ECE321 ELECTRONICS I
FALL 2006

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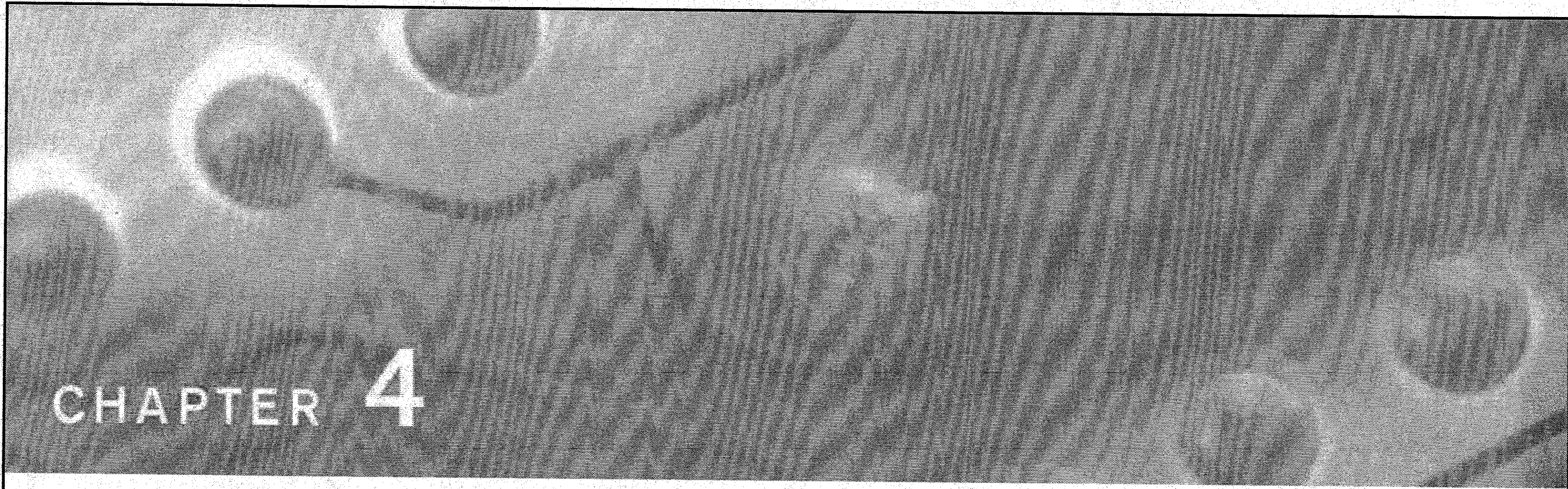
Lecture 16

21st November, 2006



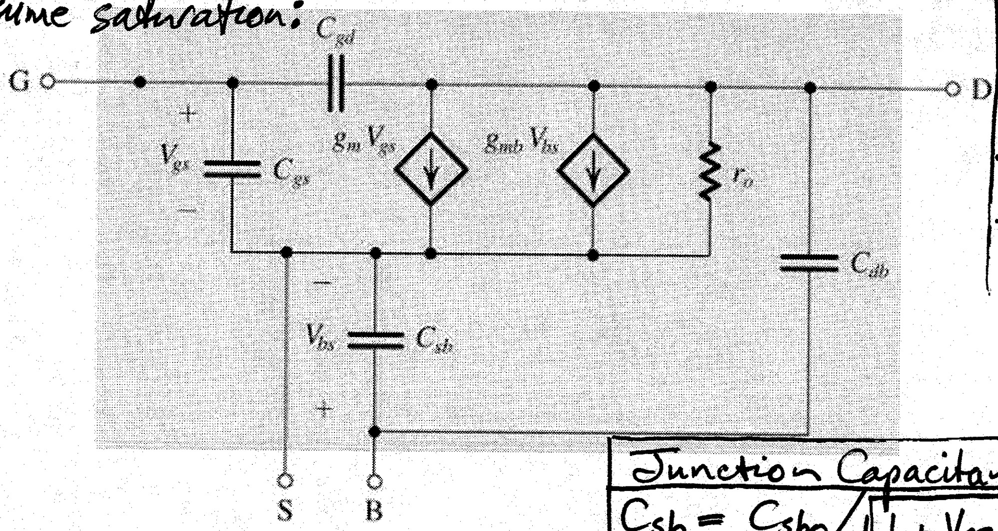
MOS Field-Effect Transistors (MOSFETs)

4.8 High Frequency Effects (MOSFET parasitics)

4.9 CS Amplifier Frequency Response (Bypass/coupling C's)

MOSFET Parasitic Capacitors

① Assume saturation:



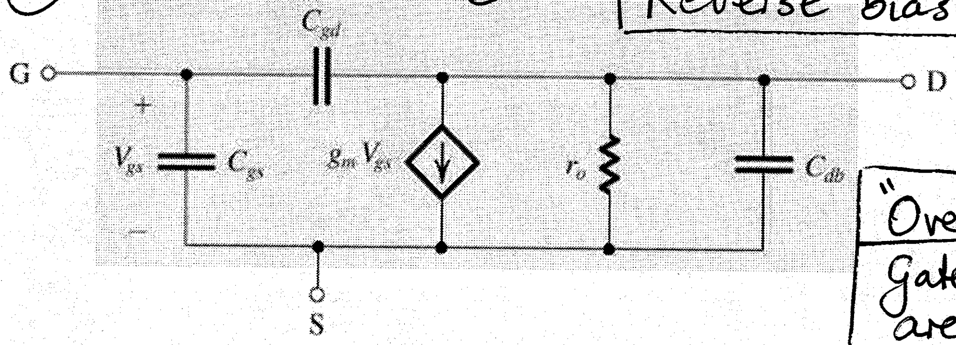
(a)

Gate Capacitances

Triode: $C_{gs} = C_{gd} = \frac{1}{2} WL.C_{ox}$ Gate "connects" through channel to S & D approx. equally.
Saturation: $C_{gs} \approx \frac{2}{3} WL.C_{ox}$, $C_{gd} \approx 0$ Channel pinched off at D
Cutoff: $C_{gs} = C_{gd} = 0$, $C_{gb} = WL.C_{ox}$

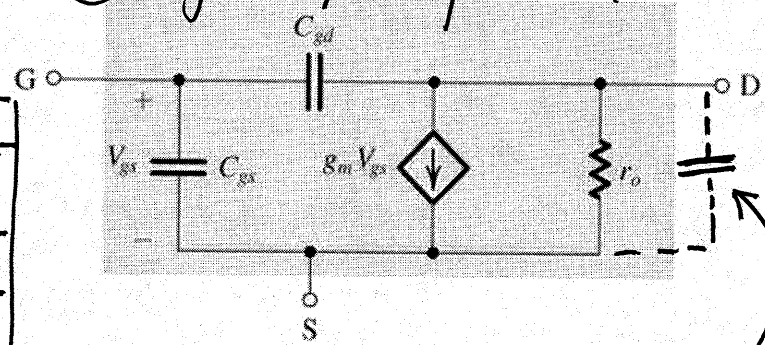
Junction Capacitances
$C_{sb} = C_{sbo} / \sqrt{1 + V_{SB}/V_o}$
$C_{db} = C_{dbo} / \sqrt{1 + V_{DB}/V_o}$
Reverse biased

② Connect S to B:-



(b)

③ High frequency model:



(c)

C_{db} (negligible) + approx C_{gd} (Miller Effect)

"Overlap" capacitances
Gate overlaps S, D diffusion areas by $L_{ov} \sim 0.05$ to $0.1 L$ $C_{ov} = W L_{ov}.C_{ox}$

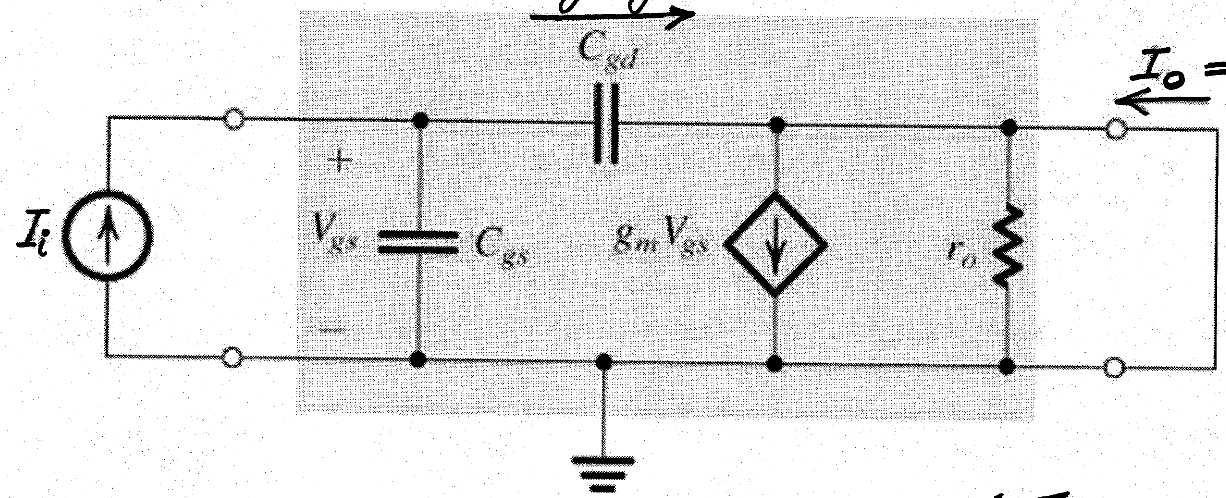
and $C_{gs}' \rightarrow C_{gs} + C_{ov}$, $C_{gd}' \rightarrow C_{gd} + C_{ov}$

Figure 4.47 **(a)** High-frequency equivalent circuit model for the MOSFET. **(b)** The equivalent circuit for the case in which the source is connected to the substrate (body). **(c)** The equivalent circuit model of (b) with C_{db} neglected (to simplify analysis).

Note: In saturation, $C_{gd} \approx C_{ov}$ ie. small.

Short Circuit Current gain I_o/I_i

$sC_{gd}V_{gs}$



$$I_o = g_m V_{gs} - sC_{gd}V_{gs}$$

$$\approx g_m V_{gs} \quad \text{(Note 1)}$$

$$V_{gs} = \frac{I_i}{s(C_{gs}+C_{gd})} \quad \text{(Note 2)}$$

Note 1: $sC_{gd}V_{gs}$ neglected in comparison with $g_m V_{gs}$

Note 2: $sC_{gd}V_{gs}$ included

Valid if $g_m V_{gs} \gg I_i$

ie. high current gain

$$\therefore I_o/I_i = \frac{g_m}{s(C_{gs}+C_{gd})}$$

& $|I_o/I_i| \rightarrow 1$ when

$$\omega_T = \frac{g_m}{C_{gs}+C_{gd}} \quad *$$

$$= k_n' \frac{W}{L} \frac{V_{ov}}{C_{gs}+C_{gd}}$$

$$= \sqrt{2k_n'\frac{W}{L}}\sqrt{I_D}/C_{gs}+C_{gd}$$

$$= (2I_D/V_{ov})/(C_{gs}+C_{gd})$$

Figure 4.48 Determining the short-circuit current gain I_o/I_i.

Note 1 is equivalent to ignoring the feedback effects.

See back to Miller Effect and BJT.

But here, output is short circuited $\therefore$ voltage gain = 0

Exercise 4.36

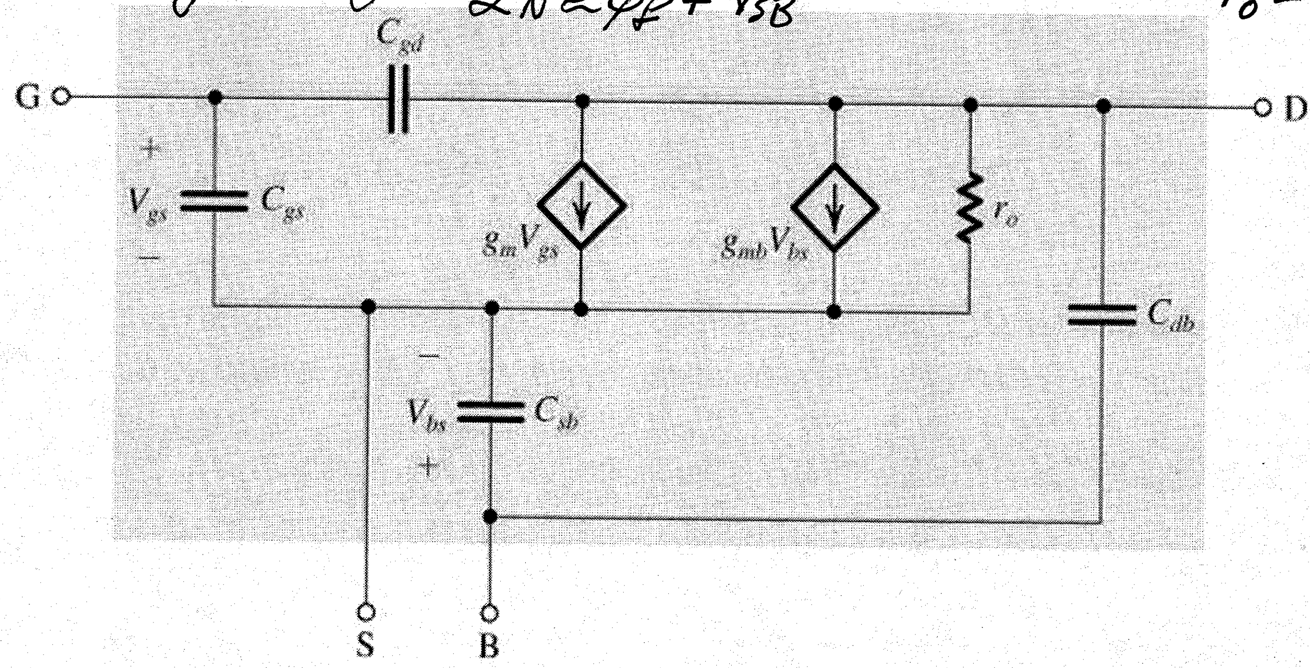
Exercise 4.37

MOSFET High Frequency Model Summary (Assume saturation)

$$g_m = \mu_n C_{ox} \frac{W}{L} V_{ov} = \sqrt{2 \mu_n C_{ox} \frac{W}{L} I_D} = \frac{2 I_D}{V_{ov}}$$

$$g_{mb} = \chi g_m = g_m \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}}$$

$$r_o = V_A / I_D$$



$$C_{gs} = \frac{2}{3} WL \cdot C_{ox} + W L_{ov} C_{ox}$$

$$C_{gd} = W L_{ov} C_{ox}$$

$$C_{sb} = C_{sbo} / \sqrt{1 + V_{SB}/V_0}$$

Table 4.5

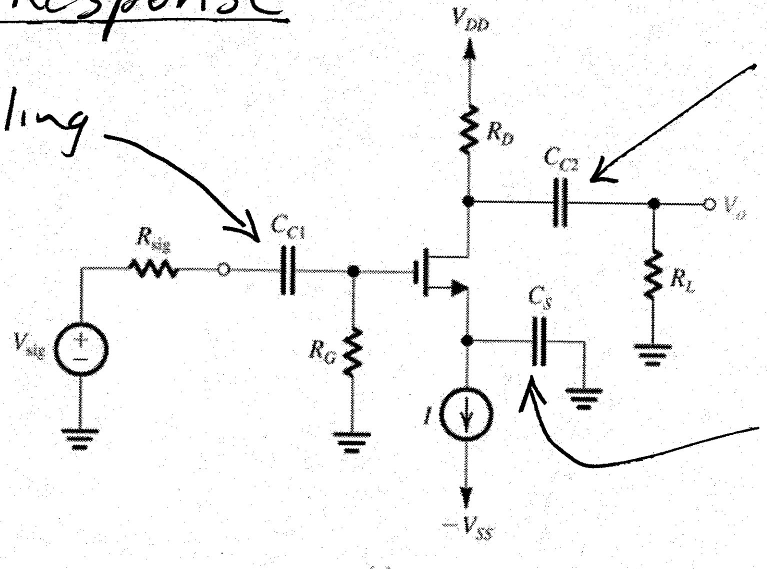
$$C_{db} = C_{dbo} / \sqrt{1 + V_{DB}/V_0}$$

$$f_T = \frac{g_m}{2\pi (C_{gs} + C_{gd})}$$

CS Frequency Response

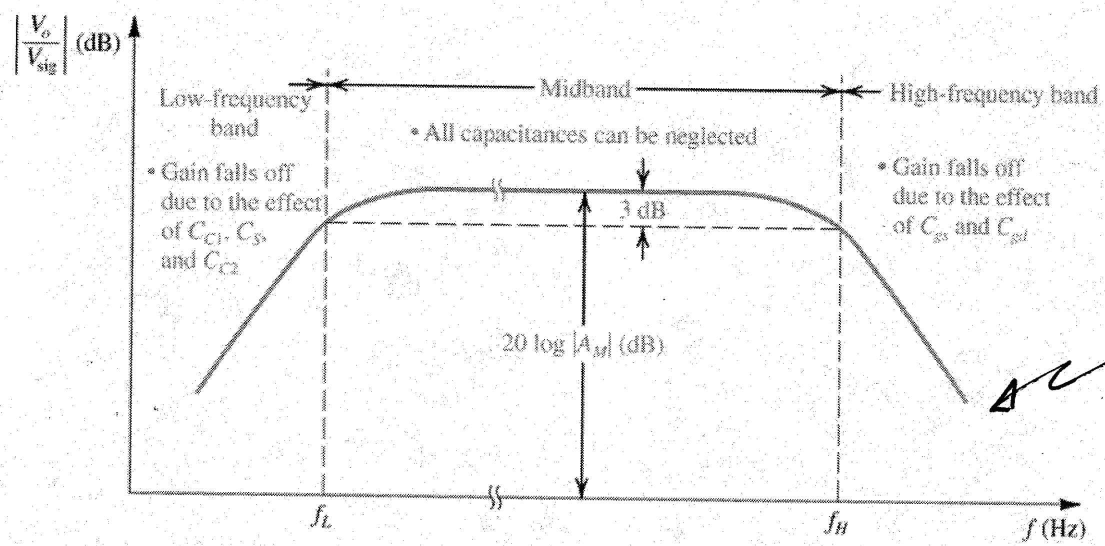
Coupling

Coupling



Bypass

(a)



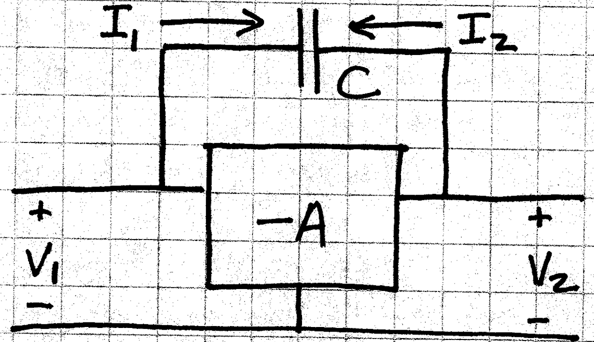
(b)

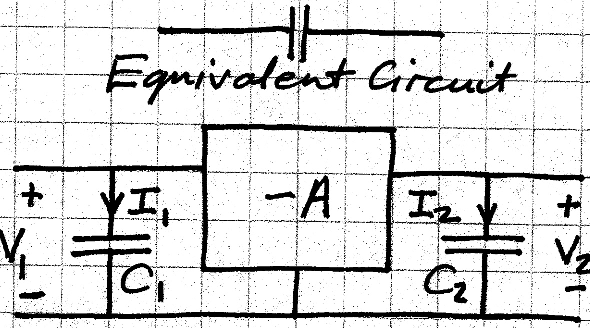
Figure 4.49 **(a)** Capacitively coupled common-source amplifier. **(b)** A sketch of the frequency response of the amplifier in (a) delineating the three frequency bands of interest.

Remember:
There is actually another higher frequency breakpoint due to $C_{gd} + C_{db}$ in output circuit.

Traditional Miller's Theorem treatment

Consider inverting amplifier of gain $-A$ with feedback capacitor C



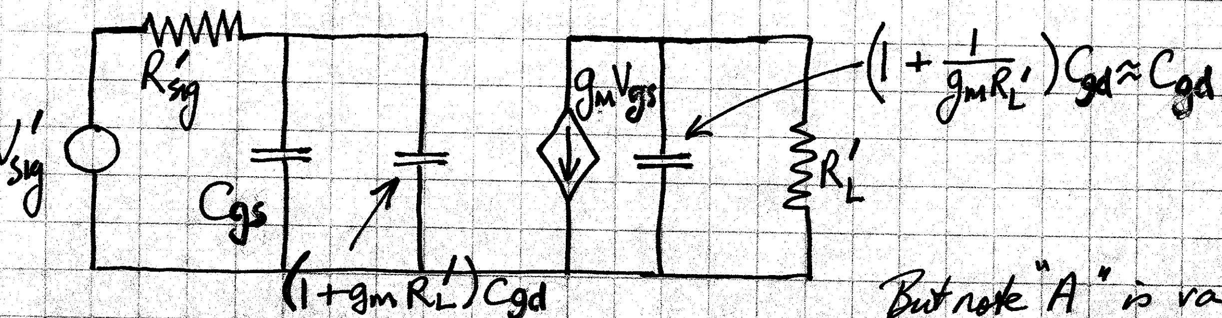


$$I_2 = sC(V_2 - V_1)$$
$$= sC\left(V_2 - \frac{V_2}{-A}\right)$$
$$= sC\left(1 + \frac{1}{A}\right)V_2 \longrightarrow \therefore \quad C_2 = \left(1 + \frac{1}{A}\right)C$$

$$I_2 = sC_2 V_2$$

$$I_1 = sC(V_1 - V_2)$$
$$= sC(V_1 - (-A)V_1)$$
$$= sC(1 + A)V_1 \longrightarrow \therefore \quad C_1 = (1 + A)C$$

$$I_1 = sC_1 V_1$$



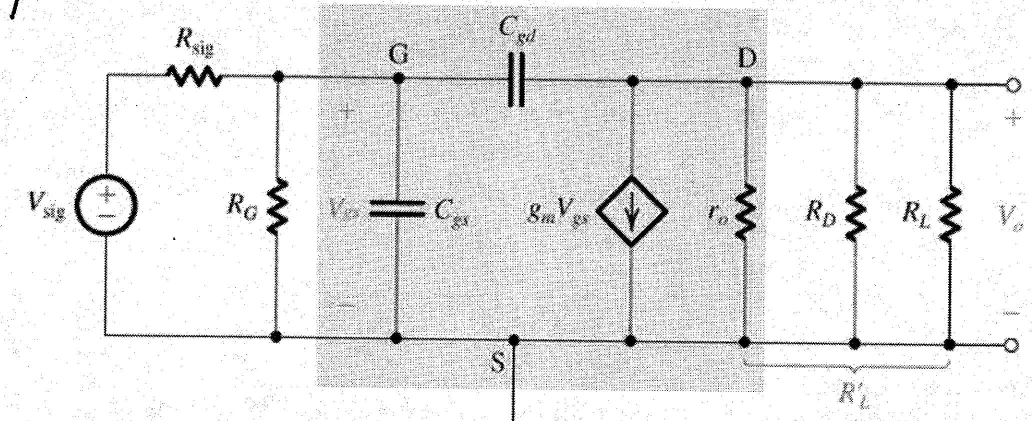
$$\omega_1 = (R'_{sig} C_{in})^{-1}$$

$$C_{in} = C_{gs} + (1 + g_m R_L')C_{gd}$$

$$\omega_2 = (R_L' C_{gd})^{-1}$$

But note "A" is varying with frequency too!

High-frequency roll-off



(a)

Mid-band:

$v_o = v_{ds} = -g_m R_L' v_{gs}$

<u>Find the effect of C_{gd}</u>

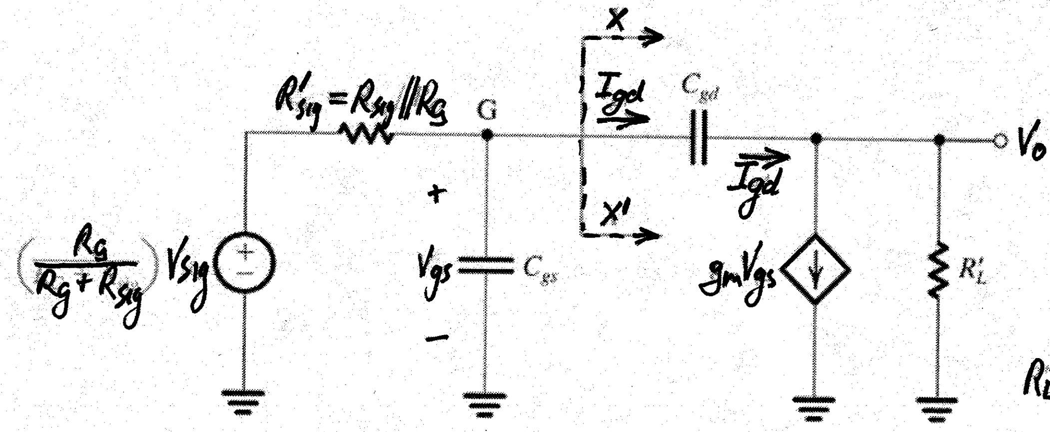
$I_{gd} = sC_{gd}(V_{gs} - V_o)$

$= sC_{gd}V_{gs}(1-(-g_m R_L')$

using the mid-band gain

$= sC_{gd}(1+g_m R_L')V_{gs}$

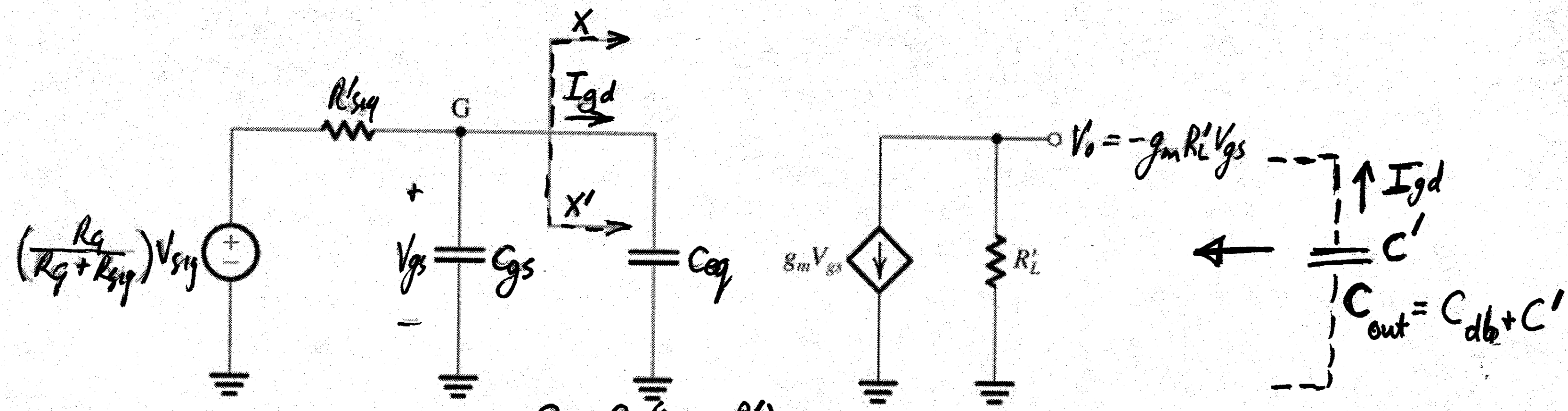
$= s\,C_{eq}\,V_{gs}$



$R_L' = r_o \| R_D \| R_L$

(b)

Figure 4.50 Determining the high-frequency response of the CS amplifier: **(a)** equivalent circuit; **(b)** the circuit of (a) simplified at the input and the output;



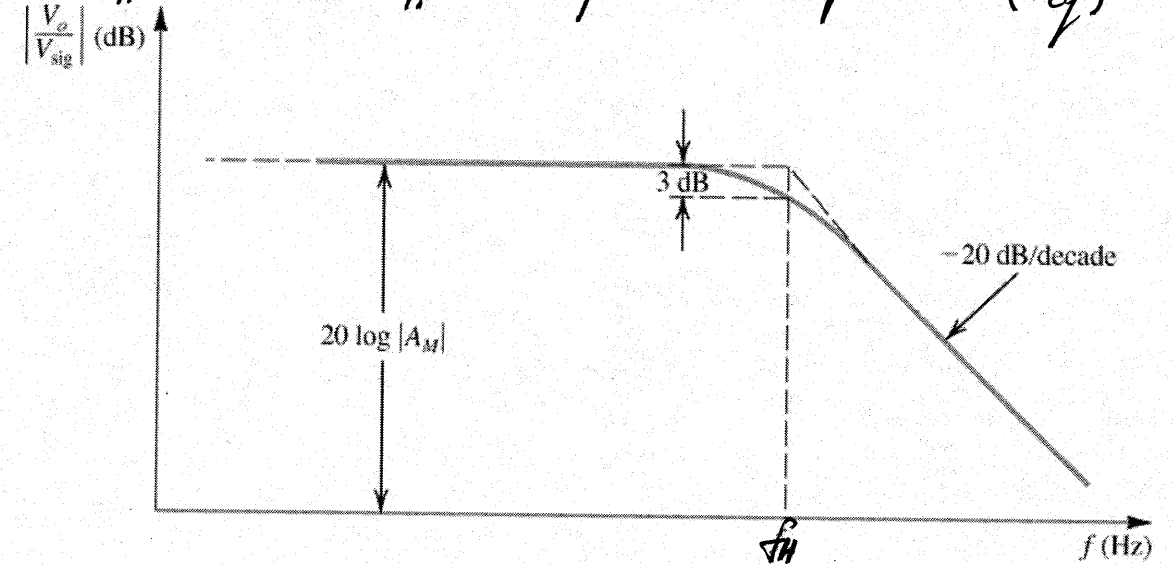
$$C_{eq} = C_{gd}(1 + g_m R'_L)$$

$$C_{in} = C_{gs} + C_{eq}$$

This is effectively the Miller capacitance (C_{eq})

(c)

$$\frac{V_o}{V_{sig}} = -\frac{R_G}{R_G+R_{sig}}\, g_m R'_L \,\frac{1}{1 + s/\omega_H}$$



$$= \frac{1}{2\pi R'_{sig} C_{in}}$$

(d)

Figure 4.50 *(Continued)* **(c)** the equivalent circuit with C_{gd} replaced at the input side with the equivalent capacitance C_{eq}; **(d)** the frequency response plot, which is that of a low-pass single-time-constant circuit.

Could add the second Miller capacitance easily

$$I_{gd} = sC_{gd}(1+g_m R'_L)V_{gs}$$

$$= -sC' V_o$$

$$= sC_{gd}(V_{gs} - V_o)$$

$$= -sC_{gd}\left(V_o - \left(\frac{-V_o}{g_m R'_L}\right)\right)$$

$$= -sV_o\left(1 + \frac{1}{g_m R'_L}\right)C_{gd}$$

$$\therefore C' = C_{gd}\left(1 + \frac{1}{g_m R'_L}\right)$$

$$\approx C_{gd}$$

as expected from the Miller formula.

Exercise 4.38

Exercise 4.39

Low Frequency Response

$$V_g = \frac{R_g}{R_g + R_{sig} + \frac{1}{sC_{c1}}} V_{sig}$$

$$\frac{V_g}{V_{sig}} = \frac{R_g}{R_g + R_{sig}} \frac{1}{1 + \frac{1}{sC_{c1}(R_g + R_{sig})}}$$

$$\therefore \omega_{p1} = \frac{1}{sC_{c1}(R_g + R_{sig})}$$

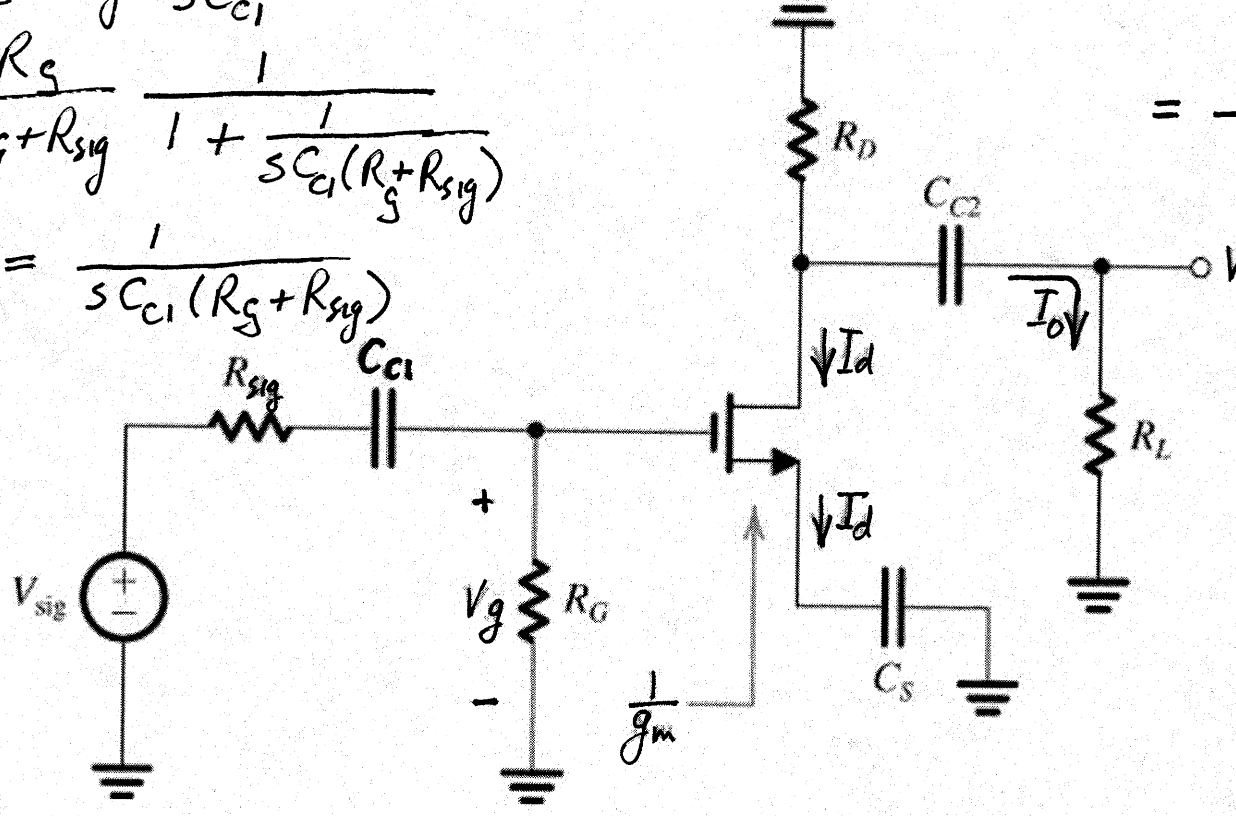
$$I_o = \frac{R_D}{R_D + R_L + \frac{1}{sC_{c2}}}(-I_D)$$

by current division

$$V_o = I_o R_L = -\frac{R_D R_L}{R_D + R_L + \frac{1}{sC_{c2}}} I_D$$

$$= -\left(\frac{R_D R_L}{R_D + R_L}\right) \frac{I_D}{1 + \frac{1}{sC_{c2}(R_D + R_L)}}$$

$$\therefore \omega_{p3} = \frac{1}{(R_D + R_L)C_{c2}}$$



From the T-equivalent circuit: $I_d = \dfrac{V_g}{1/g_m + 1/sC_s} = \dfrac{g_m V_g}{1 + \frac{1}{sC_s(\frac{1}{g_m})}}$

$$\therefore \omega_{p2} = g_m / C_s$$

Figure 4.51 Analysis of the CS amplifier to determine its low-frequency transfer function. For simplicity, r_o is neglected.

$$\frac{V_o}{V_{sig}} = -\frac{R_g}{R_g + R_{sig}}\, g_m (R_D \| R_L)\, \frac{s}{s+\omega_{p1}} \cdot \frac{s}{s+\omega_{p2}} \cdot \frac{s}{s+\omega_{p3}}$$

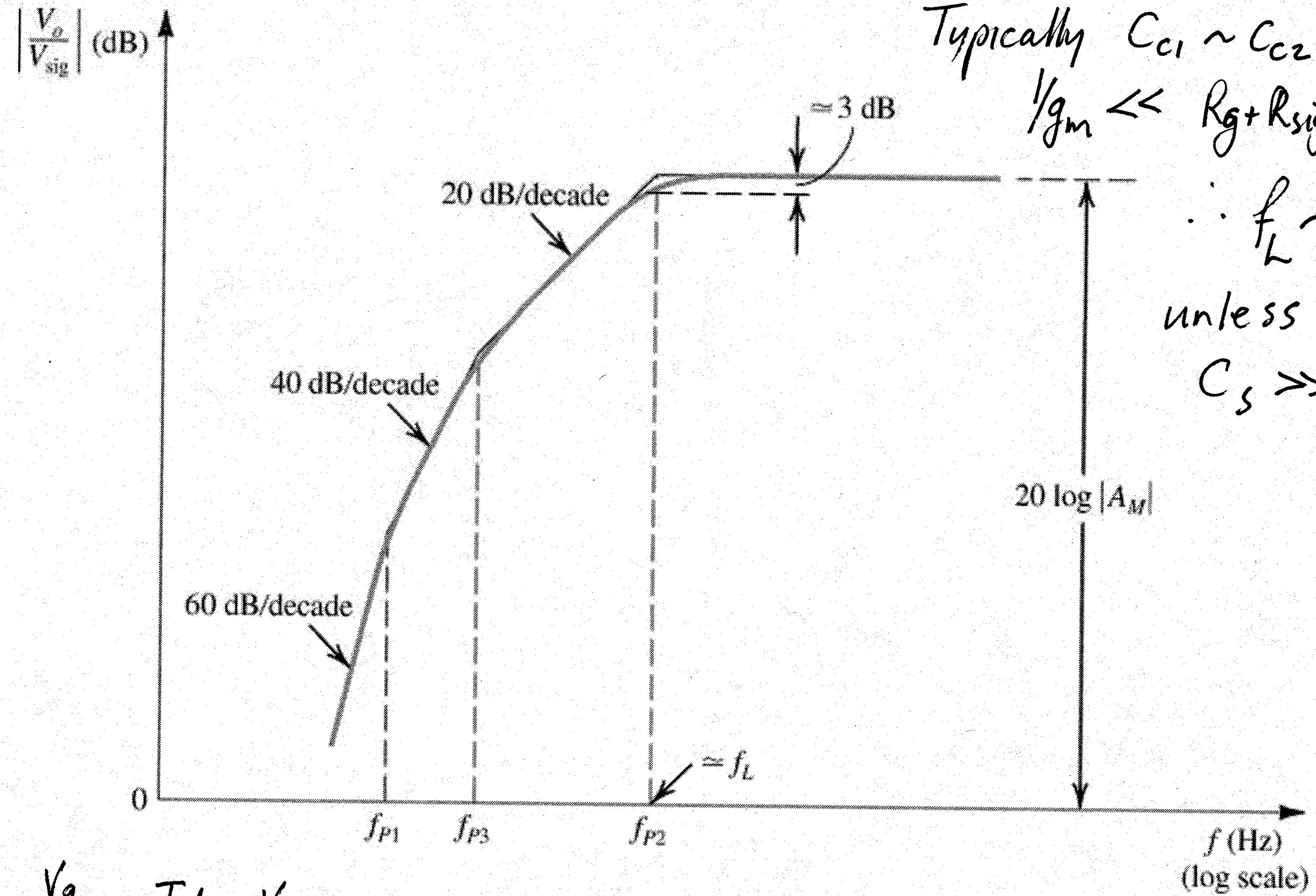
Typically $C_{C1} \sim C_{C2}$ and

$1/g_m \ll R_g + R_{sig},\ R_L + R_D$

$\therefore f_L \sim f_{p2}$

unless

$C_S \gg C_{C1}, C_{C2}$



$$\frac{V_o}{V_{sig}} = \frac{V_g}{V_{sig}} \cdot \frac{I_d}{V_g} \cdot \frac{V_o}{I_d}$$

1 2 3

Figure 4.52 Sketch of the low-frequency magnitude response of a CS amplifier for which the three break frequencies are sufficiently separated for their effects to appear distinct.

Exercise 4.40

Assignment #8

*5.156

5.159 & 5.160

4.92 & 4.93

4.101 & 4.102

Ex 4.36 n-channel MOSFET $t_{ox} = 10nm$ $L = 1.0\mu m$ $W = 10\mu m$

$L_{ov} = 0.05\mu m$ $C_{sb0} = C_{db0} = 10fF$

$V_{SB} = 1V$ $V_{DS} = 2V$

$\uparrow V_{DB}?$

Calculate C_{ox}, C_{ov}, C_{gs}, C_{gd}, C_{sb}, C_{db}

Ex 4.37 Calculate f_T for MOSFET above, operating at $100\mu A$

with $k_n' = 160\mu A/V^2$

Ex 4.36

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.45\times10^{-11}\ F/m}{10\times10^{-9}\ m} = 3.45\times10^{-3}\ F/m^2$$

$$= 3.45\ fF/\mu m^2$$

$$C_{ov} = W L_{ov} \cdot C_{ox} = 10\mu m \times .05\mu m \times 3.45\ fF/\mu m^2$$

$$= 1.725\ fF$$

$$C_{gs} = \frac{2}{3} W L C_{ox} + C_{ov} = \frac{2}{3} \cdot 10\mu m\ 1\mu m\ 3.45\ fF/\mu m^2 + 1.725\ fF$$

$$= 23 + 1.725 = 24.725\ fF$$

$$C_{gd} = C_{ov} = 1.725\ fF$$

Note
$V_0 \sim 0.6v$
typ.

$$C_{sb} = \frac{C_{sb0}}{\sqrt{1 + \frac{V_{SB}}{V_0}}} = \frac{10\ fF}{(1 + 1/.6)^{1/2}} = 6.1\ fF$$

$$C_{db} = \frac{C_{db0}}{\sqrt{1 + \frac{V_{DB}}{V_0}}} = \frac{10\ fF}{\left(1 + \frac{2}{.6}\right)^{1/2}} = 4.1\ fF$$

4.37 $$f_T = \frac{g_m}{2\pi(C_{gs}+C_{gd})}$$

$$\frac{W}{L} = \frac{10\,\mu m}{1\,\mu m} = 10$$

$$g_m = \sqrt{2k_n' \frac{W}{L} I_D} = \left(2\times 160\times 10^{-6}\times 10\times 100\times 10^{-6}\right)^{1/2}$$

$$= \sqrt{2}\; 4\; 10^{-4} = 0.5656\times 10^{-3}$$

$$= 565.6\,\mu A/V$$

$$\therefore f_T = \frac{565.6\times 10^{-6}}{2\pi(24.725+1.725)10^{-15}} = \frac{565.6}{2\pi\; 26.45}10^{9}$$

$$= 3.4\ GHz$$ (3.7 GHz in book because uses $W/L = 12$)

Ex 4.38 For CS amplifier of Example 4.12, find A_M & f_H when R_{sig} reduced from 100KΩ to 10KΩ.

$R_G = 4.7M\Omega$ $R_D = R_L = 15K\Omega$ $g_m = 1mA/V$ $r_o = 150K\Omega$

$C_{gs} = 1pF$ $C_{gd} = 0.4pF$

Ex 4.39 For same C_{gs} but smaller C_{gd}, what is max C_{gd} for $f_H \geq 1MHz$? ($R_{sig} = 100K\Omega$)

Ex 4.38 $A_M = -\frac{R_g}{R_g + R_{sig}} \underset{\uparrow}{g_m} \underset{\uparrow}{R_L'}$

From Example 4.12 $\quad 1\,mA/V \quad 7.14\,K\Omega$

$r_o \| R_L \| R_D$

$$= -\frac{4.7 \times 10^6}{4.7 \times 10^6 + 10 \times 10^3} \times 10^{-3} \times 7.14 \times 10^3$$

$$= -7.14 \frac{4.7}{4.71} = -7.12$$

(compare -7 for $R_{sig} = 100K$)

$$f_H = \frac{1}{2\pi C_{in} (R_{sig} \| R_g)}$$

$C_{in} = C_{gs} + (1 + g_m R_L') C_{gd}$
$= 4.26\,pF$
(unchanged from Example 4.12)

$$= \frac{1}{2\pi\ 4.26 \times 10^{-12} \frac{10 \times 4700}{4710} 10^3}$$

$$= 3.7\,MHz.$$

Ex 4.39 For $f_H \geq 1MHz$.

$$f_H = \frac{1}{2\pi\, C_{in}\, (R_{sig} \| R_g)}$$

$$= \frac{1}{2\pi\,(\underset{\uparrow\ 1pF}{C_{gs}} + C_{eq})\,\underset{\uparrow\ 98K\Omega}{\frac{(.1)(4.7)}{4.8}} \times 10^6}$$

0.98

$$C_{eq} = (1 + g_m R_L')\, C_{gd}$$
$$= (1 + 10^{-3} \times 7.14 \times 10^3)\, C_{gd}$$
$$= 8.14\, C_{gd}$$
$$= 8.14\, C_{gd}'\ pF$$

$$\therefore \frac{1}{2\pi\ 98\ 10^3\ 10^{-12}(1 + 8.14\, C_{gd}')} \geq 10^6$$

$$C_{gd}' \leq \left(\frac{10^3}{2\pi\ 98} - 1\right)/8.14$$

$$\leq 0.077\, pF = 77\, fF$$

Ex 4.40 CS amplifier $C_{C1} = C_{C2} = C_S = 1\mu F$

$R_G = 10M\Omega$ $R_{sig} = 100K\Omega$

$R_L = R_D = 10K\Omega$ $g_m = 2mA/V$

Find A_M, f_{P1}, f_{P2}, f_{P3}, f_L

Ex. 4.40

$$A_M = -\frac{R_G}{R_G+R_{sig}} \cdot g_m \left(R_L \| R_D\right)$$

$$= -\frac{10M}{10M+.1M}\, 2\times10^{-3}\, \frac{10\times10}{10+10} 10^3$$

$$= -\frac{10}{10.1} \times \cancel{2}\, \frac{\cancel{100}^{\,10}}{\cancel{20}\ \cancel{10}}\, 10^{-3}\, \cancel{10^3} = -9.9$$

$$f_{p1} = \frac{1}{2\pi C_{C1}\left(R_G+R_{sig}\right)} = \frac{1}{2\pi\, 10^{-6}\, 10.1\times10^{6}} = \frac{1}{20\cdot 2\pi} = 0.016\ Hz$$

$$f_{p2} = \frac{g_m}{2\pi C_S} = \frac{2\times10^{-3}}{2\pi\, 10^{-6}} = \frac{10^3}{\pi} = 318.3\ Hz.$$

$$f_{p3} = \frac{1}{2\pi C_{C2}\left(R_L+R_D\right)} = \frac{1}{2\pi\, 10^{-6}\, 20\times10^{3}} = \frac{10^2}{4\pi} = 7.96\ Hz.$$

$$\therefore f_L \approx f_{p2} = 318.3\ Hz.$$