EE230-02 RFIC II
Fall 2018

Lecture 6: LNA1

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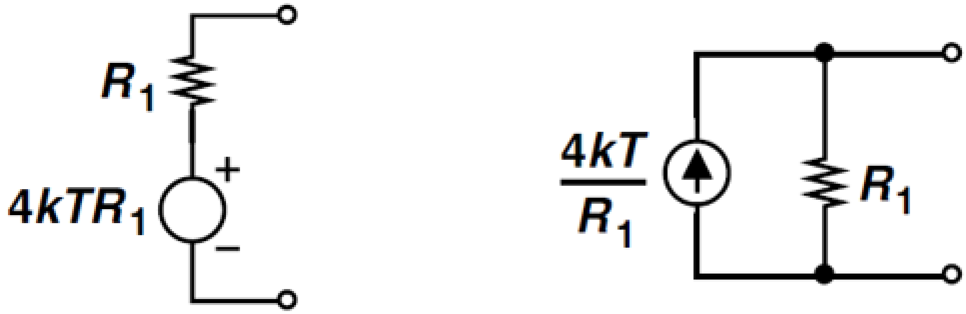
ENG-259

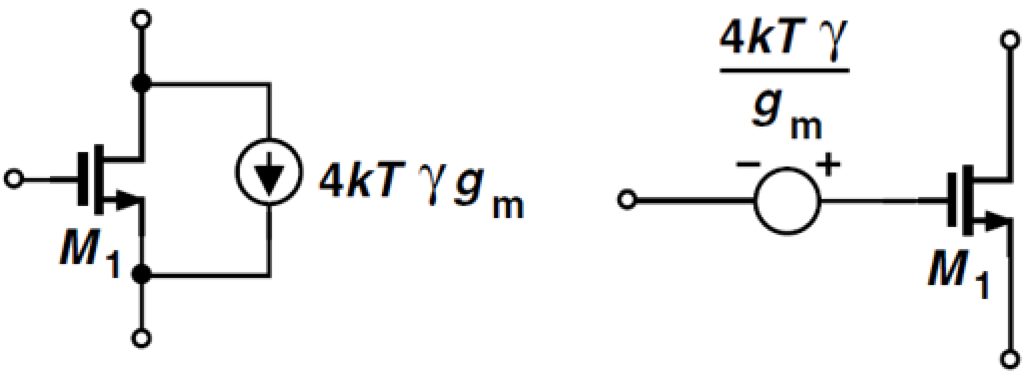
LNA General Considerations

- Noise Figure
- Gain
- Input Return Loss
- Stability
- Linearity
- Bandwidth
- Power Dissipation

Noise Review



Resistor Noise

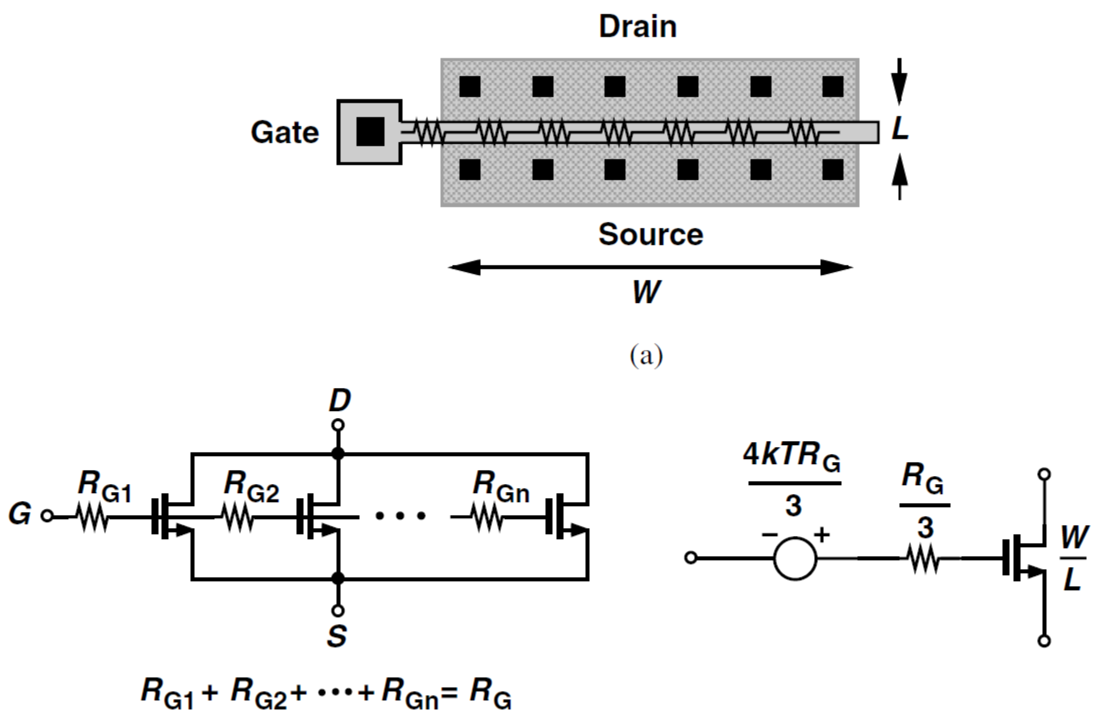


MOSFET Thermal Noise

$$\overline{V_n^2} = \frac{K}{WLC_{ox}} \frac{1}{f}$$

MOSFET 1/f Noise

Gate Resistance



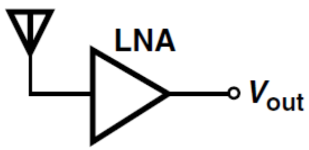
(a)

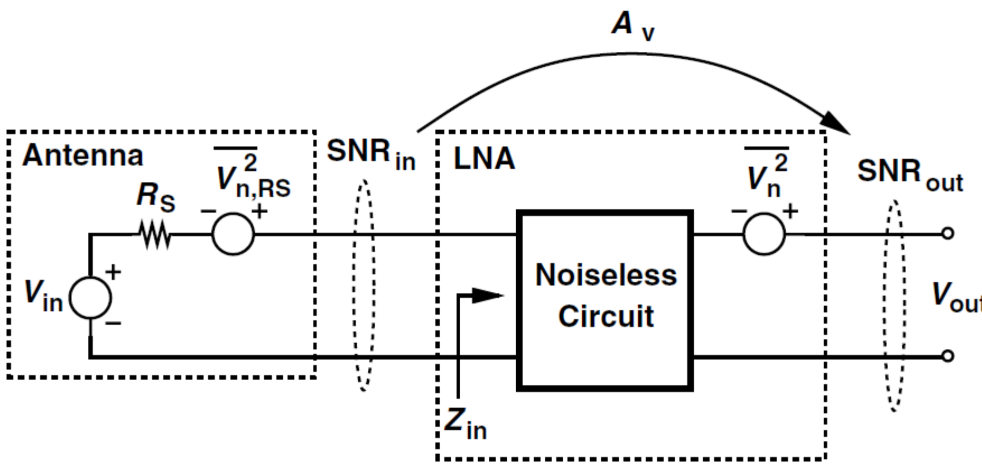
(b)

(c)

Design for $\boxed{4kT\frac{R_G}{3} \ll \frac{4kT\gamma}{g_m}}$

Noise Figure





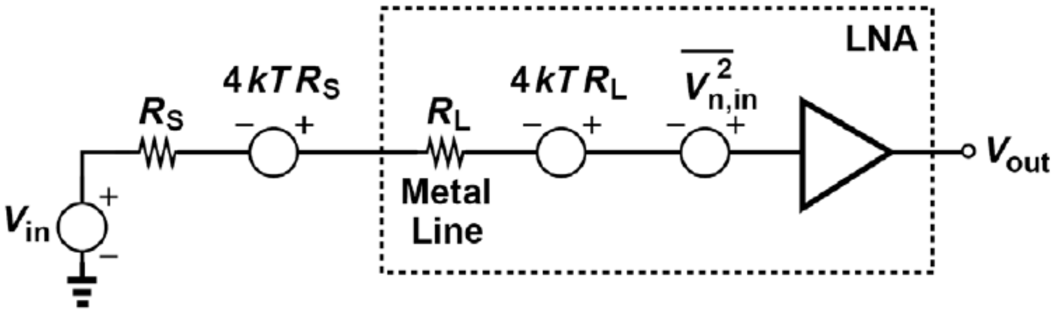
$$\mathrm{NF} = \frac{SNR_{in}}{SNR_{out}} \qquad SNR_{in} = \frac{|\alpha|^2 V_{in}^2}{|\alpha|^2 \overline{V_{RS}^2}} \qquad SNR_{out} = \frac{V_{in}^2 |\alpha|^2 A_v^2}{\overline{V_{RS}^2}|\alpha|^2 A_v^2 + \overline{V_n^2}}$$

$$\mathrm{NF} = \frac{V_{in}^2}{4kTR_S} \cdot \frac{\overline{V_{RS}^2}|\alpha|^2 A_v^2 + \overline{V_n^2}}{V_{in}^2 |\alpha|^2 A_v^2} = \frac{1}{4kTR_S} \cdot \frac{\overline{V_{n,out}^2}}{A_0^2} = \frac{\textit{Total Output Noise}}{\textit{Output Noise due to Source}}$$

$$= \frac{\textit{Noise due to Source} + \textit{Noise due to Circuit}}{\textit{Noise due to Source}} = 1 + \frac{\textit{Noise due to Circuit}}{\textit{Noise due to Source}}$$

Metal Resistance on NF

A student lays out an LNA and connects its input to a pad through a metal line 200 μm long. In order to minimize the input capacitance, the student chooses a width of 0.5 μm for the line. Assuming a noise figure of 2 dB for the LNA and a sheet resistance of 40 mΩ/ □ for the metal line, determine the overall noise figure.



$$\begin{aligned}
\mathrm{NF_{tot}} &= 1 + \frac{\overline{V_{n,in}^2} + 4kTR_L}{4kTR_S} \\
&= 1 + \frac{\overline{V_{n,in}^2}}{4kTR_S} + \frac{R_L}{R_S} \\
&= \mathrm{NF_{LNA}} + \frac{R_L}{R_S},
\end{aligned}$$

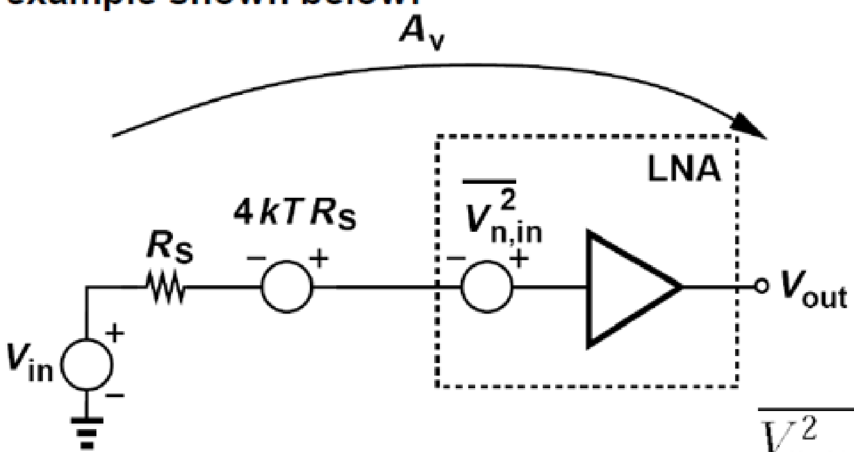
where NF_{LNA} denotes the noise figure of the LNA without the line resistance. Since NF_{LNA} = 2 dB ≡ 1.58 and R_L = (200/0.5) × 40 mΩ/□ = 16 Ω, we have

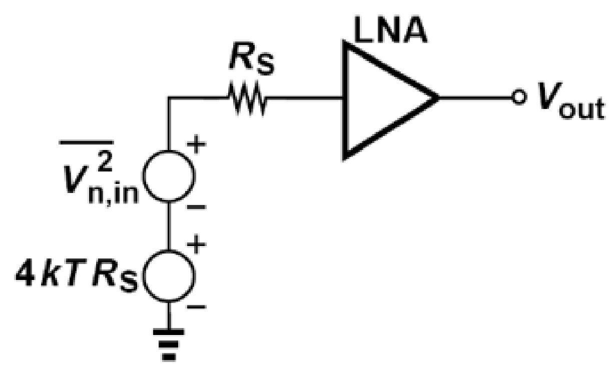
$$\mathrm{NF_{tot}} = 2.79\ \mathrm{dB}$$

Noise Figure

- The noise figure of the LNA directly adds to that of the receiver.

It is expected that the LNA contributes 2 to 3 dB of noise figure. Consider the simple example shown below:

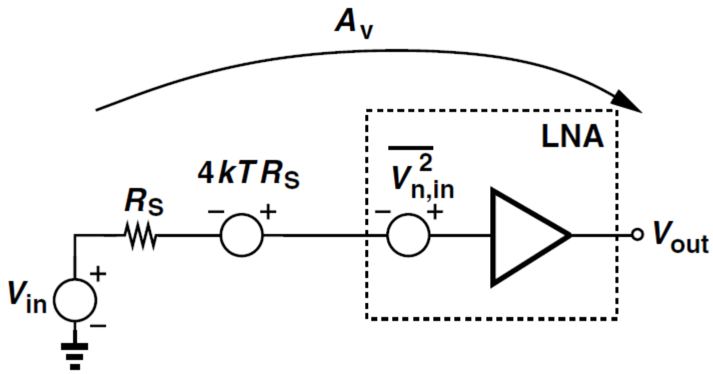


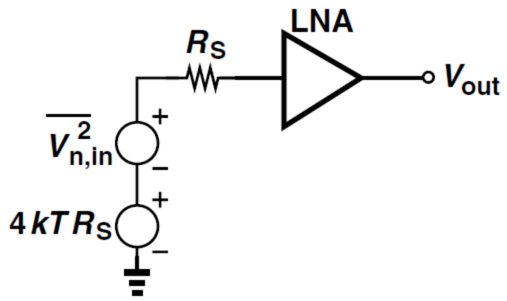


$$
\begin{aligned}
\mathrm{NF} &= \frac{\overline{V_{n,out}^2}}{A_v^2} \cdot \frac{1}{4kTR_S} \\
&= 1 + \frac{\overline{V_{n,in}^2}}{4kTR_S}.
\end{aligned}
$$

Noise Figure

How much is the noise voltage for the 2 dB NF?





$$\mathrm{NF} = \frac{\overline{V_{n,out}^2}}{A_v^2} \cdot \frac{1}{4kTR_S}$$

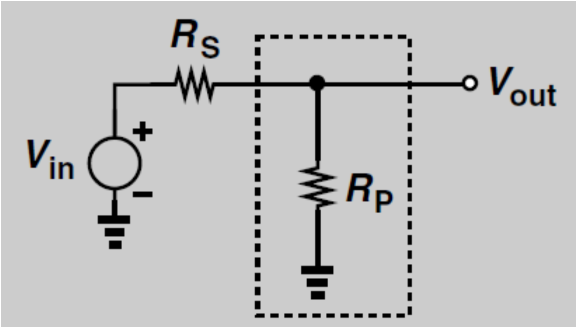
$$= 1 + \frac{\overline{V_{n,in}^2}}{4kTR_S}.$$

2 dB = 1.58

$$\frac{\overline{V_{n,in}^2}}{4kTR_S} = 0.58, \quad Rs = 50\Omega$$

$$\Rightarrow \quad \sqrt{\overline{V_{n,in}^2}} = 0.696\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$$

Noise Figure Calculation Example



Total output noise

$$\overline{V_{n,out}^2} = 4kT\,(R_s||R_p)$$

Gain

$$A_v = \frac{V_{out}}{V_{in}} = \frac{R_p}{R_s + R_p}$$

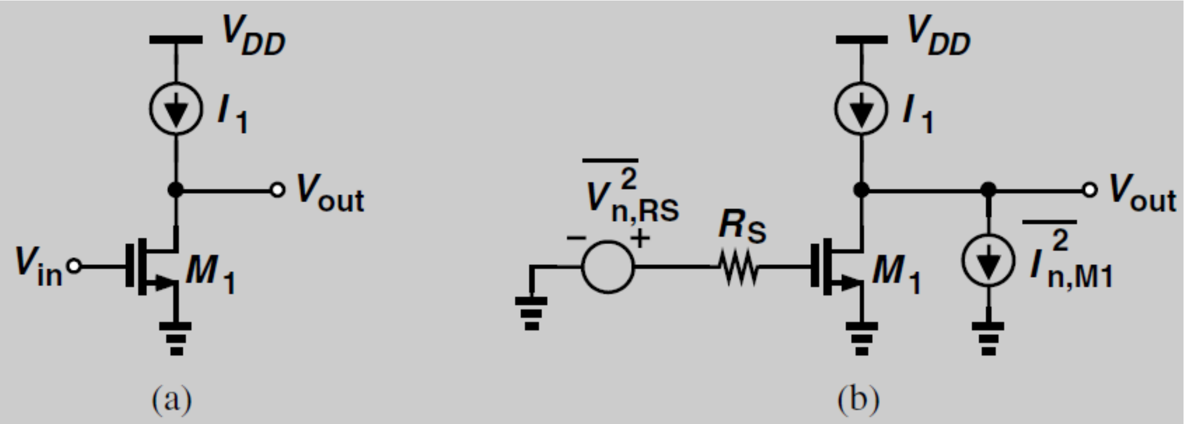
$$NF = \frac{Total\ Output\ Noise}{Output\ Noise\ due\ to\ Source}$$

$$= \frac{4kT\,(R_s||R_p)}{4kTR_s \cdot {A_v}^2} = \frac{\dfrac{R_s \cdot R_p}{R_s + R_p}}{R_s \cdot \left(\dfrac{R_p}{R_s + R_p}\right)^2} = \frac{R_s + R_p}{R_p} = 1 + \frac{R_s}{R_p}$$

The NF is therefore minimized by *maximizing* R_P. Note that if $R_P = R_S$ to provide impedance matching, then the NF cannot be less than 3 dB.

Noise Figure Calculation Example

Determine the noise figure of the common-source stage shown below with a source impedance R_S. Neglect the capacitances and flicker noise of M1 and assume I_1 is ideal.

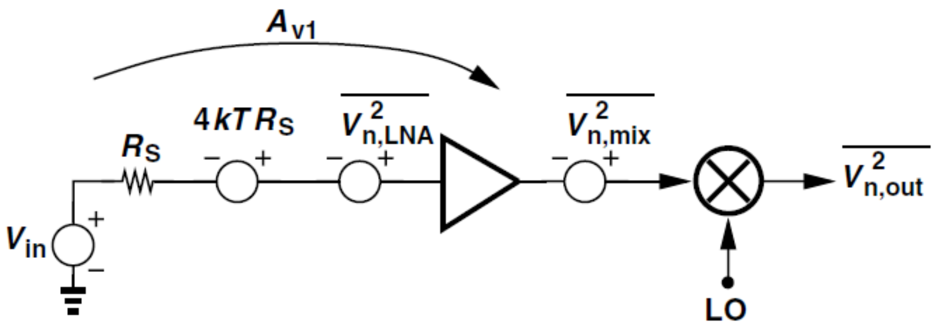


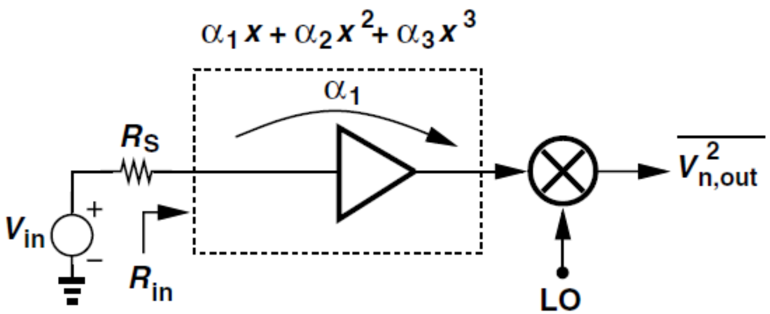
$$NF = \frac{Total\ Output\ Noise}{Output\ Noise\ due\ to\ Source}$$

$$= \frac{(4kT\gamma g_m)r_o^2 + 4kTR_s(g_m r_o)^2}{4kTR_s(g_m r_o)^2} \quad = \frac{\gamma}{g_m R_s} + 1$$

Gain of LNA

- Must be large enough to minimize noise contributed by mixer
- Trade with IP3





$$NF_{tot} = NF_1 + \frac{NF_2 - 1}{A_{P1}}$$

$$\frac{1}{\mathrm{IP}^2_{3,\mathrm{tot}}} = \frac{1}{\mathrm{IP}^2_{3,\mathrm{LNA}}} + \frac{\alpha_1^2}{\mathrm{IP}^2_{3,\mathrm{mixer}}}$$

Cascade IP3 Example

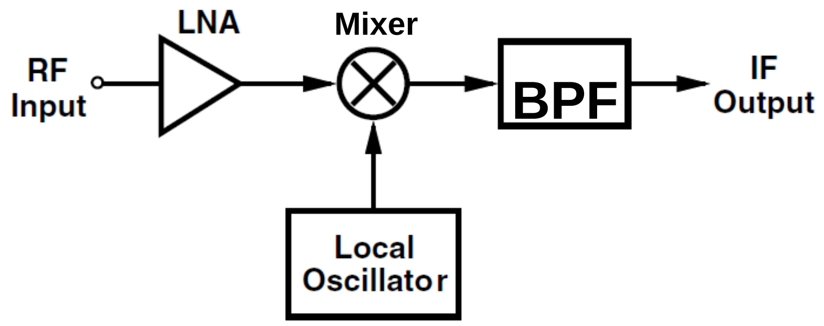
<u>LNA</u>

IP3 = -10 dBm

Gain = 20 dB

<u>Mixer</u>

IP3 = +4 dBm



Which stage limits the IP3 of the cascade more?

$$\frac{1}{\mathrm{IP}_{3,\mathrm{tot}}^2} = \frac{1}{\mathrm{IP}_{3,\mathrm{LNA}}^2} + \frac{\alpha_1^2}{\mathrm{IP}_{3,\mathrm{mixer}}^2}$$

$$\boldsymbol{IP3, LNA = -10\ dBm}$$

$$\boldsymbol{\frac{IP3, Mixer}{\alpha_1} = -16\ dBm}$$

Mixer limits the overall IP3 more.

Input Return Loss

- The quality of the input match is expressed by the input "return loss," defined as the reflected power divided by the incident power. For a source impedance of R_S, the return loss is given by:

$$\Gamma = \left| \frac{Z_{in} - R_S}{Z_{in} + R_S} \right|^2$$

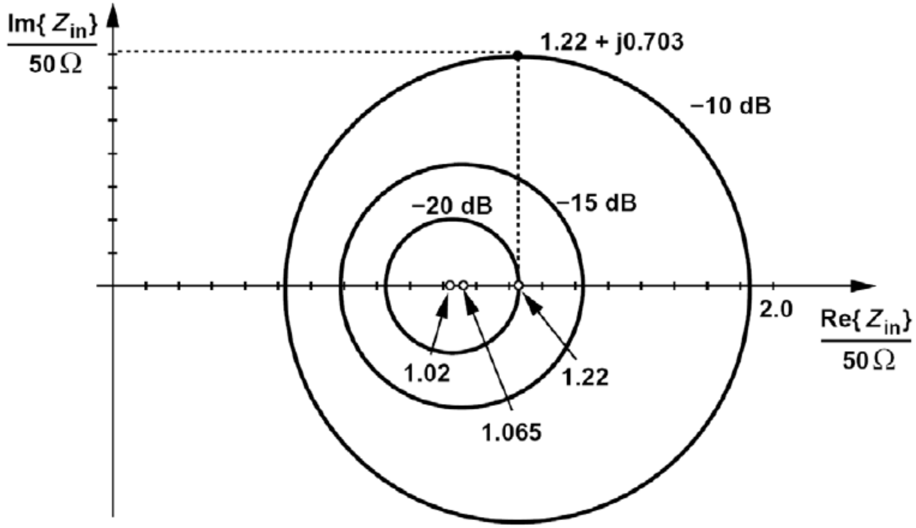


Figure above plots contours of constant Γ in the Z_{in} plane. Each contour is a circle with its center shown.

- **An input return loss of -10 dB signifies that one tenth of the power is reflected → A typically acceptable value.**
- **In practice, a Γ of about -15 dB is targeted so as to allow margin for package parasitics, etc.**

Stability

Stern Stability Factor

$$K = \frac{1 + |\Delta|^2 - |S_{11}|^2 - |S_{22}|^2}{2|S_{21}||S_{12}|}$$

$$\Delta = S_{11}S_{22} - S_{12}S_{21}$$

If $K > 1$ and $\Delta < 1$, then the circuit is unconditionally stable

- LNAs can be stabilized by maximizing their reverse isolation.
- A high reverse isolation is also necessary for suppressing the LO leakage to the input of the LNA.

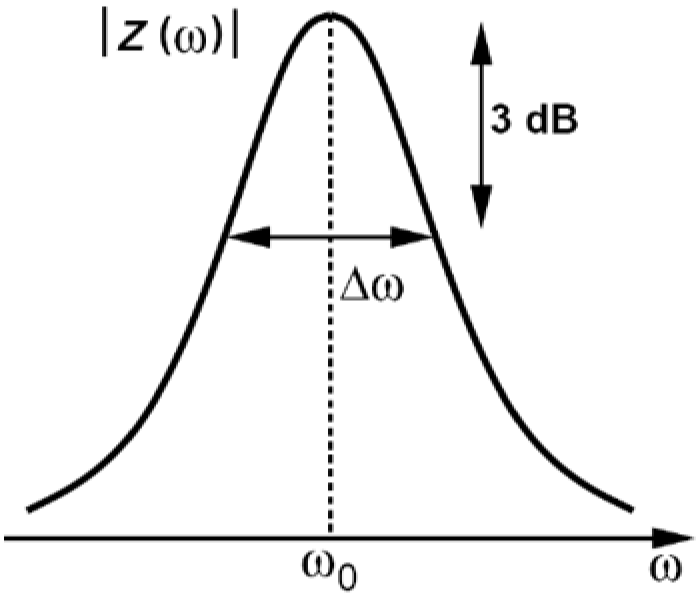
Bandwidth

- The LNA must provide a relatively flat response for the frequency range of interest, preferably with less than 1 dB of gain variation.
- The LNA -3dB bandwidth must therefore be substantially larger than the actual band so that the roll-off at the edges remains below 1 dB.

An 802.11a LNA must achieve a -3-dB bandwidth from 5 GHz to 6 GHz. If the LNA incorporates a second-order *LC* tank as its load, what is the maximum allowable tank *Q*?

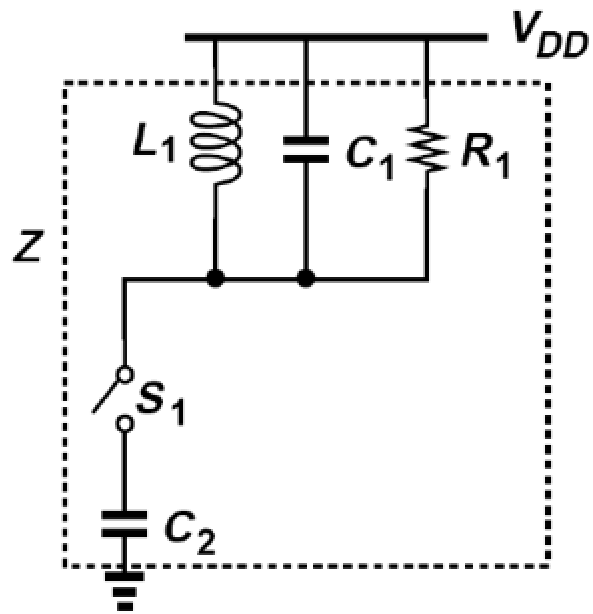
Fractional bandwidth

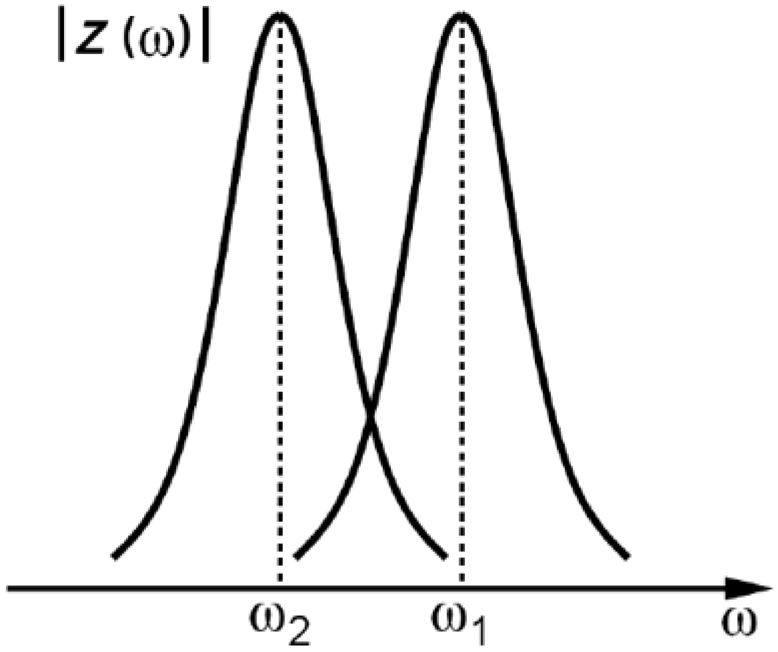
$$\frac{\Delta\omega}{\omega_o} = \frac{1G}{5.5G} = \frac{1}{5.5} = \frac{1}{Q}$$



Band Switching

LNA designs that must achieve a relatively large fractional bandwidth may employ a mechanism to *switch* the center frequency of operation.



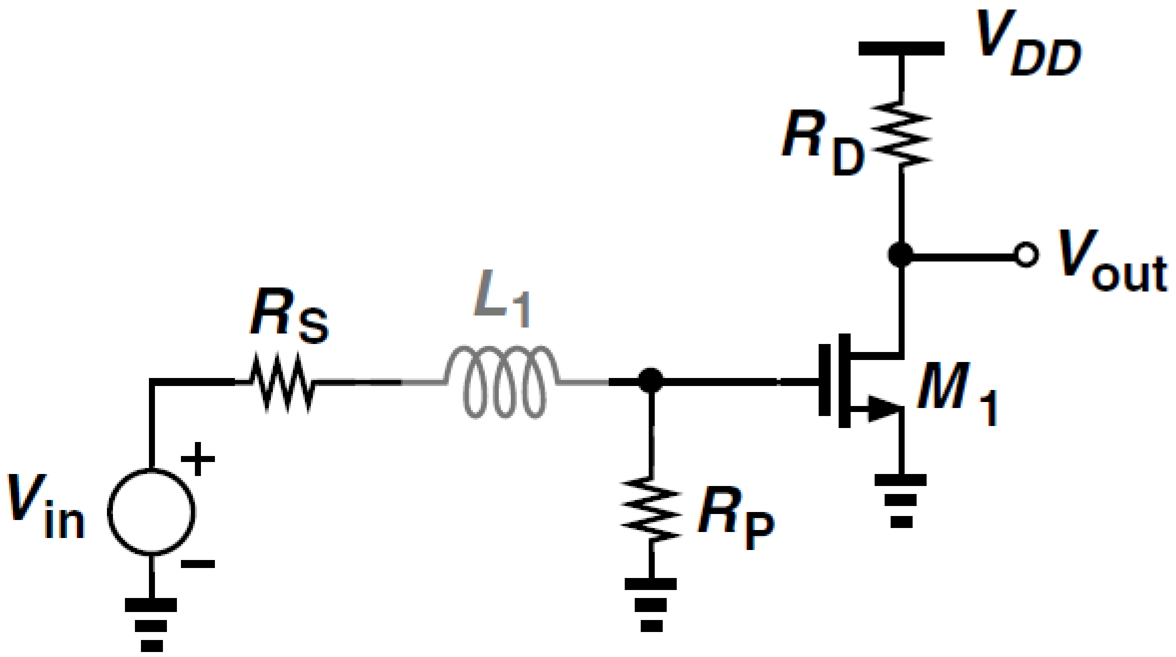


LNA Topologies

Common–Source Stage with	Common–Gate Stage with	Broadband Topologies
▪ Inductive Load ▪ Resistive Feedback ▪ Cascode, Inductive Load, Inductive Degeneration	▪ Inductive Load ▪ Feedback ▪ Feedforward ▪ Cascode and Inductive Load	▪ Noise–Cancelling LNAs ▪ Reactance–Cancelling LNAs

Mainly Focus on this!

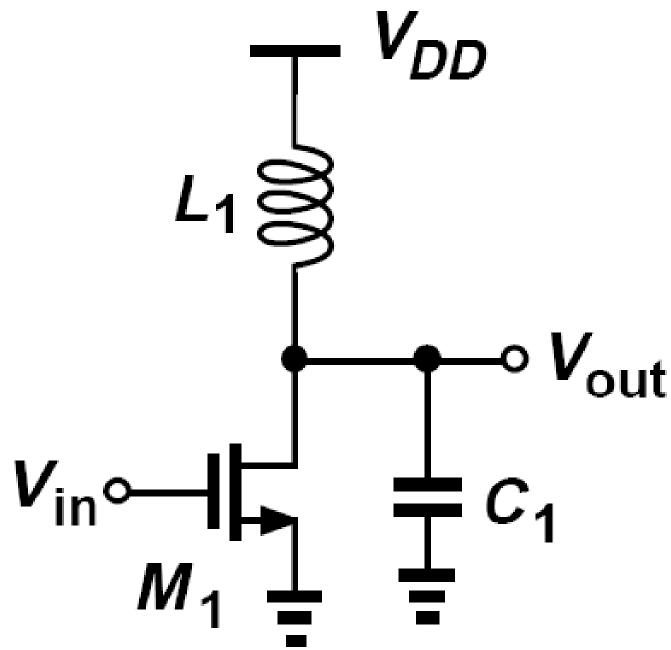
Resistor Input Matching



For $R_P \approx R_S$, the NF exceeds 3 dB—perhaps substantially.

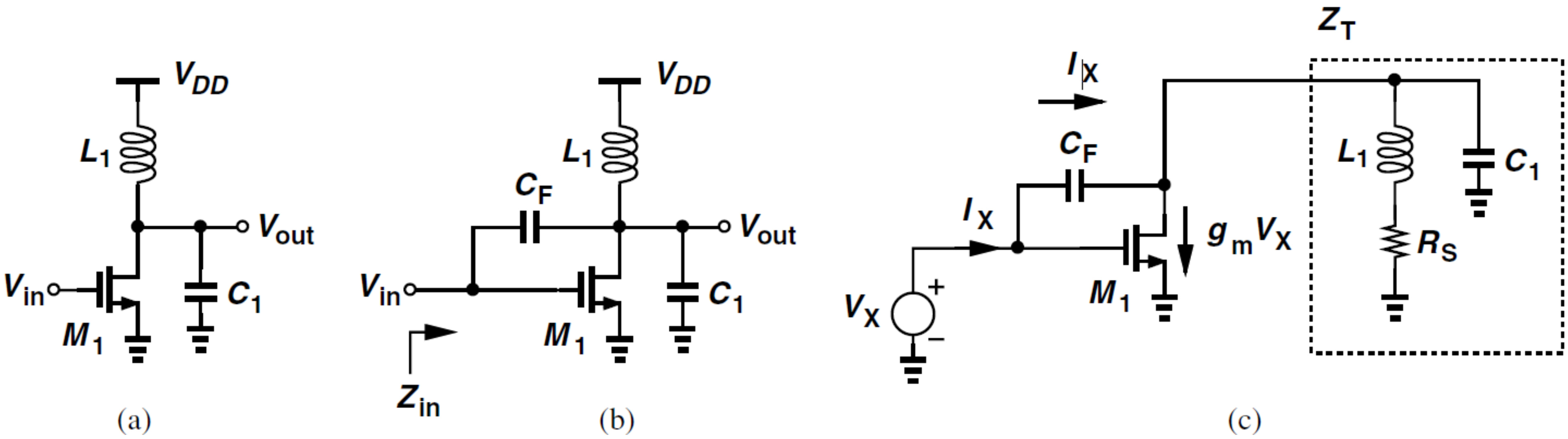
Common Source with Inductive Load

- Can operate with very low supply voltages
- L_1 resonates with the total capacitance at the output node, affording a much higher operation frequency than does the resistively-loaded counterpart



How about the input matching?

Common Source with Inductive Load



$$Z_{in}(s) = \frac{V_X}{I_X} = \frac{L_1(C_1 + C_F)s^2 + R_S(C_1 + C_F)s + 1}{[L_1 C_1 s^2 + (R_S C_1 + g_m L_1)s + 1 + g_m R_S]C_F s}$$

While providing the possibility of Re{Z_{in}} = 50 Ω at the frequency of interest, the feedback capacitance C_F gives rise to a negative input resistance at other frequencies, potentially causing instability.