrt{1+\epsilon^2}}\right) = 2$$

$$\Rightarrow 1+\epsilon^2 = 10^{0.2}$$

$$\Rightarrow \boxed{\epsilon = 0.7647}$$

→ $$Q_1 = \frac{1}{2\cos(22.5)} = 0.5411$$

$$Q_2 = \frac{1}{2\cos(67.5)} = 1.3065$$

→ Transfer function of a 4^{th} order prototype Butterworth filter =

$$\frac{1}{\left(s^2+\frac{1}{Q_1}s+1\right)\left(s^2+\frac{1}{Q_2}s+1\right)}$$

$$= \frac{1}{\left(S^2 + \frac{1}{0.541}S + 1\right)\left(S^2 + \frac{1}{1.3065}S + 1\right)}$$

→ For maximally flat response filter

$$|T_n(j\omega)|^2_{mf} = \frac{1}{1+\epsilon^2\omega^{2n}}$$

For butterworth

$$|T_n(j\omega)|^2 = \frac{1}{1+\omega^{2n}}$$

For any pass band edge $\omega_{p,B}$.

$$|T_n(j\omega)|_{\omega_p,mf} = |T_n(j\omega)|_{\omega_p,B}$$

$$\left(\frac{\omega}{\omega_{p,mf}}\right)^{2n}\epsilon^2 = \left(\frac{\omega}{\omega_{p,BP}}\right)^{2n}$$

$$\Rightarrow \boxed{\omega_{P,B} = \epsilon^{-1/n}\omega_{p,mf}} \Rightarrow \omega_{p,B} = (0.7647)^{-0.25} \times (110\times10^6 \times 2\pi)$$

$$= 739.095\text{ M rad/sec}$$

→ Finding the values of L_1, C_1, L_2, C_2.

$$R_1 = R_2 = 1K\Omega$$

$$Q_1 = \frac{1}{R_1}\sqrt{\frac{L_1}{C_1}} \quad -(1) \text{ and } \omega_p = \frac{1}{\sqrt{L_1C_1}} \quad -(2)$$

Multiplying (1) and (2)

$$\Rightarrow Q_1\omega_{p,b} = \frac{1}{R_1C_1} \quad \Rightarrow C_1 = \frac{1}{Q_1\omega_{p,b}R_1}$$

$$= \frac{1}{0.541\times739.095\times10^6\times10^3} = \underline{\underline{2.5pF}}$$

$$L_1 = Q_1^2 R_1^2 C_1$$
$$= (0.541)^2 \times (10^3)^2 \times 2.5 \times 10^{-12}$$
$$L_1 = 0.731 \mu H$$

Similarly,

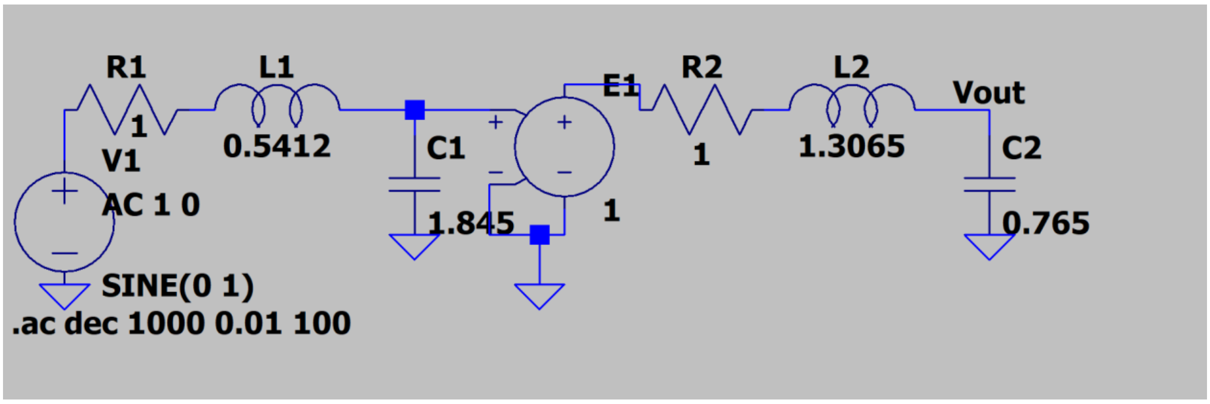
$$C_2 = \frac{1}{Q_2 \omega_{pb} R_2}$$
$$= \frac{1}{1.3065 \times 739.095 \times 10^6 \times 10^3}$$
$$= 1.0355 pF$$

$$L_2 = 1.0355 \times 10^{-12} \times (1.3065)^2 \times (10^3)^2$$
$$= 1.767 \mu H$$

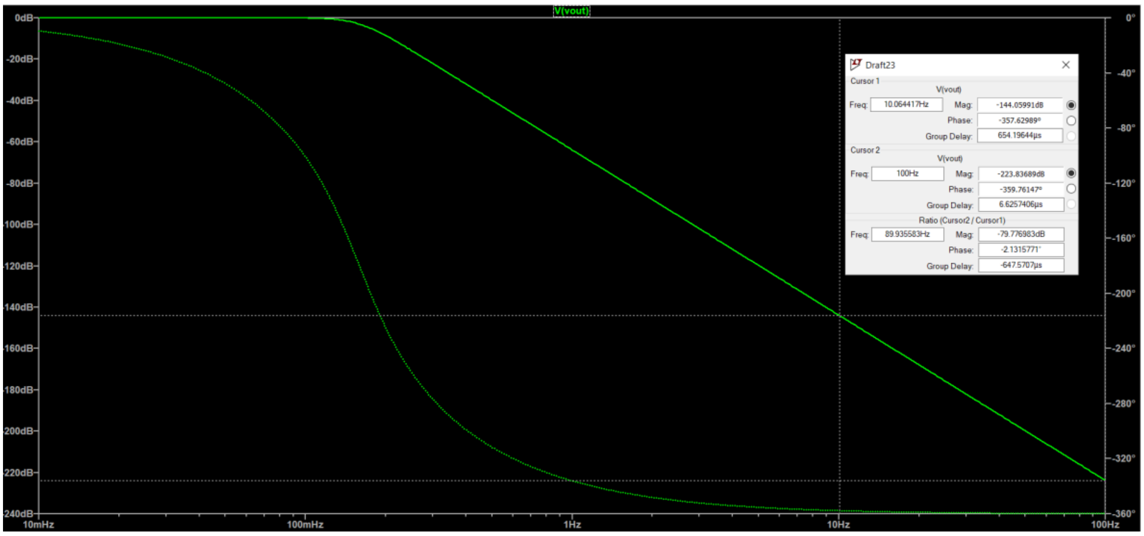
$\therefore$

$R_1 = 1k\Omega$	$R_2 = 1k\Omega$
$L_1 = 0.731 \mu H$	$L_2 = 1.767 \mu H$
$C_1 = 2.5 pF$	$C_2 = 1.0355 pF$

Circuit: (Prototype)



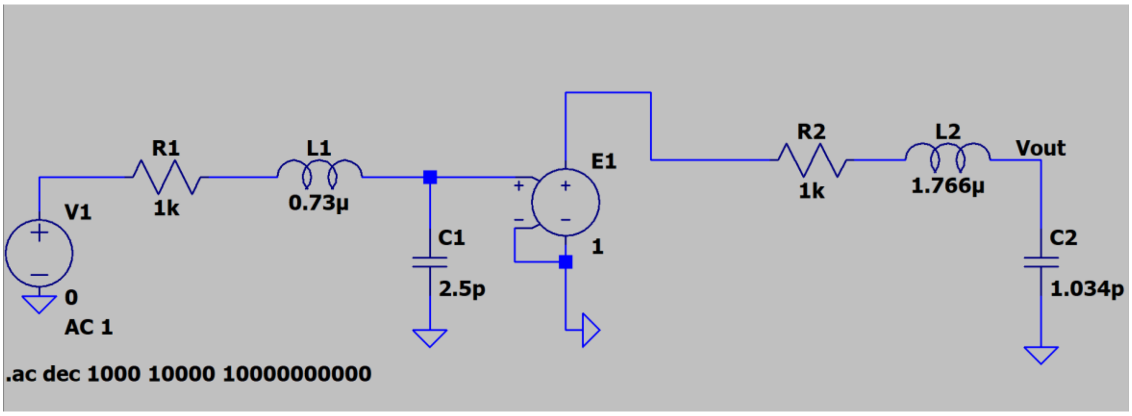
Waveforms:



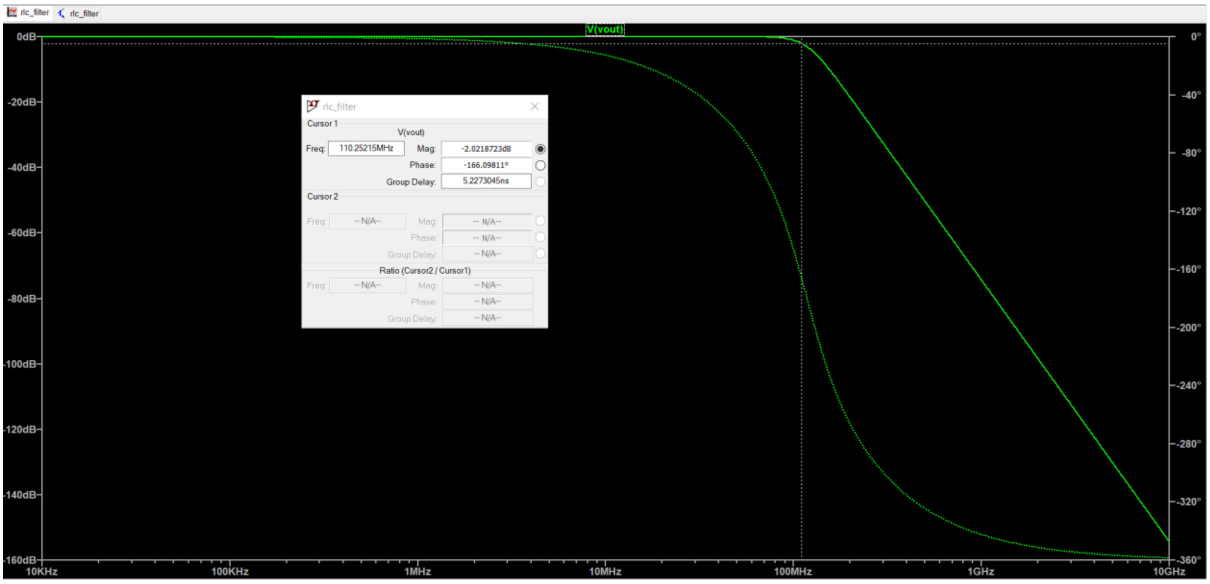
II. For the given Maximally flat response, corresponding Butterworth pass band edge has been found out.

III. Using the new butterworth pass band edge and given transconductance Gm=1mS, R1, L1, C1 and R2, C2, L2 are calculated.

<u>Circuit:</u>

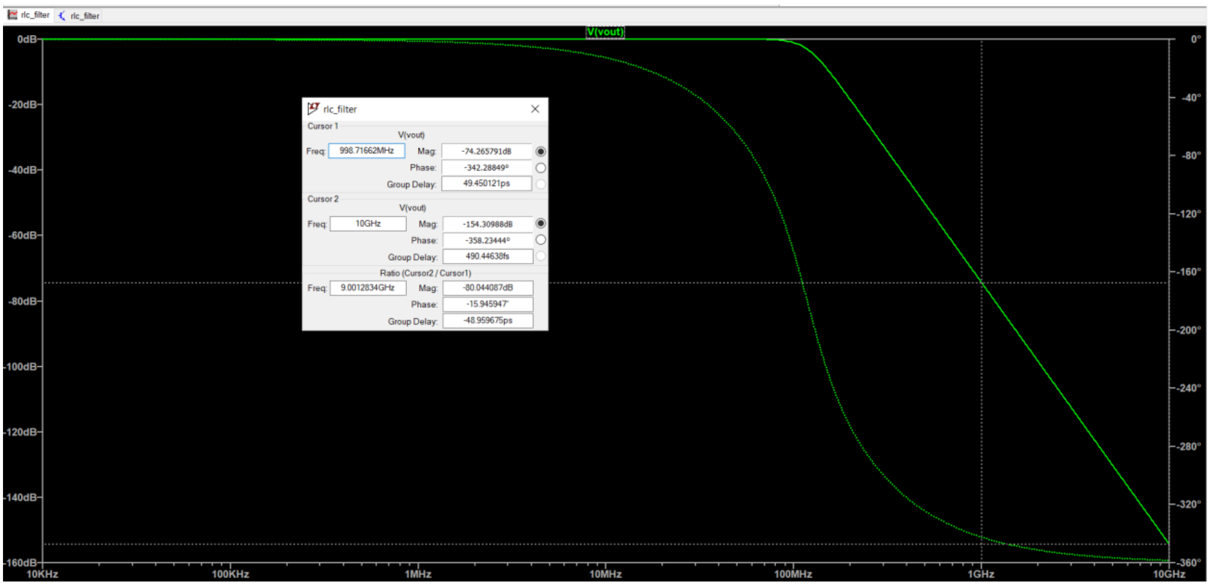


Waveforms:



From the graph,

At frequency 110 MHz, Gain obtained = **-2.02dB** (Attenuation=2 dB)



From the Graph,

Roll-off obtained at wp=110MHz is **-80.044087** which is equal to the roll-off of a 4th butterworth response -20x4= -80

b) Ideal Gm-C filter for the specifications using macromodel for the Gm.

I. As 4th order Butterworth Low Pass Filter is obtained by cascading 2 second order low pass filters, each 2nd low pass filter is obtained using Gm and C and are cascaded directly without any buffer as there is no loading effect.

<u>Design:</u>

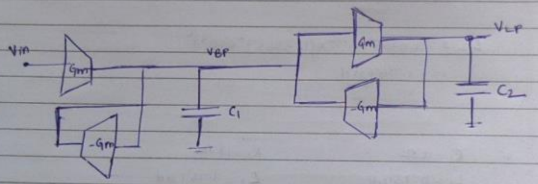
b Given: $G_m = 1mS$

We know that $L = \frac{C}{g_m^2}$

$$\omega_0 = \frac{1}{\sqrt{LC_1}} \qquad Q = \frac{R}{\sqrt{\frac{L}{C}}}$$

$$\omega_0 = \frac{1}{\sqrt{\frac{C_2}{g_m^2} \times C_1}} \qquad = \frac{1/G_m}{\sqrt{\frac{C_2}{G_m^2 \times C_1}}}$$

$$\Rightarrow \omega_0 = \frac{G_m}{\sqrt{C_1 C_2}} \qquad \Rightarrow Q = \sqrt{\frac{C_1}{C_2}}$$



For the 2nd order filter with quality factor as Q_1, the capacitor values are C_1 and C_2.

$$\Rightarrow \omega_0 Q_1 = \frac{G_m}{C_2}$$

$$\Rightarrow C_2 = \frac{g_m}{\omega_0 Q_1} = \frac{1 \times 10^{-3}}{739.095 \times 10^6 \times 0.541}$$

$$C_2 = 2.5pF$$

$$\Rightarrow C_1 = Q_1^2 C_2 = 0.73pF$$

For the 2nd order filter with Quality factor as Q_2, the capacitor values are C_3 and C_4.

$$\Rightarrow \omega_0 Q_2 = \frac{G_m}{C_4}$$

$$\Rightarrow C_4 = \frac{1 \times 10^{-3}}{739.095 \times 10^6 \times 1.3065}$$

$$= 1.035pF$$

$$\Rightarrow C_3 = Q_2^2 C_4$$

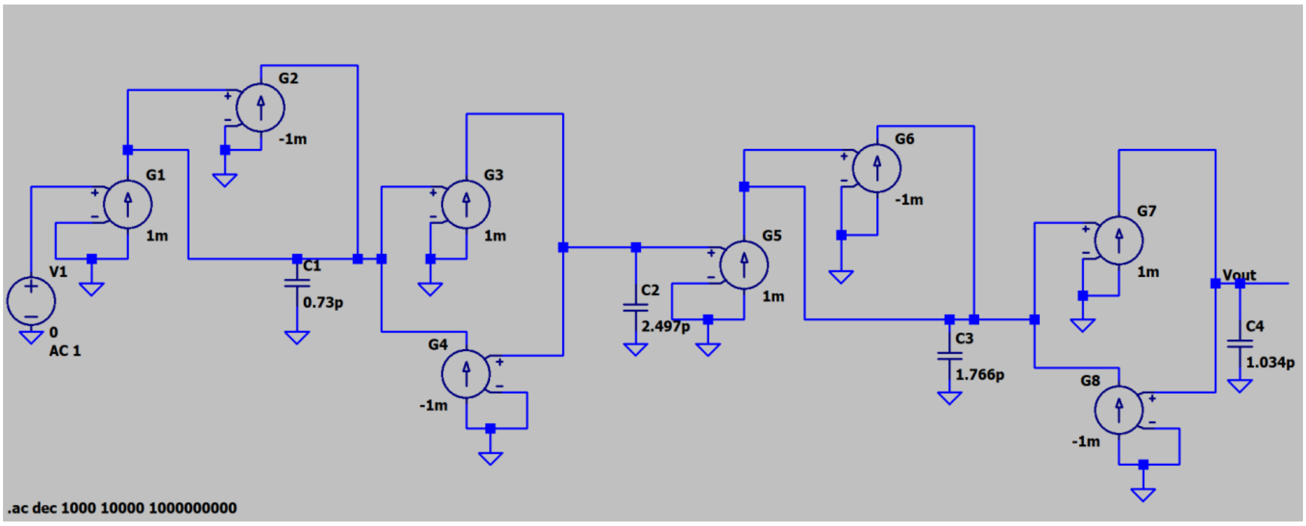
$$= (1.3065)^2 \times 1.035 \times 10^{-12}$$

$$= 1.767pF$$

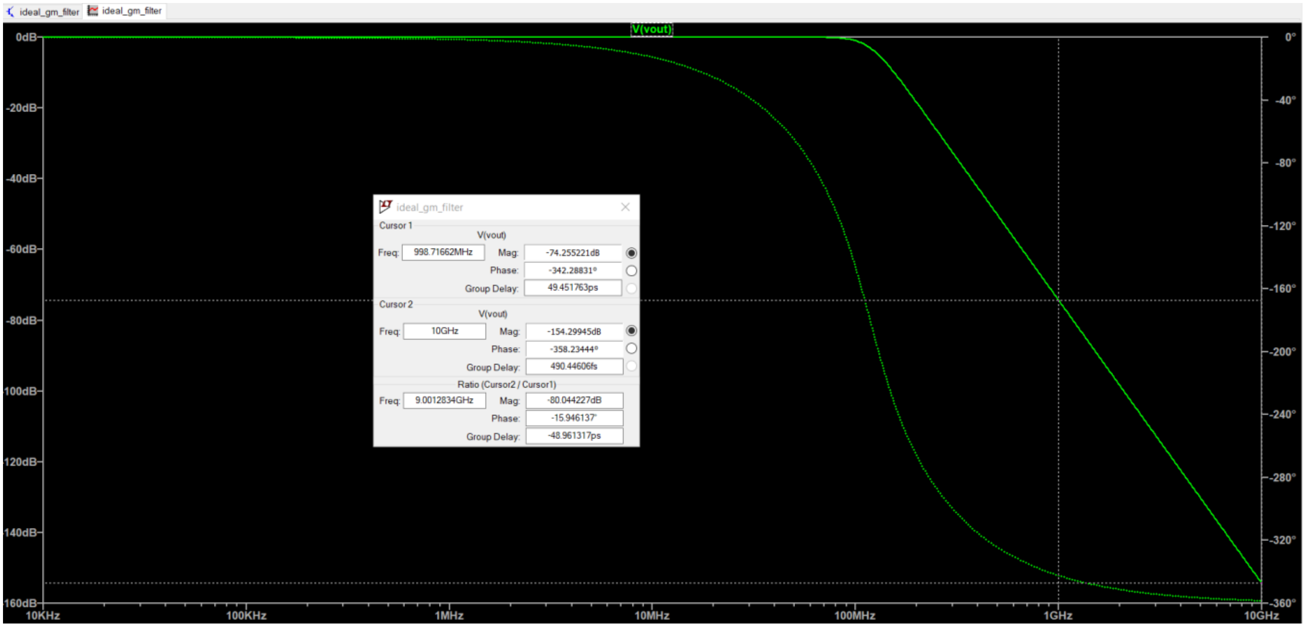
$\therefore$ $C_1 = 0.73pF$ $\qquad$ $C_3 = 1.767pF$

$C_2 = 2.5pF$ $\qquad$ $C_4 = 1.035pF$

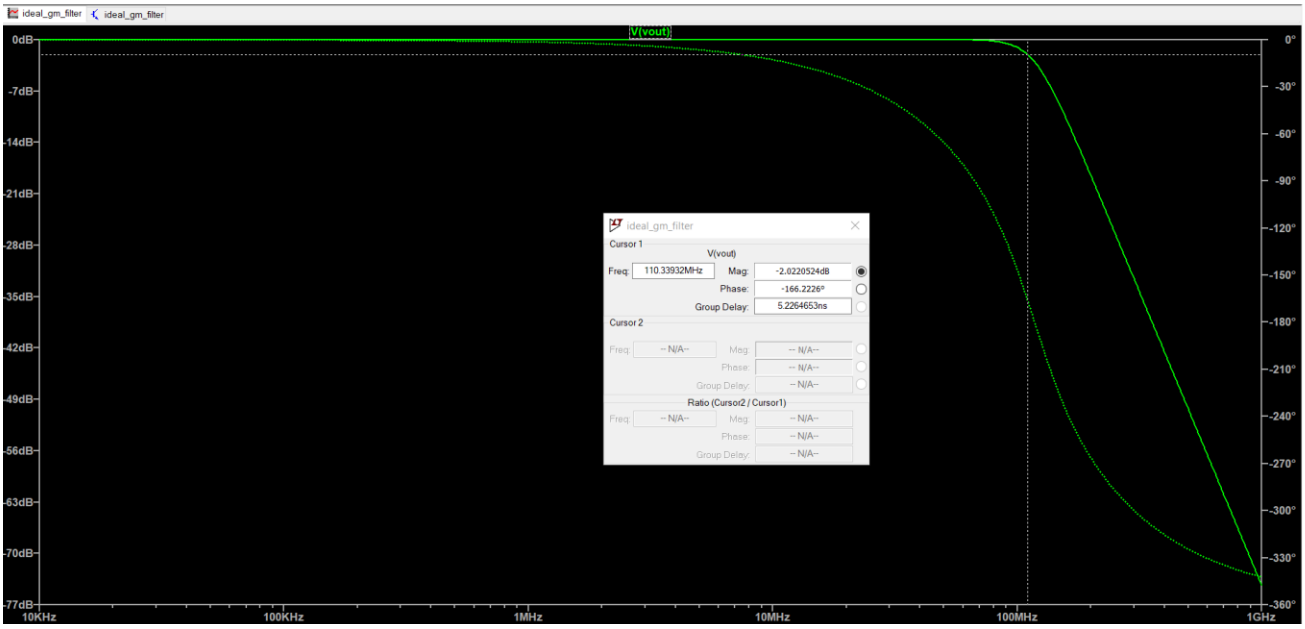
Circuit:



Waveforms:



From the graph,
Gain at wp=110MHz is -2.0220524dB (Attenuation=2dB approximately)



From the graph,

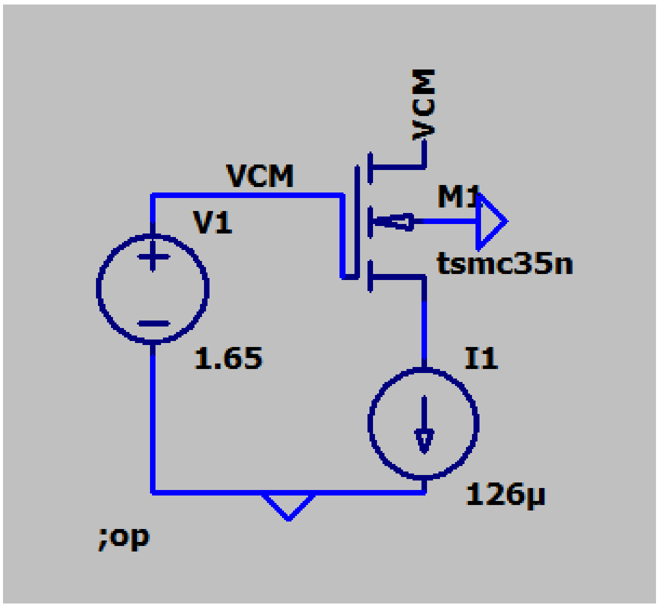
Roll-off measured in between 1GHz and 10GHz is -80.0442 which is equal to the roll-off of a 4th butterworth response -20x4= -80dB.

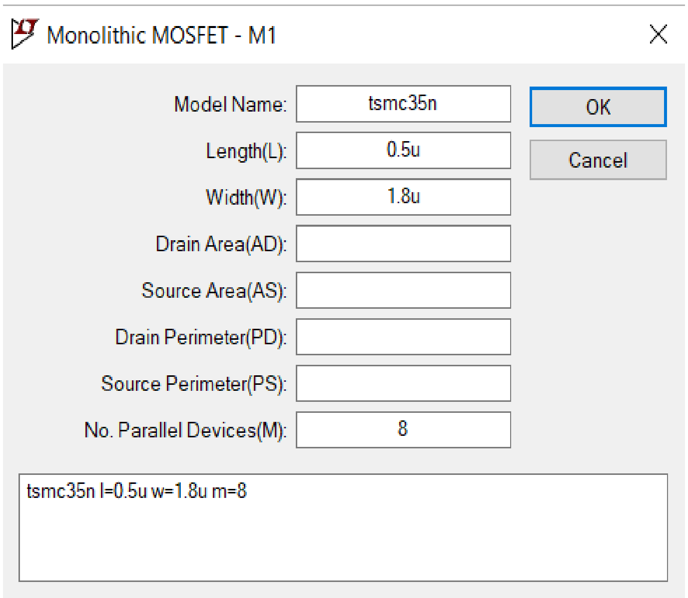
2. Designing the transconductor in 0.35 µm CMOS technology node from TSMC and validating its use as a Gm-C integrator.

Transconductance = 1 mS

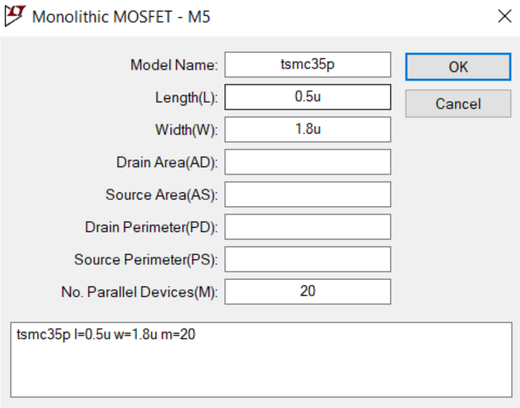
Vds,sat = 200 mV

NMOS Specifications tuned:

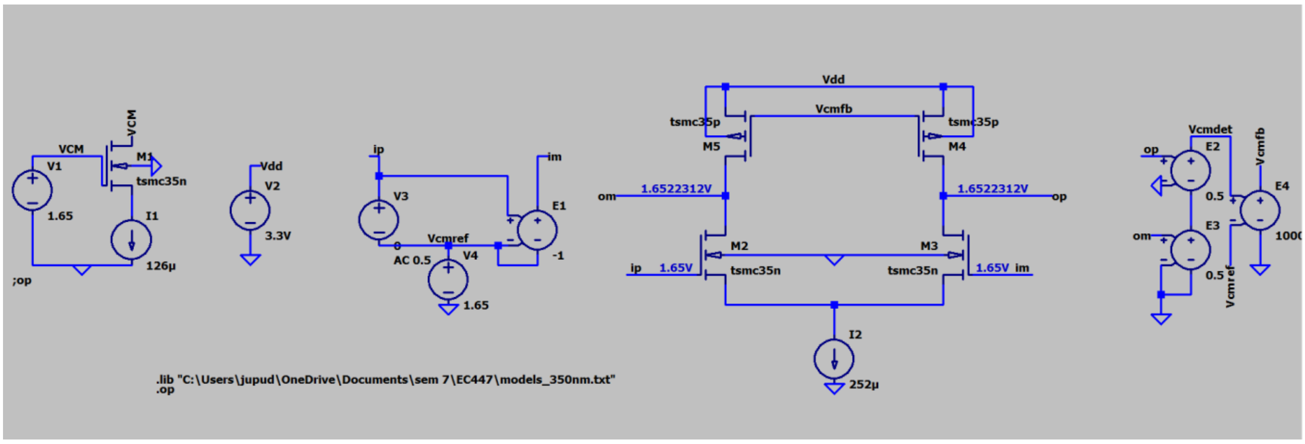




PMOS specifications obtained:



Circuit:



SPICE Error Log Results:

SPICE Error Log: C:\Users\jupud\OneDrive\Documents\sem 7\EC447\gm_macro.log

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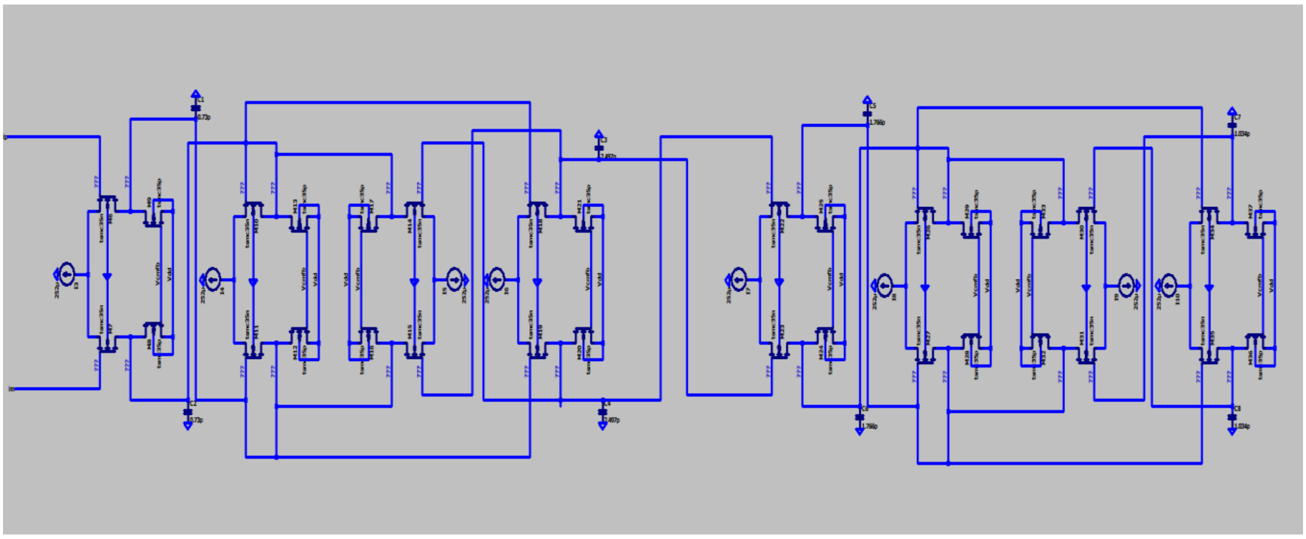
Circuit: * C:\Users\jupud\OneDrive\Documents\sem 7\EC447\gm_macro.asc

Ignoring BSIM parameter XL
Ignoring BSIM parameter XW
Ignoring BSIM parameter XL
Ignoring BSIM parameter XW
Warning: Pd = 0 is less than W.
Warning: Ps = 0 is less than W.
Warning: Pd = 0 is less than W.
Warning: Ps = 0 is less than W.
Direct Newton iteration for .op point succeeded.
Semiconductor Device Operating Points:
                        --- BSIM3 MOSFETS ---
Name:         m5          m4          m3          m2          m1
Model:     tsmc35p     tsmc35p     tsmc35n     tsmc35n     tsmc35n
Id:       -1.26e-04   -1.26e-04    1.26e-04    1.26e-04    1.26e-04
Vgs:      -1.07e+00   -1.07e+00    1.09e+00    1.09e+00    1.09e+00
Vds:      -1.65e+00   -1.65e+00    1.09e+00    1.09e+00    1.09e+00
Vbs:       0.00e+00    0.00e+00   -5.60e-01   -5.60e-01   -5.60e-01
Vth:      -8.05e-01   -8.05e-01    8.40e-01    8.40e-01    8.40e-01
Vdsat:    -2.39e-01   -2.39e-01    2.02e-01    2.02e-01    2.02e-01
Gm:        8.18e-04    8.18e-04    1.00e-03    1.00e-03    1.00e-03
Gds:       1.46e-05    1.46e-05    1.58e-05    1.58e-05    1.58e-05
Gmb        1.65e-04    1.65e-04    2.14e-04    2.14e-04    2.14e-04
Cbd:       0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cbs:       0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgsov:     6.46e-15    6.46e-15    3.37e-15    3.37e-15    3.37e-15
Cgdov:     6.46e-15    6.46e-15    3.37e-15    3.37e-15    3.37e-15
Cgbov:     1.00e-15    1.00e-15    3.63e-16    3.63e-16    3.63e-16
```

Required values of Vdsat and Gm are obtained by tuning W, number of fingers and Current value in the current source and the functioning of Gm-C integrator is verified.

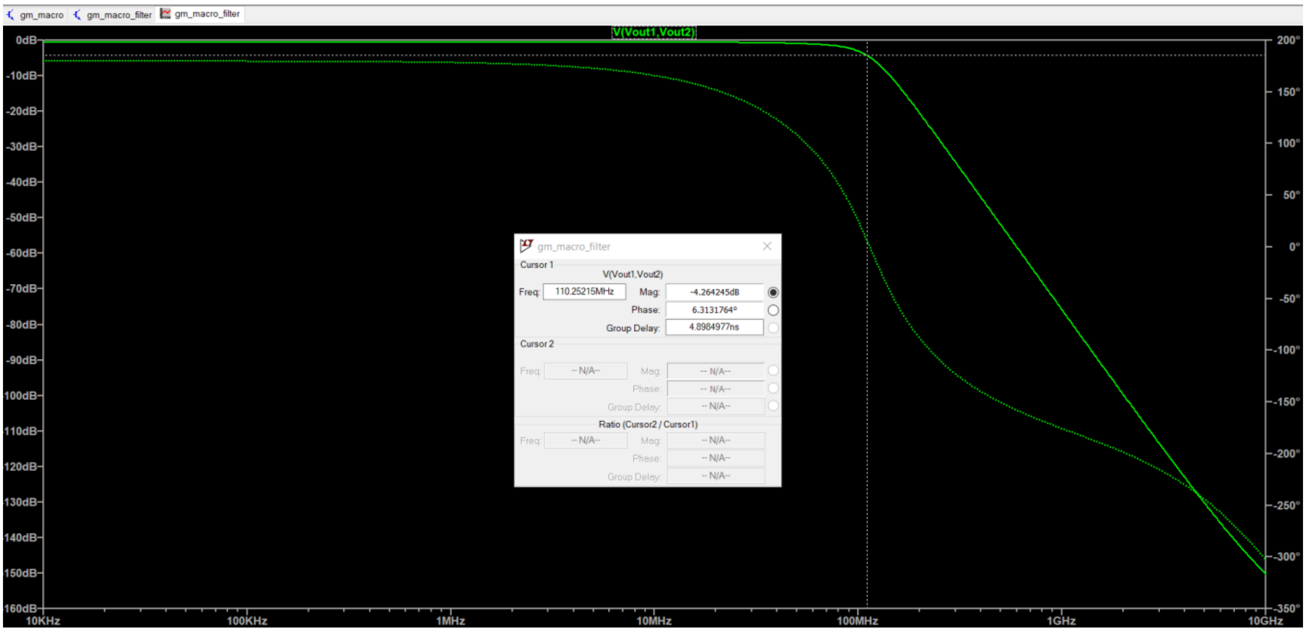
3. 4^{th}-order Low Pass Butterworth Filter realization using Gm implemented in the previous step:

   Circuit:



   Waveforms:

   The input given is differential input, so the differential voltage is measured across the output.



   From the graph,

   Gain obtained at pass band edge=**-4.264245dB**.

   DC Gain obtained= **-565.58289mdB**.

   There is a slight deviation than the required gain which is due to non-idealities like parasitic capacitances and output resistances of all the transconductors.

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