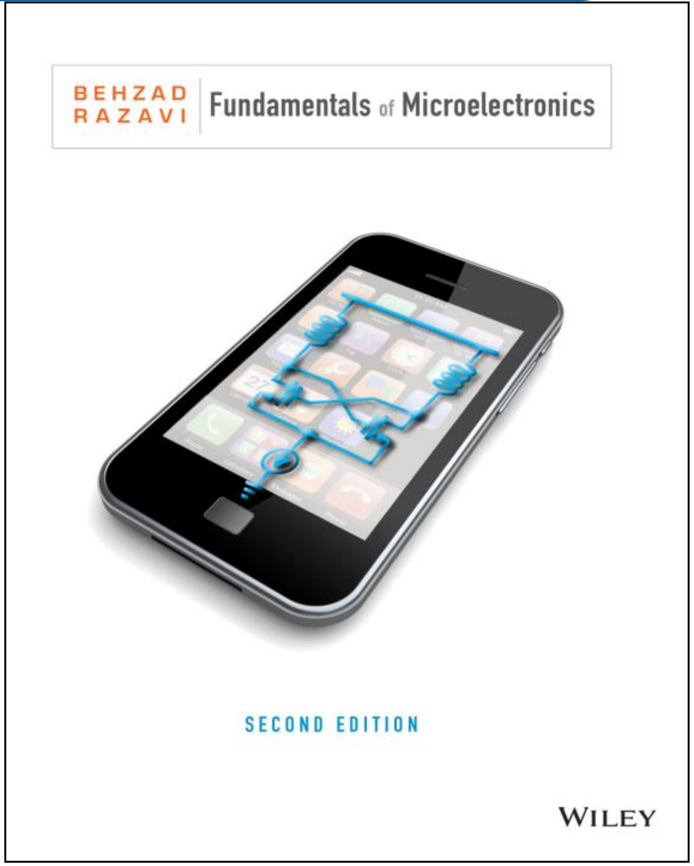
Frequency Response

- Fundamental Concepts
- High-Frequency Models of Transistors
- Analysis Procedure
- Frequency Response of CS Stages
- Frequency Response of CG Stages
- Frequency Response of Followers
- Frequency Response of Cascode Stage
- Frequency Response of Differential Pairs
- Additional Examples



Ref books:
Behzad Razavi, "Fundamentals of Microelectronics, 2nd Edition", Chapter 11
Behzad Razavi, "Design of Analog CMOS Integrated Circuits, 2nd Edition", Chapter 6

Outline

Fundamental Concepts

- Bode's Rules
- Association of Poles with Nodes
- Miller's Theorem

→

High-Frequency Models of Transistors

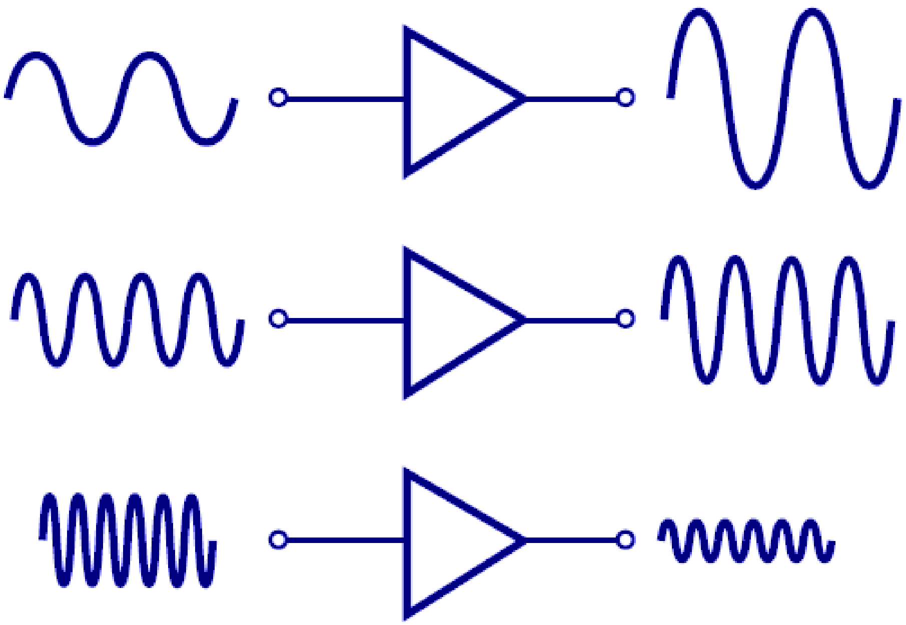
- MOS Model
- Transit Frequency

→

Frequency Response of Circuits

- CS Stages
- CG Stages
- Followers
- Cascode Stage
- Differential Pair

High Frequency Roll-off of Amplifier



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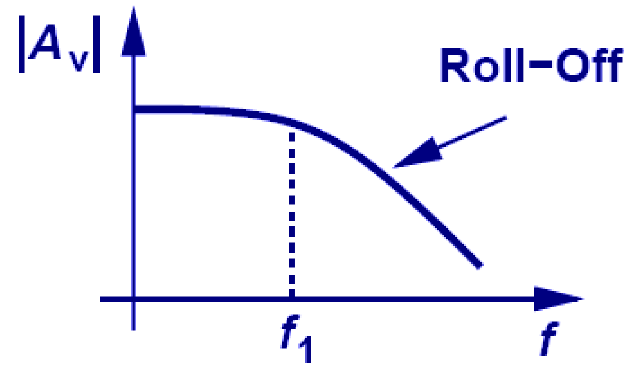
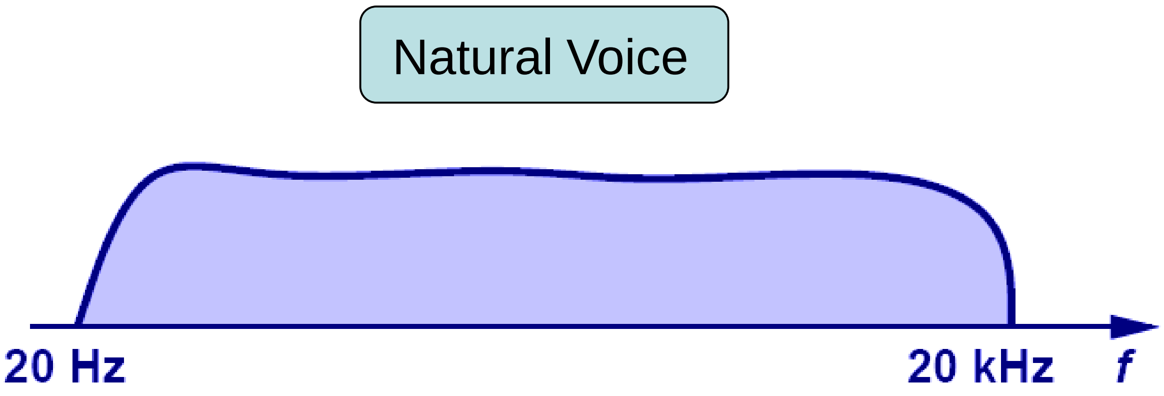


(b)

- As frequency of operation increases, the gain of amplifier decreases. This chapter analyzes this problem.

Example: Human Voice I



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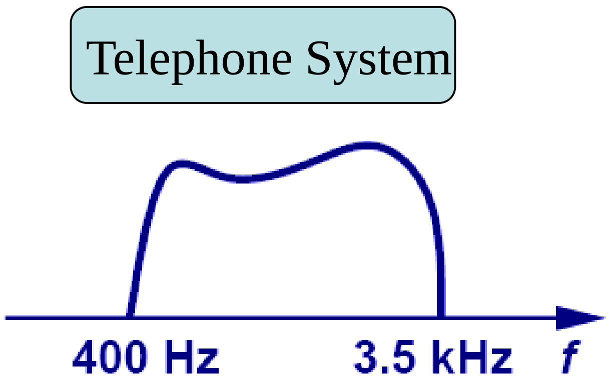
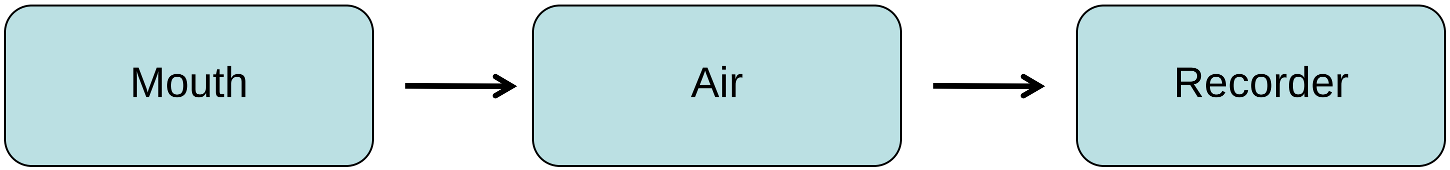


(b)

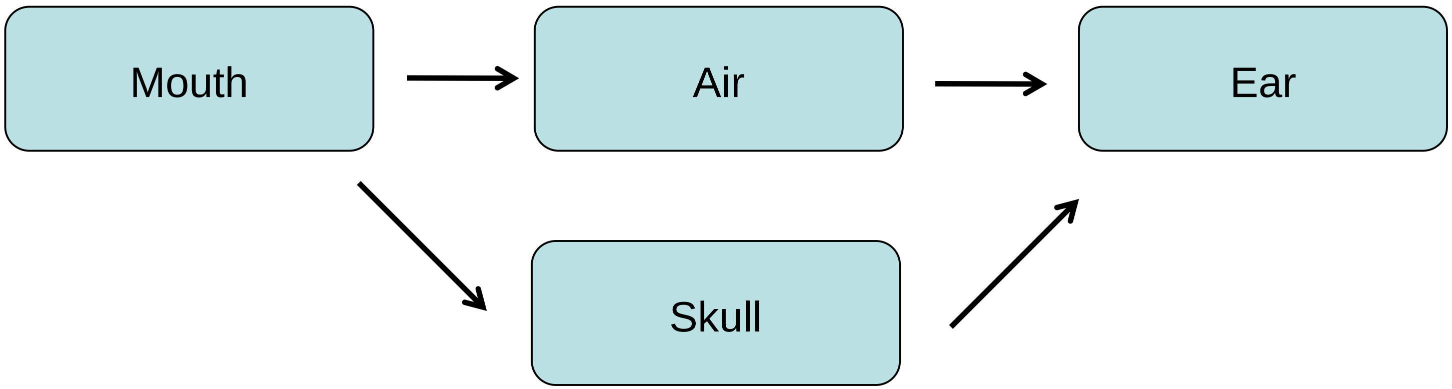
- **Natural human voice spans a frequency range from 20Hz to 20KHz, however conventional telephone system passes frequencies from 400Hz to 3.5KHz. Therefore phone conversation differs from face-to-face conversation.**

Example: Human Voice II

Path traveled by the human voice to the voice recorder

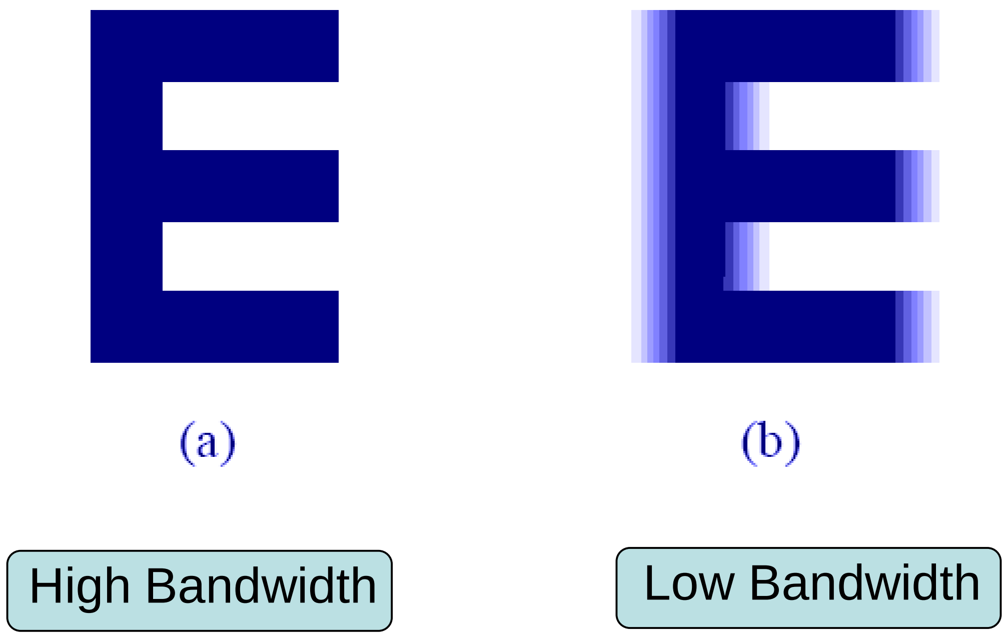


Path traveled by the human voice to the human ear



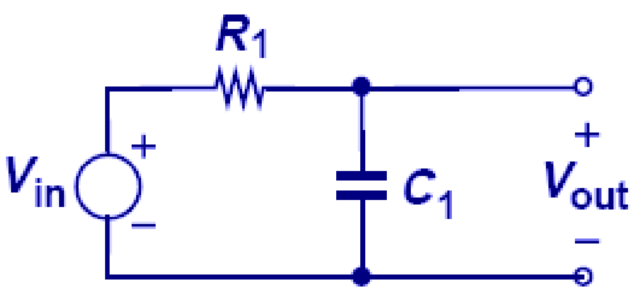
- **Since the paths are different, the results will also be different.**

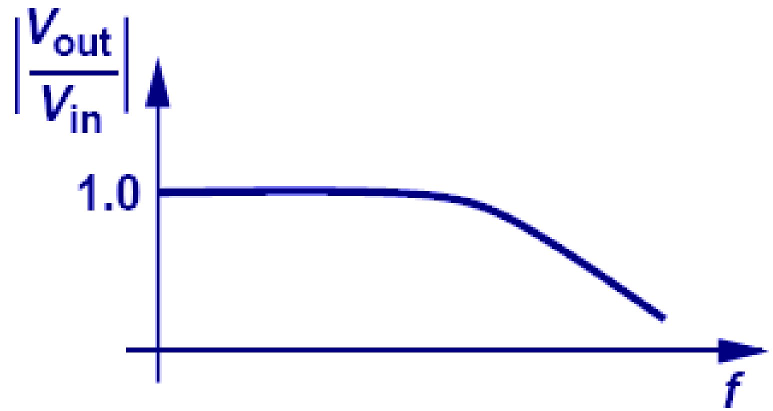
Example: Video Signal



- **Video signals without sufficient bandwidth become fuzzy as they fail to abruptly change the contrast of pictures from complete white into complete black.**

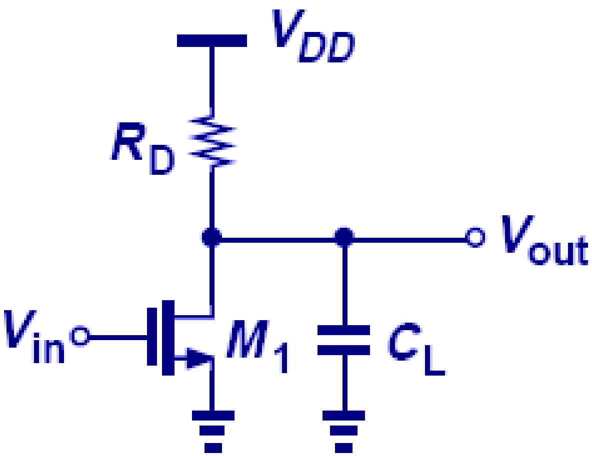
Gain Roll-off: Simple Low-pass Filter





- **In this simple example, as frequency increases the impedance of C_1 decreases and the voltage divider consists of C_1 and R_1 attenuates V_{in} to a greater extent at the output.**

Gain Roll-off: Common Source



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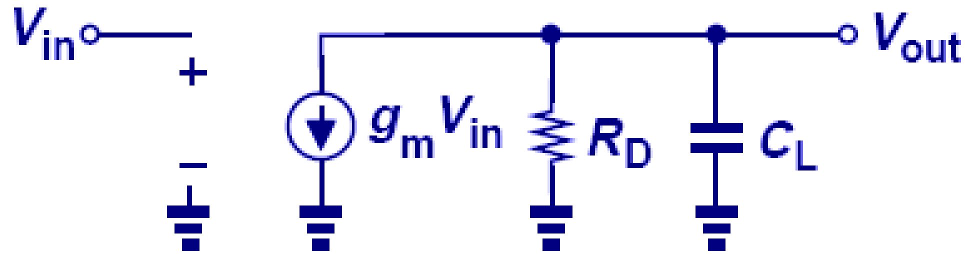
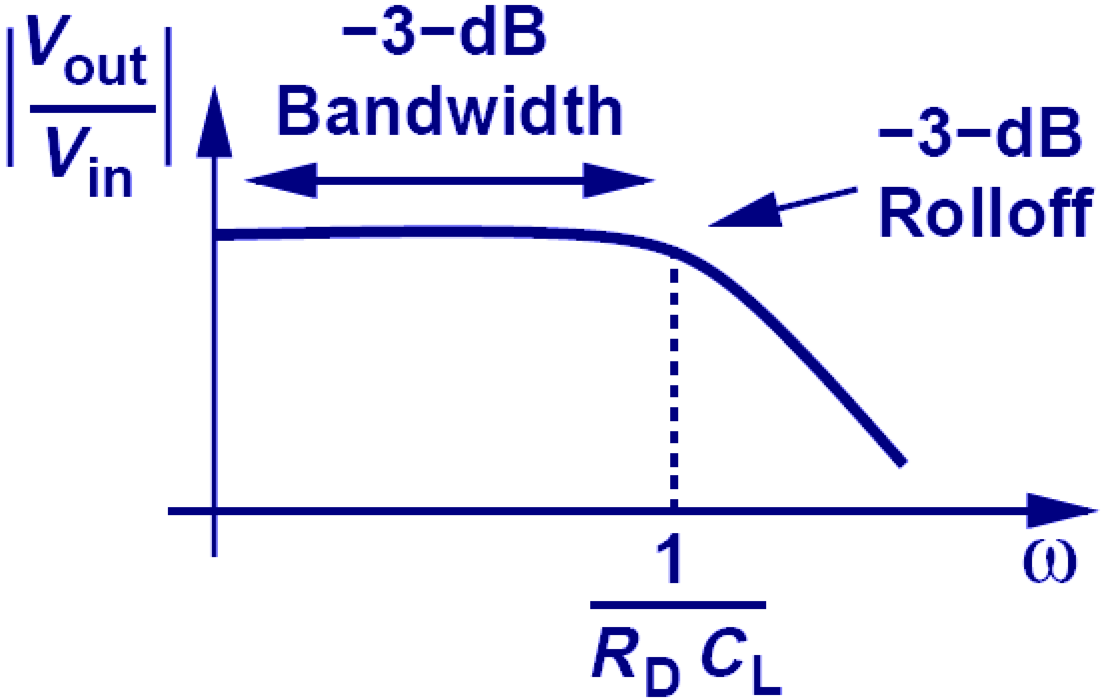


(b)

$$V_{out} = -g_m V_{in}\left(R_D \,\|\, \frac{1}{C_L s}\right)$$

- **The capacitive load, C_L, is the culprit for gain roll-off since at high frequency, it will "steal" away some signal current and shunt it to ground.**

Frequency Response of the CS Stage



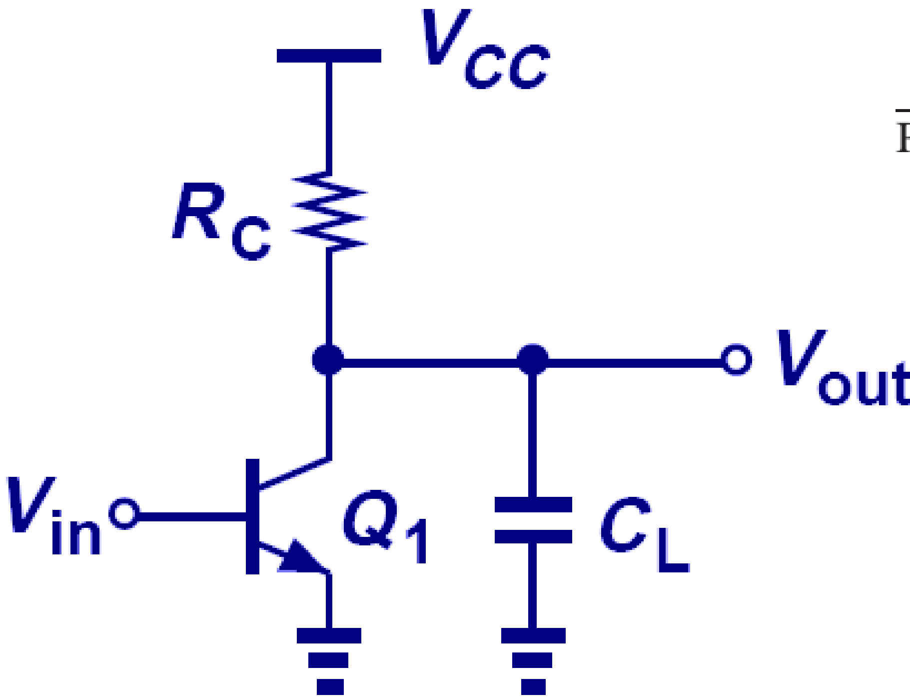
$$\left|\frac{V_{out}}{V_{in}}\right| = \frac{g_m R_D}{\sqrt{R_D^2 C_L^2 \omega^2 + 1}}$$

$\omega = 1/(R_D C_L)$ $\quad \left|\frac{V_{out}}{V_{in}}\right| = \frac{g_m R_D}{\sqrt{2}}$

$20\log(1/\sqrt{2}) = -3dB$

- **At low frequency, the capacitor is effectively open and the gain is flat. As frequency increases, the capacitor tends to a short and the gain starts to decrease. A special frequency is $\omega=1/(R_D C_L)$, where the gain drops by 3dB.**

Example: Figure of Merit



$$\frac{\text{Gain} \times \text{Bandwidth}}{\text{Power Consumption}} = \frac{\frac{I_C}{V_T} R_C \times \frac{1}{R_C C_L}}{I_C \cdot V_{CC}}$$

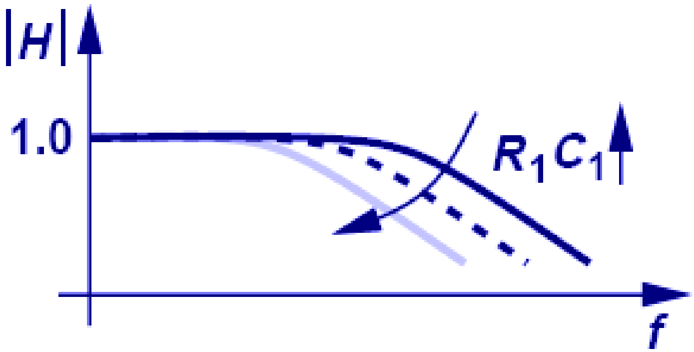
$$= \frac{1}{V_T \cdot V_{CC}} \frac{1}{C_L}.$$

$$\boxed{F.O.M. = \frac{1}{V_T V_{CC} C_L}}$$

$$V_T = \frac{kT}{q} = 25.8mV$$

- **This metric quantifies a circuit's gain, bandwidth, and power dissipation. In the bipolar case, low temperature, supply, and load capacitance mark a superior figure of merit.**

Example: Relationship between Frequency Response and Step Response



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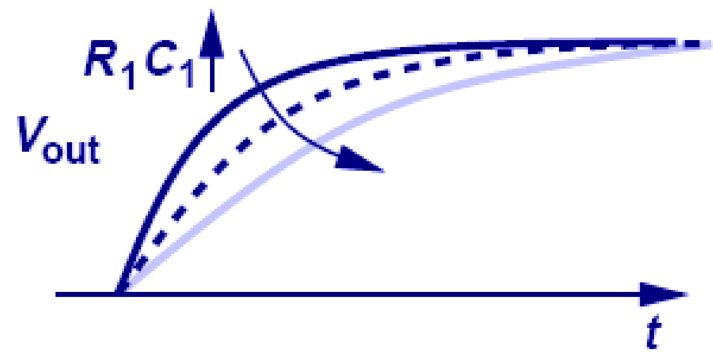


(b)

$$\left|H\left(s=j\omega\right)\right|=\frac{1}{\sqrt{R_1^2C_1^2\omega^2+1}}$$

$$V_{out}\left(t\right)=V_0\left(1-\exp\frac{-t}{R_1C_1}\right)u\left(t\right)$$

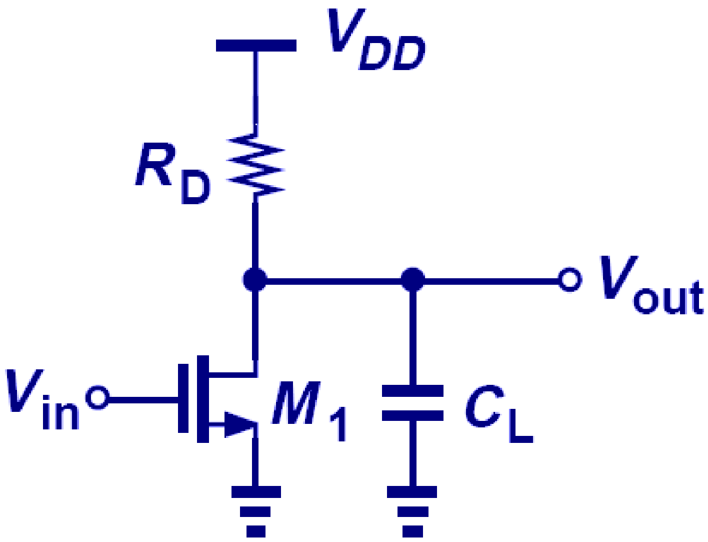
- **The relationship is such that as R_1C_1 increases, the bandwidth *drops* and the step response becomes *slower.***

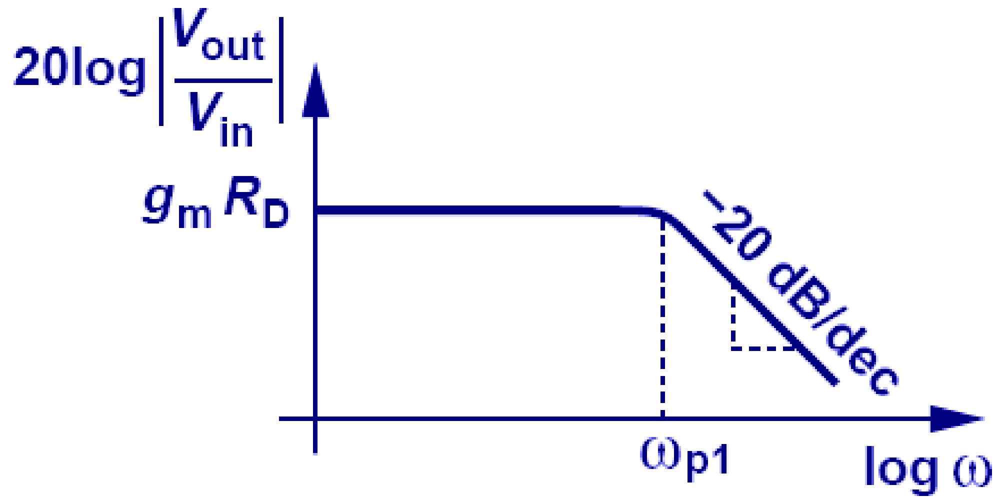
Bode Plot

$$H(s) = A_0 \frac{\left(1+\frac{s}{\omega_{z1}}\right)\left(1+\frac{s}{\omega_{z2}}\right)\cdots}{\left(1+\frac{s}{\omega_{p1}}\right)\left(1+\frac{s}{\omega_{p2}}\right)\cdots}$$

- **When we hit a zero, ω_{zj}, the Bode magnitude rises with a slope of +20dB/dec.**
- **When we hit a pole, ω_{pj}, the Bode magnitude falls with a slope of -20dB/dec**

Example: Bode Plot

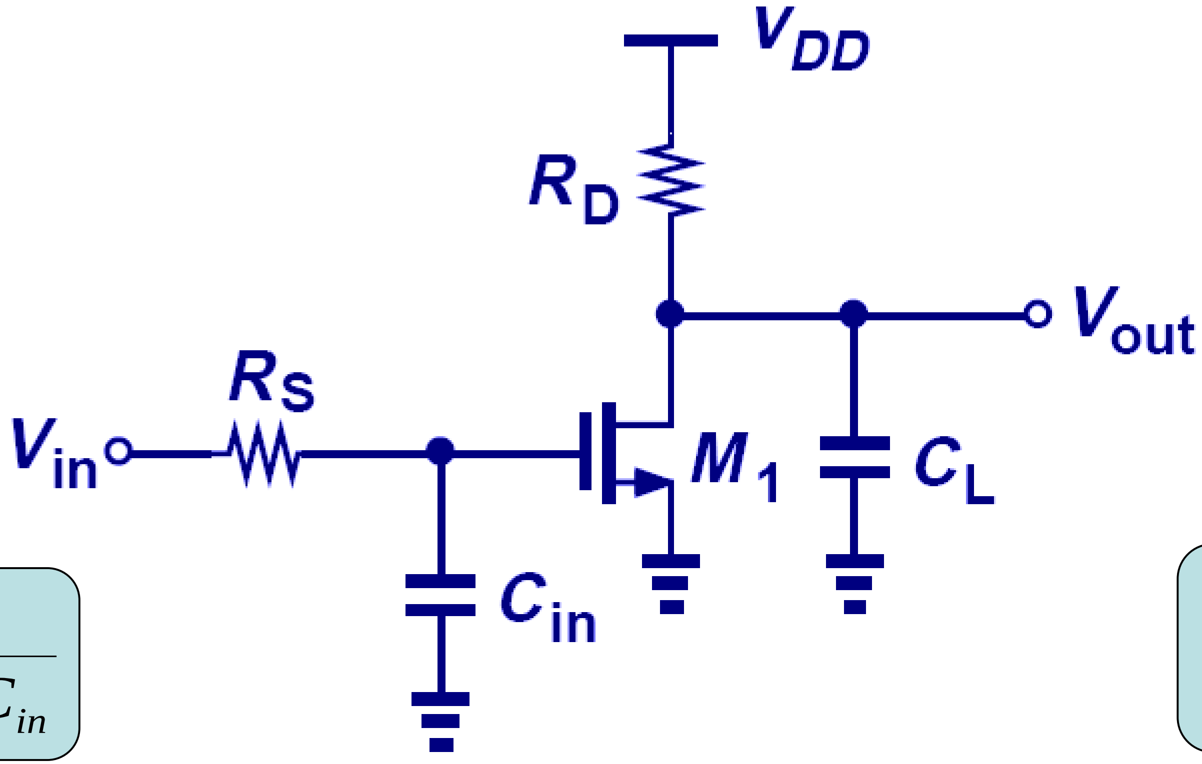




$$\left|\omega_{p1}\right| = \frac{1}{R_D C_L}$$

- **The circuit only has one pole (no zero) at 1/($R_D C_L$), so the slope drops from 0 to -20dB/dec as we pass ω_{p1}.**

Pole Identification Example I

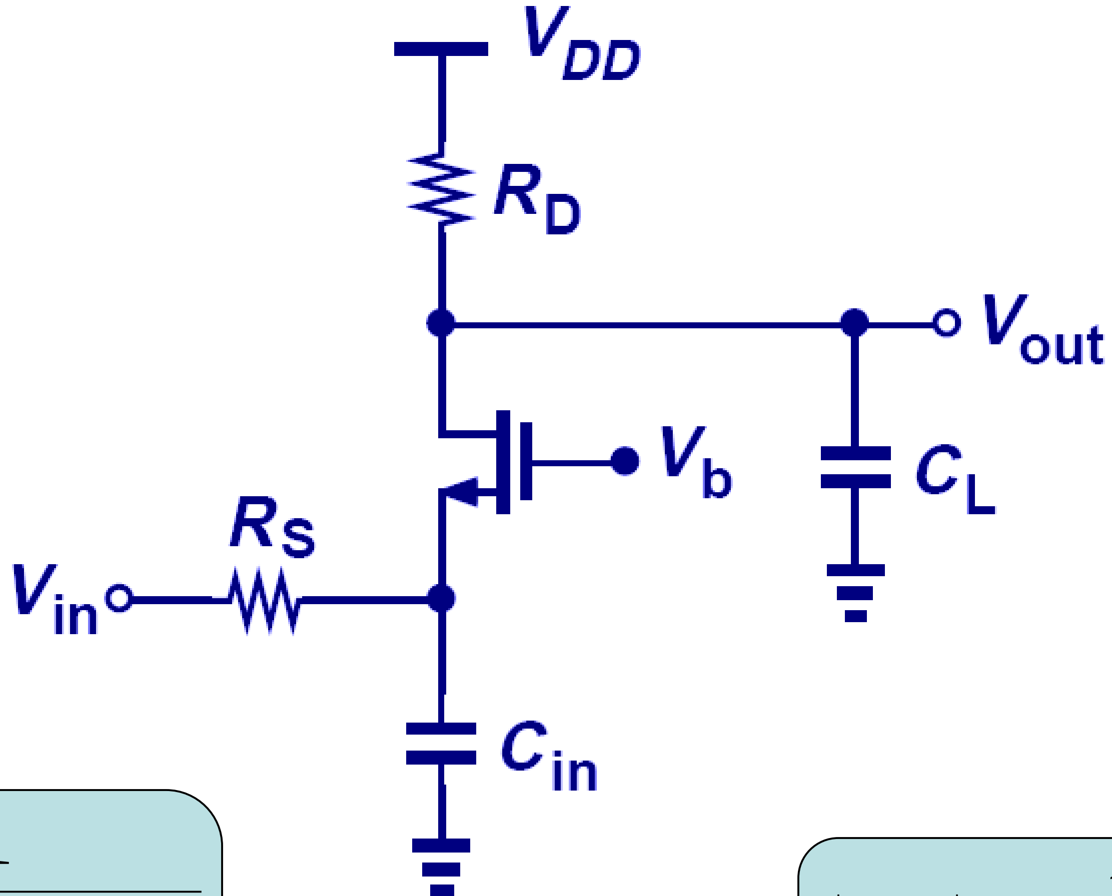


$$\left|\omega_{p1}\right| = \frac{1}{R_S C_{in}}$$

$$\left|\omega_{p2}\right| = \frac{1}{R_D C_L}$$

$$\left|\frac{V_{out}}{V_{in}}\right| = \frac{g_m R_D}{\sqrt{\left(1+\omega^2/\omega_{p1}^2\right)\left(1+\omega^2/\omega_{p2}^2\right)}}$$

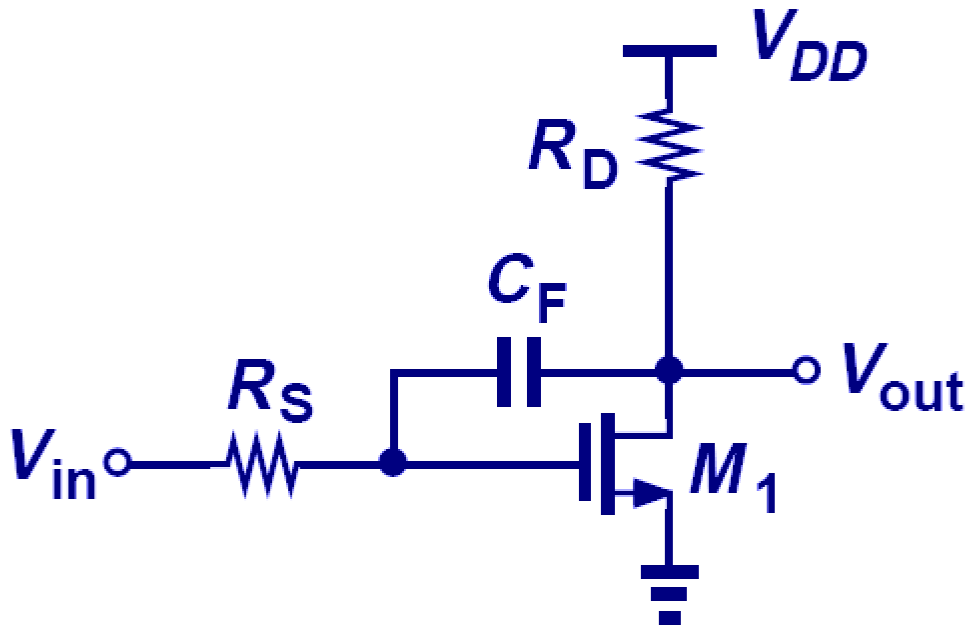
Pole Identification Example II



$$|\omega_{p1}| = \frac{1}{\left(R_S \parallel \frac{1}{g_m}\right) C_{in}}$$

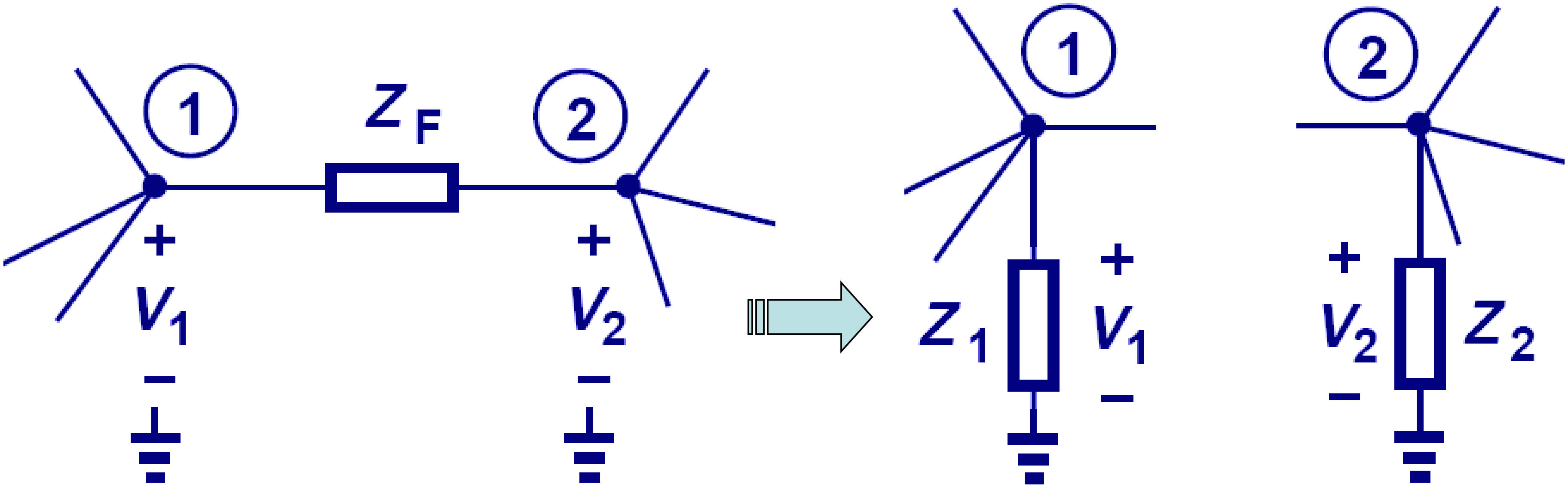
$$|\omega_{p2}| = \frac{1}{R_D C_L}$$

Circuit with Floating Capacitor



- The pole of a circuit is computed by finding the effective resistance and capacitance from a node to GROUND.
- The circuit above creates a problem since neither terminal of C_F is grounded.

Miller's Theorem



$$Z_1 = \frac{Z_F}{1 - A_v}$$

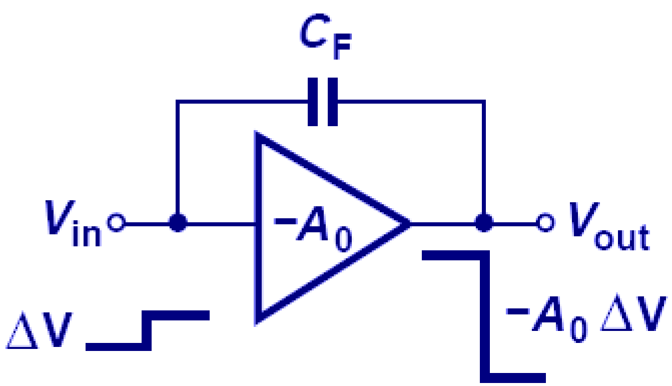
$$Z_2 = \frac{Z_F}{1 - 1/A_v}$$

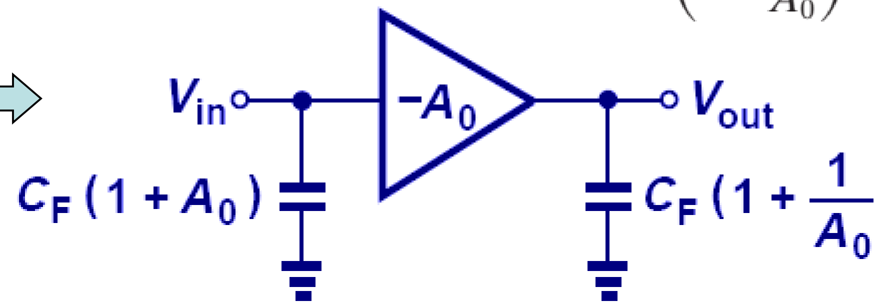
- If A_v is the gain from node 1 to 2, then a floating impedance Z_F can be converted to two grounded impedances Z_1 and Z_2.

Miller Multiplication

$$Z_1 = \frac{Z_F}{1 - A_v} = \frac{1}{(1 + A_0)C_F s}$$

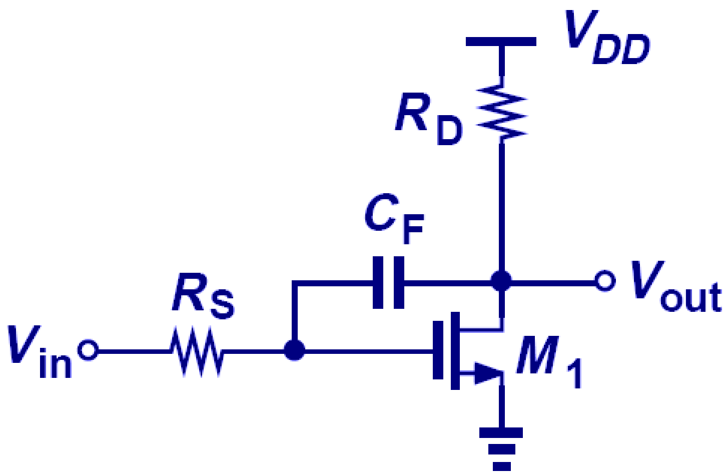
$$Z_2 = \frac{Z_F}{1 - \frac{1}{A_v}} = \frac{1}{\left(1 + \frac{1}{A_0}\right)C_F s}$$

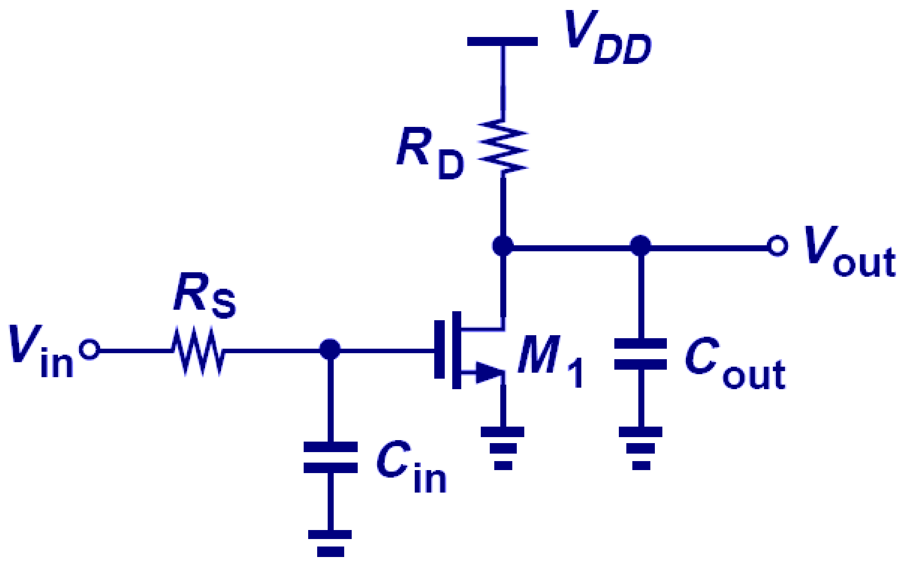




- **With Miller's theorem, we can separate the floating capacitor. However, the input capacitor is larger than the original floating capacitor. We call this Miller multiplication.**

Example: Miller Theorem

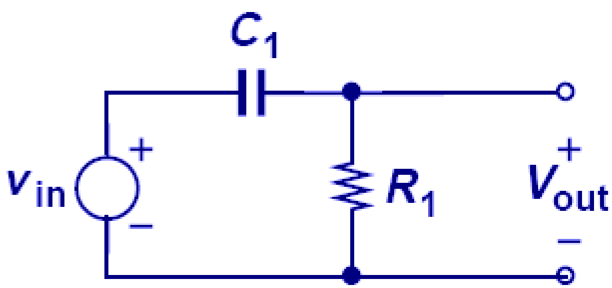


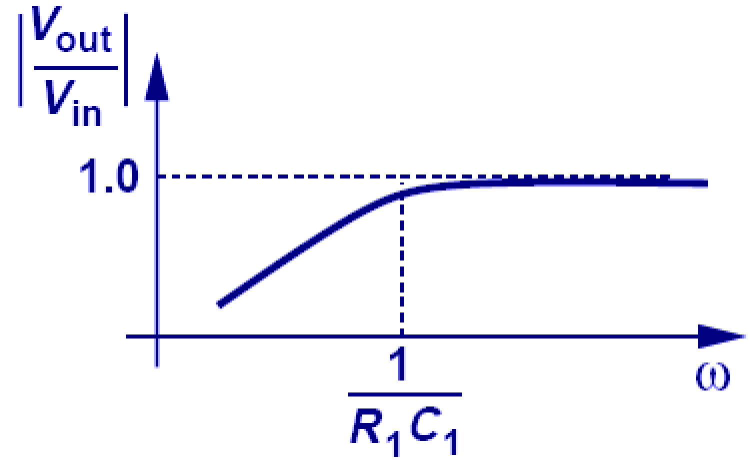


$$\omega_{in} = \frac{1}{R_S(1+g_m R_D)C_F}$$

$$\omega_{out} = \frac{1}{R_D\left(1+\dfrac{1}{g_m R_D}\right)C_F}$$

High-Pass Filter Response

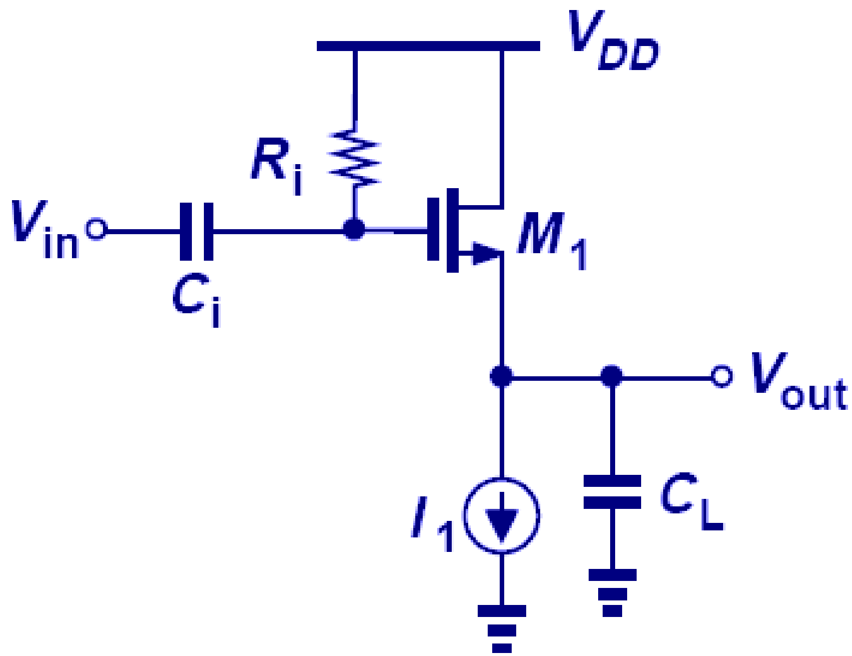




$$\left|\frac{V_{out}}{V_{in}}\right| = \frac{R_1C_1\omega}{\sqrt{R_1^2C_1^2\omega_1^2+1}}$$

- The voltage division between a resistor and a capacitor can be configured such that the gain at low frequency is reduced.

Example: Audio Amplifier



$$C_i = 79.6nF$$

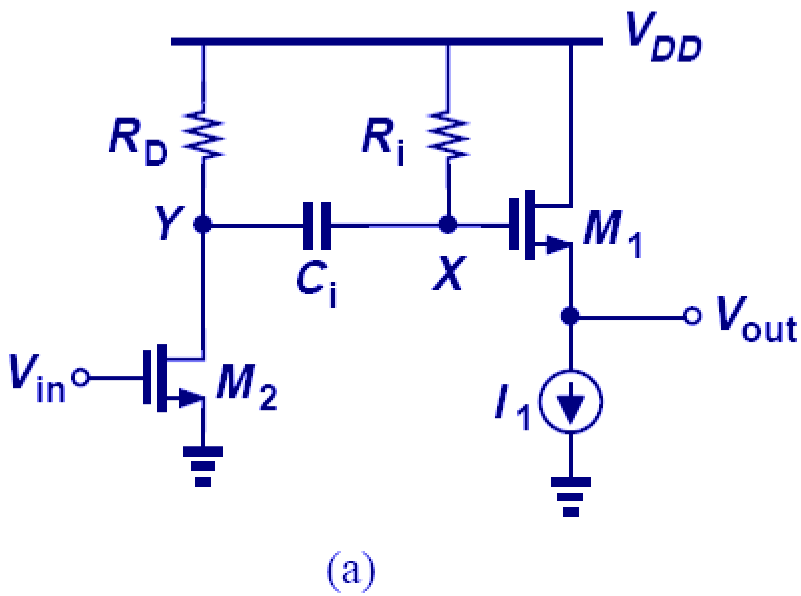
$$C_L = 39.8nF$$

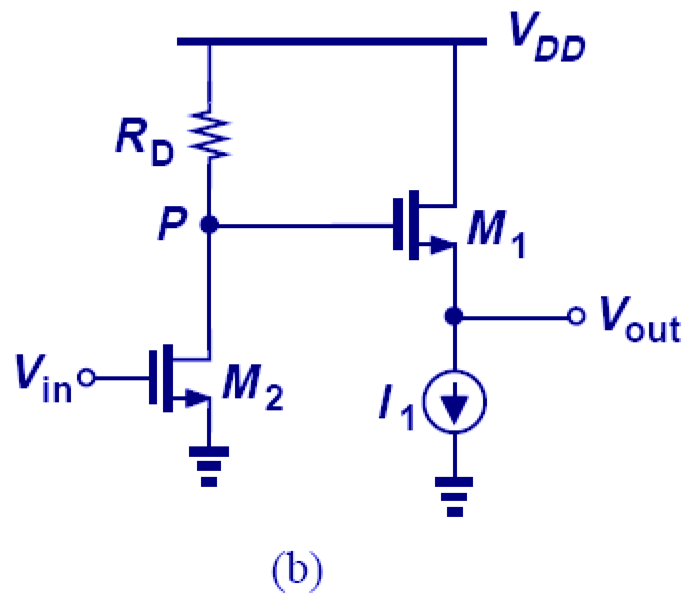
$$R_i = 100K\Omega$$

$$g_m = 1/200\Omega$$

- In order to successfully pass audio band frequencies (20 Hz-20 KHz), large input and output capacitances are needed.

Capacitive Coupling vs. Direct Coupling



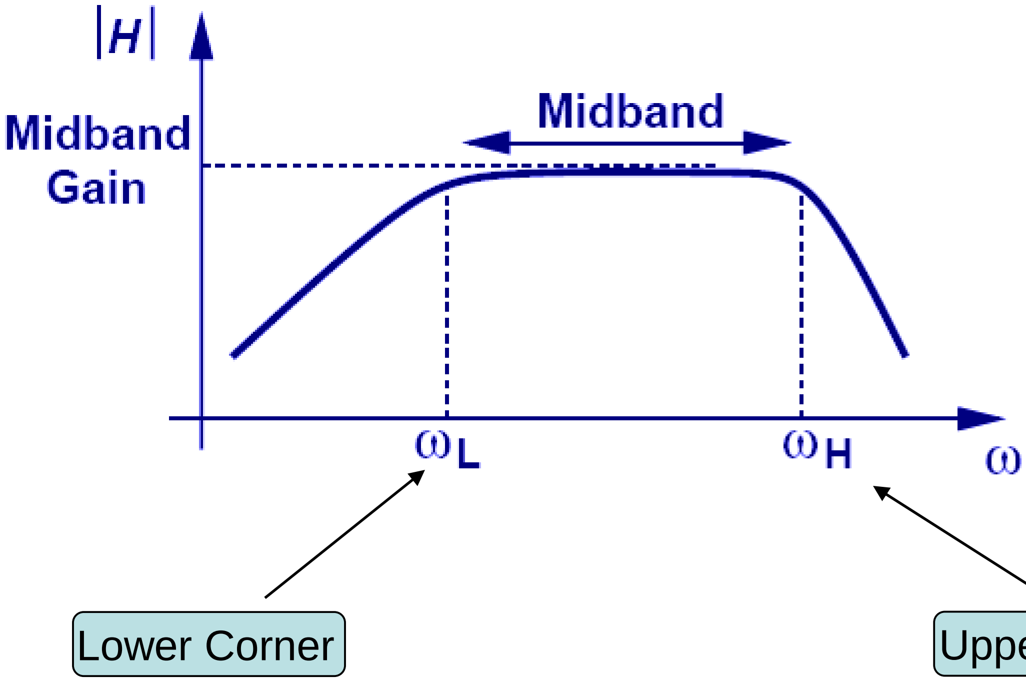


Capacitive Coupling

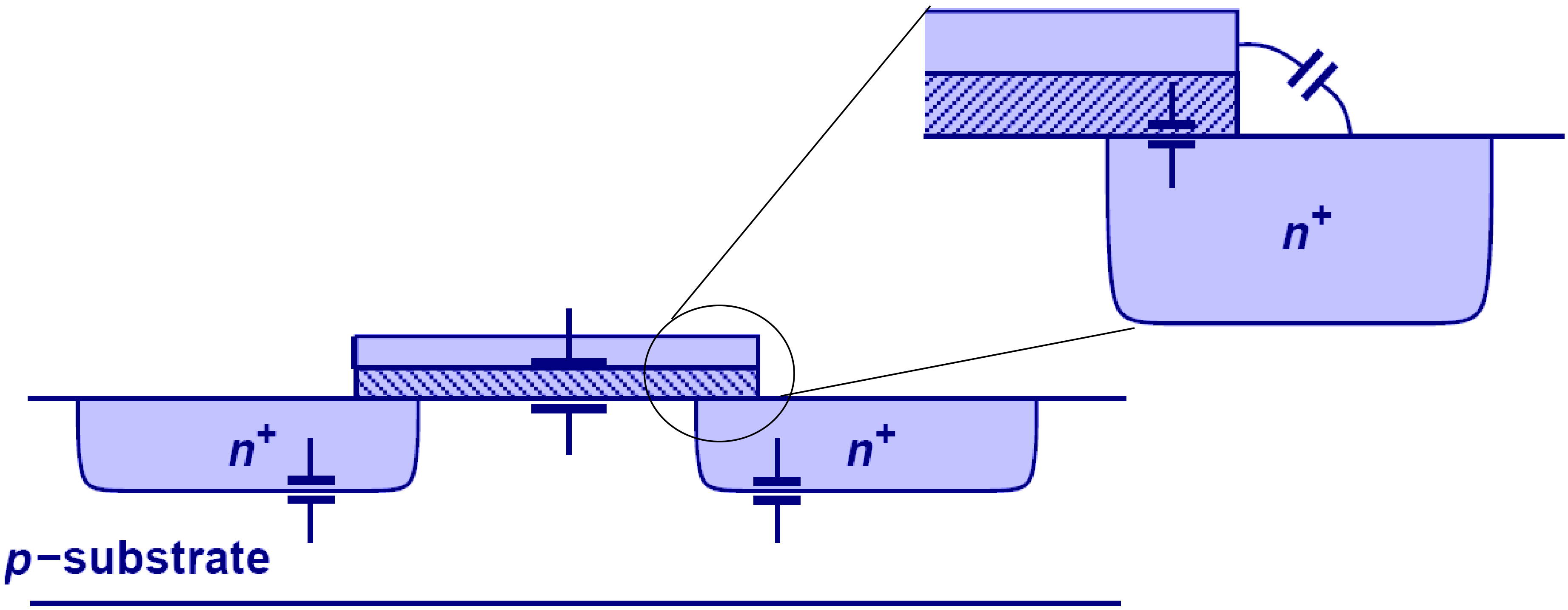
Direct Coupling

- Capacitive coupling, also known as AC coupling, passes AC signals from Y to X while blocking DC contents.
- This technique allows independent bias conditions between stages. Direct coupling does not.

Typical Frequency Response

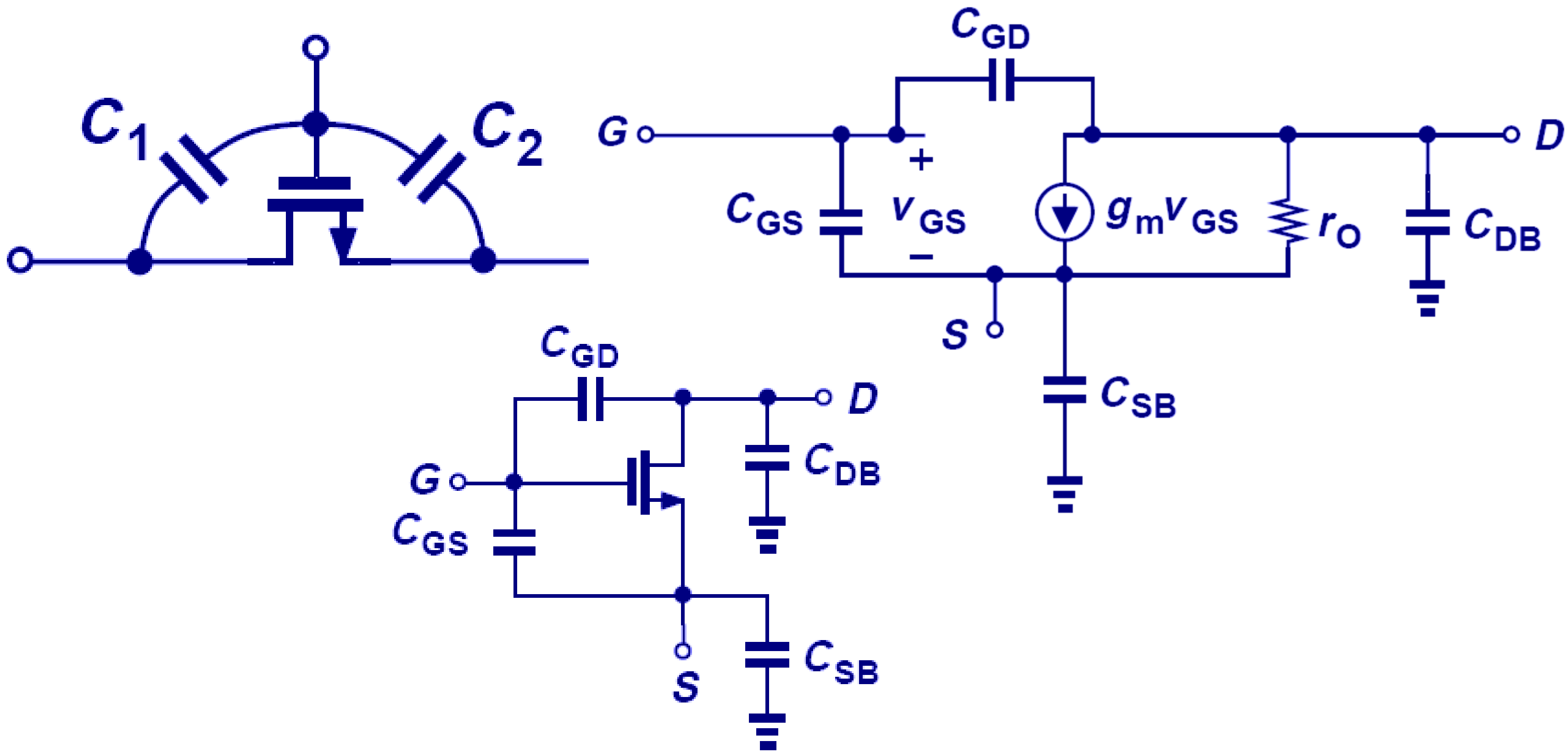


MOS Intrinsic Capacitances



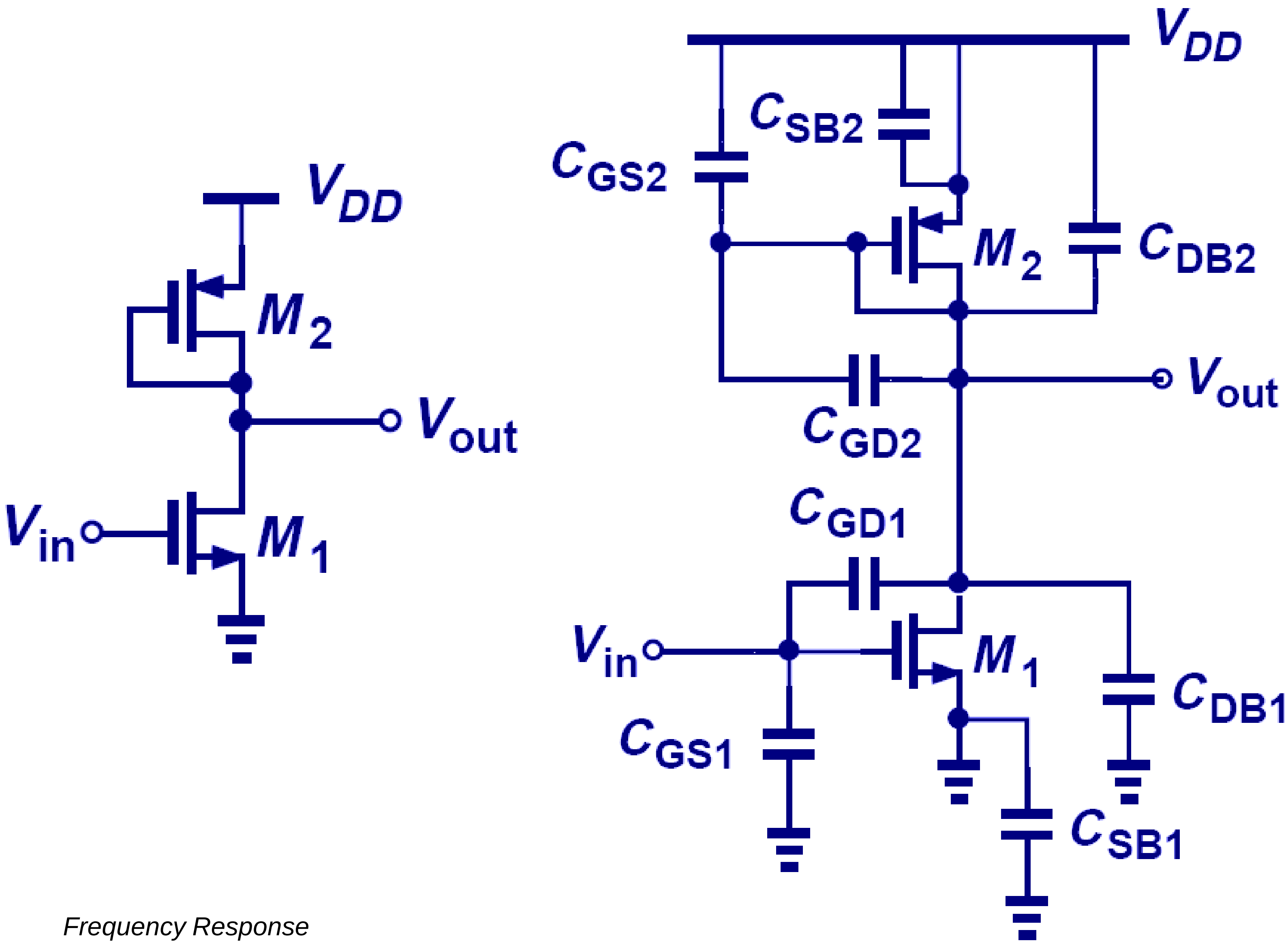
- For a MOS, there exist oxide capacitance from gate to channel, junction capacitances from source/drain to substrate, and overlap capacitance from gate to source/drain.

Gate Oxide Capacitance Partition and Full Model

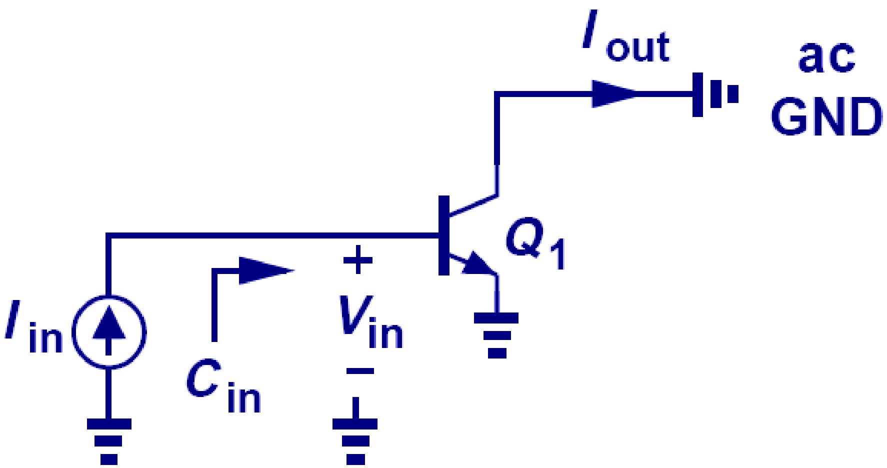


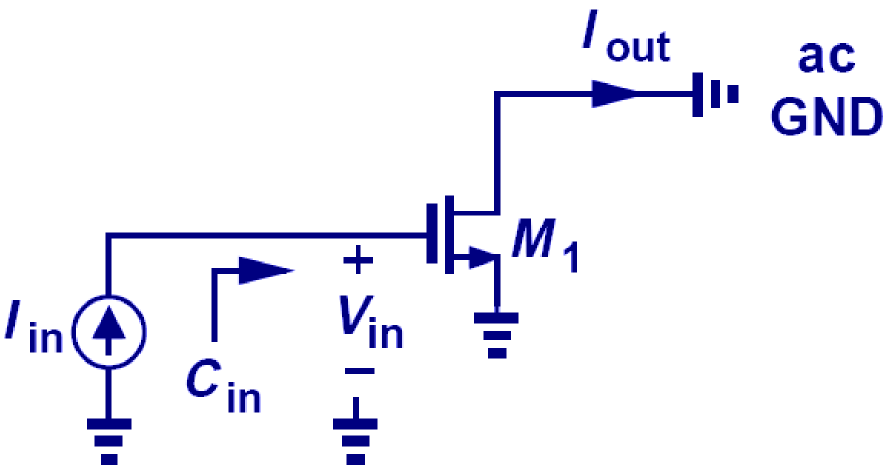
- **The gate oxide capacitance is often partitioned between source and drain. In saturation, $C_2 \sim C_{gate}$, and $C_1 \sim 0$. They are in parallel with the overlap capacitance to form C_{GS} and C_{GD}.**

Example: Capacitance Identification



Transit Frequency



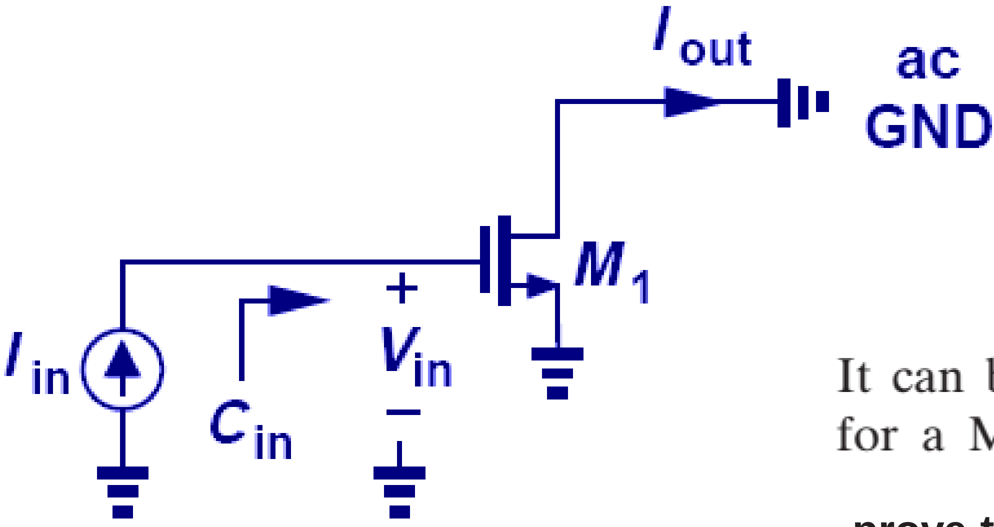


$$2\pi f_T = \frac{g_m}{C_\pi}$$

$$2\pi f_T = \frac{g_m}{C_{GS}}$$

- **Transit frequency, f_T, is defined as the frequency where the current gain from input to output drops to 1.**

Example: Transit Frequency Calculation



It can be shown that $C_{GS} \approx (2/3)WLC_{ox}$ for a MOSFET operating in saturation.

prove that:

$$2\pi f_T = \frac{3}{2}\frac{\mu_n}{L^2}\left(V_{GS} - V_{TH}\right)$$

$$L = 65nm$$
$$V_{GS} - V_{TH} = 100mV$$
$$\mu_n = 400cm^2/(V.s)$$
$$f_T = 226GHz$$

Note that f_T increases with the overdrive voltage and the $\frac{1}{L^2}$

Example: Transit Frequency Calculation

- The minimum channel length of MOSFETs has been scaled from 1 μm in the late 1980s to 65 nm today. Also, the inevitable reduction of the supply voltage has reduced the gate-source overdive voltage from about 400 mV to 100 mV. By what factor has the f_T of MOSFETs increased?

Solution:

It can be proved that $$2\pi f_T = \frac{3}{2}\frac{\mu_n}{L^2}\left(V_{GS} - V_{TH}\right)$$

Thus, the transit frequency has increased by approximately a factor of 59. For example, if μ_n = 400cm^2/(V·s), then 65 nm devices having an overdrive of 100 mV exhibit an f_T of 226 GHz.

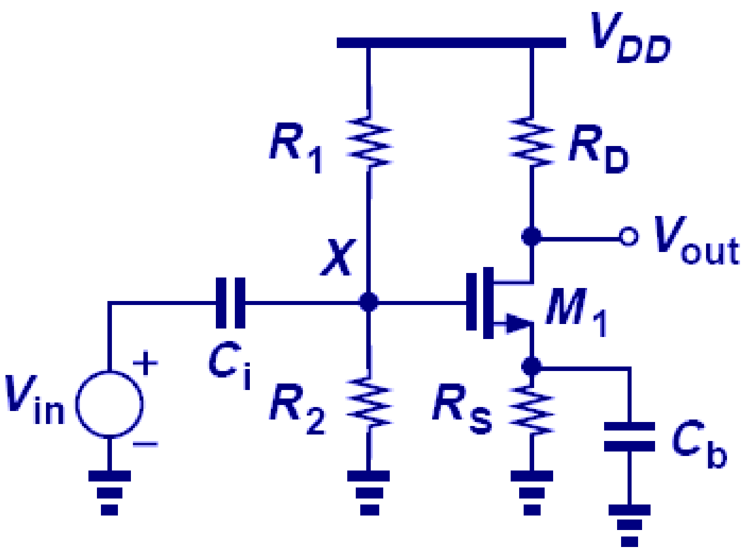
Analysis Summary

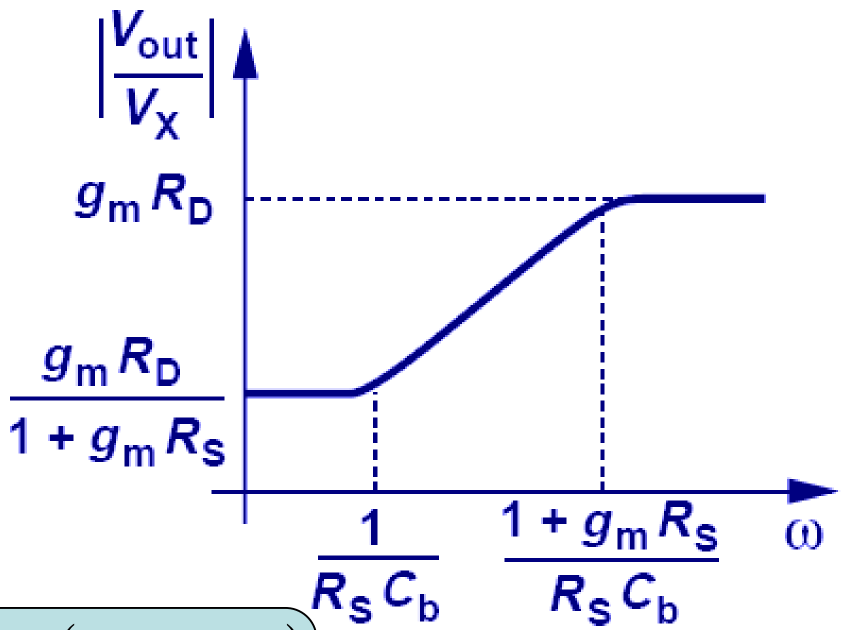
- **The frequency response refers to the magnitude of the transfer function.**
- **Bode's approximation simplifies the plotting of the frequency response if poles and zeros are known.**
- **In general, it is possible to associate a pole with each node in the signal path.**
- **Miller's theorem helps to decompose floating capacitors into grounded elements.**
- **Bipolar and MOS devices exhibit various capacitances that limit the speed of circuits.**

High Frequency Circuit Analysis Procedure

- **Determine which capacitor impact the low-frequency region of the response and calculate the low-frequency pole (neglect transistor capacitance).**
- **Calculate the midband gain by replacing the capacitors with short circuits (neglect transistor capacitance).**
- **Include transistor capacitances.**
- **Merge capacitors connected to AC grounds and omit those that play no role in the circuit.**
- **Determine the high-frequency poles and zeros.**
- **Plot the frequency response using Bode's rules or exact analysis.**

Frequency Response of CS Stage with Bypassed Degeneration

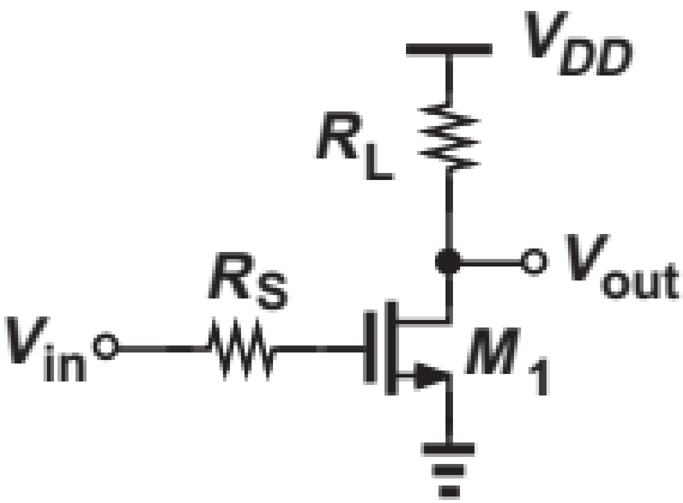


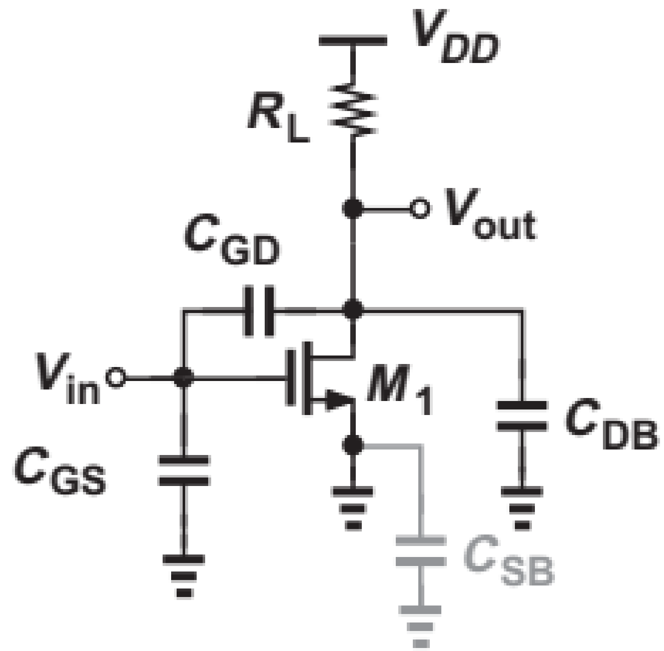


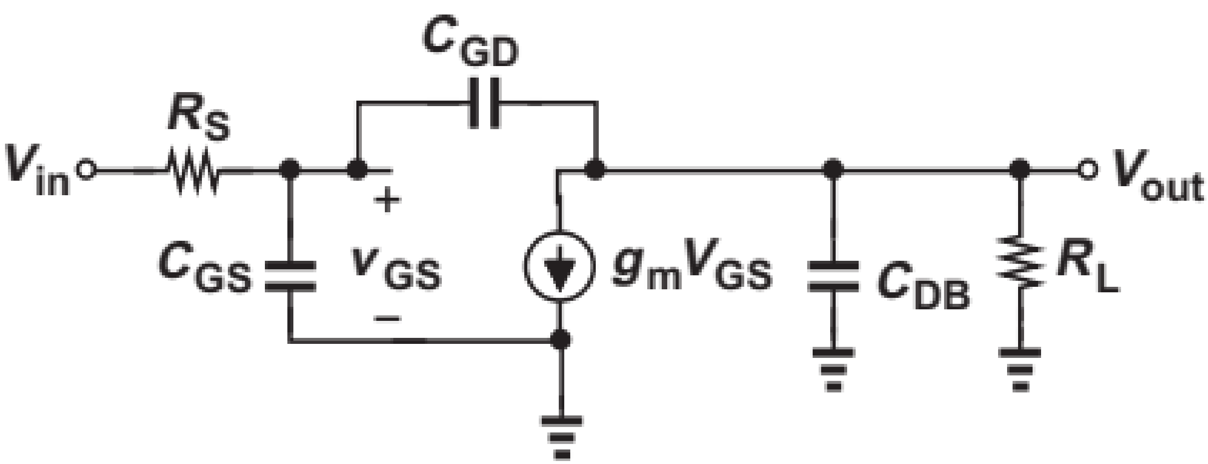
$$\left|\frac{V_{out}}{V_X}(s)\right| = \frac{-g_m R_D (R_S C_b s + 1)}{R_S C_b s + g_m R_S + 1}$$

- **In order to increase the midband gain, a capacitor C_b is placed in parallel with R_s.**
- **The pole frequency must be well below the lowest signal frequency to avoid the effect of degeneration.**

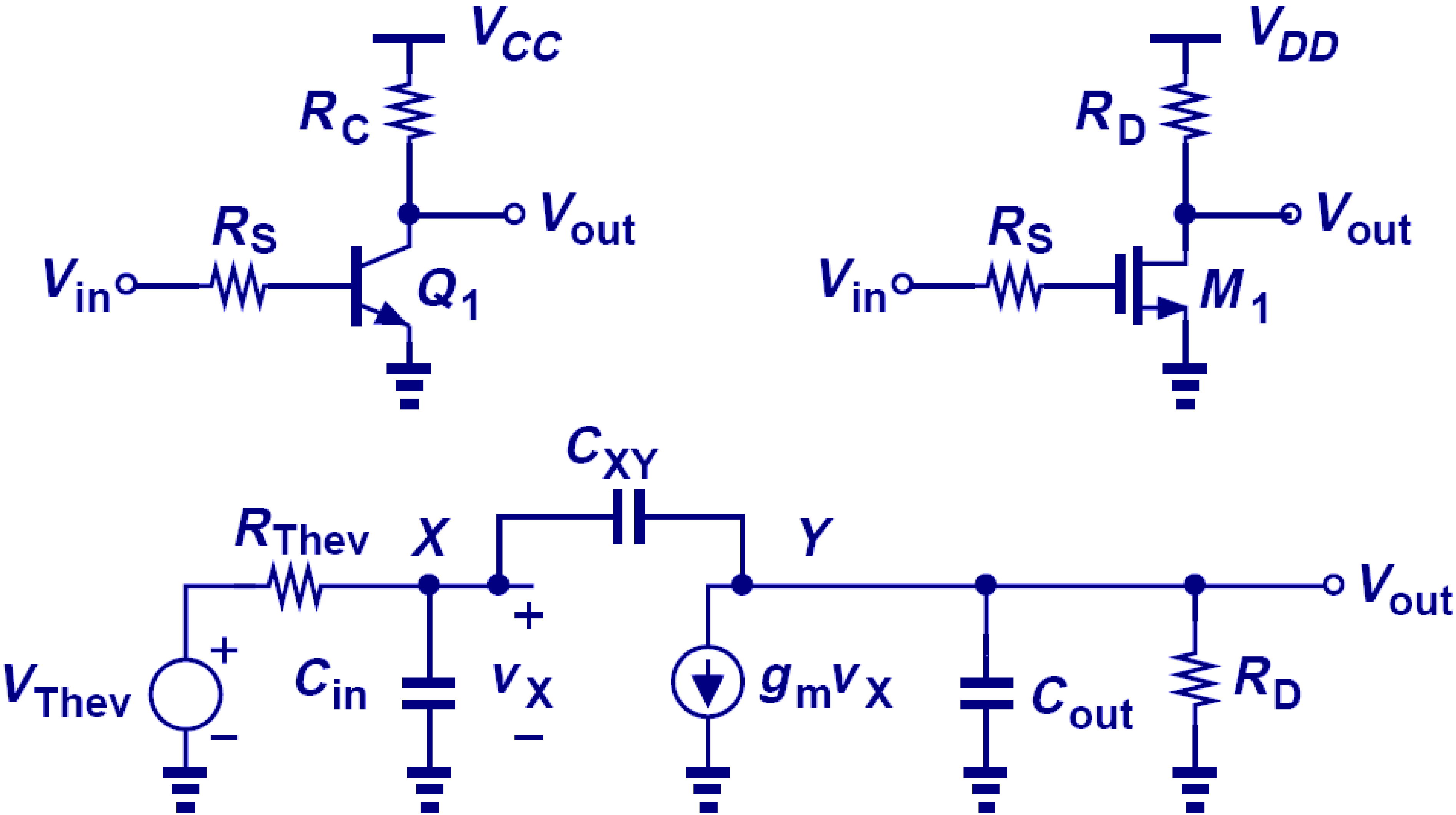
Small signal equivalents of CS stage



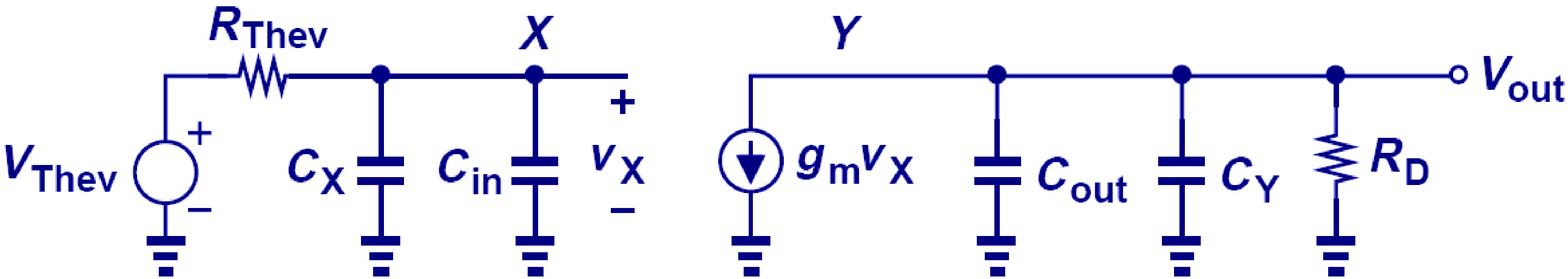




Unified Model for CE and CS Stages



Unified Model Using Miller's Theorem



CS Stage

$V_{Thev} = V_{in}$

$R_{Thev} = R_S$

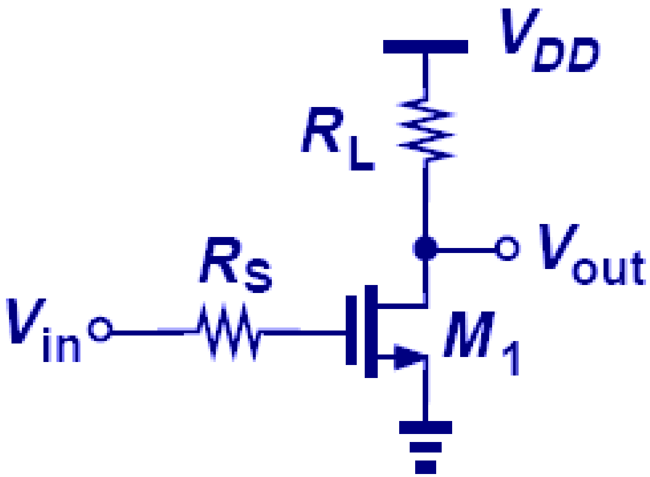
$C_X = C_{GD}\,(1 + g_m R_D)$

$C_Y = C_{GD}\,\left(1 + \dfrac{1}{g_m R_D}\right)$

$$|\omega_{p,in}| = \frac{1}{R_{Thev}[C_{in} + (1 + g_m R_L)C_{XY}]}$$

$$|\omega_{p,out}| = \frac{1}{R_L\left[C_{out} + \left(1 + \dfrac{1}{g_m R_L}\right)C_{XY}\right]}$$

Example: Half Width CS Stage



$$W \downarrow 2X$$

All capacitors are halved

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

$$\left|\omega_{p,in}\right| = \frac{1}{R_S\left[\frac{C_{in}}{2} + \left(1 + \frac{g_m R_L}{2}\right)\frac{C_{XY}}{2}\right]}$$

$$\left|\omega_{p,out}\right| = \frac{1}{R_L\left[\frac{C_{out}}{2} + \left(1 + \frac{2}{g_m R_L}\right)\frac{C_{XY}}{2}\right]}$$

Direct Analysis of CS Stages

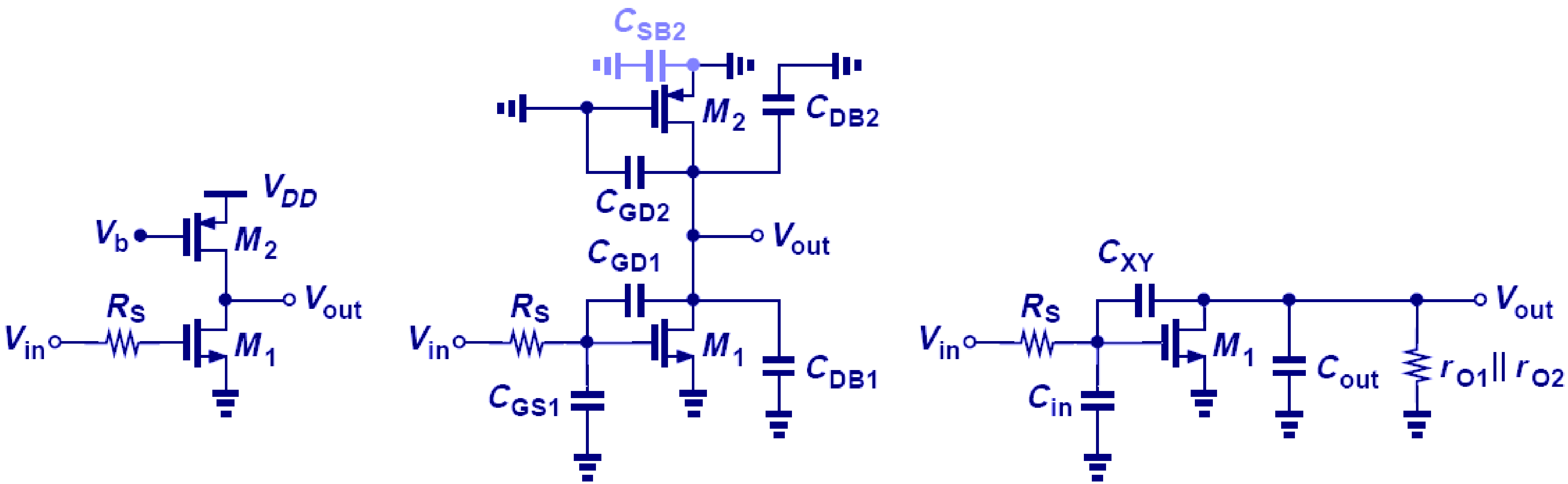
$$|\omega_z| = \frac{g_m}{C_{XY}}$$

$$|\omega_{p1}| = \frac{1}{(1+g_m R_L)C_{XY}R_{Thev} + R_{Thev}C_{in} + R_L(C_{XY} + C_{out})}$$

$$|\omega_{p2}| = \frac{(1+g_m R_L)C_{XY}R_{Thev} + R_{Thev}C_{in} + R_L(C_{XY} + C_{out})}{R_{Thev}R_L(C_{in}C_{XY} + C_{out}C_{XY} + C_{in}C_{out})}$$

- **Direct analysis yields different pole locations and an extra zero.**

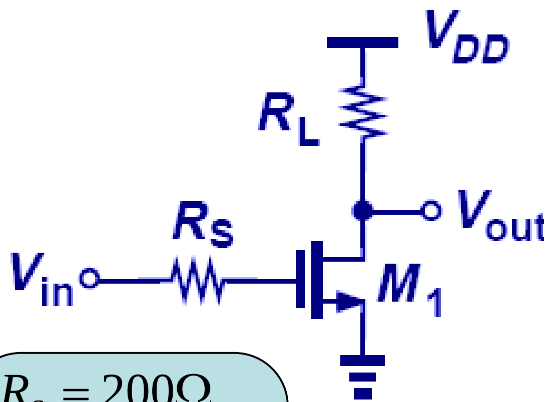
Example: CS Direct Analysis



$$\omega_{p1} \approx \frac{1}{\left[1+g_{m1}\left(r_{O1} \parallel r_{O2}\right)\right]C_{XY}R_S + R_S C_{in} + \left(r_{O1} \parallel r_{O2}\right)\left(C_{XY} + C_{out}\right)}$$

$$\omega_{p2} \approx \frac{\left[1+g_{m1}\left(r_{O1} \parallel r_{O2}\right)\right]C_{XY}R_S + R_S C_{in} + \left(r_{O1} \parallel r_{O2}\right)\left(C_{XY} + C_{out}\right)}{R_S\left(r_{O1} \parallel r_{O2}\right)\left(C_{in}C_{XY} + C_{out}C_{XY} + C_{in}C_{out}\right)}$$

Example: Comparison Between Different Methods



$R_S = 200\Omega$

$C_{GS} = 250\ fF$

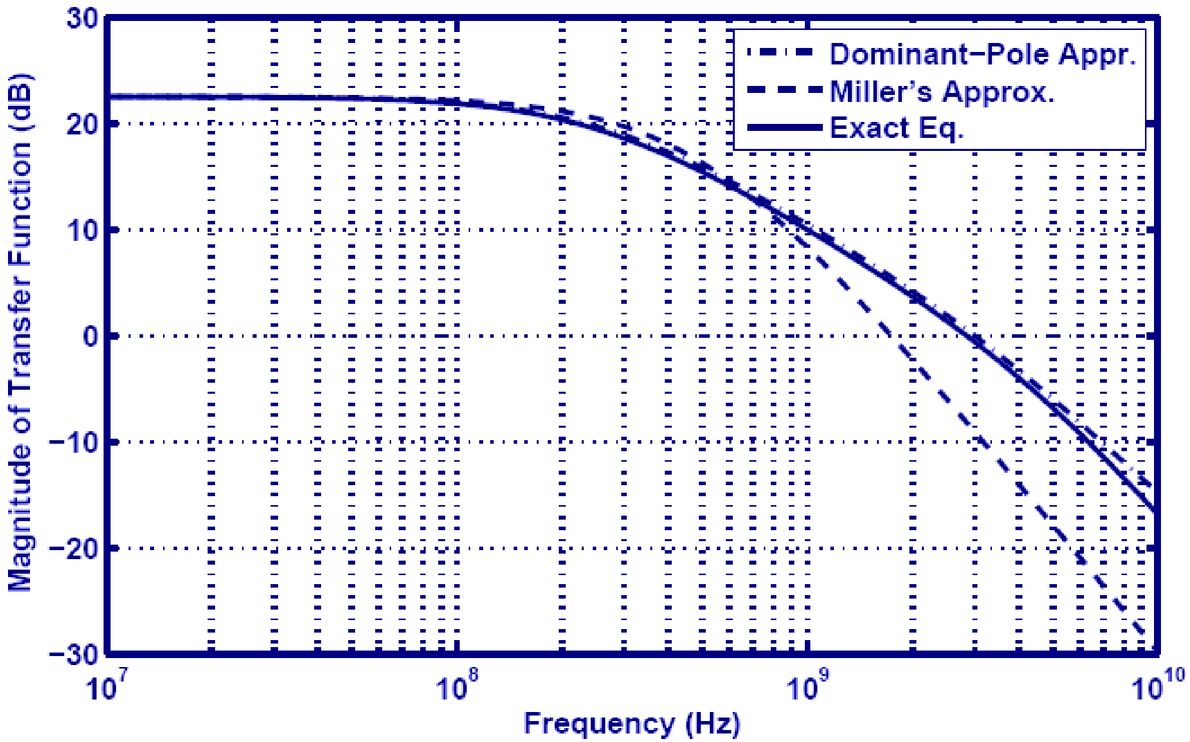
$C_{GD} = 80\ fF$

$C_{DB} = 100\ fF$

$g_m = (150\Omega)^{-1}$

$\lambda = 0$

$R_L = 2K\Omega$



Miller's

$$|\omega_{p,in}| = 2\pi \times (571MHz)$$

$$|\omega_{p,out}| = 2\pi \times (428MHz)$$

Exact

$$|\omega_{p,in}| = 2\pi \times (264MHz)$$

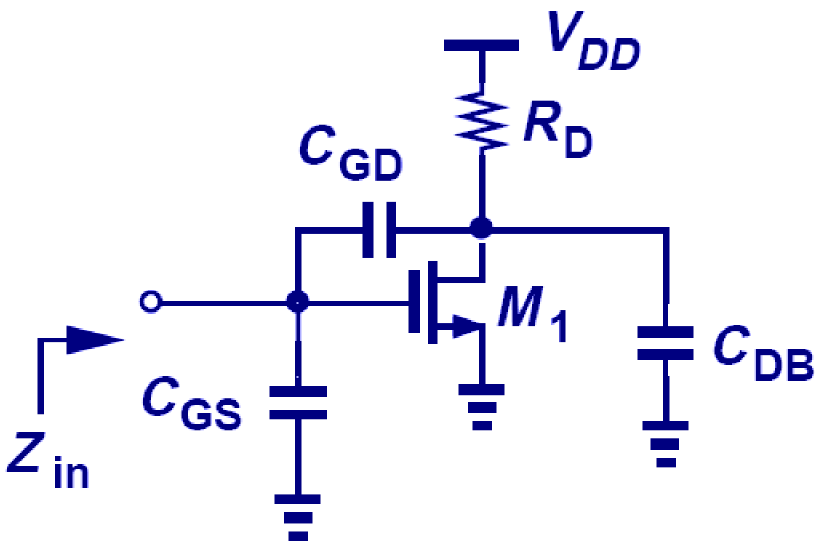
$$|\omega_{p,out}| = 2\pi \times (4.53GHz)$$

Dominant Pole

$$|\omega_{p,in}| = 2\pi \times (249MHz)$$

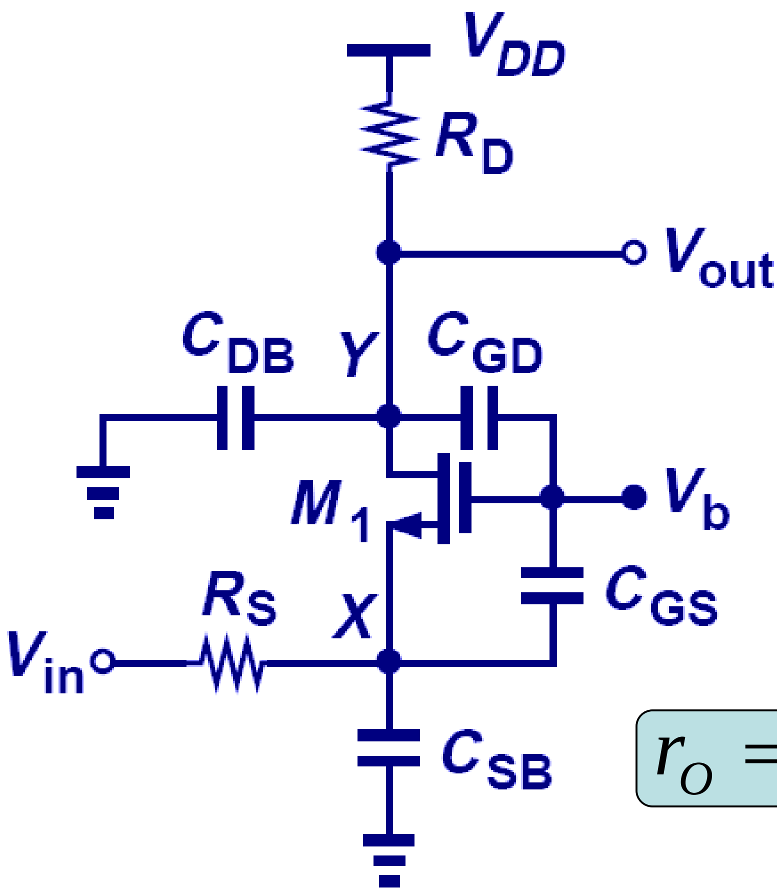
$$|\omega_{p,out}| = 2\pi \times (4.79GHz)$$

Input Impedance of CS Stages



$$Z_{in} \approx \frac{1}{\left[C_{GS} + (1 + g_m R_D) C_{GD}\right] s}$$

Frequency Response of CG Stage



$$r_O = \infty$$

$$\omega_{p,X} = \frac{1}{\left(R_S \parallel \frac{1}{g_m}\right) C_X}$$

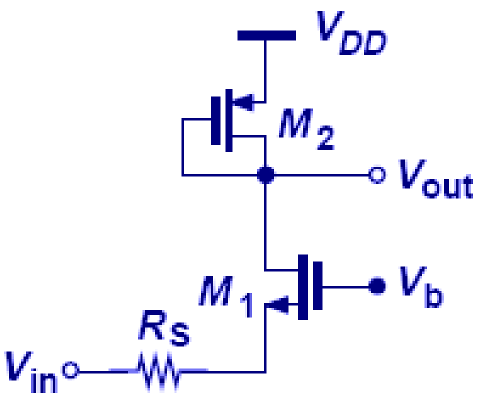
$$C_X = C_{GS} + C_{SB}$$

$$\omega_{p,Y} = \frac{1}{R_D C_Y}$$

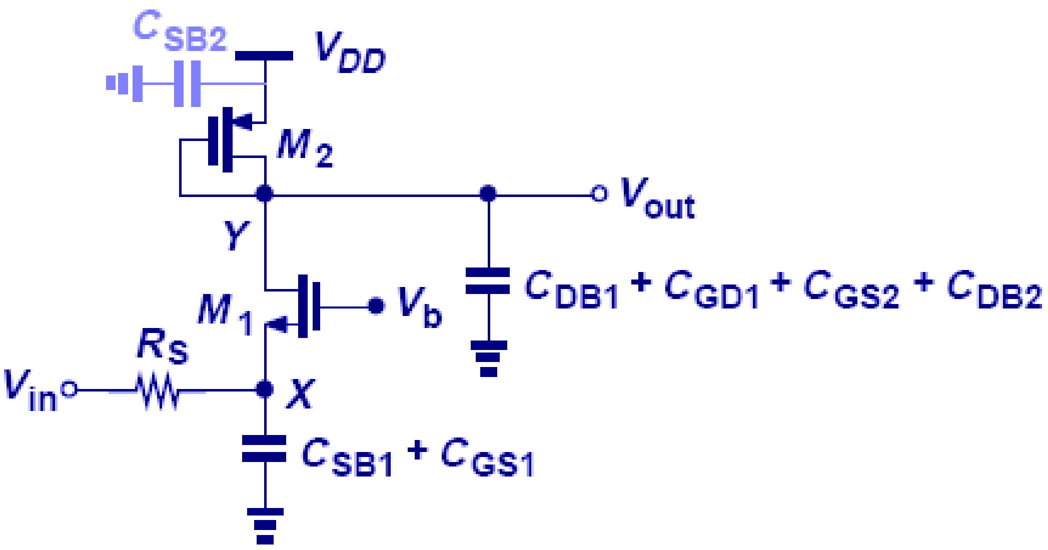
$$C_Y = C_{GD} + C_{DB}$$

- Similar to a CB stage, the input pole is on the order of f_T, so rarely a speed bottleneck.

Example: CG Stage Pole Identification



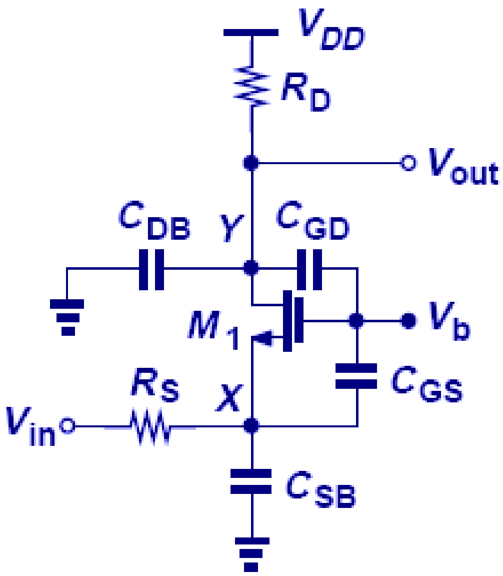
(a)



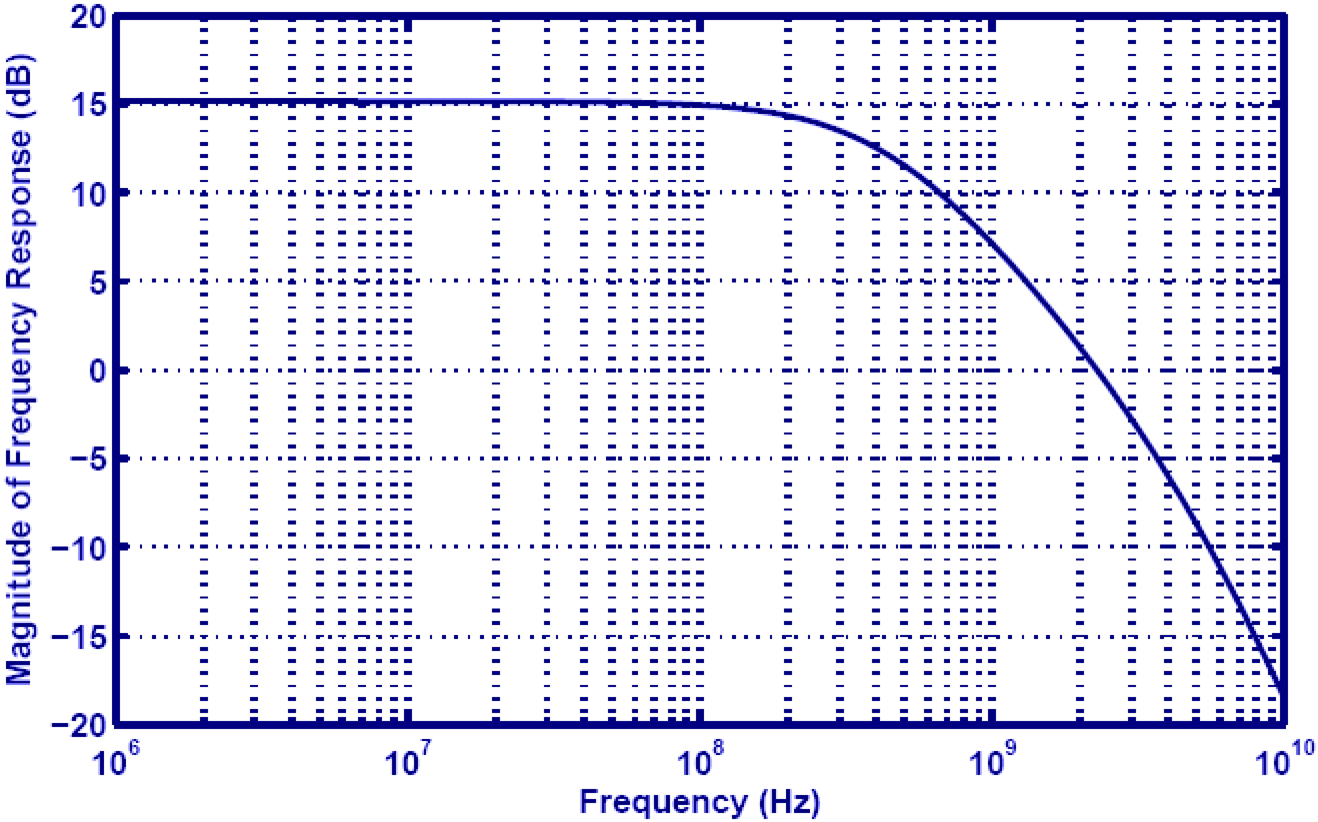
(b)

$$\omega_{p,X} = \frac{1}{\left(R_S \parallel \frac{1}{g_{m1}}\right)(C_{SB1} + C_{GS1})} \qquad \omega_{p,Y} = \frac{1}{\frac{1}{g_{m2}}(C_{DB1} + C_{GD1} + C_{GS2} + C_{DB2})}$$

Example: Frequency Response of CG Stage

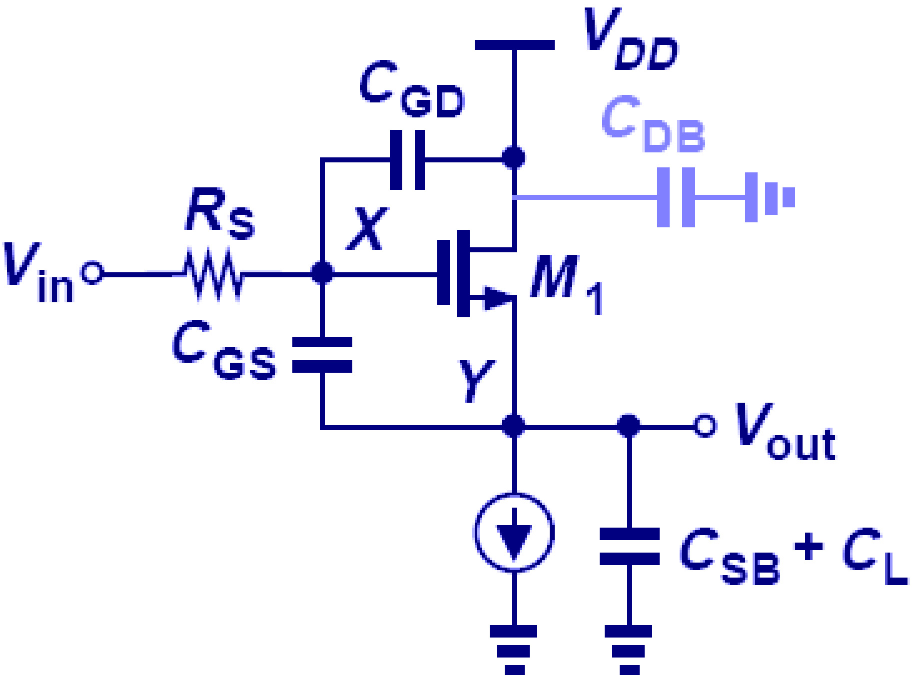


$$R_S = 200\Omega$$
$$C_{GS} = 250\ fF$$
$$C_{GD} = 80\ fF$$
$$C_{DB} = 100\ fF$$
$$g_m = (150\Omega)^{-1}$$
$$\lambda = 0$$
$$R_d = 2K\Omega$$



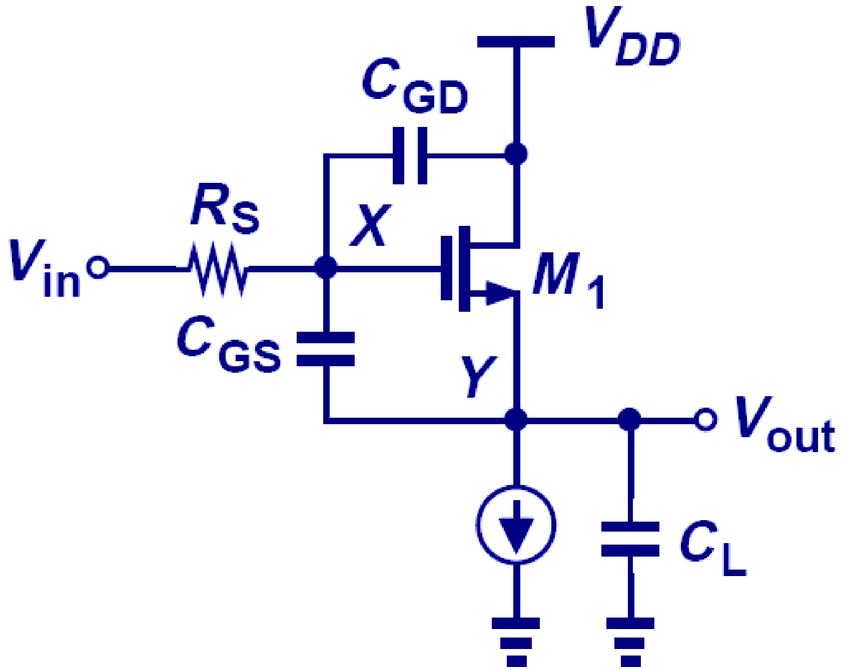
$$\left|\omega_{p,X}\right| = 2\pi \times (5.31GHz)$$
$$\left|\omega_{p,Y}\right| = 2\pi \times (442MHz)$$

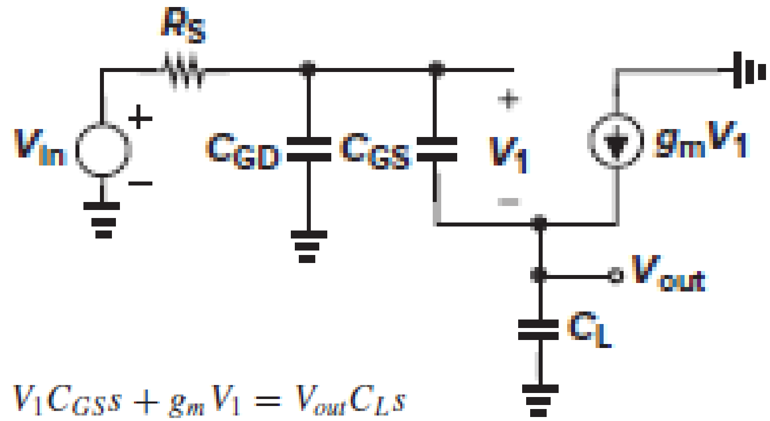
Source Followers



- **The following will discuss the frequency response of source followers using direct analysis.**

Direct Analysis of Source Follower Stage





$$V_1 C_{GS} s + g_m V_1 = V_{out} C_L s$$

$$V_1 = \frac{C_L s}{g_m + C_{GS} s} V_{out}$$

$$V_{in} = R_S[V_1 C_{GS} s + (V_1 + V_{out}) C_{GD} s] + V_1 + V_{out}$$

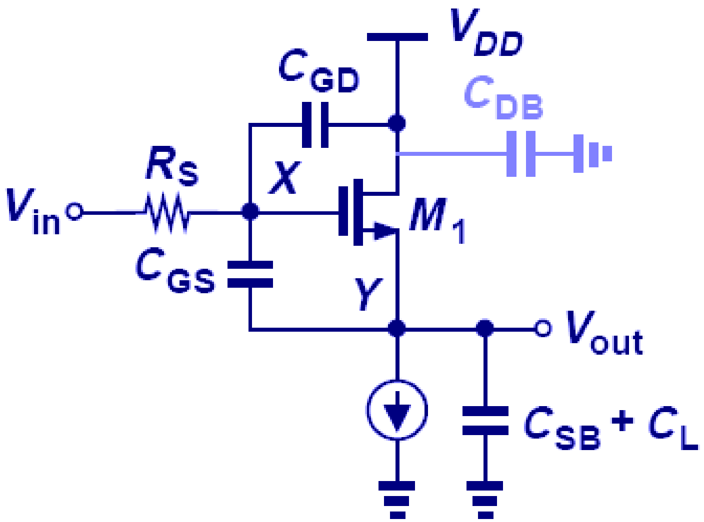
$$\frac{V_{out}}{V_{in}}(s) = \frac{g_m + C_{GS} s}{R_S(C_{GS}C_L + C_{GS}C_{GD} + C_{GD}C_L)s^2 + (g_m R_S C_{GD} + C_L + C_{GS})s + g_m}$$

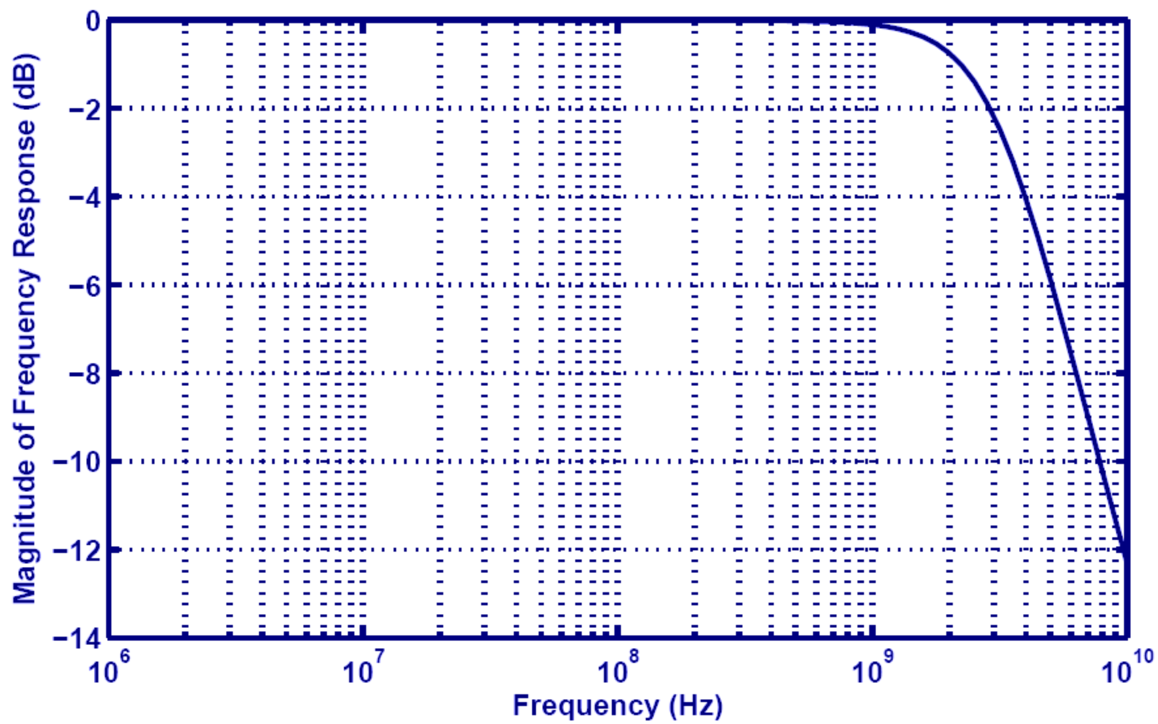
$$\frac{V_{out}}{V_{in}} = \frac{1 + \dfrac{C_{GS}}{g_m} s}{as^2 + bs + 1}$$

$$a = \frac{R_S}{g_m}\left(C_{GD}C_{GS} + C_{GD}C_L + C_{GS}C_L\right)$$

$$b = R_S C_{GD} + \frac{C_{GS} + C_L}{g_m}$$

Example: Frequency Response of Source Follower

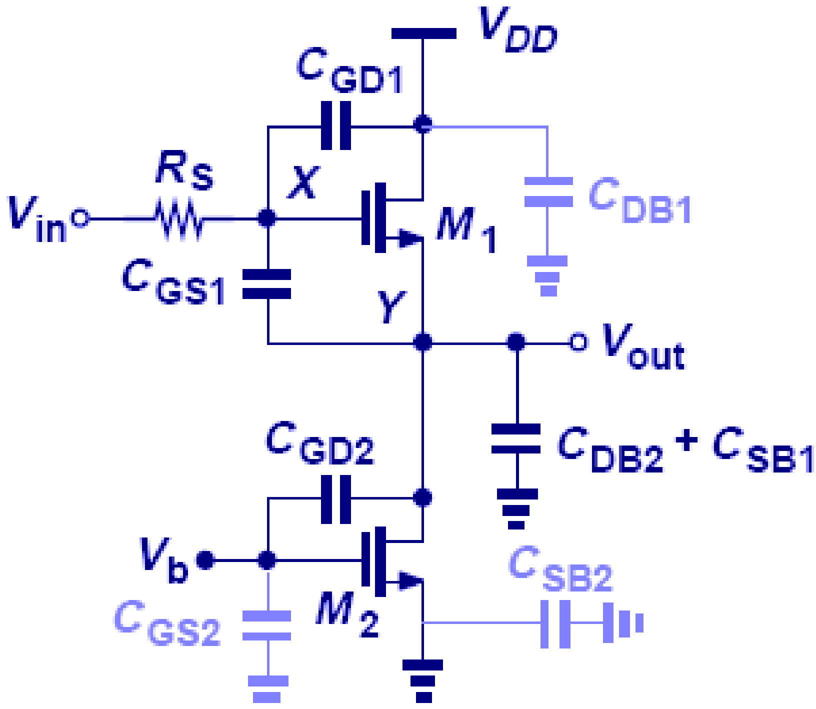




$$R_S = 200\Omega$$
$$C_L = 100\ fF$$
$$C_{GS} = 250\ fF$$
$$C_{GD} = 80\ fF$$
$$C_{DB} = 100\ fF$$
$$g_m = (150\Omega)^{-1}$$
$$\lambda = 0$$

$$\omega_{p1} = 2\pi[-1.79GHz + j(2.57GHz)]$$
$$\omega_{p2} = 2\pi[-1.79GHz - j(2.57GHz)]$$

Example: Source Follower



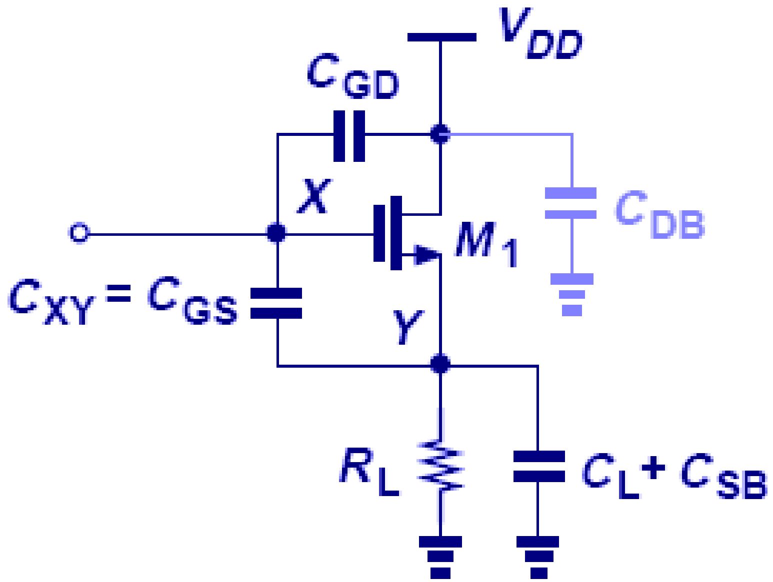
$$\frac{V_{out}}{V_{in}} = \frac{1 + \frac{C_{GS}}{g_m} s}{as^2 + bs + 1}$$

$$C_L = C_{DB2} + C_{SB1} + C_{GD2}$$

$$a = \frac{R_S}{g_{m1}} \left[C_{GD1} C_{GS1} + (C_{GD1} + C_{GS1})(C_{SB1} + C_{GD2} + C_{DB2}) \right]$$

$$b = R_S C_{GD1} + \frac{C_{GS1} + C_{SB1} + C_{GD2} + C_{DB2}}{g_{m1}}$$

Input Capacitance of Source Follower

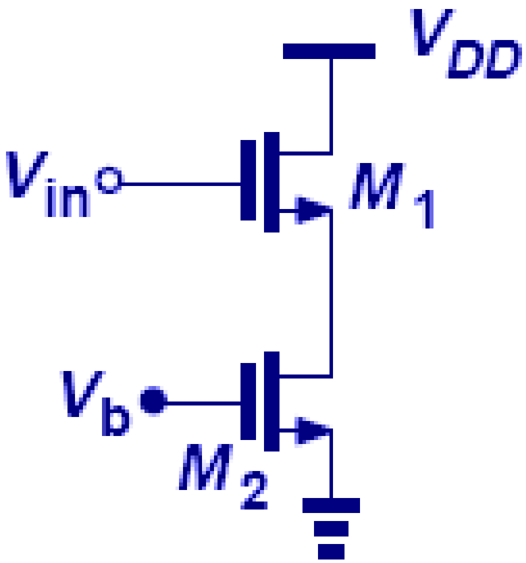


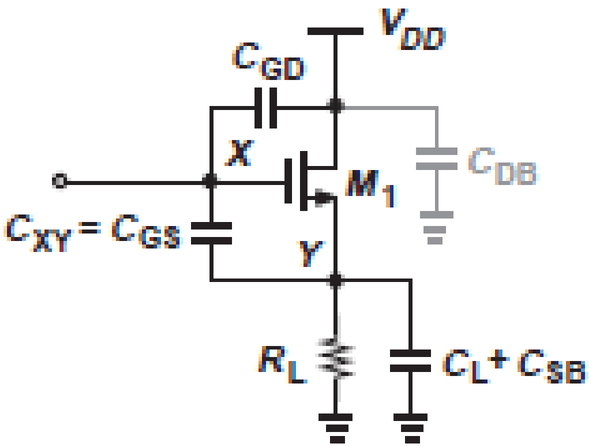
$$A_v = \frac{R_L}{R_L + \frac{1}{g_m}}$$

$$C_X = (1 - A_v)C_{XY}$$
$$= \frac{1}{1 + g_m R_L} C_{XY}$$

$$C_{in} = C_{GD} + \frac{C_{GS}}{1 + g_m R_L}$$

Example: Source Follower Input Capacitance





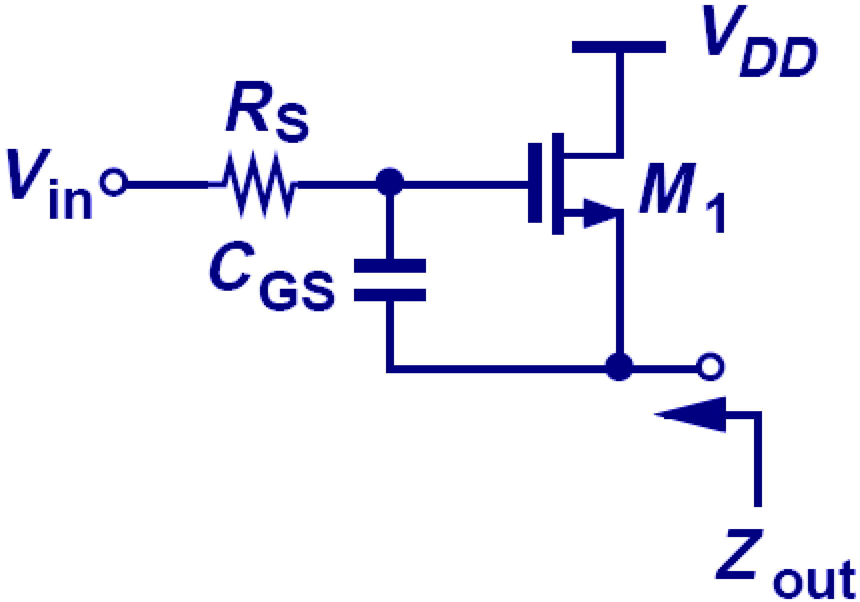
$$A_v = \frac{r_{O1} \| r_{O2}}{r_{O1} \| r_{O2} + \frac{1}{g_{m1}}}.$$

$$C_{in} = C_{GD1} + (1 - A_v) C_{GS1}$$

$$= C_{GD1} + \frac{1}{1 + g_{m1}(r_{O1} \| r_{O2})} C_{GS1}$$

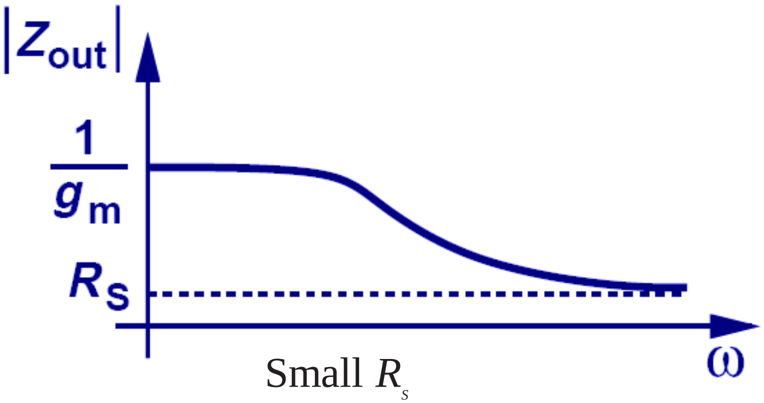
$$C_{in} = C_{GD1} + \frac{1}{1 + g_{m1}\left(r_{O1} \| r_{O2}\right)} C_{GS1}$$

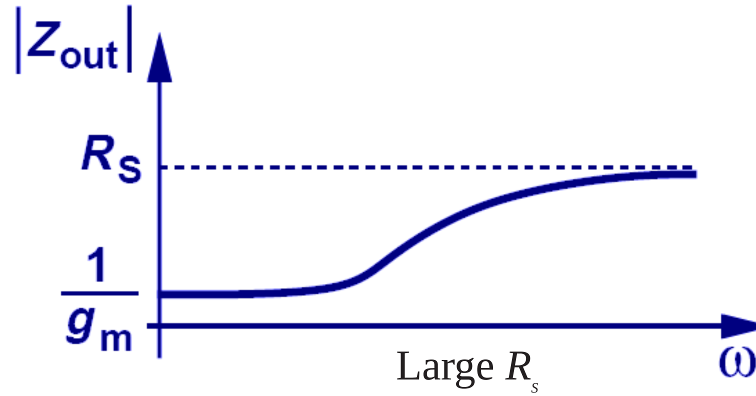
Output Impedance of Source Follower



$$\frac{V_X}{I_X} = \frac{R_S C_{GS} s + 1}{C_{GS} s + g_m}$$

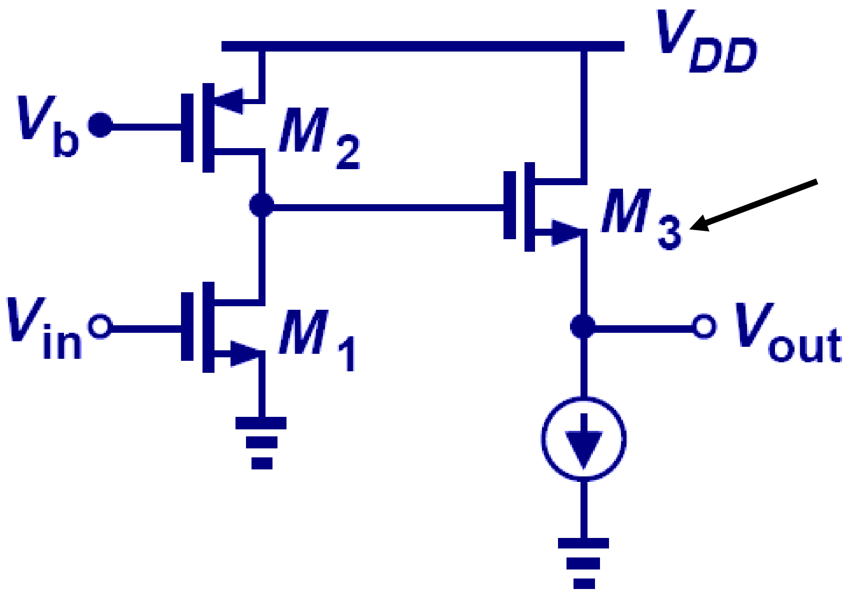
Active Inductor



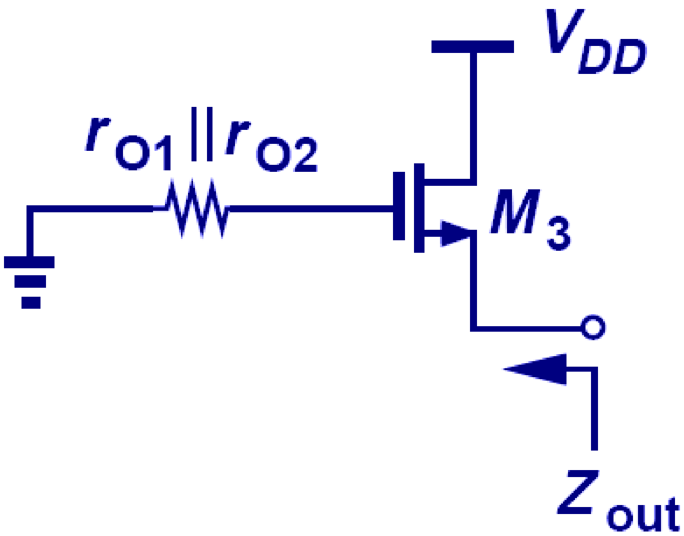


- **The plot above shows the output impedance of source followers. Since a follower's primary duty is to lower the driving impedance ($R_S>1/g_m$), the "active inductor" characteristic on the right is usually observed.**

Example: Output Impedance

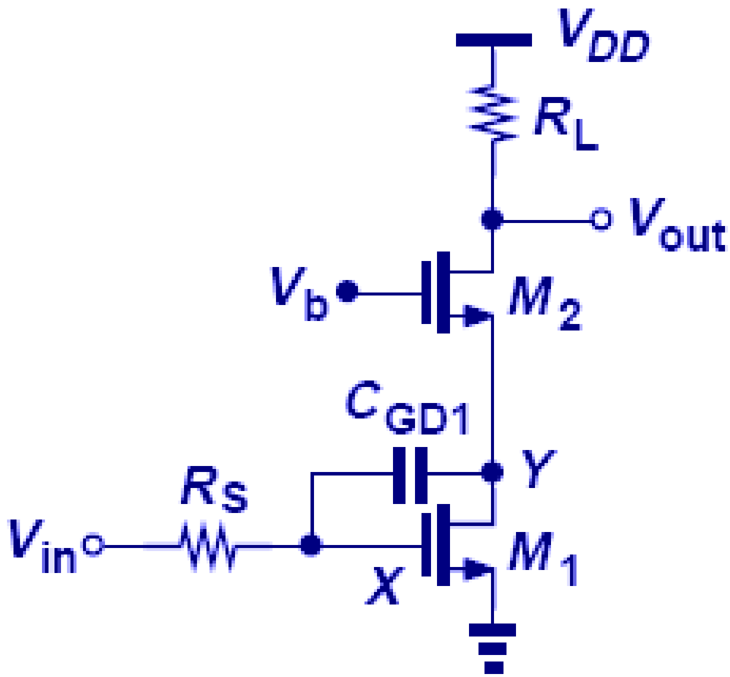


$r_O = \infty$



$$\frac{V_X}{I_X} = \frac{(r_{O1} \| r_{O2}) C_{GS3} s + 1}{C_{GS3} s + g_{m3}}$$

Frequency Response of Cascode Stage



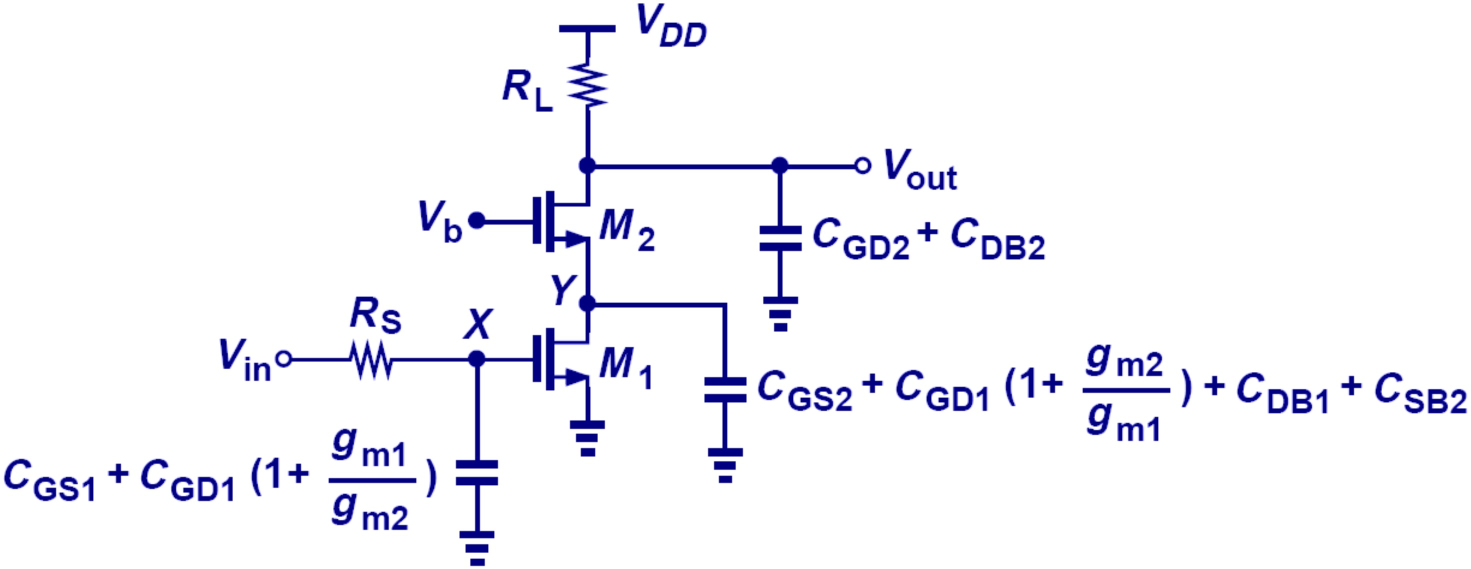
$$A_{v,XY} = \frac{-g_{m1}}{g_{m2}} \approx -1 \qquad C_x \approx 2C_{XY}$$

- For cascode stages, there are three poles and Miller multiplication is smaller than in the CE/CS stage.

Poles of MOS Cascode

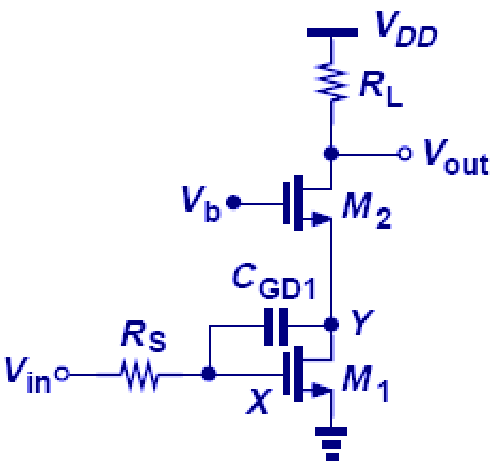
$$\omega_{p,X} = \frac{1}{R_S\left[C_{GS1} + \left(1 + \frac{g_{m1}}{g_{m2}}\right)C_{GD1}\right]}$$

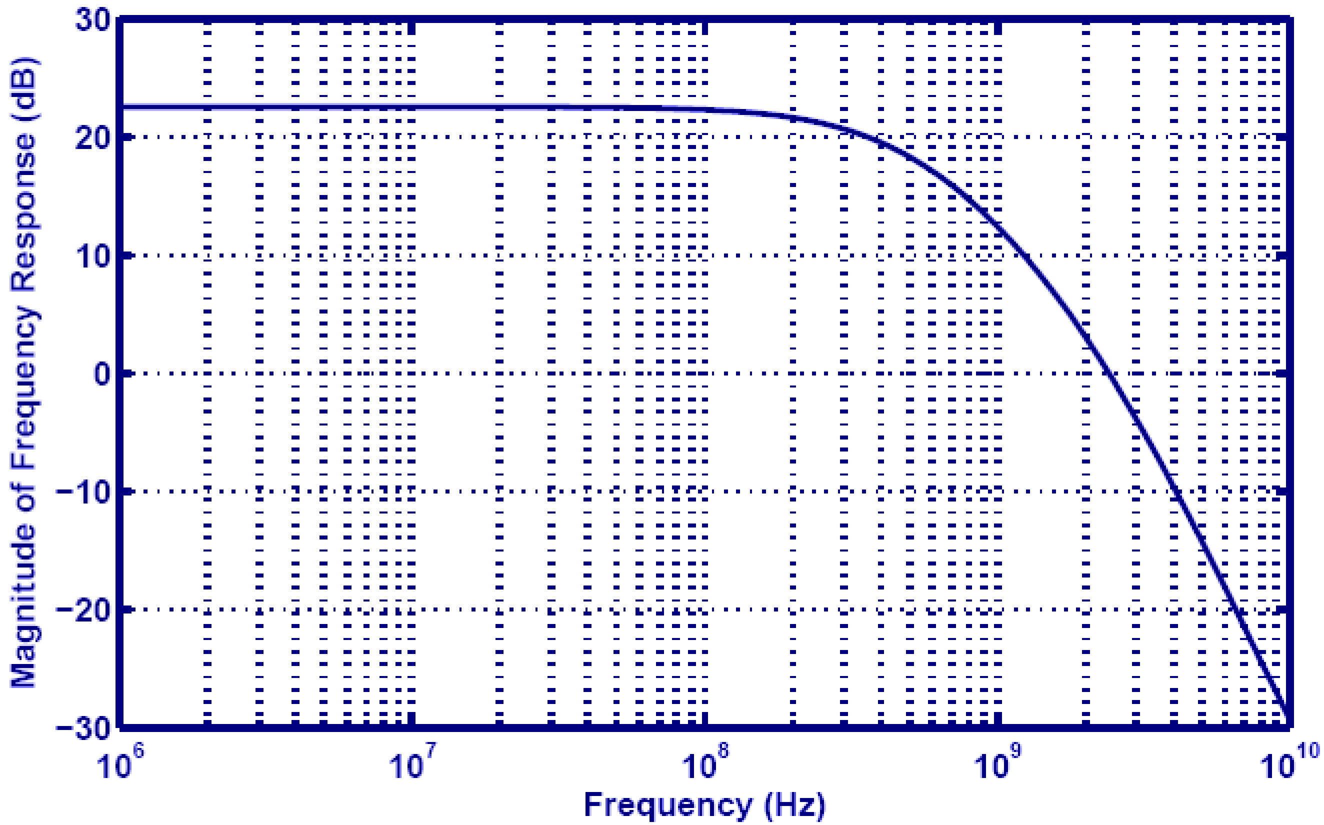
$$\omega_{p,out} = \frac{1}{R_L\left(C_{DB2} + C_{GD2}\right)}$$



$$\omega_{p,Y} = \frac{1}{\frac{1}{g_{m2}}\left[C_{DB1} + C_{GS2} + \left(1 + \frac{g_{m2}}{g_{m1}}\right)C_{GD1}\right]}$$

Example: Frequency Response of Cascode





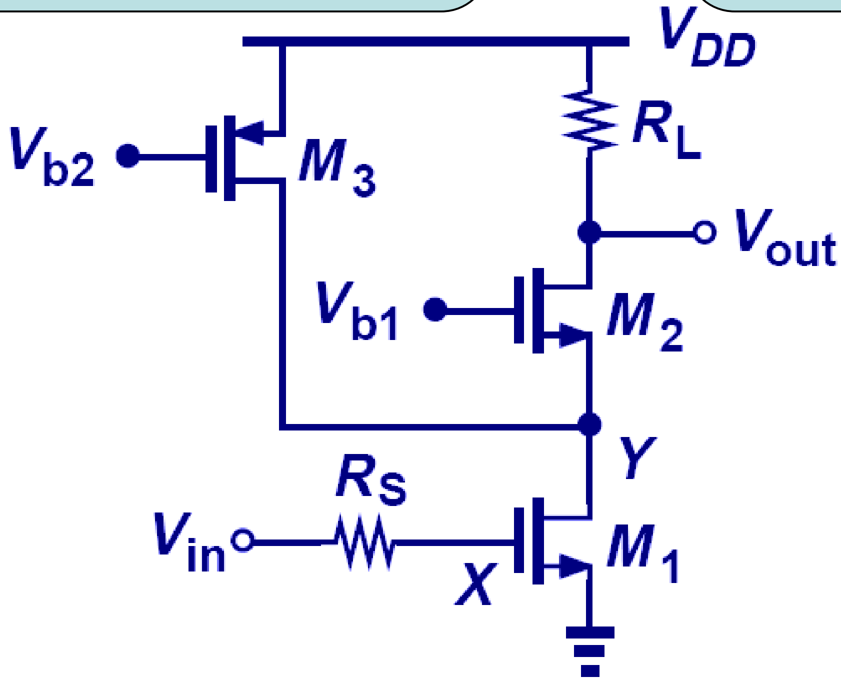
$$R_S = 200\Omega$$
$$C_{GS} = 250\ fF$$
$$C_{GD} = 80\ fF$$
$$C_{DB} = 100\ fF$$
$$g_m = (150\Omega)^{-1}$$
$$\lambda = 0$$
$$R_L = 2K\Omega$$

$$|\omega_{p,X}| = 2\pi \times (1.95GHz)$$
$$|\omega_{p,Y}| = 2\pi \times (1.73GHz)$$
$$|\omega_{p,out}| = 2\pi \times (442MHz)$$

MOS Cascode Example

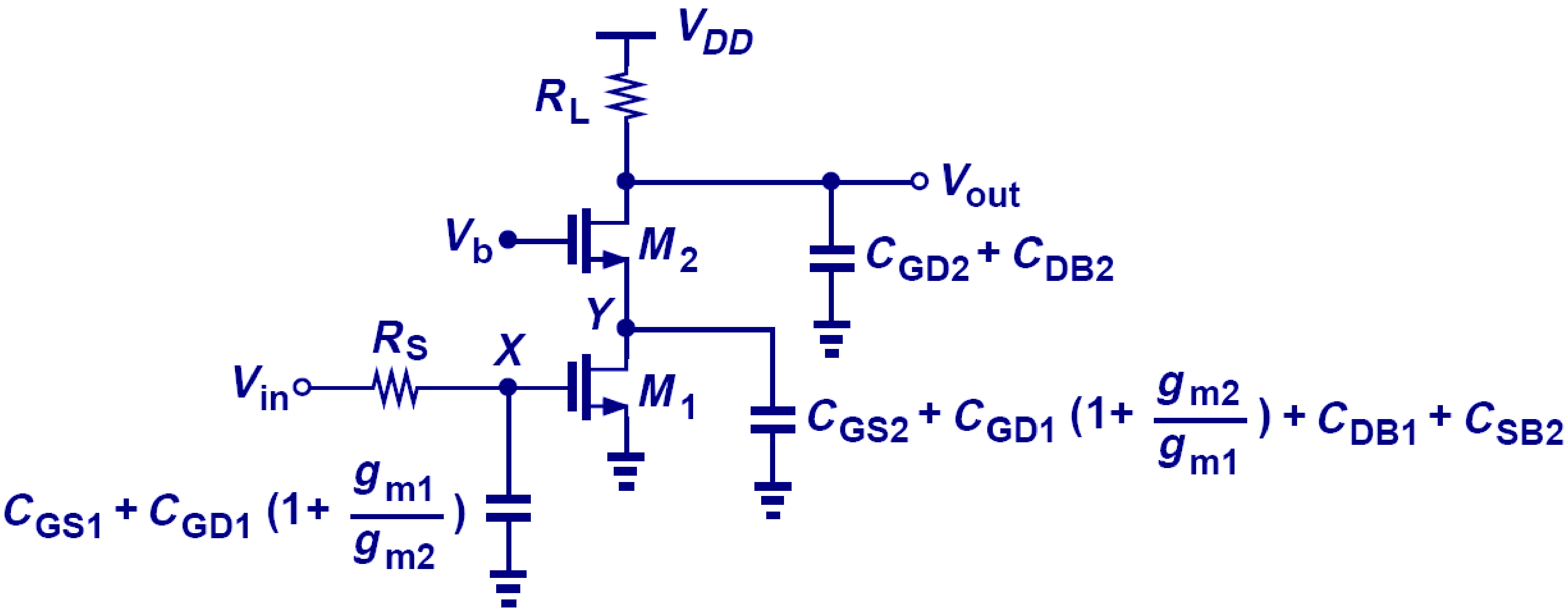
$$\omega_{p,X} = \frac{1}{R_S\left[C_{GS1} + \left(1 + \frac{g_{m1}}{g_{m2}}\right)C_{GD1}\right]}$$

$$\omega_{p,out} = \frac{1}{R_L\left(C_{DB2} + C_{GD2}\right)}$$



$$\omega_{p,Y} = \frac{1}{\frac{1}{g_{m2}}\left[C_{DB1} + C_{GS2} + \left(1 + \frac{g_{m2}}{g_{m1}}\right)C_{GD1} + C_{GD3} + C_{DB3}\right]}$$

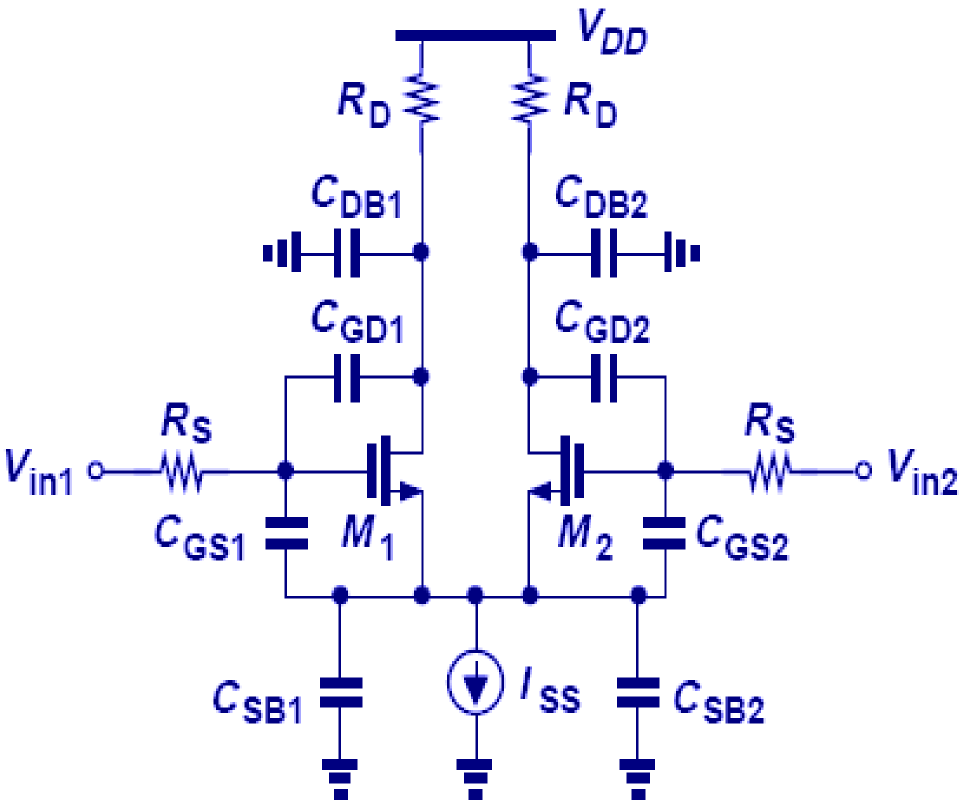
I/O Impedance of MOS Cascode

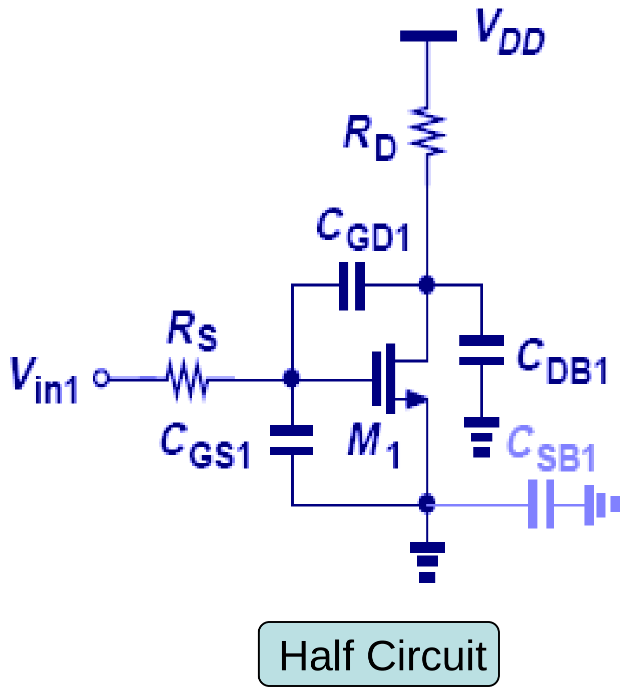


$$Z_{in} = \frac{1}{\left[C_{GS1} + \left(1+\frac{g_{m1}}{g_{m2}}\right)C_{GD1}\right]s}$$

$$Z_{out} = R_L \parallel \frac{1}{\left(C_{GD2} + C_{DB2}\right)s}$$

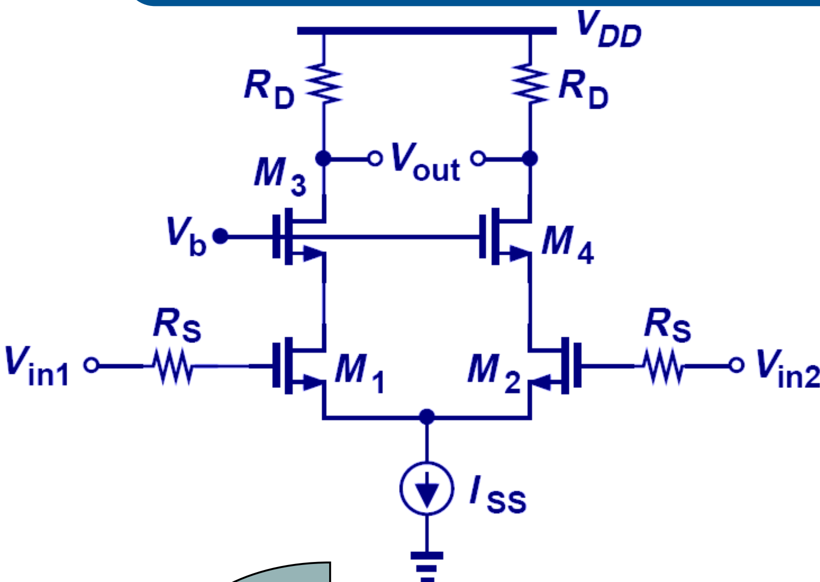
MOS Differential Pair Frequency Response





- Since MOS differential pair can be analyzed using half-circuit, its transfer function, I/O impedances, locations of poles/zeros are the same as that of the half circuit's.

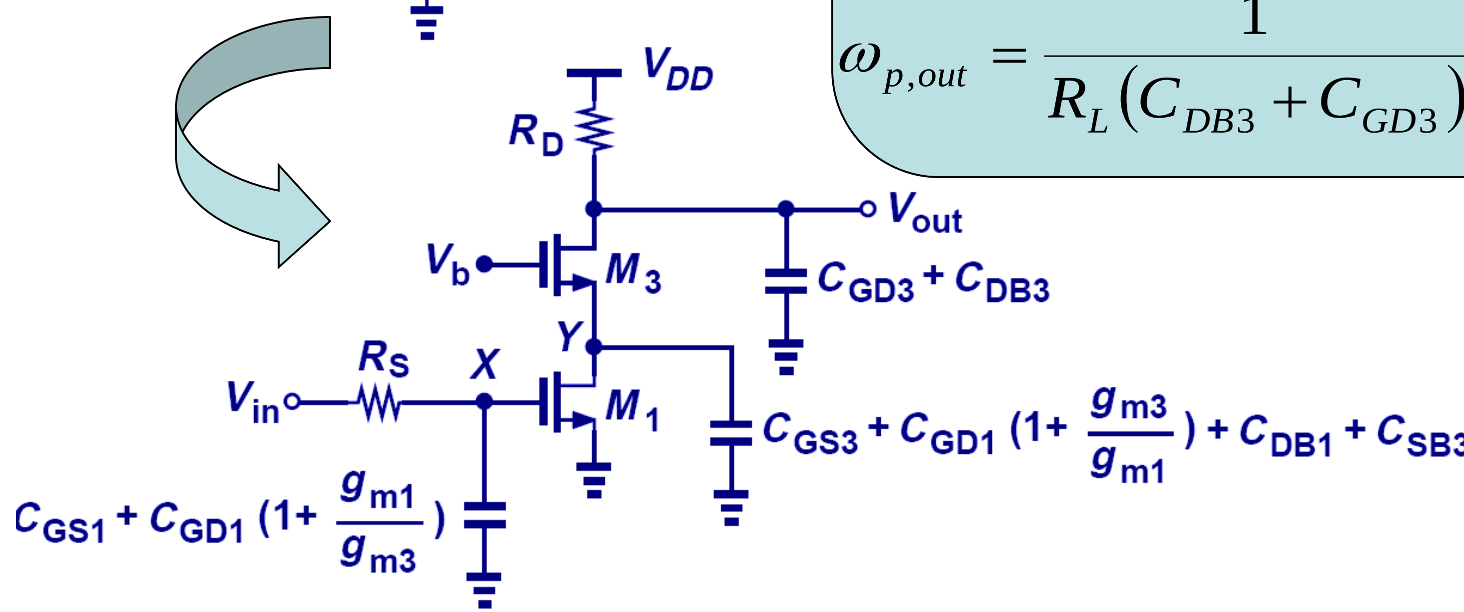
Example: MOS Differential Pair



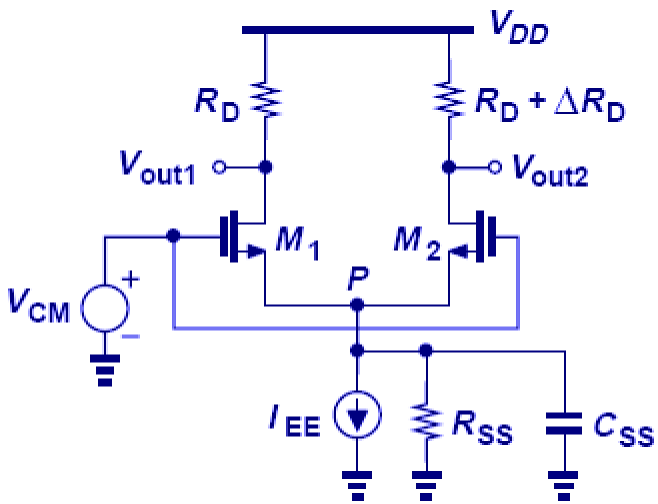
$$\omega_{p,X} = \frac{1}{R_S[C_{GS1} + (1 + g_{m1}/g_{m3})C_{GD1}]}$$

$$\omega_{p,Y} = \frac{1}{\frac{1}{g_{m3}}\left[C_{DB1} + C_{GS3} + \left(1 + \frac{g_{m3}}{g_{m1}}\right)C_{GD1}\right]}$$

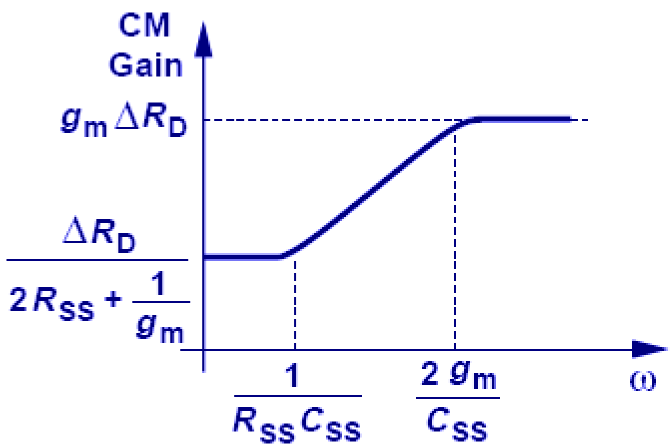
$$\omega_{p,out} = \frac{1}{R_L(C_{DB3} + C_{GD3})}$$



Common Mode Frequency Response



(a)



(b)

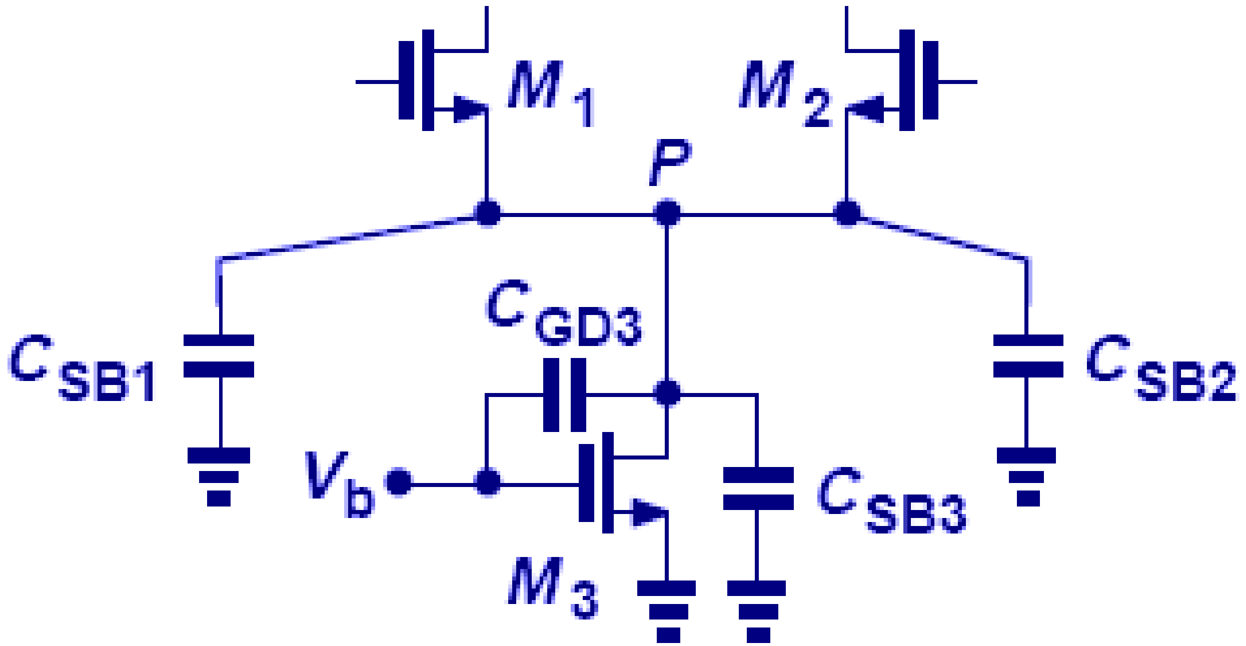
$$2g_m R_{SS} \gg 1$$

$$\left|\frac{\Delta V_{out}}{\Delta V_{CM}}\right| = \frac{g_m \Delta R_D (R_{SS}C_{SS} + 1)}{R_{SS}C_{SS}s + 2g_m R_{SS} + 1}$$

$$|\omega_z| = \frac{1}{R_{SS}C_{SS}} \qquad |\omega_p| = \frac{2g_m}{C_{SS}}$$

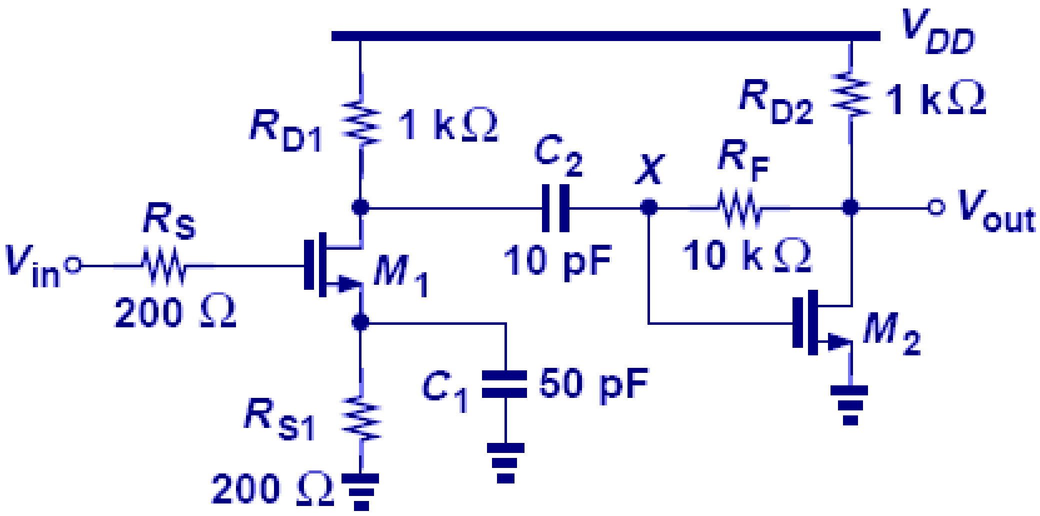
- **C_{ss} will lower the total impedance between point P to ground at high frequency, leading to higher CM gain which degrades the CM rejection ratio.**

Tail Node Capacitance Contribution



- Source-Body Capacitance of M_1, M_2 and M_3
- Gate-Drain Capacitance of M_3

Example: IC Amplifier – Low Frequency Design

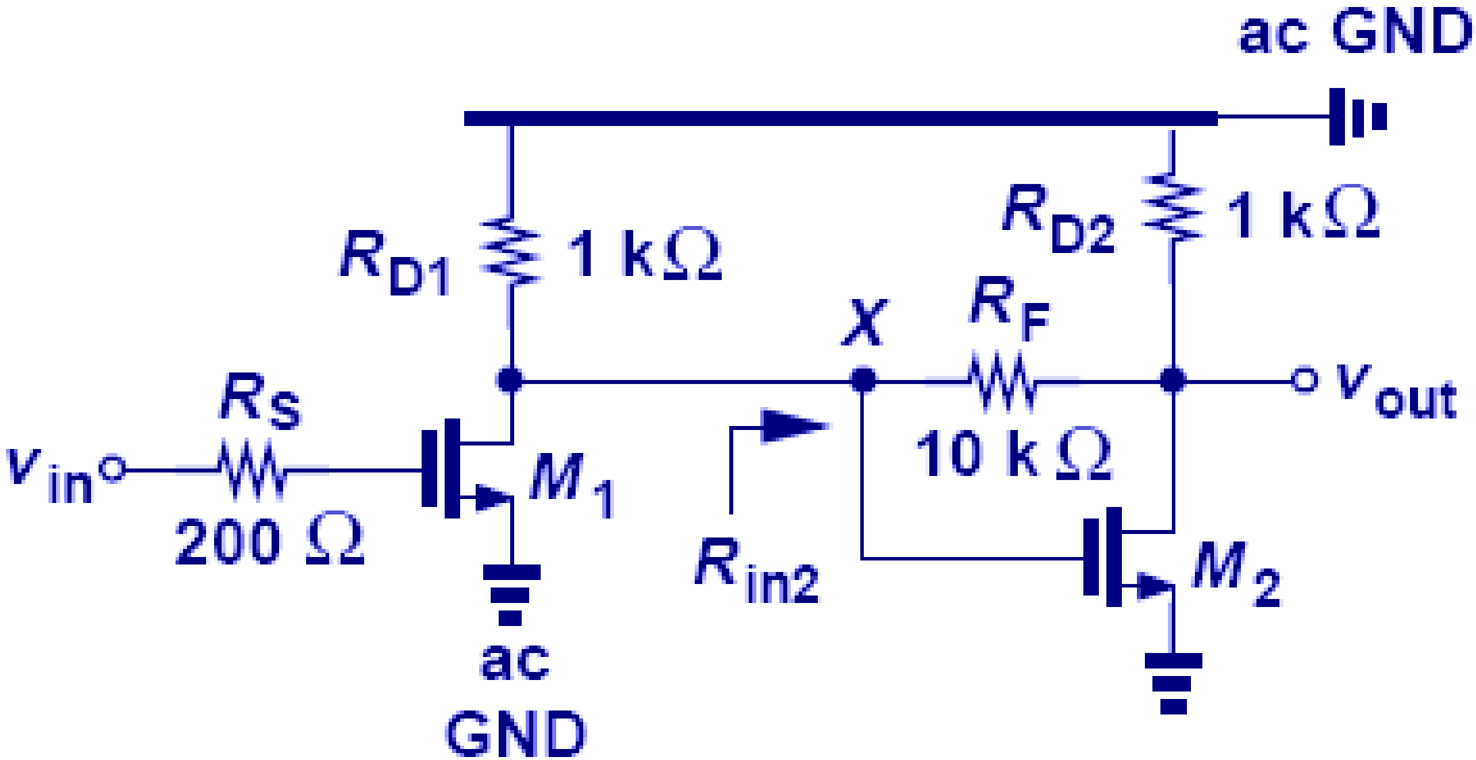


$$R_{in2} = \frac{R_F}{1 - A_{v2}}$$

$$\omega_{L1} = \frac{g_{m1}R_{S1} + 1}{R_{S1}C_1} = 2\pi \times (42.4MHz)$$

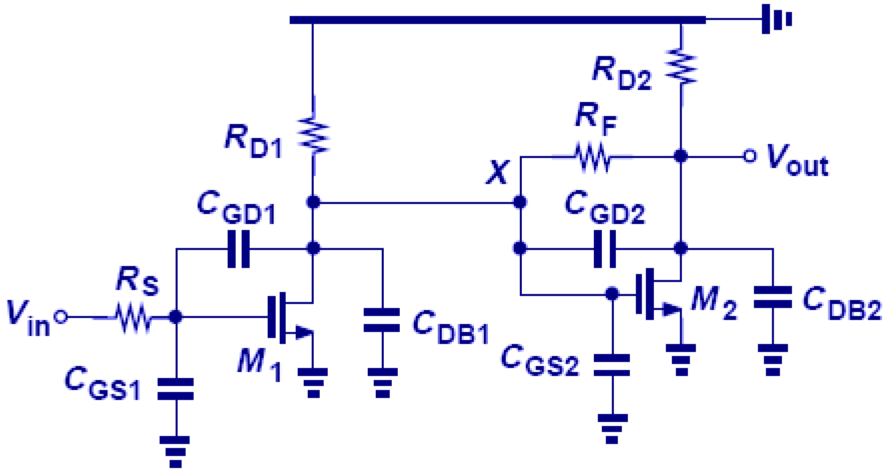
$$\omega_{L2} = \frac{1}{(R_{D1} + R_{in2})C_2} = 2\pi \times (6.92MHz)$$

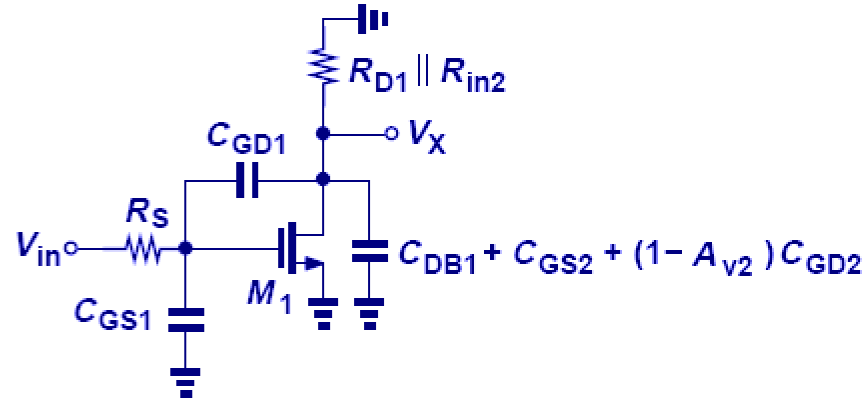
Example: IC Amplifier – Midband Design

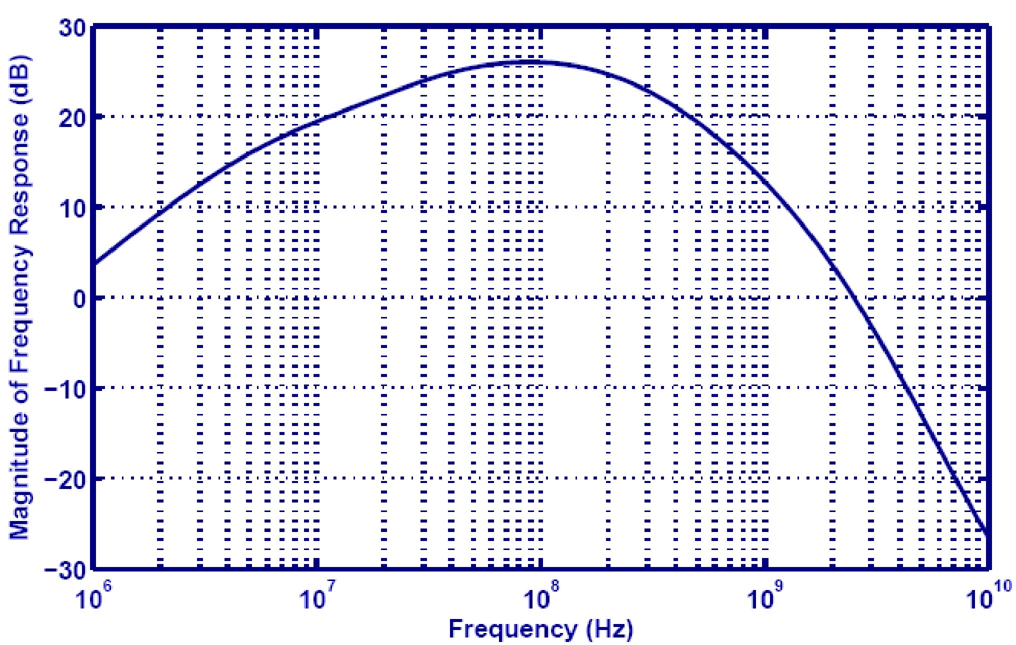


$$\frac{v_X}{v_{in}} = -g_{m1}\left(R_{D1} \,\|\, R_{in2}\right) = -3.77$$

Example: IC Amplifier – High Frequency Design







$$|\omega_{p1}| = 2\pi \times (242\ MHz)$$

$$|\omega_{p2}| = 2\pi \times (2.74\ GHz)$$

$$|\omega_{p3}| = \frac{1}{R_{L2}(1.15C_{GD2} + C_{DB2})}$$

$$= 2\pi \times (0.829\ GHz)$$