Lecture 5

*of*

EEE307

# Electronics for Communications

**Department of Electrical & Electronic Engineering**

Xi'an Jiaotong-Liverpool University (XJTLU)

Friday, 11th October 2019

- ❑ Gain Calculation Example
- ❑ Amplifier Circuit Analysis
  - ➢ transistor amplifier
  - ➢ unity gain frequency

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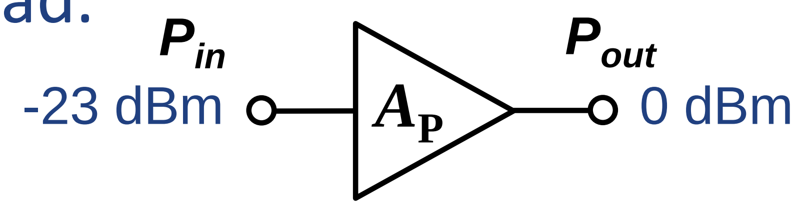
# Calculation Example - Amplifier

(power level & signal amplitude)

- An amplifier senses a sinusoidal signal and delivers a power of 0 dBm to a load resistance of 50 Ω. Determine the **<u>peak-to-peak</u> voltage $V_{pp}$** swing across the load.




Solution:

- 0 dBm = 1 mW; $P_{out} = \dfrac{V_{rms}^2}{R_L} = \dfrac{V_{pp}^2}{8R_L} = 10^{-3}\ \text{W where } R_L = 50\Omega$

$$\Rightarrow V_{pp} = \sqrt{8P_{out}R_L} = \sqrt{8(10^{-3})\,(50)} = 632\ \text{mV}$$

$$\Rightarrow V_p = V_{pp}/2 = 316\ \text{mV and } V_{rms} = \frac{V_p}{\sqrt{2}} = 224\ \text{mV}$$

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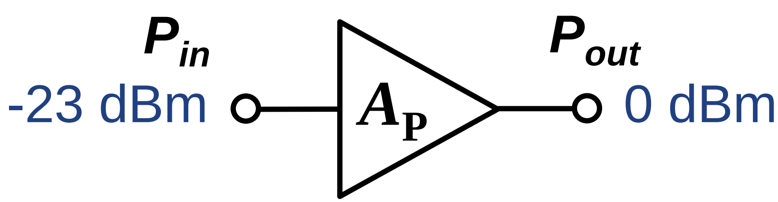
# Calculation Example – Amplifier (cont'd)

(amplifier gain & signal amplitude)

- What is the **power gain** of such an amplifier? Assuming *matched* **input** and **output impedance** of 50 Ω, what is the **voltage gain**? What is the **peak-to-peak voltage $V_{inpp}$** swing at the input.




Solution:

- $$A_P = \frac{P_{out}}{P_{in}} \text{ or } A_P\Big|_{dB} = 10\log\left(\frac{P_{out}}{P_{in}}\right)$$

$$A_P\Big|_{dB} = 0\,\text{dBm} - (-23\,\text{dBm}) = 23\,\text{dB}$$

$$23\,\text{dB} = 20\,\text{dB} + 3\,\text{dB} \Rightarrow A_P = 200$$

20 dB correspond to $A_p = 100$

3 dB correspond to $A_p = 2$

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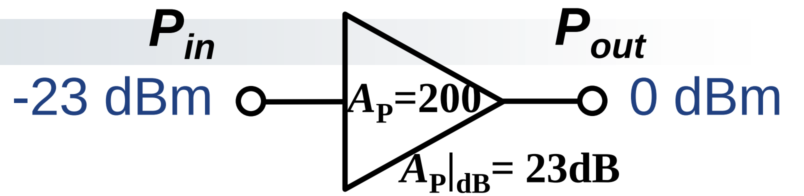
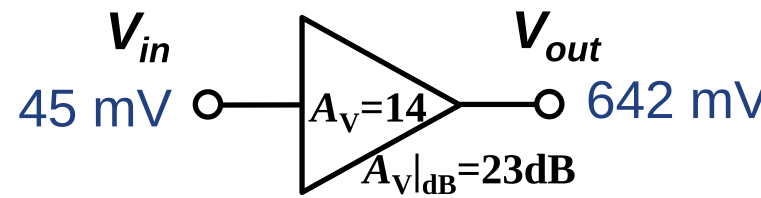
# Calculation Example – Amplifier (cont'd)

## (amplifier gain & signal amplitude)




Solution: (cont'd)

- Assume *matched* **input** and **output impedance**




$$A_P = \frac{P_{out}}{P_{in}} = \frac{V_{out}^{\,2}/R_{m0}}{V_{in}^{\,2}/R_{m0}} = \left(\frac{V_{out}}{V_{in}}\right)^2$$

$$\Rightarrow A_P\big|_{dB} = 10\log\left(\frac{V_{out}^{\,2}}{V_{in}^{\,2}}\right) = 20\log\left(\frac{V_{out}}{V_{in}}\right) = A_V\big|_{dB}$$

$$A_V\big|_{dB} = A_P\big|_{dB} = 23\,\mathrm{dB} \Rightarrow A_V = \sqrt{200} = 14$$

$$A_P = \left(\frac{V_{out}}{V_{in}}\right)^2 = \left(A_V\right)^2$$

$$A_V = \frac{V_{out}}{V_{in}} \Rightarrow V_{inpp} = \frac{V_{outpp}}{A_V} = \frac{632\,\mathrm{mV}}{14} = 45\,\mathrm{mV}$$

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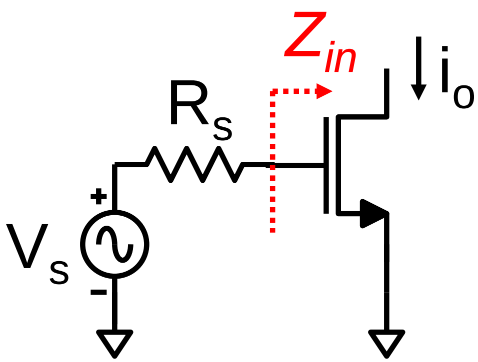
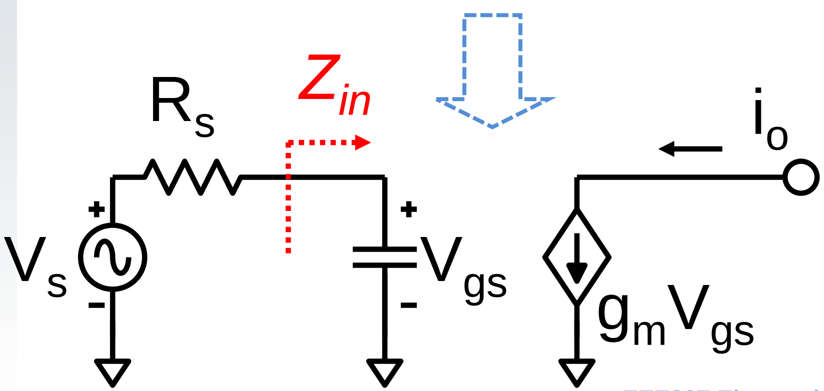
# Circuit Analysis - Amplifier Gain

(effective transconductance)

- In the common-source (CS) amplifier configuration, the **amplification gain** can be calculated first by determining the *effective* **transconductance** $G_{meff}$.




$$G_{meff} = \frac{i_o}{V_s} = \frac{g_m \cdot Z_{in}}{R_s + Z_{in}}$$




$$G_{meff} = \frac{g_m \left( \dfrac{1}{j\omega C_{gs}} \right)}{R_s + \dfrac{1}{(j\omega C_{gs})}} = \frac{g_m}{j\omega C_{gs} R_s + 1}$$

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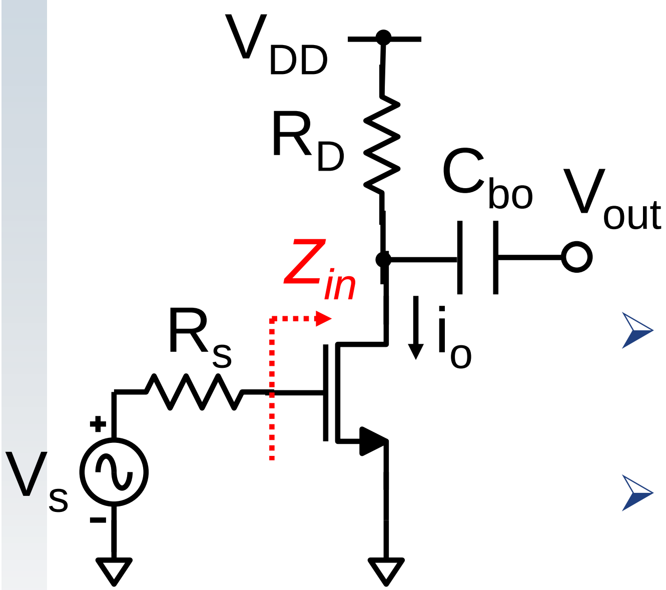
# Circuit Analysis - Amplifier Gain

(voltage gain)

- The overall **voltage gain** can then be calculated by multiplying the *effective* **transconductance** $G_{meff}$ and the equivalent output impedance.




$$A_V = G_{meff}\left(R_D // r_o\right) = \frac{g_m}{j\omega C_{gs} R_s + 1}\left(R_D // r_o\right)$$

$$r_o = \frac{1}{\lambda I_{Dbias}}$$

- $r_o$ is the ***small-signal*** **drain output resistance** of the MOS transistor.
- $\lambda$ is the **channel-length modulation coefficient** of the MOS transistor.

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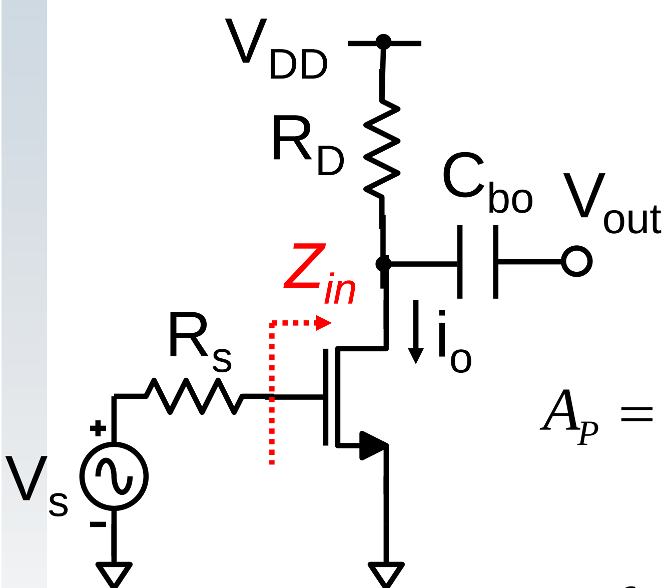
# Circuit Analysis - Amplifier Gain

(power gain from voltage gain)

- Assuming *matched* **input** and **output impedance**, the overall **power gain** would be the square of the magnitude of the **voltage gain**.




$$A_P = \left|A_V\right|^2 = \left|\frac{g_m}{j\omega C_{gs} R_s + 1}\left(R_D // r_o\right)\right|^2$$

$$A_P = \frac{g_m{}^2\left(R_D // r_o\right)^2}{1+\omega^2 (C_{gs} R_s)^2} \approx \frac{g_m{}^2\left(R_D // r_o\right)^2}{\omega^2 (C_{gs} R_s)^2} \approx \frac{\omega_T{}^2\left(R_D // r_o\right)^2}{\omega^2 R_s{}^2}$$

$$\omega_T = 2\pi f_T \approx \frac{g_m}{C_{gs} + C_{gd}} \approx \frac{g_m}{C_{gs}}$$

# Small-Signal Transistor Amplifier

(unity gain frequency $f_T$)

- From the circuit analysis of the common-source (CS) amplifier configuration, it can be inferred that the **power gain** decreases with the inverse square of the operation frequency ***f***.

$$A_P \approx \frac{g_m{}^2 (R_D // r_o)^2}{\omega^2 (C_{gs} R_s)^2} \approx \left(\frac{\omega_T}{\omega}\right)^2 \left(\frac{R_D // r_o}{R_s}\right)^2 \propto \left(\frac{f_T}{f}\right)^2$$

- The **unity gain frequency $f_T$** of the transistor is an important parameter of consideration in the design of the radio-frequency (RF) amplifiers including LNA.

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

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# Transistor Amplifiers

(trade-off of $\boldsymbol{g_m}$ & $\boldsymbol{C_{gs}}$)

- In CMOS RF integrated circuits, MOSFETs are used for making LNA circuits. For a given technology (e.g. 90nm CMOS process), a large transistor size (*W*/*L*) will cause larger $\boldsymbol{C_{gs}}$ (as well as $\boldsymbol{C_{gd}}$).

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

  - $\boldsymbol{f_T}$ does not increase with the transistor size.
  - $\boldsymbol{f_T}$ may be increased by using a larger biasing current for increasing $\boldsymbol{g_m}$. However, the improved signal gain comes at the expense of more power consumption.
  - Such a ***trade-off*** between different **performance factors** is very common in engineering areas.
  - Typically, $\boldsymbol{f_T}$ is more or less a constant in a given transistor technology.

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# Large-Signal Amplifiers

(trade-off of $g_m$ & $C_{gs}$)

- Note that $f_T$ is a parameter of interest in ***small-signal*** **amplification**.

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

- In ***large-signal*** circuits (e.g. **power amplifiers**), $f_T$ does not tell very much the maximum operation frequency of the transistors and hence how high the speed of the circuits built from the transistors.
  - In large-signal circuits with high current AC signals (1000 mA), the transistor is usually of very large size. While $g_m$ is very high (e.g. 5000 mS) in such transistors, the capacitances (e.g. $C_{gs}$ & $C_{gd}$) are also very large (e.g. > 10 pF).

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# RF Circuit Construction

(discrete transistors)

- In the construction of RF circuits using ***discrete*** transistors, choose the transistors with the specifications showing clearly that $f_T$ is well above the operation frequency of the circuit.
- Pay attention to the $g_m$ value(s) given in the transistor's data sheets and the corresponding biasing conditions (e.g. voltage & current).
  - Find out also the critical capacitances of the transistors ($C_{gs}$ in MOSFETs and $C_{be}$ in BJTs).
  - Always start with hand calculations of e.g. the amplifier gain before circuit construction.
  - Make good use of approximation!

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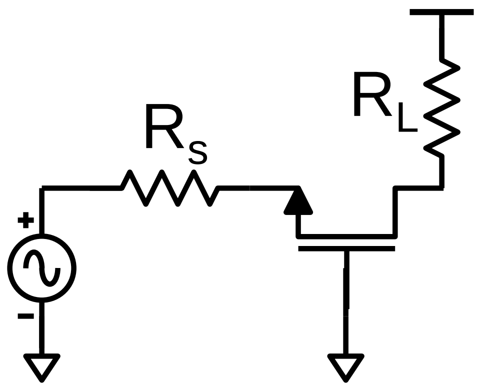
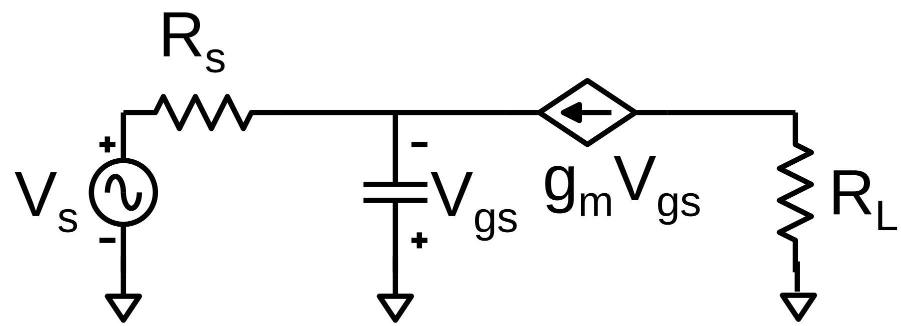
# Circuit Analysis – CG Amplifier
## (effective transconductance)

- In the common-gate (CG) amplifier configuration, similar techniques can be used by determining the *effective* **transconductance** $G_{meff}$.




$$G_{meff} = \frac{i_o}{V_s} = \frac{-g_m}{1 + g_m R_s + j\omega C_{gs} R_s}$$

$$A_V = G_{meff}(R_L // r_o) = \frac{-g_m (R_L // r_o)}{1 + g_m R_s + j\omega C_{gs} R_s}$$

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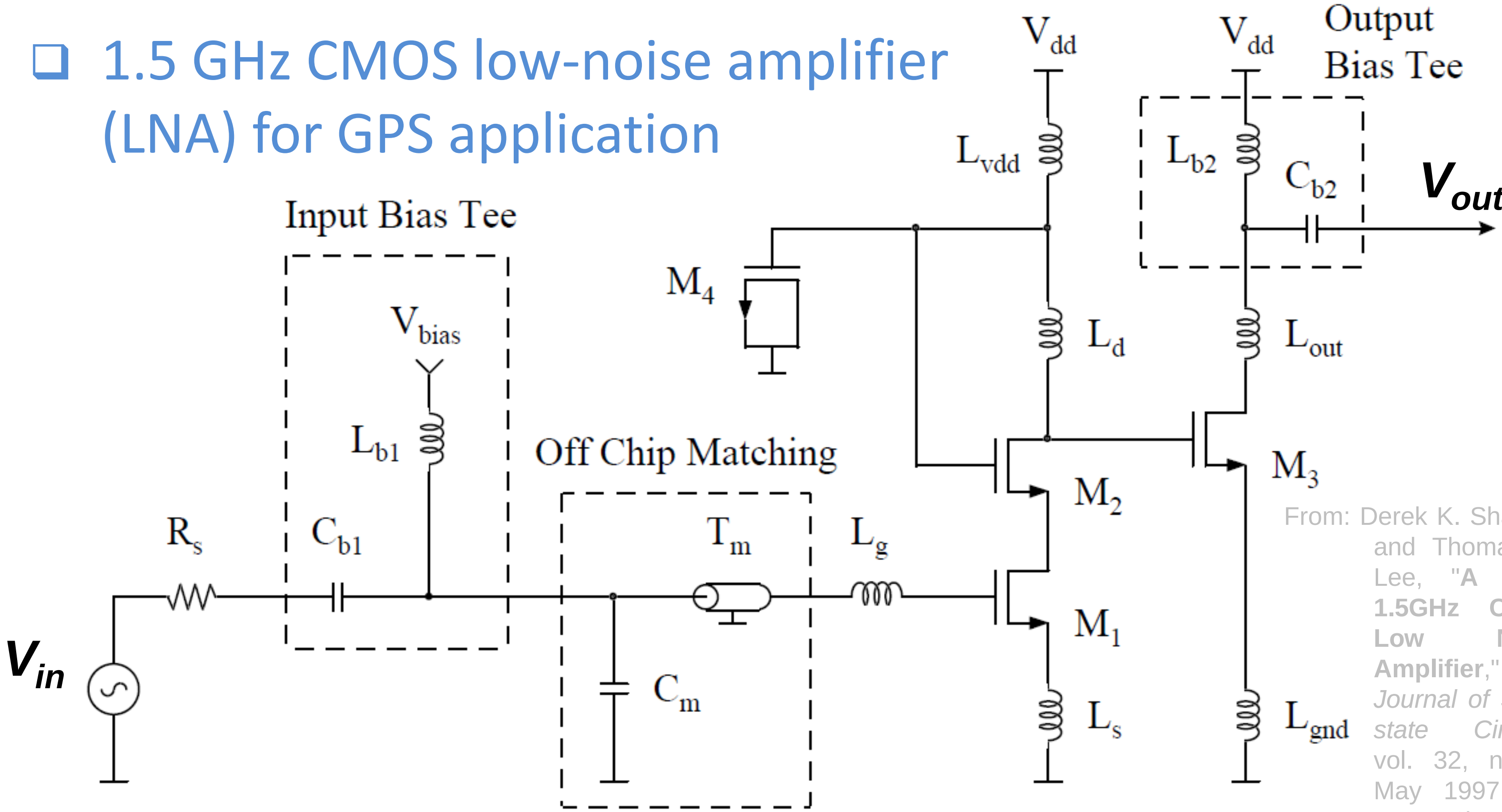
# LNA Example

(3-stage transistor amplifier)

- 1.5 GHz CMOS low-noise amplifier (LNA) for GPS application



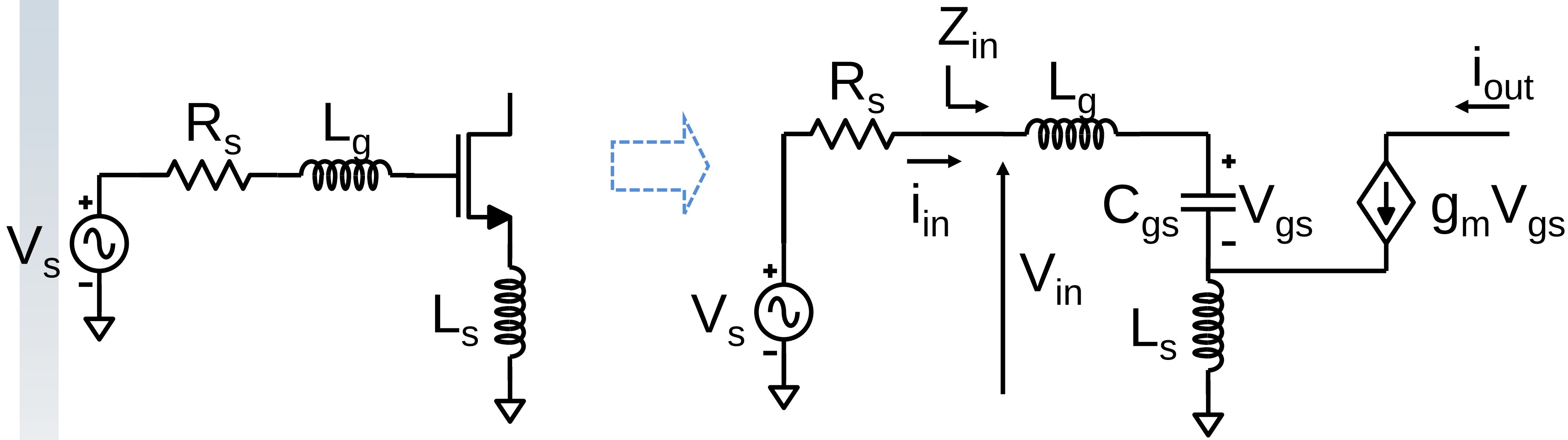

From: Derek K. Shaeffer and Thomas H. Lee, "**A 1.5V, 1.5GHz CMOS Low Noise Amplifier**," *IEEE Journal of Solid-state Circuits*, vol. 32, no. 5, May 1997 (pp. 745-759).

- CS, CG and CS amplifiers connected together
  - Note the source-degeneration CS configuration.

# Circuit Analysis – LNA

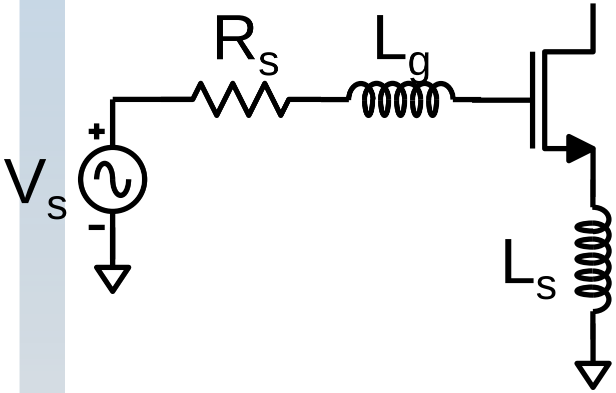
(inductor source-degeneration)

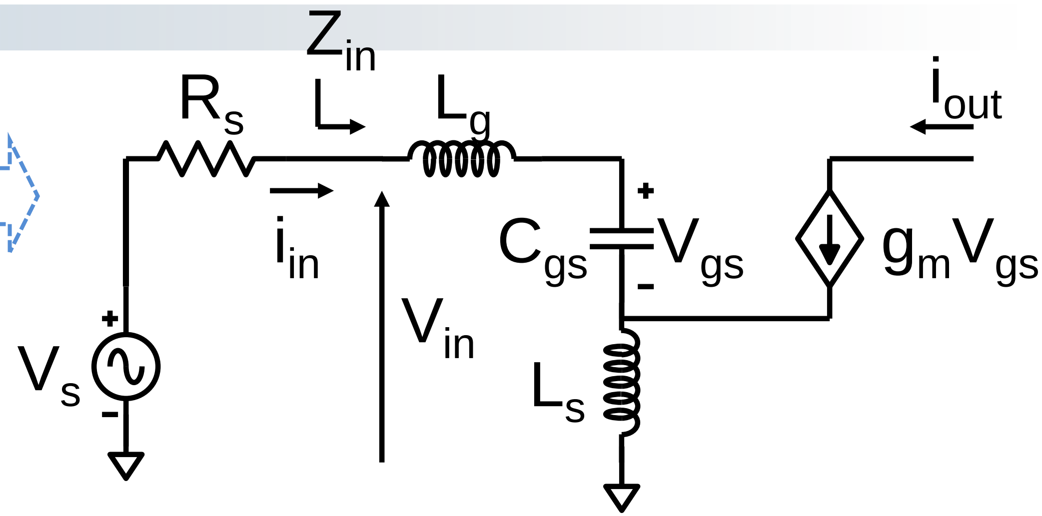
- In the CS LNA configuration with inductor source-degeneration, similar circuit analysis can be applied in the ***small-signal*** **equivalent circuit**.



# Circuit Analysis – LNA

(inductor source-degeneration)




- The *effective* **transconductance** $G_{meff}$ may be determined using the short-cut formula.

$$G_{meff} = \frac{I_{out}}{V_s} = \frac{g_m / (j\omega C_{gs})}{R_s + Z_{in}}$$

$$= \frac{g_m}{1 + j\omega(R_s C_{gs} + g_m L_s) - \omega^2 C_{gs}(L_g + L_s)}$$

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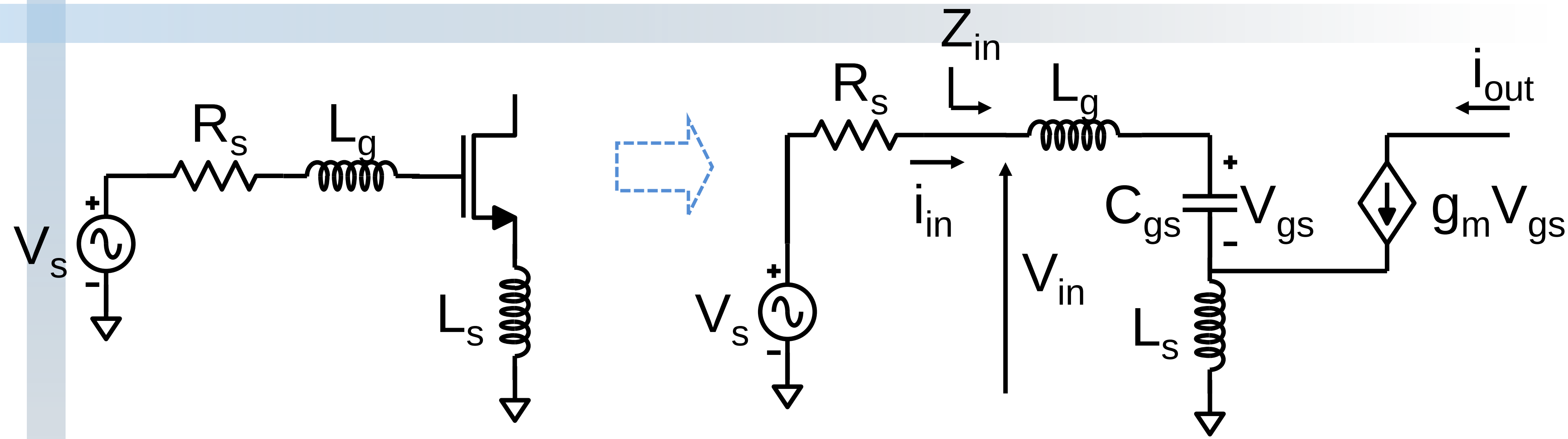
# Circuit Analysis – LNA

## (inductor source-degeneration)




$$V_{in} = I_{in}(j\omega L_g) + I_{in}\frac{1}{j\omega C_{gs}} + (I_{in} + g_m V_{gs})(j\omega L_s)$$

$$= I_{in}(j\omega L_g) + I_{in}\frac{1}{j\omega C_{gs}} + (I_{in} + g_m I_{in}\frac{1}{j\omega C_{gs}})(j\omega L_s)$$

$$= I_{in}\left[\boxed{j\omega(L_g + L_s) + \frac{1}{j\omega C_{gs}} + \frac{g_m L_s}{C_{gs}}}\right] \leftarrow Z_{in}$$

- The input impedance can be optimised for matching e.g. 50Ω.

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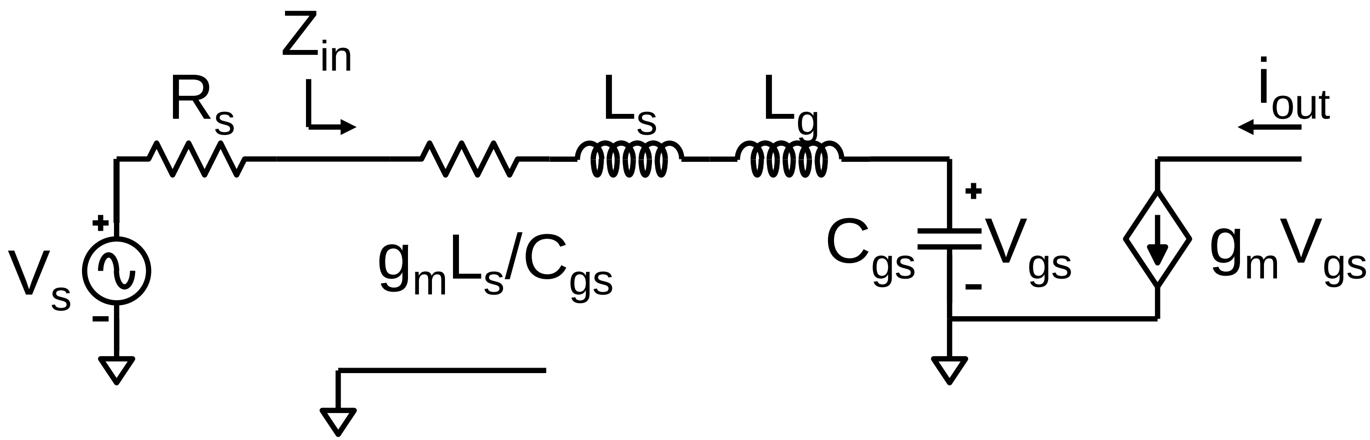
# Circuit Analysis – LNA

## (input impedance matching)




$$Z_{in} = j\omega(L_g + L_s) + \frac{1}{j\omega C_{gs}} + \frac{g_m L_s}{C_{gs}}$$

$$\omega_0^2 = \frac{1}{(L_g + L_s)C_{gs}}$$

$$\frac{g_m L_s}{C_{gs}} = R_s$$

- The input impedance matching can be achieved by the use of inductors by LC resonance.

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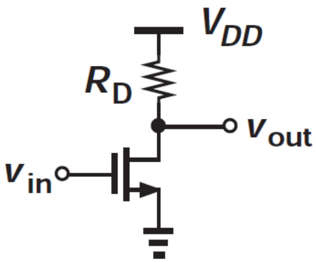
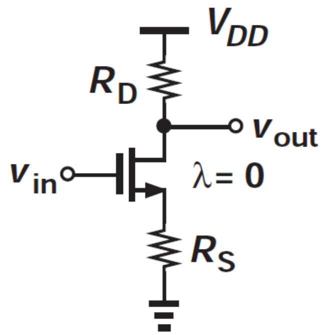
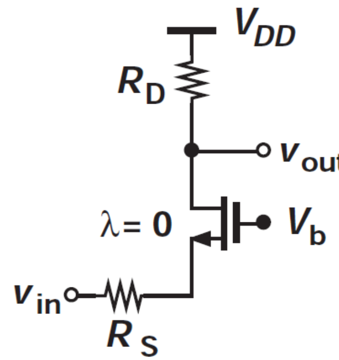
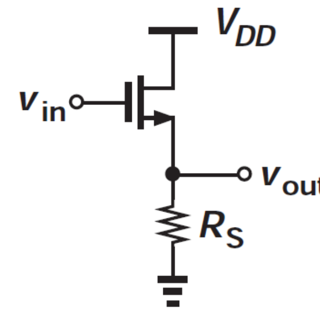
# Circuit Analysis Tricks

## (quick formulas in MOSFETs)




$$A_v = -g_m\left(R_D // r_o\right)$$

$$A_v = -\frac{g_m R_D}{1 + g_m R_S}$$

$$A_v = \frac{g_m R_D}{1 + g_m R_S}$$

$$A_v = \frac{g_m\left(R_S // r_o\right)}{1 + g_m\left(R_S // r_o\right)}$$

From: Behzad Razavi, *Fundamentals of Microelectronics*, © 2013 Wiley, USA.

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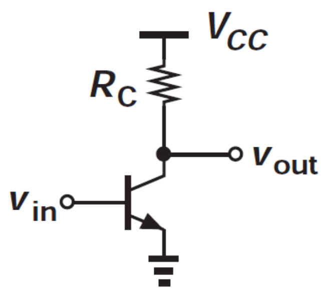
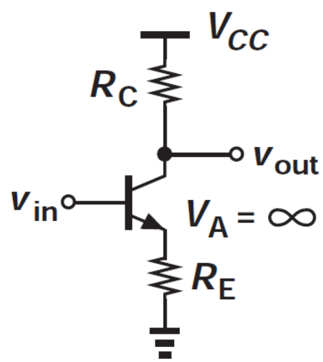
# Circuit Analysis Tricks

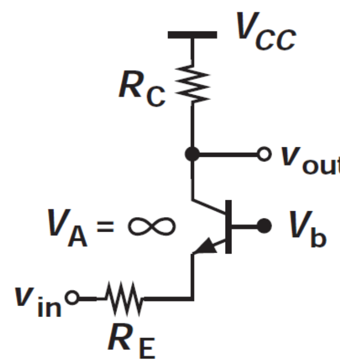
## (quick formulas in BJTs)



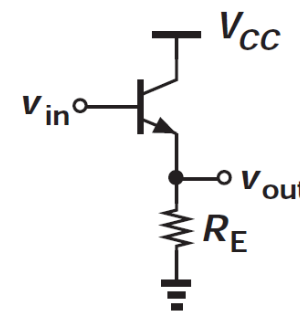

$$A_v = -g_m\left(R_C // r_o\right)$$




$$A_v = -\frac{g_m R_C}{1+g_m R_E}$$




$$A_v = \frac{g_m R_C}{1+g_m R_E}$$




$$A_v = \frac{g_m\left(R_E // r_o\right)}{1+g_m\left(R_E // r_o\right)}$$

From: Behzad Razavi, *Fundamentals of Microelectronics*, © 2013 Wiley, USA.

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