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DEPARTMENT OF ELECTRONICS ENGINEERING
ELECTRONIC CIRCUITS
Low & high frequency response of single-stage amplifier

11th **July, 2020**

Numerical 1:

The parameters of the transistor in the circuit shown in figure 1 are: $V_{BE(ON)} = 0.7V$, $\beta = 100$, $V_A = \infty$

a. Determine the quiescent and small signal parameters of the transistor.

b. Determine lower cut-off frequency due to C_{C1} and C_{C2}

c. Find the midband voltage gain in dB.

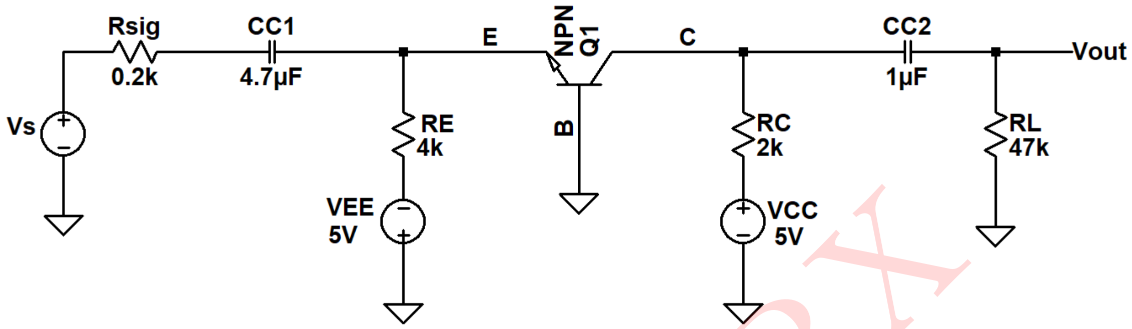

Figure 1: Circuit Diagram

Solution: The circuit shown in figure 1 is common base BJT amplifier.

a. DC analysis: All capacitors are open-circuited and DC equivalent circuit is shown in figure 2.

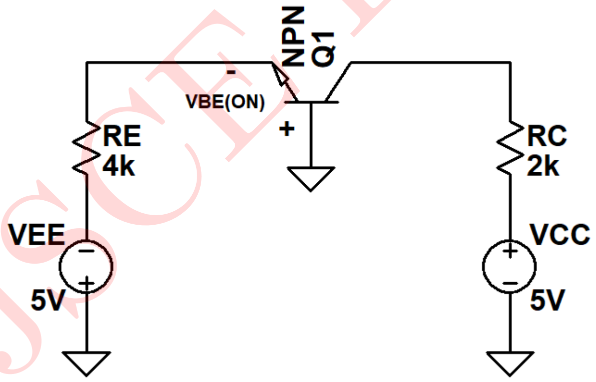

Figure 2: DC equivalent circuit

Applying KVL to B-E loop:

$$-V_{BE(ON)} - I_E R_E + 5 = 0$$

$$\therefore I_E = \frac{5 - 0.7}{4k\Omega} = 1.075\text{mA}$$

$$\therefore I_B = \frac{I_E}{1+\beta} = \frac{1.075mA}{101}$$

$$\therefore I_B = 10.6435\mu A$$

$I_C = \beta I_B$

$\therefore I_C = 100 \times 10.6435\mu A = \mathbf{1.0644mA}$

Small signal parameters:

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{100 \times 26mV}{1.0664mA} = \mathbf{2.4427k\Omega}$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{1.0664mA}{26mV} = \mathbf{40.9385mA/V}$$

b. Small signal low frequency equivalent circuit for C_{C1} alone is shown in figure 3:

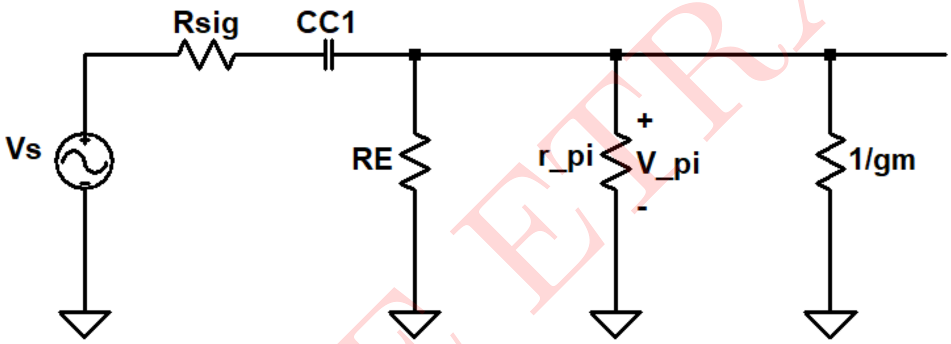

Figure 3: Small signal low frequency equivalent circuit for C_{C1} alone

Looking from C_{C1}, the equivalent resistance will be:

$$R_{eq} = R_{sig} + R_E \parallel r_\pi \parallel \frac{1}{g_m}$$

$$f_{LCC1} = \frac{1}{2\pi R_{eq} C_{C1}}$$

$$\therefore f_{LCC1} = \frac{1}{2\pi[R_{sig} + R_E \parallel r_\pi \parallel 1/g_m]C_{C1}}$$

$$\therefore f_{LCC1} = \frac{1}{2\pi[0.2k\Omega + 4k\Omega \parallel 2.4427k\Omega \parallel 0.024427k\Omega]4.7\mu F}$$

$\therefore \mathbf{f_{LCC1} = 151.1450Hz}$

Small signal low frequency equivalent circuit for C_{C2} alone is shown in figure 3:

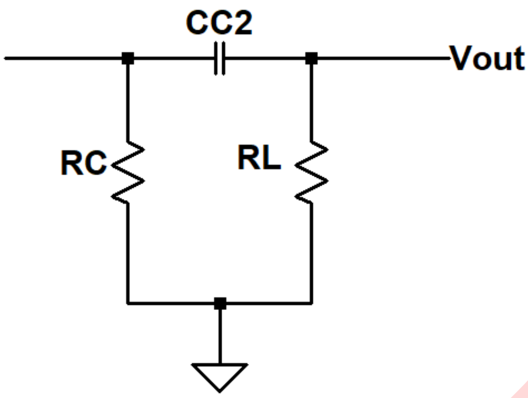

Figure 4: Small signal low frequency equivalent circuit for C_{C1} alone

Looking from C_{C2}, the equivalent resistance will be:

$R_{eq} = R_C + R_L$

$$\therefore f_{LCC2} = \frac{1}{2\pi R_{eq} C_{C2}}$$

$$\therefore f_{LCC2} = \frac{1}{2\pi [R_C + R_L] C_{C2}} = \frac{1}{2\pi [2k\Omega + 47k\Omega] 10^{-6}}$$

$$\therefore f_{LCC2} = \mathbf{3.2481Hz}$$

Lower cut-off frequency is the highest among f_{LCC1} and f_{LCC2} which is 151.1460Hz
This is the more dominant $-3dB$ frequency

$\therefore f_L$ of the amplifier is **151.1460Hz**

c. Snall signal mid-frequency equivalent circuit is shown in figure 5:

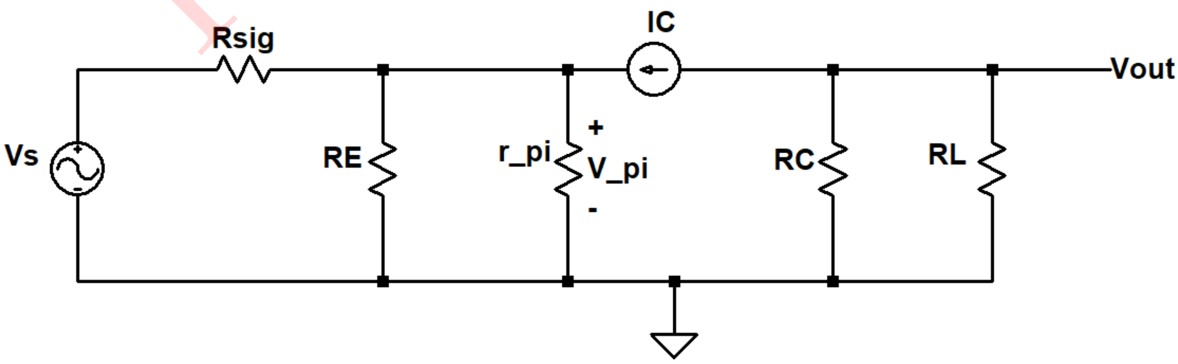

Figure 5: Small signal mid-frequency equivalent circuit

All the capacitors are short-circuited.

Voltage gain is:

$$A_V = \frac{V_{out}}{V_s} \qquad ...(1)$$

$$V_{out} = -g_m V_\pi (R_C \parallel R_L) \qquad ...(2)$$

$$V_{in} = \frac{R_E \parallel r_\pi \parallel 1/g_m}{R_{sig} + [R_E \parallel r_\pi \parallel 1/g_m]} \times V_s$$

$$\therefore \frac{1}{V_s} = \frac{R_E \parallel r_\pi \parallel 1/g_m}{R_{sig} + [R_E \parallel r_\pi \parallel 1/g_m]} \times \frac{1}{V_{in}}$$

$$\therefore \frac{1}{V_s} = \frac{R_E \parallel r_\pi \parallel 1/g_m}{R_{sig} + [R_E \parallel r_\pi \parallel 1/g_m]} \times \frac{1}{V_\pi} \qquad ...(\because V_{in} = V_{pi}) \qquad ...(3)$$

$\therefore$ From $(1), (2)$ & (3) :

$$A_V = \frac{-g_m (R_C \parallel R_L)[R_E \parallel r_\pi \parallel 1/g_m]}{R_{sig} + [R_E \parallel r_\pi \parallel 1/g_m]}$$

$$\therefore A_V = \frac{-(40.9385 \times 10^{-3})(2k\Omega \parallel 47k\Omega)[4k\Omega \parallel 2.4427k\Omega \parallel 1/(40.9385 \times 10^{-3})]}{0.2k\Omega + [4k\Omega \parallel 2.4427k\Omega \parallel 1/(40.9385 \times 10^{-3})]}$$

$$A_V = -8.4271$$

$$\therefore \mathbf{A_V = 18.5136dB}$$

SIMULATED RESULTS:
Above circuit was simulated in LTspice and results obtained are as follows:

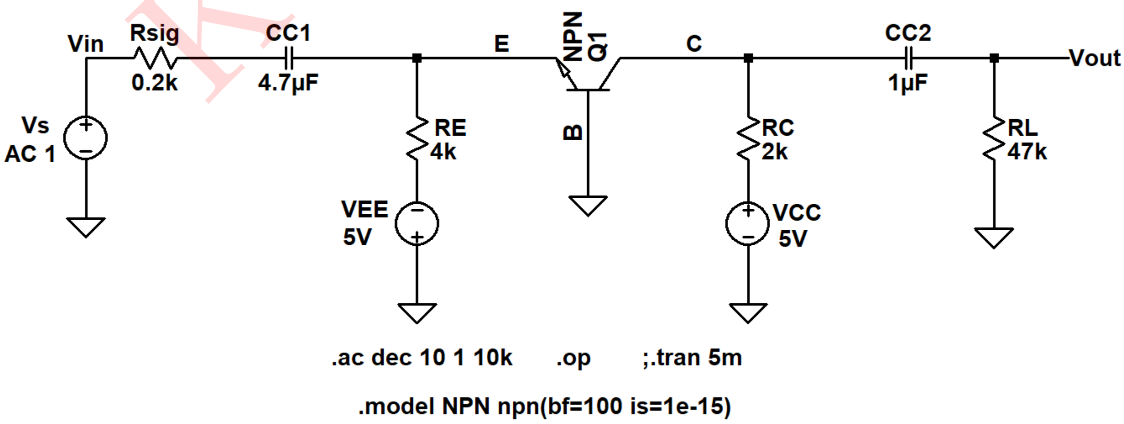

Figure 6: Circuit Schematic: Results

The frequency plots are shown in figures below:

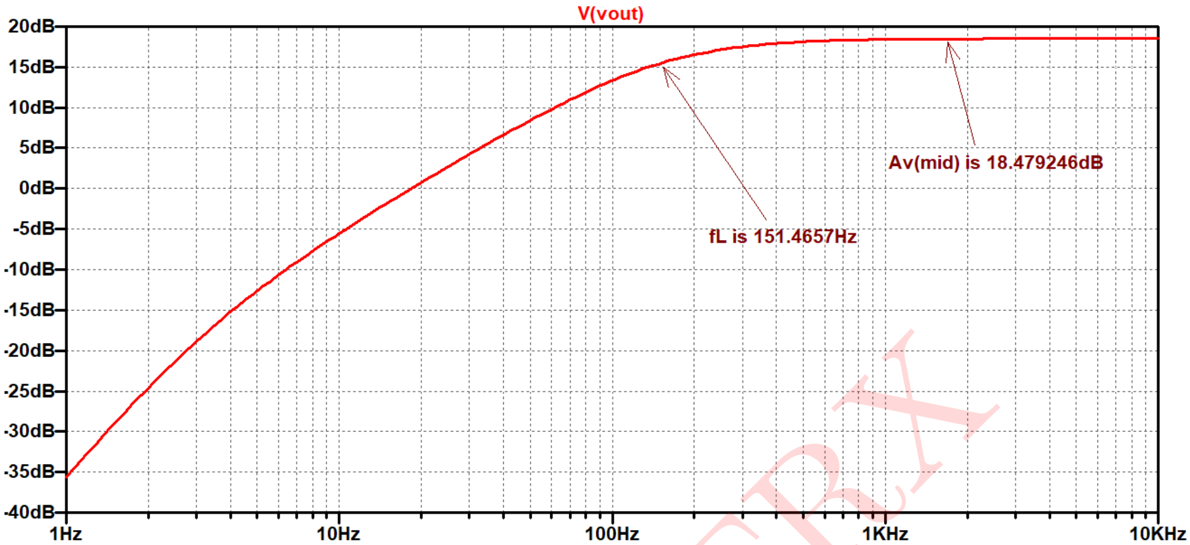

Figure 7: Low frequency response for circuit

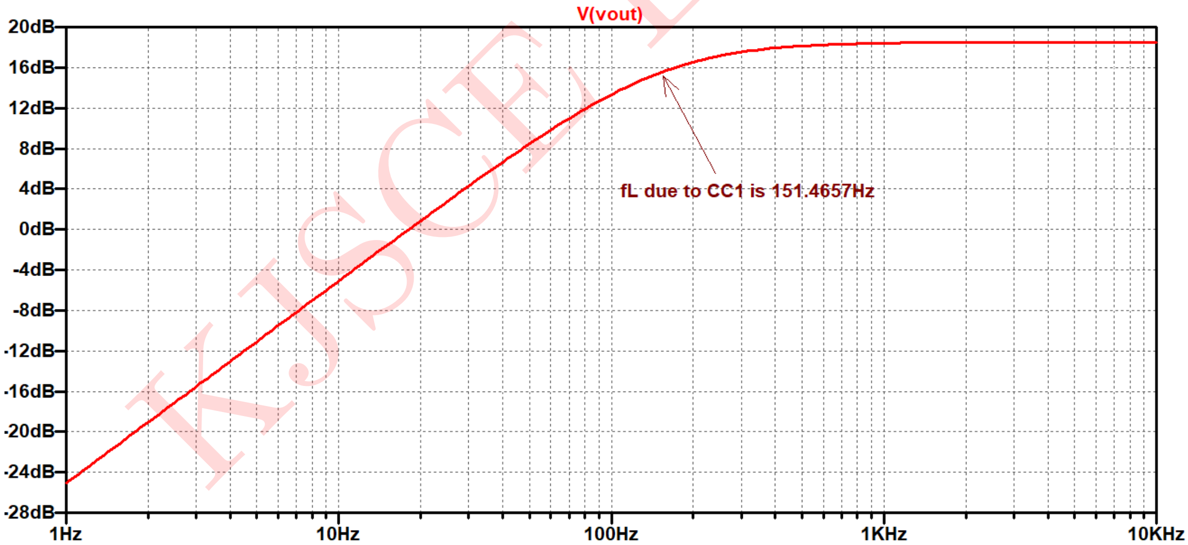

Figure 8: Low frequency response for C_{C1}

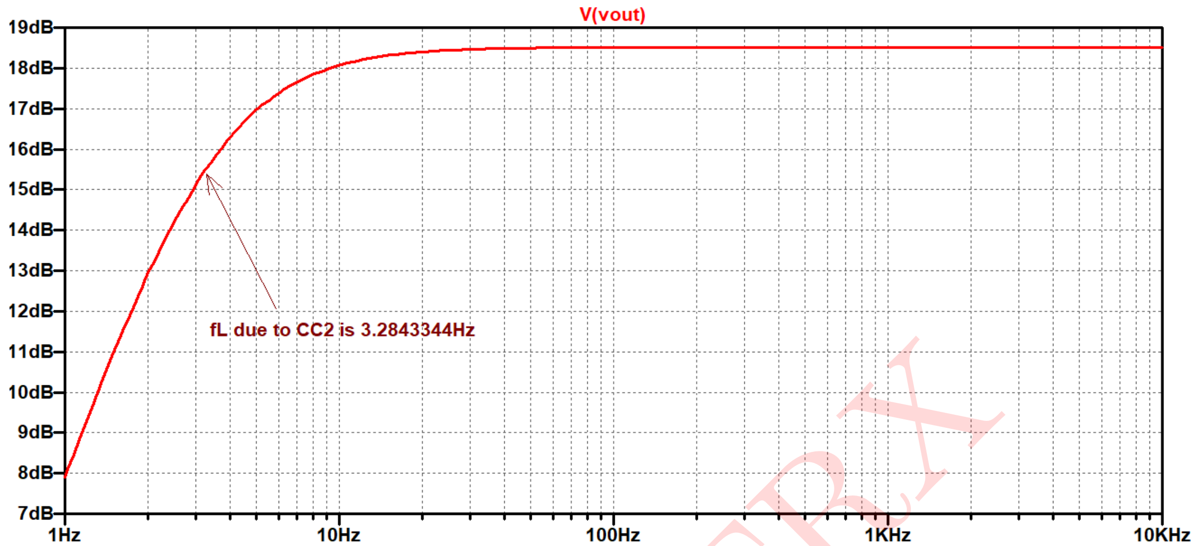

Figure 9: Low frequency response for C_{C2}

Comparsion between theoretical and simulated values:

Parameter	Theoretical value	Simulated value
I_{CQ}	1.0644mA	1.0604mA
Lower cutoff frequency due to C_{C1}	151.1460Hz	151.9911Hz
Lower cutoff frequency due to C_{C2}	3.2481Hz	3.2740Hz
Overall cutoff frequency f_L	151.1460Hz	151.8880Hz
Midband voltage gain $A_{V(mid)}$	18.5136 dB	18.3779 dB

Table 1: Design 1

Numerical 2:

For the network shown in figure 10:

a. Determine V_{GSQ} and I_{DQ}

b. Find g_{mo} & g_m

c. Calculate midband gain $A_V = \dfrac{V_o}{V_i}$

d. Determine Z_i

e. Calculate $A_{Vs} = \dfrac{V_o}{V_s}$

f. Determine f_{LCC1}, f_{LCC2} and f_{LCE}

g. Determine the lower cut-off frequency

Given: $I_{DSS} = 6mA$, $r_d = \infty$ & $V_P = -6V$

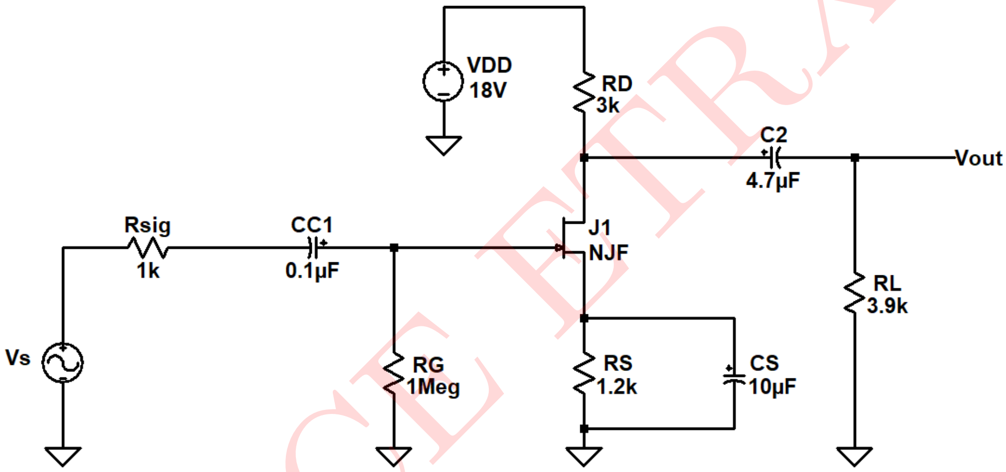

Figure 10: Circuit Diagram

Solution: Figure 10 is a common-source JFET amplifier.

a. DC analysis: All capacitors are open-circuited and DC equivalent circuit is shown in figure 11.

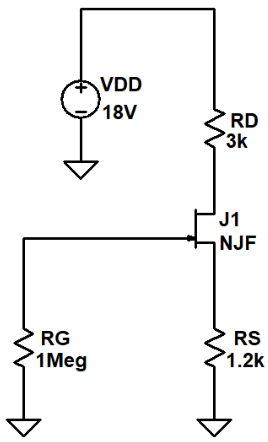

Figure 11: DC equivalent circuit

Applying KVL to G-S loop:

$V_G - V_{GSQ} - I_S R_S = 0$

$\therefore V_{GSQ} - I_D R_S = 0 \qquad ...(\because I_D = I_S)$

$\therefore -V_{GSQ} = -I_D R_S$

$$\therefore I_{DQ} = \frac{-V_{GSQ}}{R_S} = \frac{-V_{GSQ}}{1.2k\Omega} \qquad ...(1)$$

In saturation, $I_D = I_{DSS}\left[1 - \frac{V_{GS}}{V_P}\right]^2$

$$\therefore \frac{-V_{GS}}{1.2k\Omega} = (6mA)\left[1 + \frac{V_{GS}}{6}\right]^2 \qquad ...(\text{from } (1))$$

$$-V_{GS} = 7.2\left[1 + \frac{V_{GS}^2}{36} + \frac{V_{GS}}{3}\right]$$

$-V_{GS} = 7.2 + 0.2V_{GS}^2 + 2.4V_{GS}$

$\therefore 0.2V_{GS}^2 + 3.4V_{GS} + 7.2 = 0$

$\therefore V_{GS} = -2.4792V, \ -14.5208V$

Since $V_{GS} > V_P \qquad \therefore \mathbf{V_{GSQ} = -2.4792V}$

$$\therefore I_{DQ} = \frac{-(-2.4792V)}{1.2k\Omega} = \mathbf{2.0660mA}$$

b. $g_{mo} = \frac{2I_{DSS}}{|V_P|} = \frac{2 \times 6mA}{6V}$

$\therefore \mathbf{g_{mo} = 2mA/V}$

$$g_m = g_{mo}\left[1 - \frac{V_{GS}}{V_P}\right]$$

$$\therefore g_m = (2mA)\left[1 - \frac{2.4792}{6}\right]$$

$\therefore \mathbf{g_m = 1.1736mA/V}$

c. Small signal equivalent circuit is shown in figure 12:

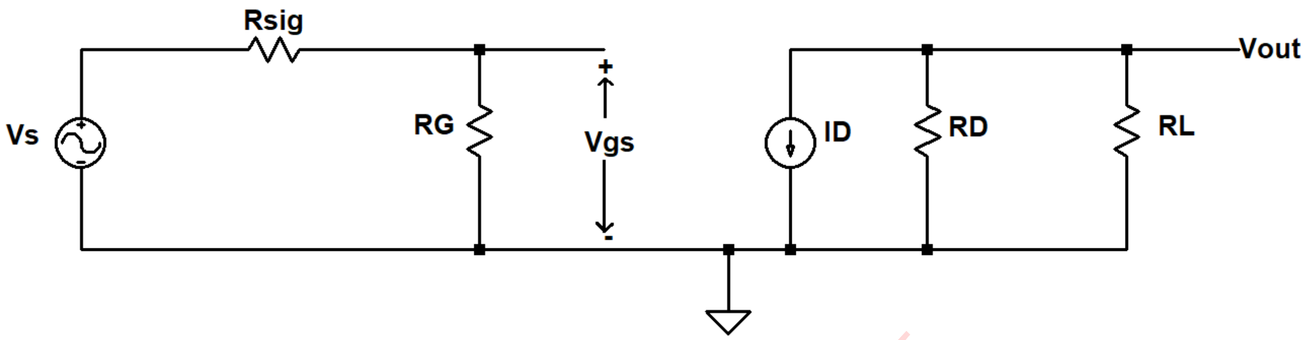

Figure 12: Small signal equivalent circuit

Voltage gain, $A_V = \dfrac{V_{out}}{V_{in}}$

$V_{out} = -g_m V_{gs}(R_D \parallel R_L) \quad ...V_{in} = V_{gs}$

$\therefore A_V = \dfrac{-g_m V_{gs}(R_D \parallel R_L)}{V_{gs}} = -g_m(R_D \parallel R_L)$

$\therefore A_V = -(-1.1736 \times 10^{-3})(3k\Omega \parallel 3.9k\Omega)$

$\therefore \mathbf{A_V = -1.9901}$ ...(2)

$\therefore \mathbf{A_V = 5.9775dB}$

d. $Z_i = R_G = 1M\Omega$

$\therefore \mathbf{Z_i = 1M\Omega}$

e. Voltage gain (with R_{sig}):

$A_{Vs} = \dfrac{V_o}{V_s} = \dfrac{V_o}{V_{in}} \times \dfrac{V_{in}}{V_s}$

$V_o = -g_m V_{gs}(R_D \parallel R_L)$

$V_{in} = V_{gs}$

$\therefore V_{in} = \dfrac{R_G}{R_{sig} + R_G} \times V_s$

$\therefore \dfrac{V_{in}}{V_s} = \dfrac{1M\Omega}{1k\Omega + 1M\Omega} = 0.999$ ...(3)

$\therefore A_{Vs} = (-1.9901)(0.999) \quad$ ...(from (2) and (3))

$\therefore \mathbf{A_{Vs} = -1.9881}$

$\therefore \mathbf{A_{Vs} = 5.9688dB}$

f. Small signal low frequency equivalent circuit for C_{C1} alone is shown in figure 13:

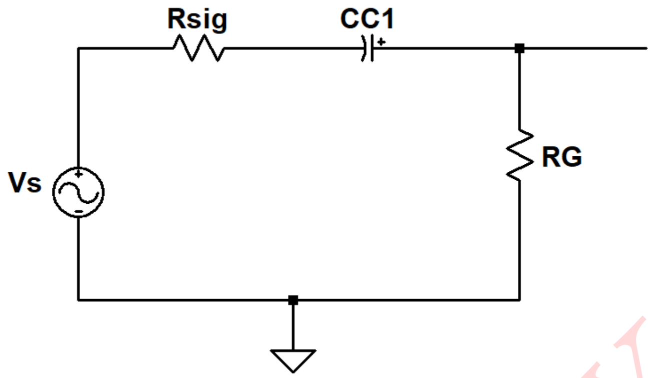

Figure 13: Small signal low frequency equivalent circuit fot C_{C1} alone

$$f_{LCC1} = \frac{1}{2\pi R_{eq} C_{C1}}$$

$R_{eq} = R_{sig} + R_G = 1k\Omega + 1M\Omega$

$\therefore R_{eq} = 1001k\Omega$

$$\therefore f_{LCC1} = \frac{1}{2\pi(1001k\Omega)(0.1\mu F)}$$

$\therefore \mathbf{f_{LCC1} = 1.5899Hz}$

Small signal low frequency equivalent circuit for C_{C2} alone is shown in figure 14:

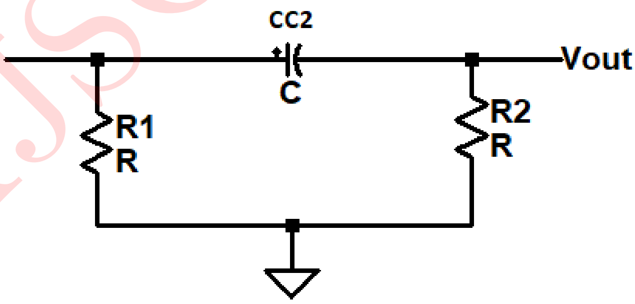

Figure 14: Small signal low frequency equivalent circuit fot C_{C2} alone

$$f_{LCC2} = \frac{1}{2\pi R_{eq} C_{C2}}$$

$R_{eq} = R_D + R_L = 3k\Omega + 3.9k\Omega$

$\therefore R_{eq} = 6.9k\Omega$

$$\therefore f_{LCC2} = \frac{1}{2\pi(6.9k\Omega)(4.7\mu F)}$$

$\therefore \mathbf{f_{LCC2} = 4.9076Hz}$

Small signal low frequency equivalent circuit for C_s alone is shown in figure 15:

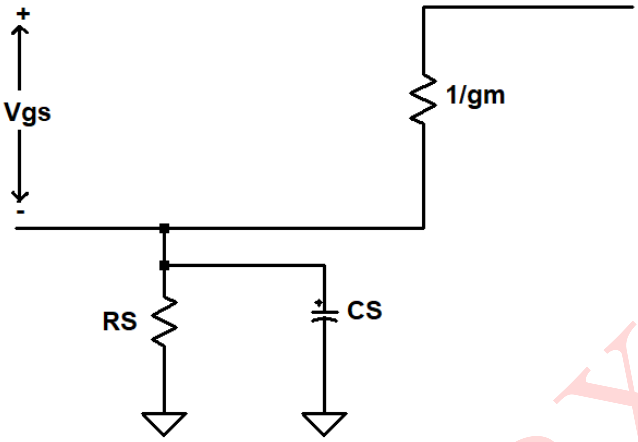

Figure 15: Small signal low frequency equivalent circuit fot C_s alone

$f_{LCS} = \dfrac{1}{2\pi R_{eq} C_s}$

$R_{eq} = R_s \parallel 1/g_m = 1.2k\Omega \parallel 852.08\Omega$

$\therefore R_{eq} = 498.3\Omega$

$f_{LCS} = \dfrac{1}{2\pi(498.3)(10\mu F)}$

$\therefore \mathbf{f_{LCS} = 31.9413Hz}$

g. Lower cut-off frequency is the highest among f_{LCC1}, f_{LCC2} and f_{LCS} which is 31.9413Hz This is the more dominant $-3dB$ frequency.

$\therefore$ Lower cut-off frequency of the given CS JFET amplifier is **31.9413Hz**

SIMULATED RESULTS:
Above circuit was simulated in LTspice and results obtained are as follows:

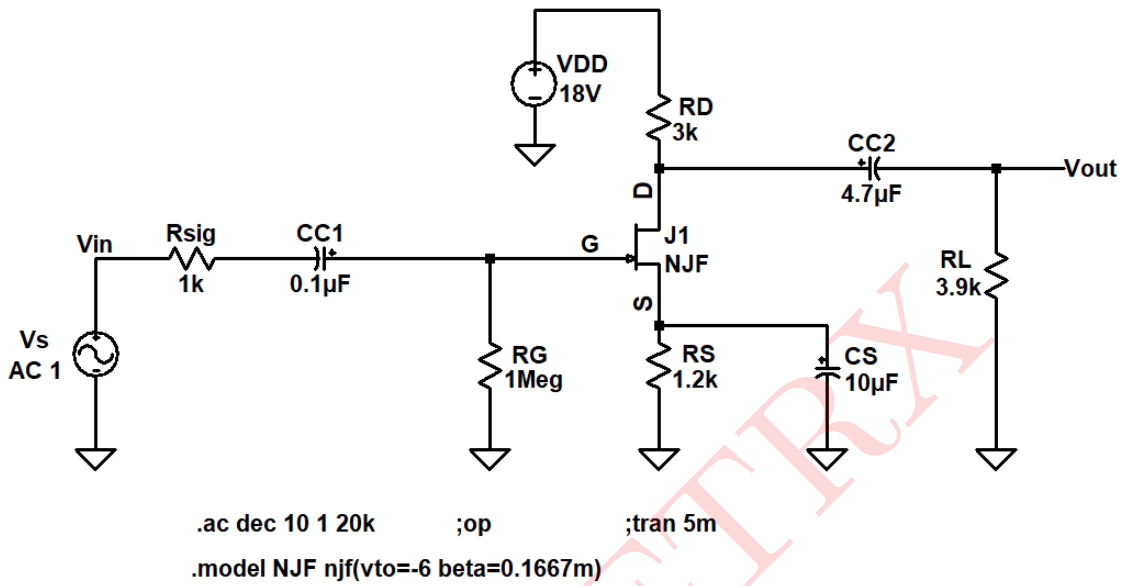

Figure 16: Circuit Schematic: Results

The frequency plots are shown in figures below:

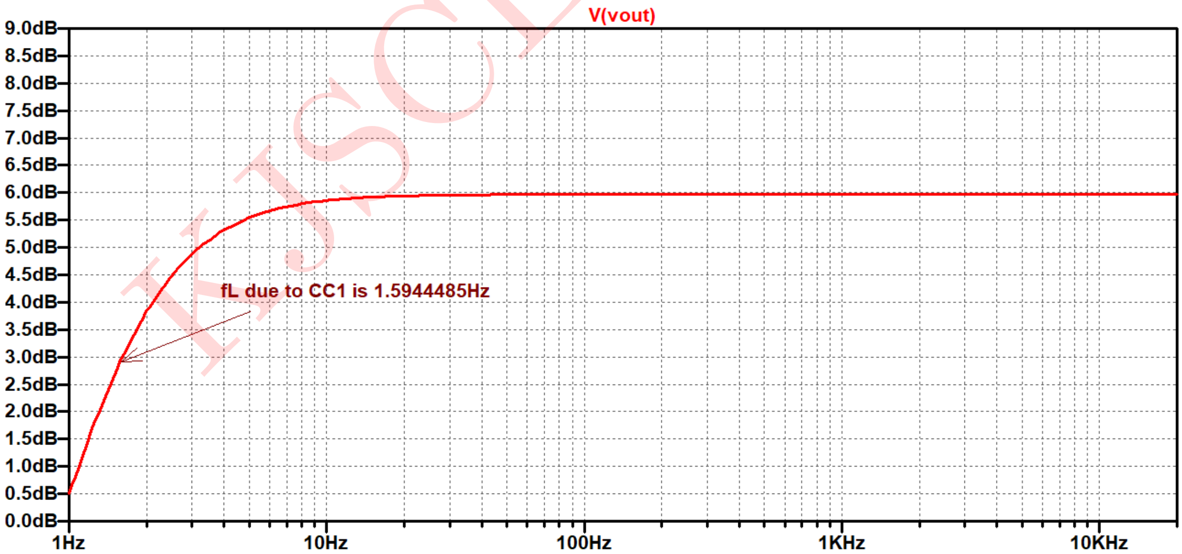

Figure 17: Low frequency response for C_{C1}

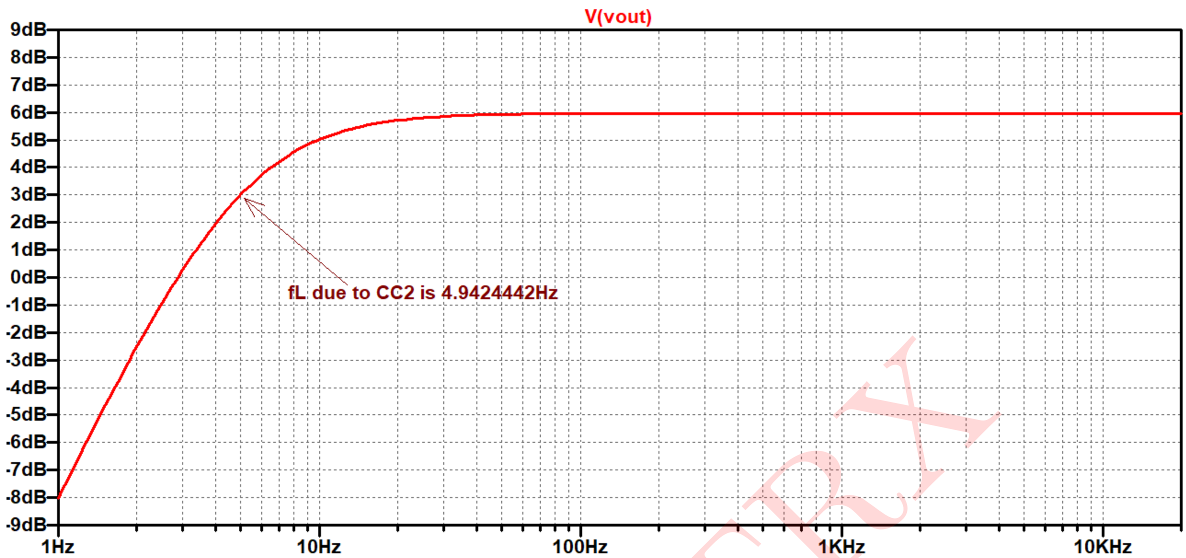

Figure 18: Low frequency response for C_{C2}

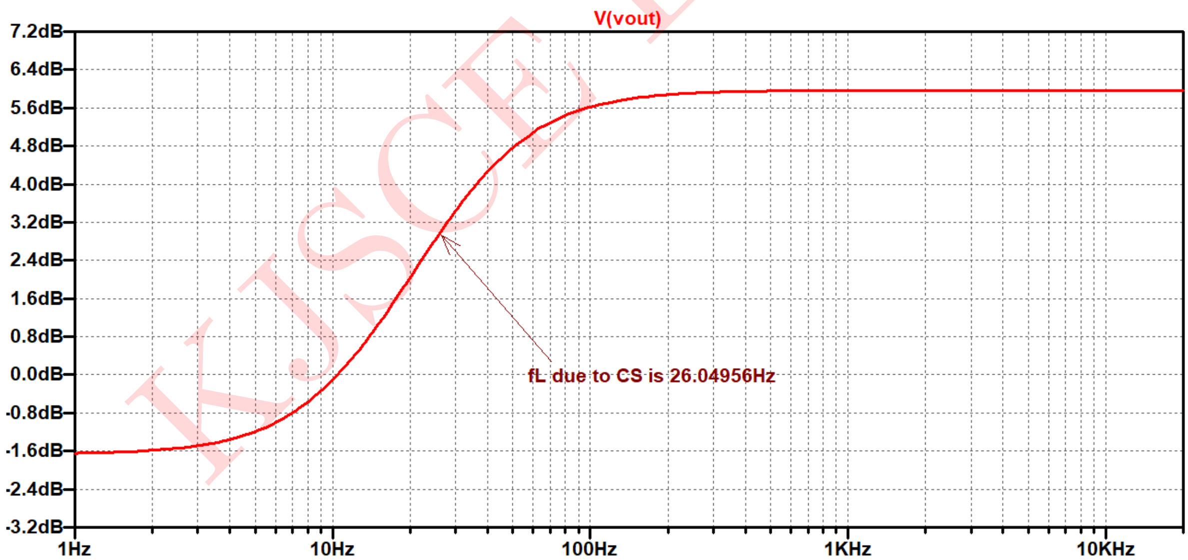

Figure 19: Low frequency response for C_s

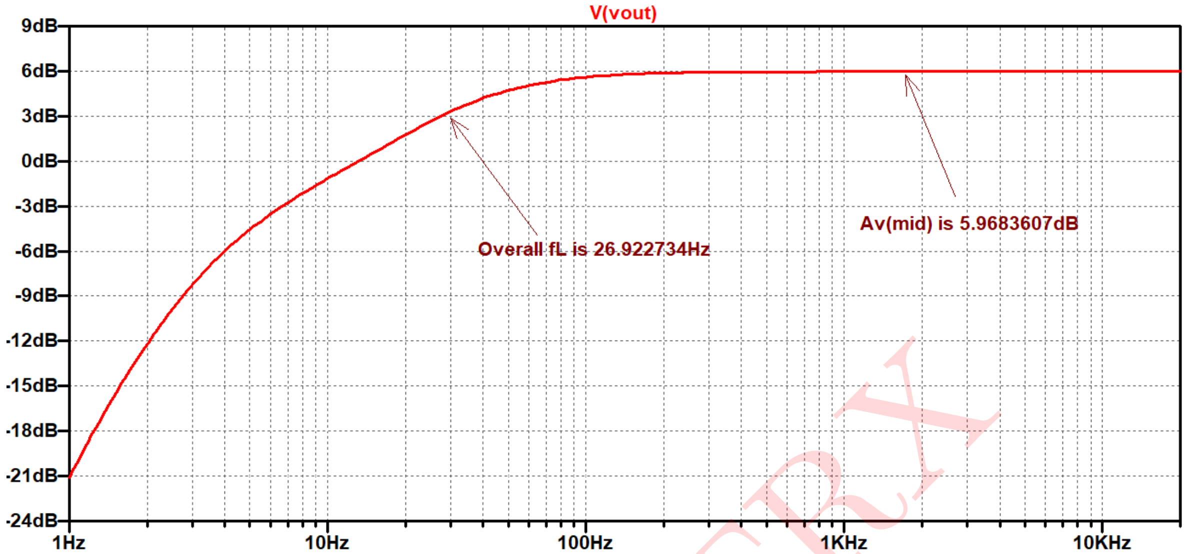

Figure 20: Low frequency response for overall circuit

Comparsion between theoretical and simulated values:

Parameter	Theoretical value	Simulated value
I_{DQ}	2.0660mA	2.0662mA
V_{GSQ}	-2.4792V	$-2.4794V$
Lower cutoff frequency due to C_{C1}	1.5899Hz	1.5800Hz
Lower cutoff frequency due to C_{C2}	4.9076Hz	4.9521Hz
Lower cutoff frequency due to C_s	31.9413Hz	26.08896Hz
Overall cutoff frequency f_L	31.9413Hz	27.4881Hz
Midband voltage gain $A_{Vs(mid)}$	5.9688dB	5.9697dB

Table 2: Numerical 2

Numerical 3:
For the network shown in figure 21:
a. Determine V_{GSQ} and I_{DQ}
b. Find g_{mo} and g_m
c. Calculate midband gain $A_V = V_o/V_s$
d. Determine Z_i
e. Calculate $A_{Vs} = V_o/V_s$
f. Determine f_{LCC1}, f_{LCC2} and f_{LCs}
g. Determine the lower cut-off frequency frequency.
h. Higher cut-off frequency of the circuit.
Given: $I_{DSS} = 6mA$, $r_d = \infty$, $V_P = -6V$, $C_{wi} = 3pF$, $C_{wo} = 5pF$, $C_{gd} = 4pF$, $C_{gs} = 6pF$, $C_{ds} = 1pF$

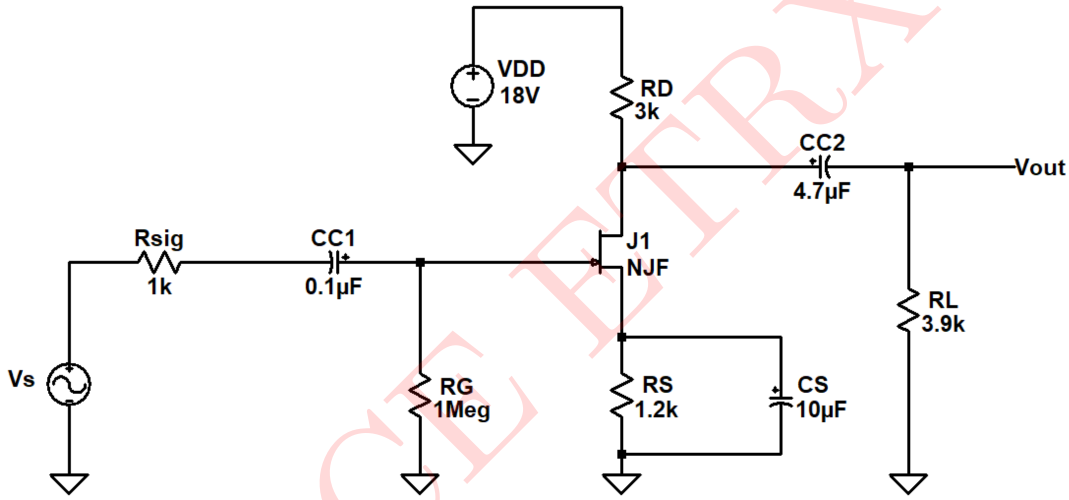

Figure 21: Circuit diagram

Solution: The circuit shown in figure 21 is a common-source JFET amplifier.

a. DC analysis: All capacitors are open-circuited and DC equivalent circuit is shown in figure 22.

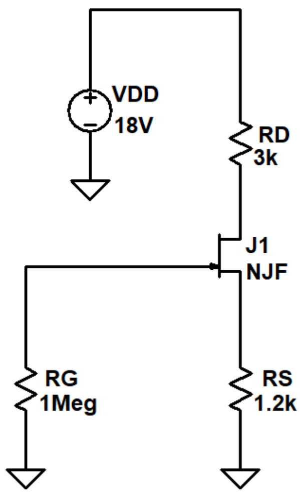

Figure 22: DC equivalent circuit

Applying KVL to G-S loop:

$V_G - V_{GSQ} - I_S R_S = 0$

$\therefore -V_{GSQ} - I_D R_S = 0 \quad ...(\because I_D = I_S \text{ and } V_G = 0V)$

$\therefore V_{GSQ} = -I_D R_S$

$$\therefore I_{DQ} = \frac{-V_{GSQ}}{R_S} = \frac{-V_{GSQ}}{1.2k\Omega} \qquad ...(1)$$

In saturation, $I_D = I_{DSS}\left[1 - \frac{V_{GS}}{V_P}\right]^2$

$$\therefore \frac{-V_{GS}}{1.2k\Omega} = (6mA)\left[1 + \frac{V_{GS}}{6}\right]^2 \quad ...(\text{from } (1))$$

$$-V_{GS} = 7.2\left[1 + \frac{V_{GS}^2}{36} + \frac{V_{GS}}{3}\right]$$

$-V_{GS} = 7.2 + 0.2V_{GS}^2 + 2.4V_{GS}$

$\therefore 0.2V_{GS}^2 + 3.4V_{GS} + 2.4V_{GS} = 0$

$\therefore V_{GS} = -2.4792V, -14.5208V$

Since $V_{GS} > V_P \quad \therefore \mathbf{V_{GSQ} = -2.4792V}$

$$\therefore I_{DQ} = \frac{-(-2.4792V)}{1.2k\Omega} = \mathbf{2.0660mA}$$

b. $g_{mo} = \dfrac{2I_{DSS}}{\mid V_P \mid} = \dfrac{2(6mA)}{6V}$

$\therefore \mathbf{g_{mo} = 2mA/V}$

$$g_m = g_{mo}\left[1 - \frac{V_{GS}}{V_P}\right] = (2mA)\left[1 - \frac{2.4792}{6}\right]$$

$\mathbf{g_m = 1.1736mA/V}$

c. Small signal equivalent circuit is shown in figure 23:

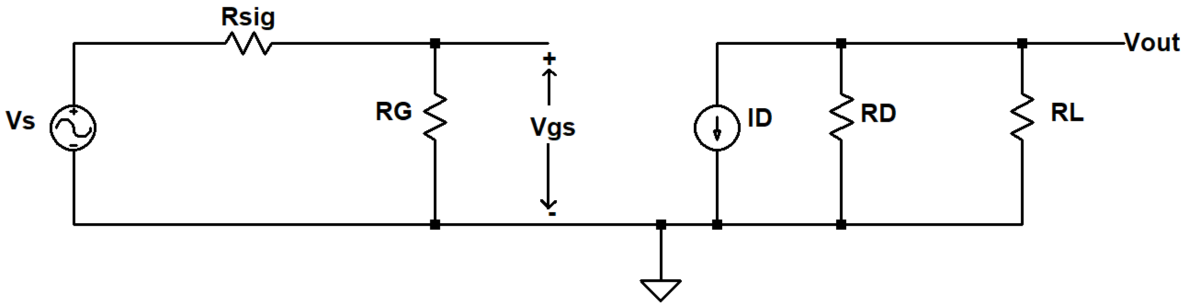

Figure 23: Small signal equivalent circuit

Voltage gain: $A_V = \dfrac{V_{out}}{V_{in}}$

$V_{out} = -g_m V_{gs}(R_D \parallel R_L)$

$V_{in} = V_{gs}$

$\therefore A_V = \dfrac{-g_m V_{gs}(R_D \parallel R_L)}{V_{gs}} = -g_m(R_D \parallel R_L)$

$\therefore A_V = -(1.1736 \times 10^{-3})(3k\Omega \parallel 3.9k\Omega)$

$\therefore \mathbf{A_V = -1.9901}$ ...(2)

$\therefore \mathbf{A_V = 5.9755dB}$

d. $Z_i = R_G = 1M\Omega$

$\therefore \mathbf{Z_i = 1M\Omega}$

e. Voltage gain (with R_{sig}):

$A_{Vs} = \dfrac{V_o}{V_s} = \dfrac{V_o}{V_{in}} \times \dfrac{V_{in}}{V_s}$

$V_o = -g_m V_{gs}(R_D \parallel R_L)$

$V_{in} = V_{gs}$

$\therefore V_{in} = \dfrac{R_G}{R_{sig} + R_G} \times V_s$

$\therefore \dfrac{V_{in}}{V_s} = \dfrac{1M\Omega}{1k\Omega + 1M\Omega} = 0.999$ ...(3)

$\therefore A_{Vs} = (-1.9901)(0.999)$ ...(from (2) and (3))

$\therefore \mathbf{A_{Vs} = -1.9881}$

$\therefore \mathbf{A_{Vs} = 5.9688dB}$

f. Small signal low frequency equivalent circuit for C_{C1} alone is shown in figure 24:

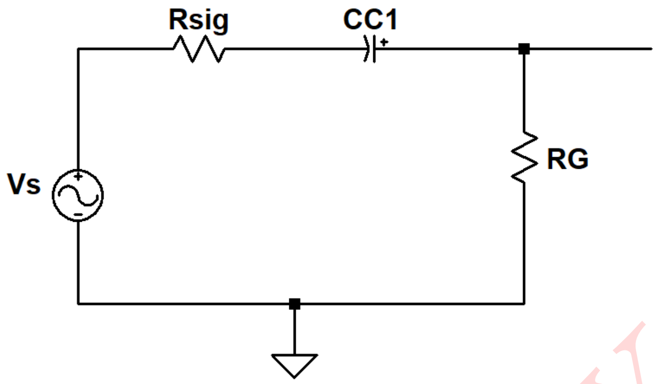

Figure 24: Small signal low frequency equivalent circuit for C_{C1} alone

$f_{LCC1} = \dfrac{1}{2\pi R_{eq} C_{C1}}$

$R_{eq} = R_{sig} + R_G = 1k\Omega + 1M\Omega$

$\therefore R_{eq} = 1001k\Omega$

$\therefore f_{LCC1} = \dfrac{1}{2\pi(1001k\Omega)(0.1\mu F)}$

$\therefore \mathbf{f_{LCC1} = 1.5899Hz}$

Small signal low frequency equivalent circuit for C_{C2} alone is shown in figure 25:

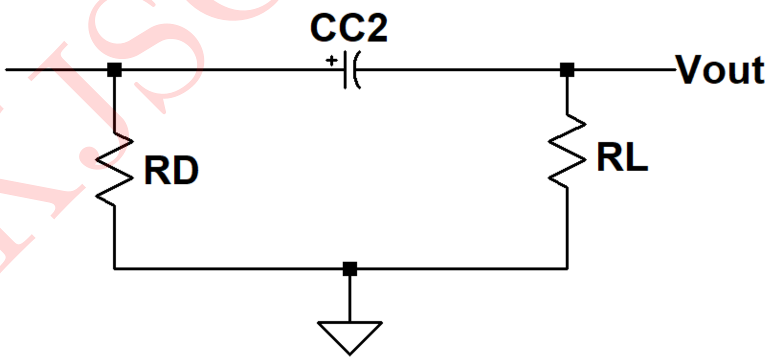

Figure 25: Small signal low frequency equivalent circuit fot C_{C2} alone

$f_{LCC2} = \dfrac{1}{2\pi R_{eq} C_{C2}}$

$R_{eq} = R_D + R_L = 3k\Omega + 3.9k\Omega$

$\therefore R_{eq} = 6.9k\Omega$

$\therefore f_{LCC2} = \dfrac{1}{2\pi(6.9k\Omega)(4.7\mu F)}$

$\therefore \mathbf{f_{LCC2} = 4.9076Hz}$

Small signal low frequency equivalent circuit for C_s alone is shown in figure 26:

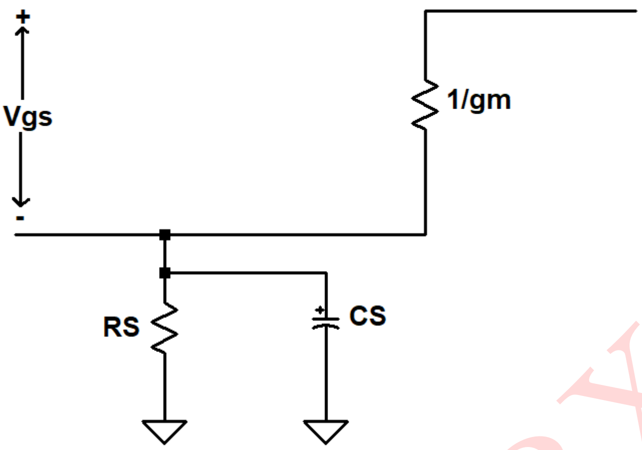

Figure 26: Small signal low frequency equivalent circuit fot C_s alone

$f_{LCS} = \dfrac{1}{2\pi R_{eq} C_s}$

$R_{eq} = R_s \parallel 1/g_m = 1.2k\Omega \parallel 852.08\Omega$

$\therefore R_{eq} = 498.3\Omega$

$f_{LCS} = \dfrac{1}{2\pi(498.3)(10\mu F)}$

$\therefore \mathbf{f_{LCS} = 31.9413Hz}$

g. Lower cut-off frequency is the highest among f_{LCC1}, f_{LCC2} and f_{LCS} which is 31.9413Hz This is the more dominant $-3dB$ frequency.
$\therefore$ Lower cut-off frequency of the given CS JFET amplifier is **31.9413Hz**

h. Small signal high frequency equivalent circuit for effect of C_i alone is shown in figure 27:

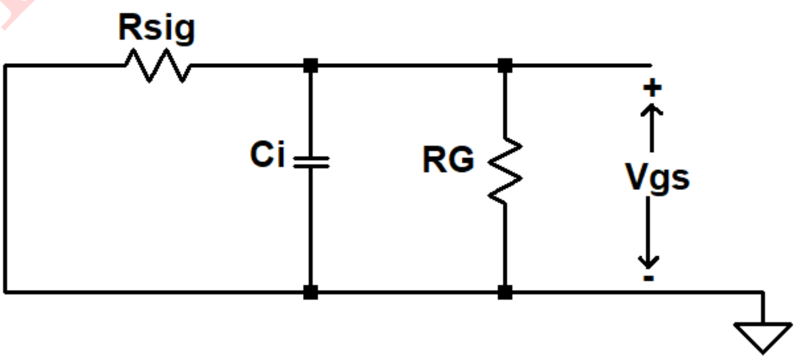

Figure 27: Small signal high frequency equivalent circuit for effect of C_i alone

$f_{Hi} = \dfrac{1}{2\pi R_{eq} C_i}$

$R_{eq} = R_{sig} \parallel R_G = 1k\Omega \parallel 1M\Omega = 1\text{k}\Omega$

$C_i = C_{mi} + C_{gs} + C_{wi}$

where $C_{mi} = C_{gd}[1 - A_{V(mid)}] = (4pF)[1 + 1.9881]$

$\therefore C_{mi} = 11.9524pF$

$\therefore C_i = 11.9524pF + 6pF + 3pF$

$\therefore f_{Hi} = \dfrac{1}{2\pi(1k\Omega)(20.9523pF)} = 7.5960MHz$

Small signal high frequency equivalent circuit for effect of C_o alone is shown in figure 28:

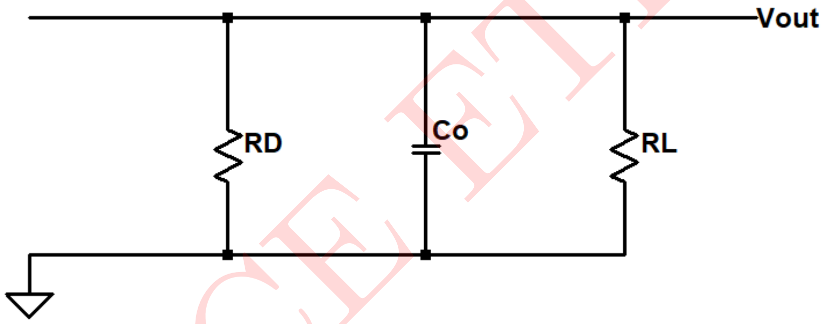

Figure 28: Small signal high frequency equivalent circuit for effect of C_o alone

$f_{Ho} = \dfrac{1}{2\pi R_{eq} C_o}$

$R_{eq} = R_o \parallel R_L = 3k\Omega \parallel 3.9k\Omega = 1.6957k\Omega$

$C_o = C_{mo} + C_{ds} + C_{wo}$

where, $C_{mo} = C_{gd}\left[1 - \dfrac{1}{A_{V(mid)}}\right] = (4pF)\left[1 + \dfrac{1}{1.9881}\right]$

$C_{mo} = 6.0120pF$

$f_{Ho} = \dfrac{1}{2\pi R_{eq} C_o} = \dfrac{1}{2\pi(1.6957k\Omega)(12.012pF)}$

$f_{Ho} = 7.8137$ MHz

Higher cut-off frequency is the lowest value among f_{Hi} and f_{Ho}

$\therefore$ Higher cut-off frequency is **7.5960MHz**

SIMULATED RESULTS:
Above circuit was simulated in LTspice and results obtained are as follows:

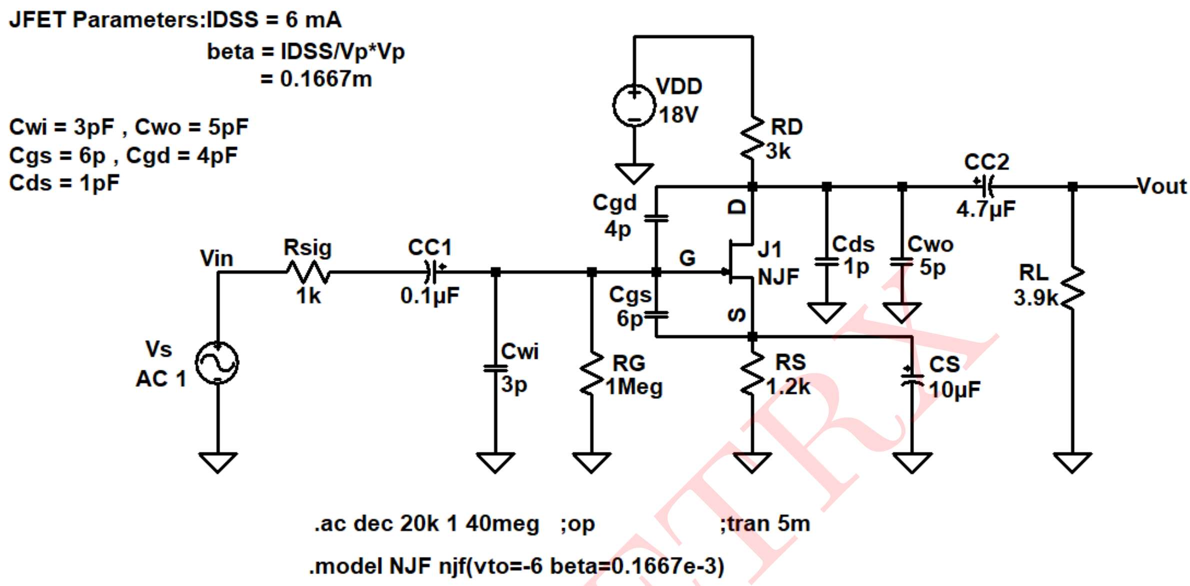

Figure 29: Circuit Schematic: Results

The frequency plots are shown in figures below:

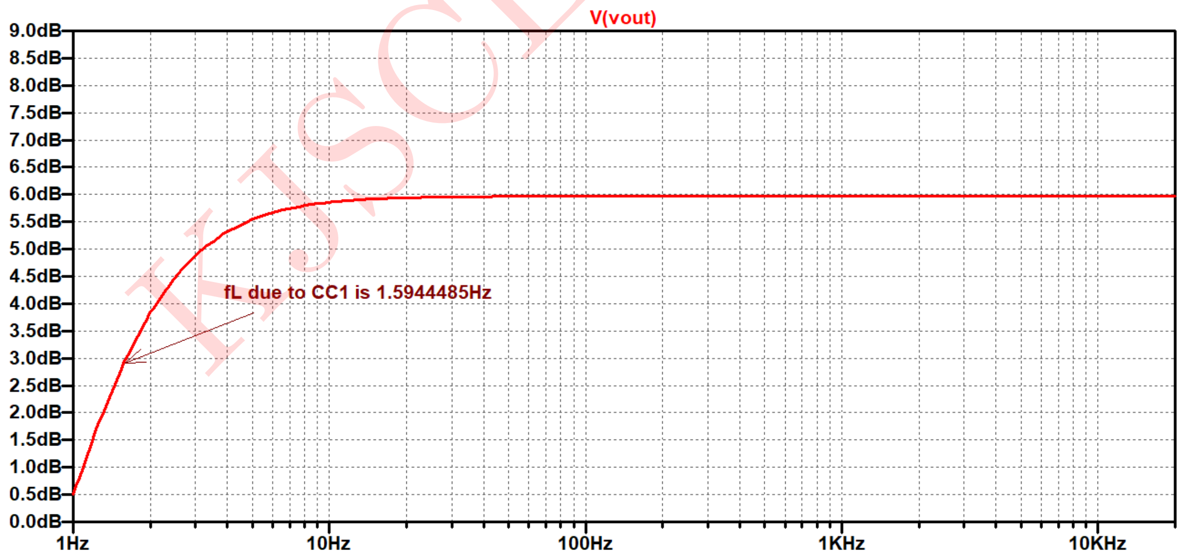

Figure 30: Low frequency response for C_{C1}

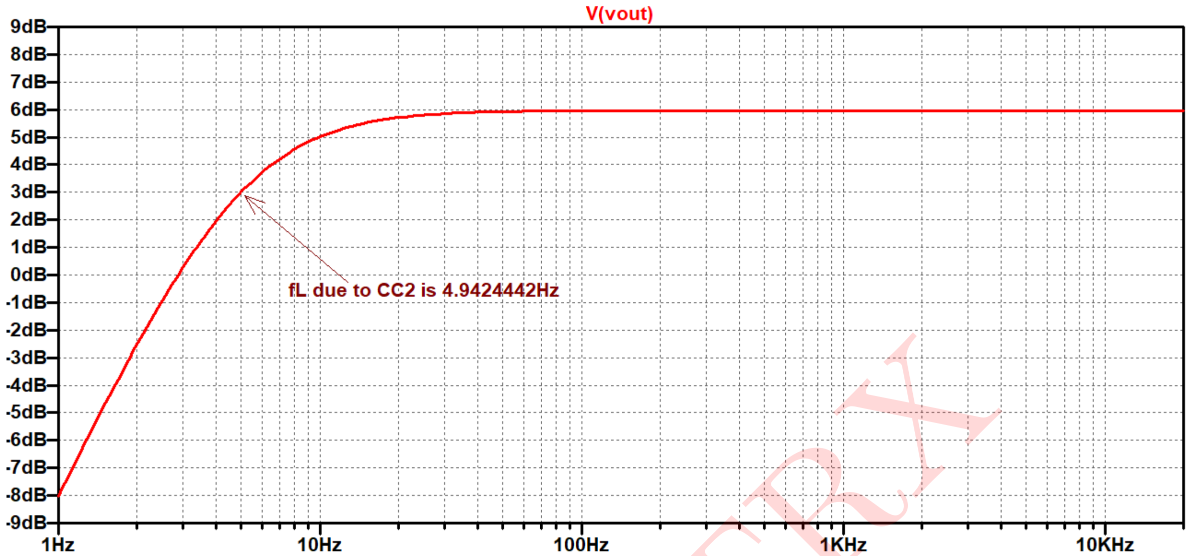

Figure 31: Low frequency response for C_{C2}

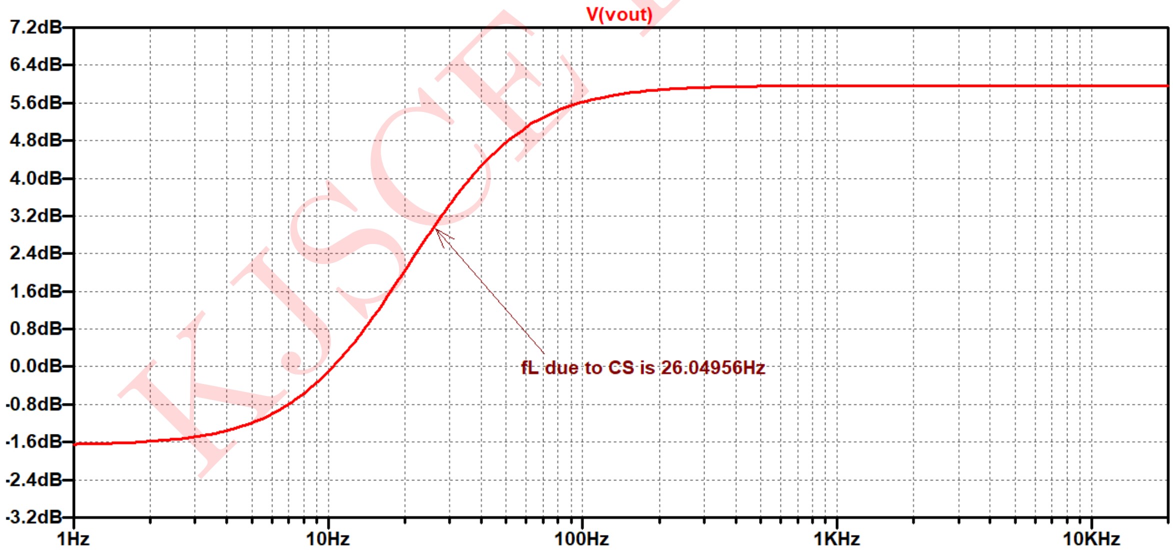

Figure 32: Low frequency response for C_s

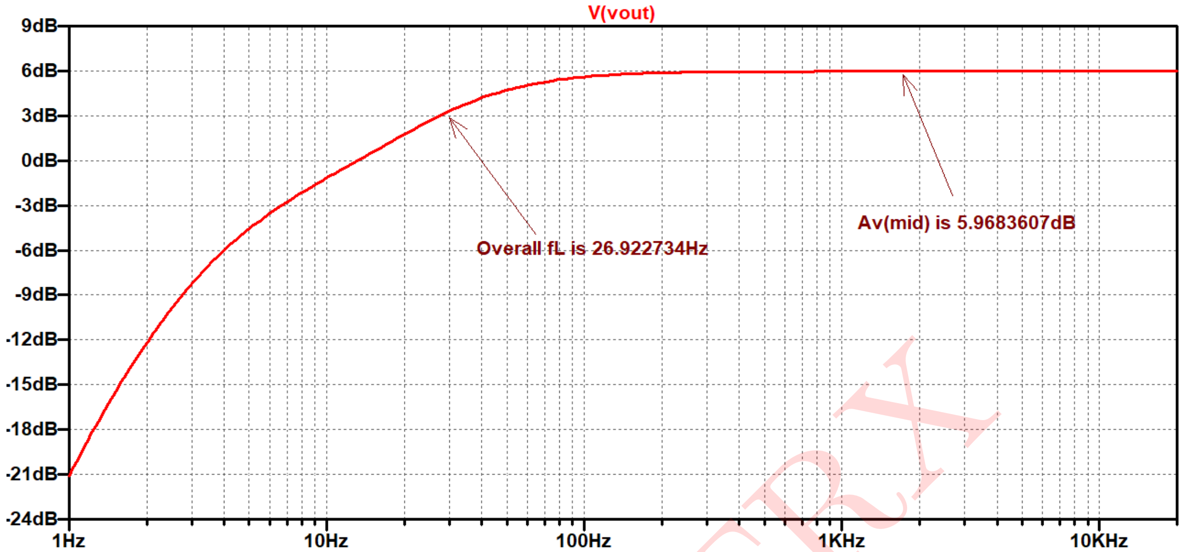

Figure 33: Overall low frequency response

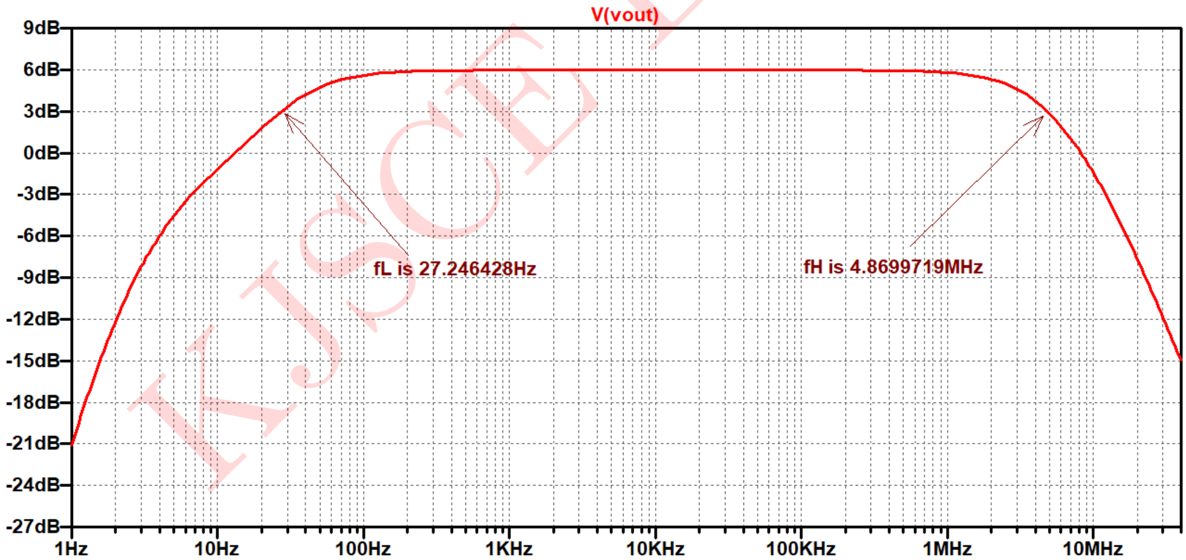

Figure 34: Total frequency response of circuit

Comparsion between theoretical and simulated values:

Parameter	Theoretical value	Simulated value
I_{DQ}	2.0660mA	2.0662mA
V_{GSQ}	$-2.4792V$	$-2.4794V$
Lower cutoff frequency due to C_{C1}	1.5899Hz	1.5800Hz
Lower cutoff frequency due to C_{C2}	4.9076Hz	4.9521Hz
Lower cutoff frequency due to C_s	31.9413Hz	27.2464Hz
Overall cutoff frequency f_L	31.9413Hz	27.2464Hz
Overall cut-off frequency f_H	7.5960 MHz	4.8699MHz
Midband voltage gain $A_{Vs(mid)}$)	5.9688dB	5.9697dB

Table 3: Numerical 3