Cairo University
Faculty of Engineering

Department of Electronics and
Communications Engineering
ELC 3060 – Spring 2023

IC Analog Design

Mini project 2

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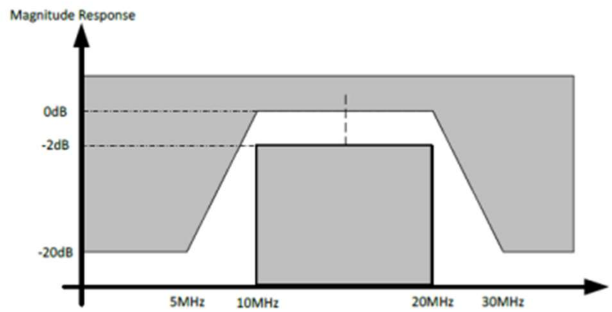
1. Hand Analysis:



As we know $f_o = \sqrt{f_1 * f_2} = \sqrt{10 * 20} = 10\sqrt{2}$ MHz,

and to achieve symmetry $\rightarrow$ $f_1 * f_2 = f_3 * f_4$ and

$f_1 * f_2 = 200$ & $f_3 * f_4 = 150$

So, to achieve symmetry we will change either the value of f_3 or f_4 but we noticed that if we changed f_4 we will get an attenuation less than 20 dB then we will change f_3.

So $\mathbf{f_3} = \frac{20}{3}$ **MHz , and** $\Omega_s = \frac{\omega_s}{\omega_p} = \frac{f_s}{f_p} = \frac{30-\frac{20}{3}}{20-10} = \frac{7}{3}$

The approximation that we used is **Chebyshev** as it's better in design than Butterworth

To get ϵ :

- $\mathbf{10\ \log_{10}(1+\epsilon) = 2 \quad \rightarrow \epsilon = 0.7647}$

To get order n :

- $\mathbf{20\ \log_{10}(\epsilon) + 20n\ \log_{10}(\Omega_s) + 6(n-1) = 20}$
  $\mathbf{n = \lceil 2.121 \rceil = 3 \quad \rightarrow \quad n = 3}$

To get transfer function :

- $\mathbf{\beta = \frac{1}{n}\ sinh^{-1}(\frac{1}{\epsilon}) = 0.36105}$
- $\mathbf{S_k = sinh(\beta)\ sin\left(\frac{2k-1}{2n}\pi\right) + j\ cosh(\beta)\ cos\left(\frac{2k-1}{2n}\pi\right) \quad \rightarrow k = 4, 5, 6}$
- $\mathbf{S_4 = -0.1845 + 0.923\,j}$
- $\mathbf{S_5 = -0.3689}$
- $\mathbf{S_6 = -0.1845 + 0.923\,j}$
- $\mathbf{then\ T(s) = \frac{1}{(S-S_4)(S-S_5)(S-S_6)} = \frac{0.3689*0.8859}{(S+0.3689)(S^2+0.369S+0.8859)} = \frac{0.3268}{S^3+0.7379\,S^2+1.022S+0.3268}}$
- **So, the transfer function of LPF is** $\mathbf{\frac{0.3268}{S^3+0.7379\,S^2+1.022S+0.3268}}$ **and to transform it to BPF transfer function we used MATLAB for simplicity.**

MATLAB code:

```
w1=2*pi*10*10^6;
w2=2*pi*20*10^6;
w3=2*pi*(20/3)*10^6;
W4=2*pi*30*10^6;
W0=2*pi*14.14*10^6 ; %square root of W1*W2
BW=w2-w1; %the bandwidth
s=tf('s');
H=(0.3268)/(s^3+0.7379*(s^2)+1.022*s+0.3268)
A=0.3268;
B=[1 0.7379 1.022 0.3268];
[X,Y]=lp2bp(A,B,W0,BW);
tf(X,Y)
Poles=[1 4.636e07 2.771e16 8.13e23 2.188e32 2.889e39 4.918e47];
roots(Poles) %to get the poles of BPF transfer function
```

BPF transfer function from MATLAB =

$$\frac{8.106 * 10^{22}\, s^3}{S^6 + 4.636 * 10^7\, S^5 + 2.771 * 10^{16}\, S^4 + 8.13 * 10^{23}\, S^3 + 2.188 * 10^{32}\, S^2 + 2.889 * 10^{39}\, S + 4.918 * 10^{47}}$$

And the poles that we got from MATLAB are:

```
  1.0e+08 *

 -0.0757 + 1.2221i
 -0.0757 - 1.2221i
 -0.1160 + 0.8820i
 -0.1160 - 0.8820i
 -0.0400 + 0.6426i
 -0.0400 - 0.6426i
```

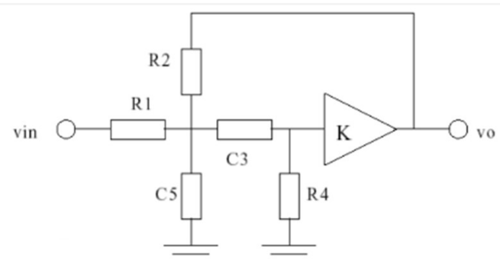
- **So, we will divide The BPF transfer function into second order transfer functions to be able to use <u>Sallen Key filter for our design.</u>**
- **Then the final transfer function will be as following:**

$$\textbf{TF}=\frac{43278167.8\,S}{S^2+0.1514*10^8\,S+1.5*10^{16}} * \frac{43278167.8\,S}{S^2+0.232*10^8\,S+0.79183*10^{16}} * \frac{43278167.8\,S}{S^2+0.08*10^8\,S+0.4145*10^{16}}$$

❖ **We got the value of $43278167.8\,S$ from $\sqrt[3]{8.106 * 10^{22}\, s^3}$**

<u>And the Sallen key BPF is as shown:</u>

➪**Sallen and Key Bandpass Filter**



<u>Design Equation:</u>

$$\frac{\frac{K}{R1C5}\,S}{S^2 + \left(\frac{1}{R1C5} + \frac{1-K}{R2C5} + \frac{1}{R4C3} + \frac{1}{R4C5}\right)S + \frac{R1+R2}{R1 * R2 * R4 * C3 * C5}}$$

→ **By solving the three transfer functions using the design equation, we got the values of R's and C's.**

➔ **We assumed all the caps are equal to $\frac{100}{6}$ p F and k =3 then**

R1= $\frac{3}{\frac{100}{6}*10^{-12}*43278167.8} =$ **4.15914KΩ** $\qquad \frac{R1+R2}{R1*R2*R4*C3*C5} = 1.5 * 10^{16} \rightarrow (1)$

$\frac{1}{R1C5} + \frac{1-K}{R2C5} + \frac{1}{R4C3} + \frac{1}{R4C5} = 0.1514 * 10^8 \rightarrow (2)$ **by solving (1) & (2)**

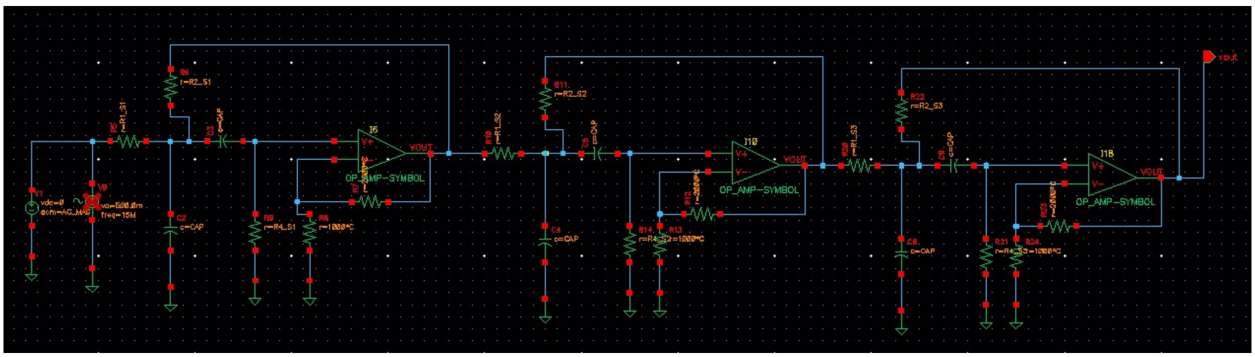
We got R2 =520.4511 *Ω* and R4=518.84 *Ω*

Repeating same steps for stage 2 and 3 we got:

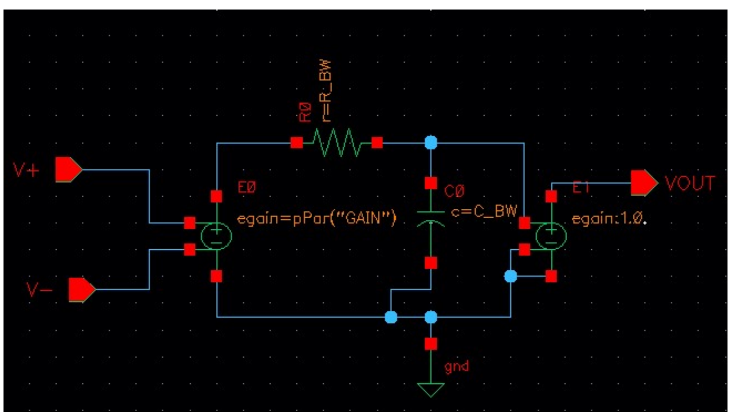
Stage 1	Stage 2	Stage 3
R1= 4.15914K*Ω*	**R1=4.15914K*Ω***	**R1=4.15914K*Ω***
R2= 520.4511 *Ω*	**R2= 752.6385 *Ω***	**R2= 1.01K*Ω***
R4= 518.84 *Ω*	**R4= 713.381 *Ω***	**R4=1.068K*Ω***
K= 3	**K= 3**	**K= 3**
C3=C5= $\frac{100}{6}$ **p F**	**C3=C5=** $\frac{100}{6}$ **p F**	**C3=C5=** $\frac{100}{6}$ **p F**

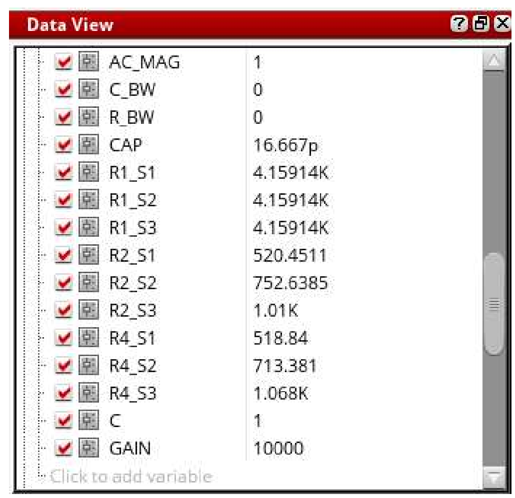
2. Simulation:

I. Schematic:



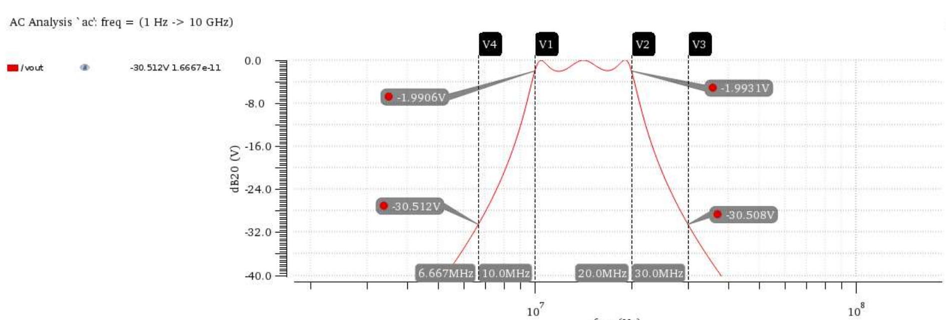
II. Ideal Op-Amp schematic:



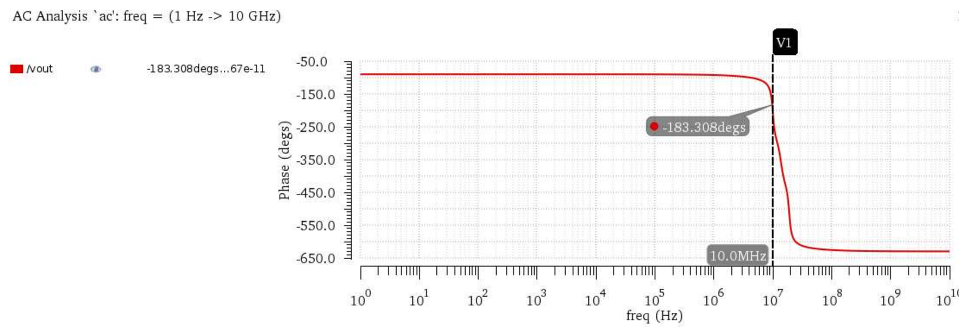


III. Ac Analysis:

Mag:



Phase:



IV. PZ Analysis:

Checking on Quality factor:

➔ **The first Stage:**

$$S^2 + 0.1514 * 10^8\, S + 1.5 * 10^{16}$$

$$\frac{\omega_o}{Q} = 0.1514 * 10^8 \;\;\&$$

$$\omega_o = \sqrt{1.5 * 10^{16}} \rightarrow Q = 8.089$$

➔ **The second Stage:**

$$S^2 + 0.232 * 10^8\, S + 0.79183 * 10^{16}$$

$$\frac{\omega_o}{Q} = 0.232 * 10^8 \;\;\&$$

$$\omega_o = \sqrt{0.79183 * 10^{16}} \rightarrow Q = 3.8355$$

➔ **The third Stage:**

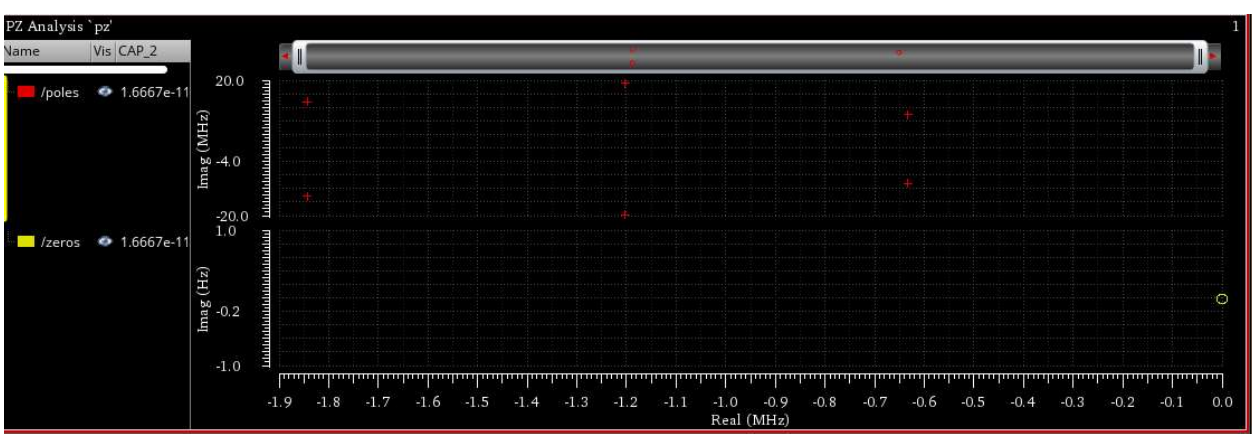
$$S^2 + 0.08 * 10^8\, S + 0.4145 * 10^{16}$$

$$\frac{\omega_o}{Q} = 0.08 * 10^8 \;\;\&$$

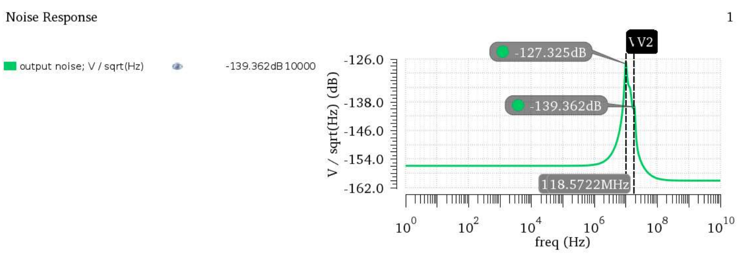
$$\omega_o = \sqrt{0.4145 * 10^{16}} \rightarrow Q = 8.0477$$

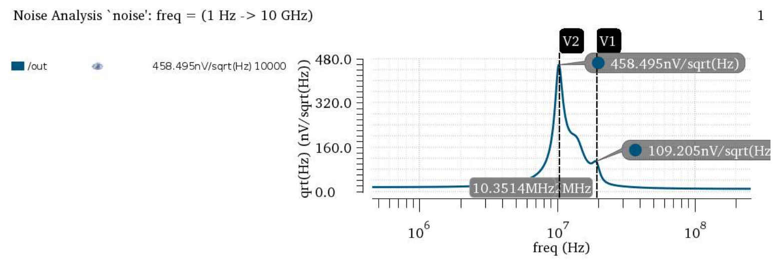
```
CAP_2=1.6667e-11

Poles(Hz)

                Real            Imaginary       Qfactor
Pole_1          -6.34056e+05    1.02304e+07     8.08288e+00
Pole_2          -6.34056e+05    -1.02304e+07    8.08288e+00
Pole_3          -1.84554e+06    1.40413e+07     3.83683e+00
Pole_4          -1.84554e+06    -1.40413e+07    3.83683e+00
Pole_5          -1.20404e+06    1.94549e+07     8.09448e+00
Pole_6          -1.20404e+06    -1.94549e+07    8.09448e+00

Zeros(Hz)

                Real            Imaginary       Qfactor
Zero_1          1.58439e-05     0.00000e+00     -5.00000e-01
Zero_2          -8.50123e+00    0.00000e+00     5.00000e-01
Zero_3          8.50127e+00     0.00000e+00     -5.00000e-01

Network function gain(magnitude)= 8.10656e+22
```

Poles and zeros locations:



V. Noise Analysis:



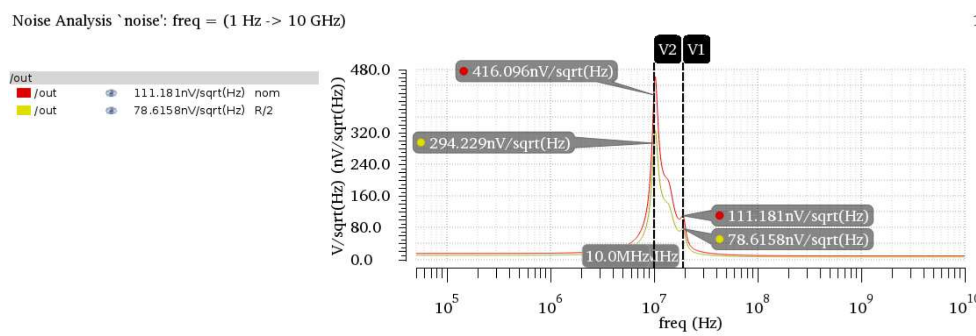


In (dB) in (nV/sqrt(Hz))

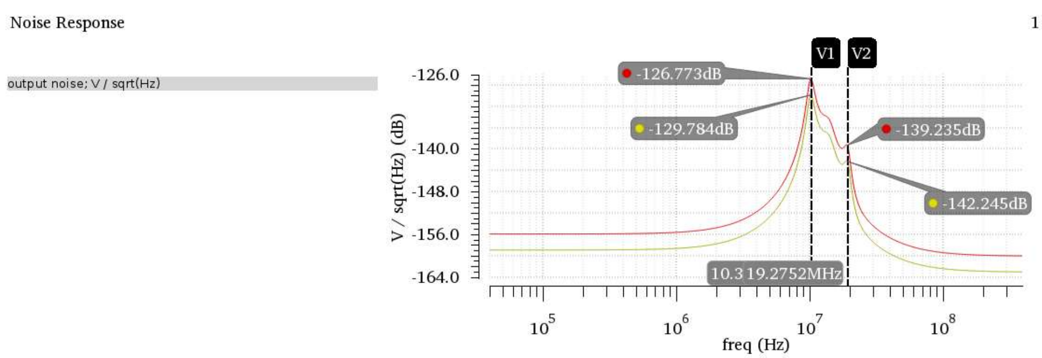
VI. Noise Analysis (Reducing R's by factor 2):

To keep the transfer function unchanged by reducing Rs by factor 2 we will reduce the values of C's by 2 too.

(nV/sqrt (Hz))



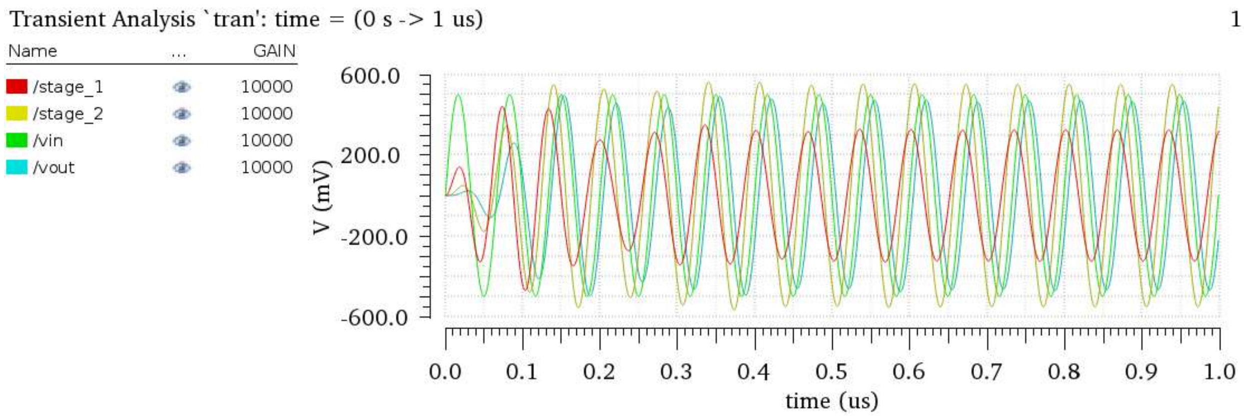
(dB)



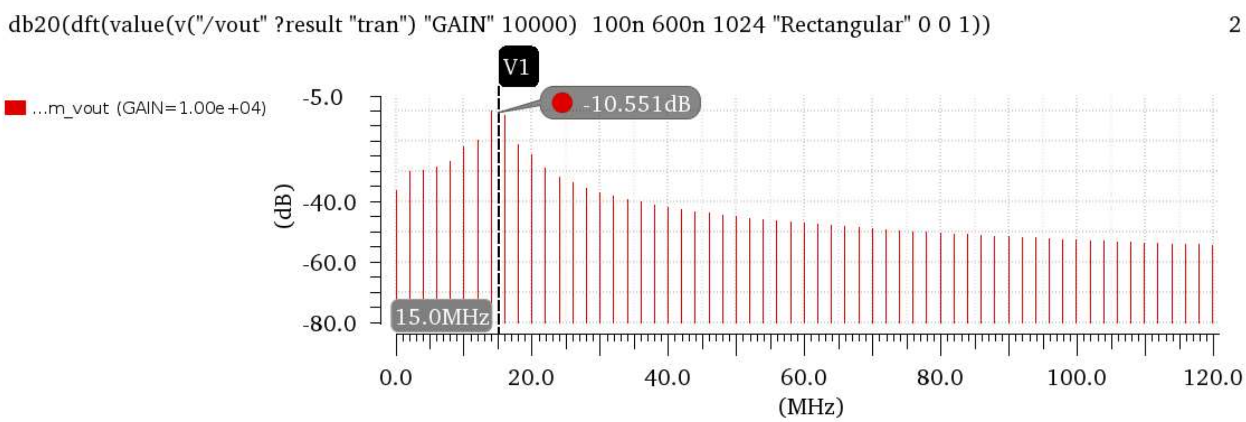
Comments:

- ➔ **As shown in the figures when all resistors reduced by factor 2, the output referred noise also will be reduced by factor 2 because the thermal noise = 4KTR.**
- ➔ **As R reduced by factor 2 the power consumption will be doubled (as the current increased) and the area will decrease to half.**

VII. Transient Response:

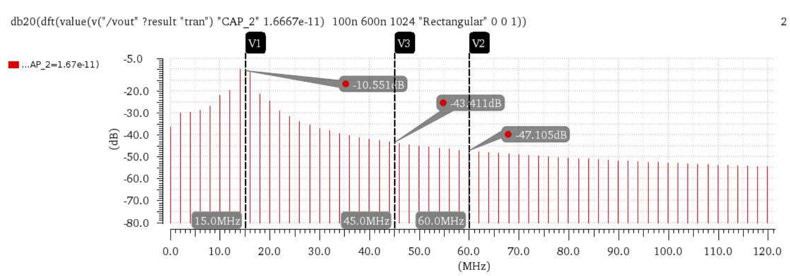


VIII. Discrete Fourier Transform:



IX. Third Harmonic distortion:

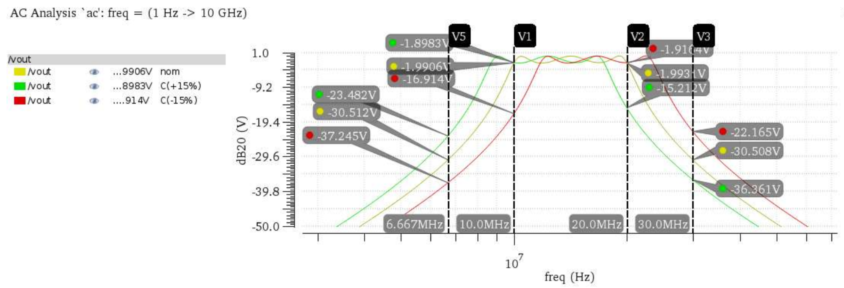
Comments:



- ➔ The fundamental harmonic is at 15 MHz is equal to -10.551 dB
- ➔ The third harmonic concluding the fundamental is at 45 MHz is equal to -43.411 dB
- ➔ Then the Third harmonic distortion in that case = -43.411-(-10.551) =-32.86 dB
- ➔ The third harmonic after the fundamental is at 60 MHz is equal to -47.105 dB
- ➔ Then the Third harmonic distortion in that case = -47.105-(-10.551) =-36.554 dB.

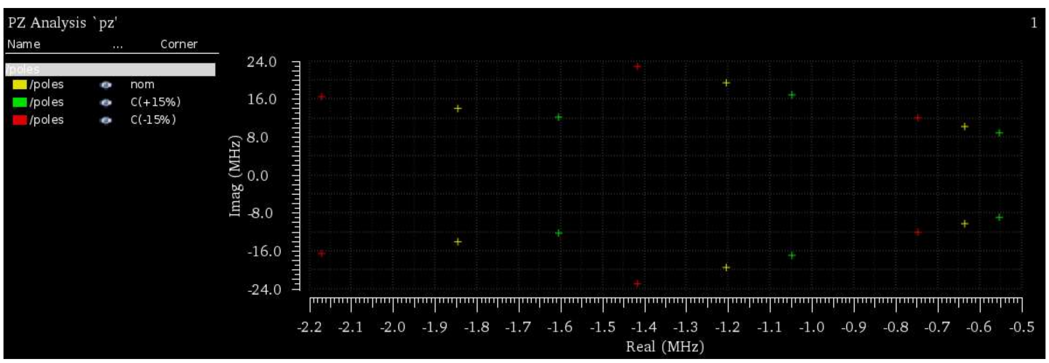
X. Varying all capacitors by ±15%:

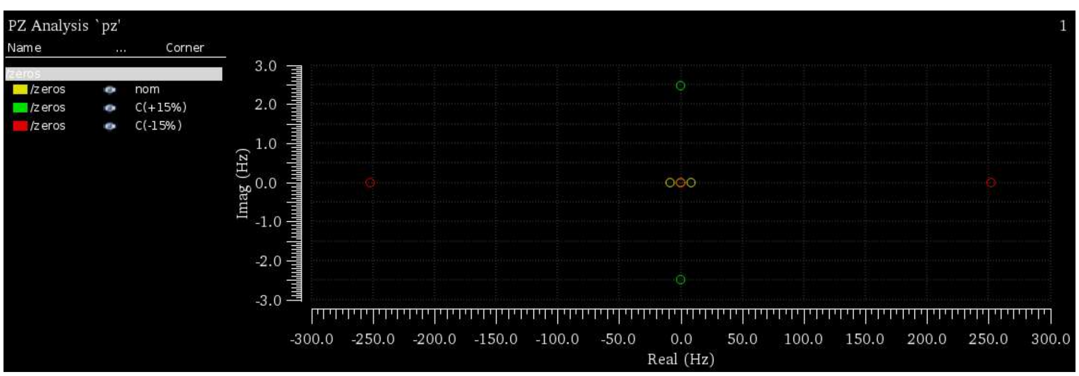
Comments:



- ➔ when all the caps are varying by +15% the bandwidth still the same but the maximum passband ripples started at frequency less than 10MHz. (As the caps increased)
- ➔ when all the caps are varying by -15% the bandwidth still the same but the maximum passband ripples started at frequency more than 10MHz. (As the caps decreased)

The effect on Poles and zeros:

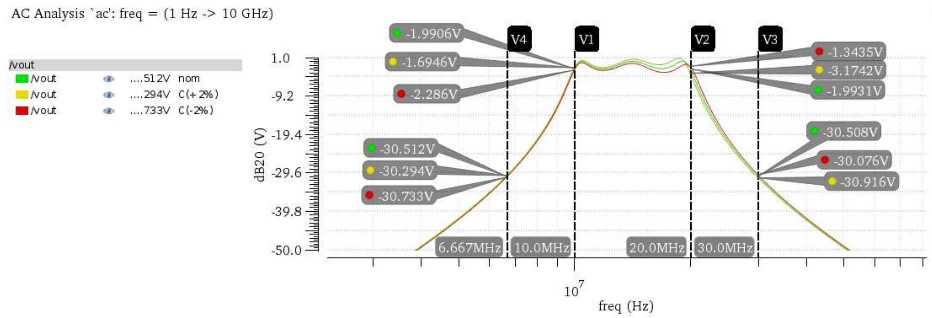




	qfactor	/poles ...1 (Hz)	qfactor	/poles ...1 (Hz)	qfactor	/poles ...1 (Hz)	qfactor	/zeros ...1 (Hz)	qfactor	/zeros ...1 (Hz)	qfactor	/zeros ...1 (Hz)
1	8.083	12.06E6	8.083	10.25E6	8.083	8.913E6	500.0E-3	18.98E-6	-500.0E-3	15.84E-6	500.0E-3	15.24E-6
2	8.083	12.06E6	8.083	10.25E6	8.083	8.913E6	500.0E-3	252.4	500.0E-3	8.501	174.6E3	2.482
3	3.837	16.66E6	3.837	14.16E6	3.837	12.31E6	-500.0E-3	252.4	-500.0E-3	8.501	174.6E3	2.482
4	3.837	16.66E6	3.837	14.16E6	3.837	12.31E6						
5	8.095	22.93E6	8.094	19.49E6	8.095	16.95E6						
6	8.095	22.93E6	8.094	19.49E6	8.095	16.95E6						

	Varying c by +15	Varying c by -15
Ap	**-1.8983**	**-16.914 (bad)**
As	**-36.361**	**-22.165 (bad)**

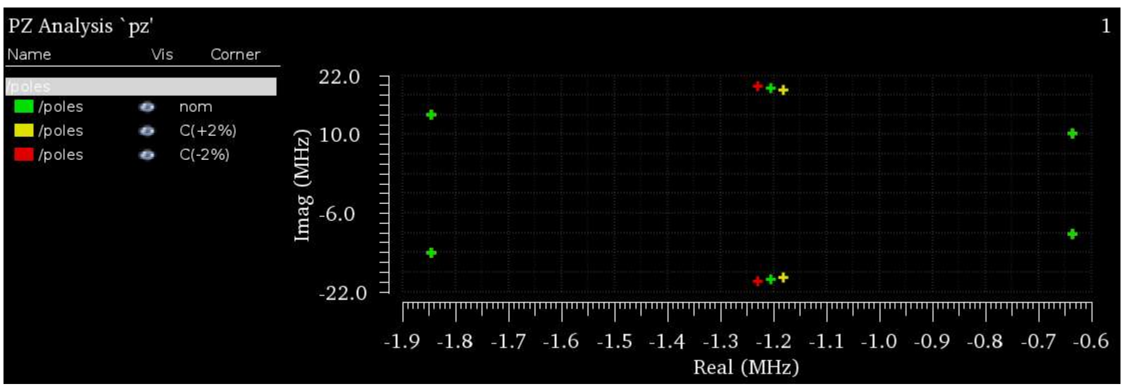
XI. Varying capacitors of 1st stage by ±2%:

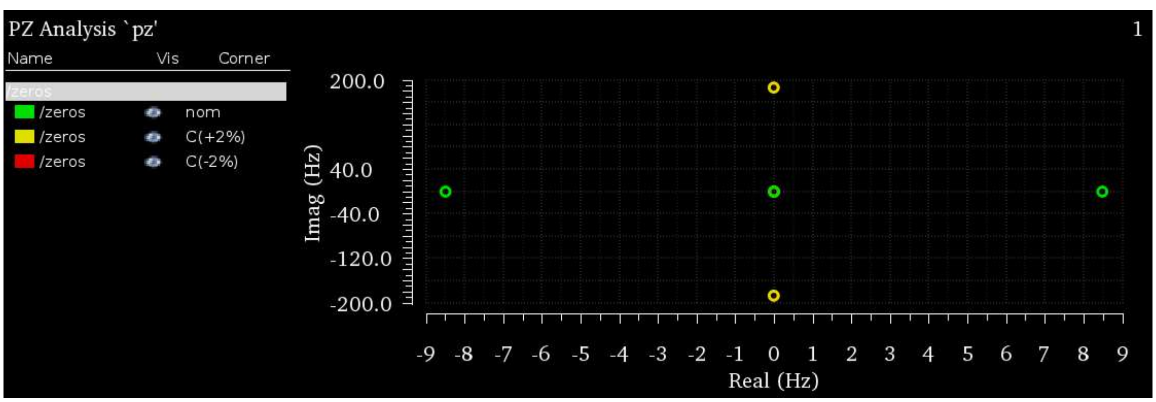


Comments:

As shown in the figure the maximum passband ripples, and the minimum stopband attenuation are almost the same and the variation in the frequency is very small so the bandwidth still the same too.

The effect on Poles and zeros:



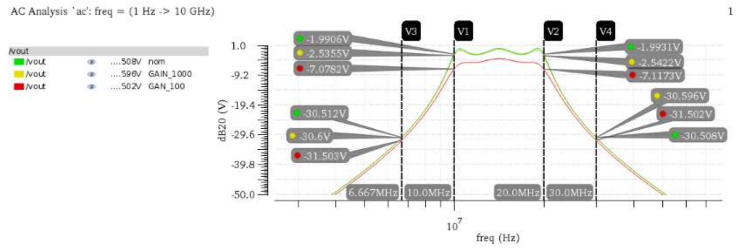


	qfactor	/poles ...1 (Hz)	qfactor	/poles ...1 (Hz)	qfactor	/poles ...1 (Hz)	qfactor	/zeros ...1 (Hz)	/zeros ...1 (Hz)	qfactor	/zeros ...1 (Hz)
1	8.083	10.25E6	8.083	10.25E6	8.083	10.25E6	-500.0E-3	9.526E-6	3.528E-6	-500.0E-3	15.84E-6
2	8.083	10.25E6	8.083	10.25E6	8.083	10.25E6	19.13E3	186.7	186.7	500.0E-3	8.501
3	3.837	14.16E6	3.837	14.16E6	3.837	14.16E6	19.13E3	186.7	186.7	-500.0E-3	8.501
4	3.837	14.16E6	3.837	14.16E6	3.837	14.16E6					
5	8.095	19.89E6	8.095	19.11E6	8.094	19.49E6					
6	8.095	19.89E6	8.095	19.11E6	8.094	19.49E6					

	Varying c by +2	Varying c by -2
Ap	**-1.6946**	**-2.286 (Bad)**
As	**-30.916**	**-30.076**

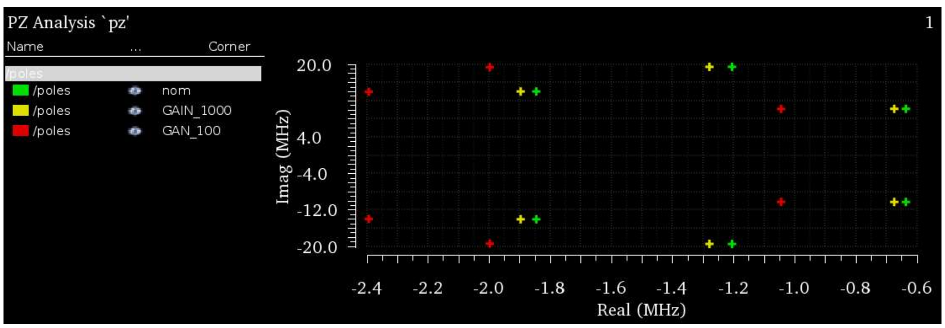
XII. Varying the gain of the Op-amps to 1000 and 100:

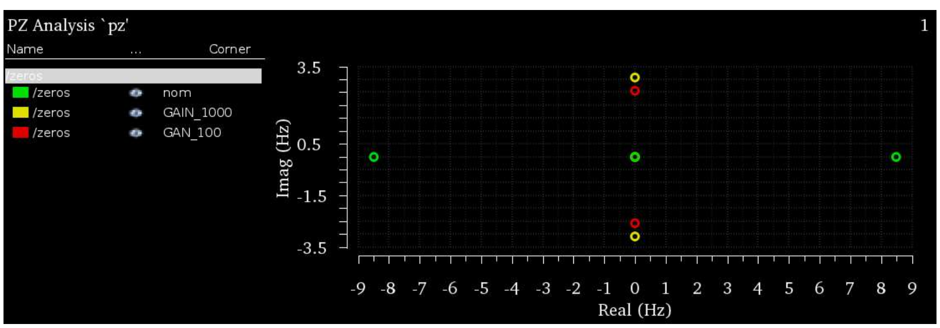
Comments:



As shown in the figure when the gain of op-amp is decreased to 1000 the maximum passband ripples, and the minimum stopband attenuation is the same (that's because the gain is high and the op-amp acts as ideal Op-Amp but when the gain of op-amp is decreased to 100 the maximum passband ripples increased to 7.0782 dB, and the minimum stopband attenuation became 31.502dB and the transfer function will change too as the op-amp is no longer ideal.

The effect on Poles and zeros:





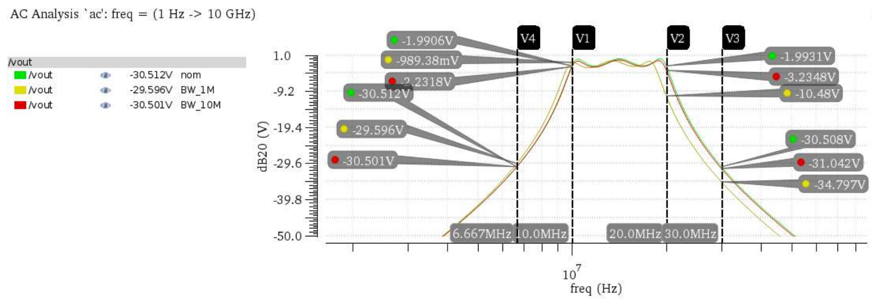
	qfactor	/poles ...0 (Hz)	qfactor	/poles ...0 (Hz)	qfactor	/poles ...0 (Hz)	qfactor	/zeros ...0 (Hz)	qfactor	/zeros ...0 (Hz)	qfactor	/zeros ...0 (Hz)
1	4.913	10.25E6	7.624	10.25E6	8.083	10.25E6	-500.0E-3	15.83E-6	500.0E-3	16.08E-6	-500.0E-3	15.84E-6
2	4.913	10.25E6	7.624	10.25E6	8.083	10.25E6	128.7E3	2.569	171.0E3	3.084	500.0E-3	8.501
3	2.957	14.16E6	3.733	14.16E6	3.837	14.16E6	128.7E3	2.569	171.0E3	3.084	-500.0E-3	8.501
4	2.957	14.16E6	3.733	14.16E6	3.837	14.16E6						
5	4.878	19.49E6	7.625	19.49E6	8.094	19.49E6						
6	4.878	19.49E6	7.625	19.49E6	8.094	19.49E6						

	Varying Gain by 1000	Varying Gain by 100
Ap	**-2.5355 (bad)**	**-7.0782 (bad)**
As	**-30.596**	**-31.502**

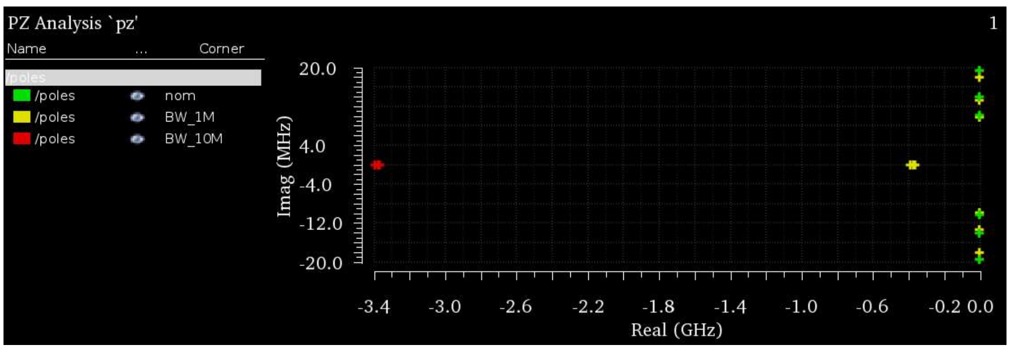
XIII. <u>Varying BW to 10MHz & 1MHz:</u>

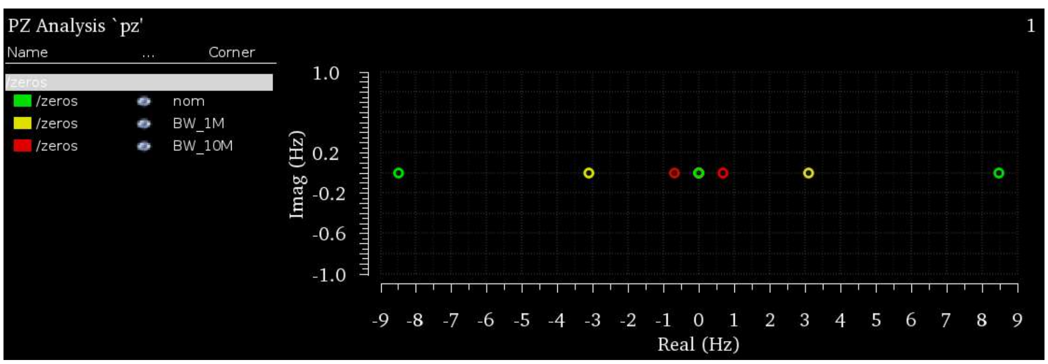
<u>Comments:</u>

As shown in the figure, at BW=10MHz specifications of the filter still the same for maximum passband and minimum stopband attenuation.
but for BW=1MHz (as we know the speed of op-amp depend on BW and since BW decreases to 1M then the speed decreases too)



<u>The effect on Poles and zeros:</u>





	qfactor	/poles ...0 (Hz)	qfactor	/poles ...0 (Hz)	qfactor	/poles ...0 (Hz)	qfactor	/zeros ...0 (Hz)	/zeros ...0 (Hz)	/zeros ...0 (Hz)
1	7.655	10.21E6	7.798	9.841E6	8.083	10.25E6	-500.0E-3	498.8E-6	621.3E-6	15.84E-6
2	7.655	10.21E6	7.798	9.841E6	8.083	10.25E6	500.0E-3	686.2E-3	3.111	8.501
3	3.754	14.08E6	3.878	13.41E6	3.837	14.16E6	-500.0E-3	686.2E-3	3.111	8.501
4	3.754	14.08E6	3.878	13.41E6	3.837	14.16E6				
5	7.682	19.33E6	7.743	18.06E6	8.094	19.49E6				
6	7.682	19.33E6	7.743	18.06E6	8.094	19.49E6				
7	500.0E-3	3.371E9	500.0E-3	362.6E6						
8	500.0E-3	3.380E9	500.0E-3	372.5E6						
9	500.0E-3	3.397E9	500.0E-3	389.3E6						

	Varying BW by 10M	Varying BW by 1M
<u>**Ap**</u>	**-2.2318 (bad)**	**-.98938**
<u>**As**</u>	**-31.042**	**-34.797**