EE230-02 RFIC II
Fall 2018

Lecture 15: Midterm Review

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ENG-259

Midterm Exam

- **Oct. 16, Tuesday 4:30 PM**
- **One-page Aid sheet on Front side only allowed**
- **Bring 2 hard copies of your Aid sheet**
  - **Use one copy during the exam**
  - **Write your name and submit another copy for extra 5 points**
- **Bring a Calculator**

Topics

1. RF Basics
2. Matching Network
3. Noise Factor of the circuit
4. Resonant circuit and Q
5. Noise Figure and IP3 of Cascade Circuits
6. LNA design

Quiz on RF Basic

Calculate the peak-to-peak voltage swing for 0 dBm signal in 50-ohm system.

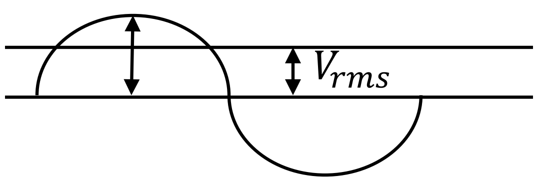
$$0\ dBm \leftrightarrow 1mW$$

$$Power = \frac{{V_{rms}}^2}{R} = \frac{{V_{rms}}^2}{50} = 0.001$$

$$V_{rms} = \sqrt{0.05} = 0.224$$

$$V_{pk-pk} = 2(0.224\ \cdot \sqrt{2}) = 0.632V$$

$$V_{pk} = V_{rms} \cdot \sqrt{2}$$



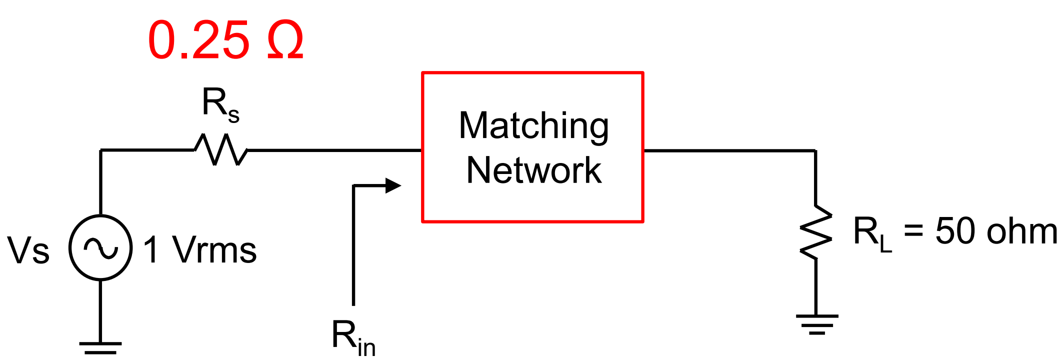
Quiz Solution

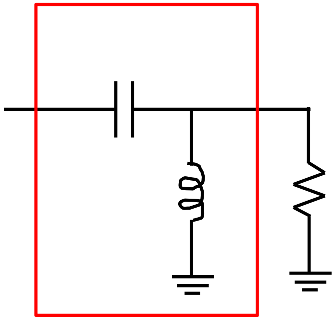
The RF amplifier shown below produces Vs = 1 Vrms signal with a source resistance of Rs.
We want to deliver 1 Watt of average power to an antenna with 50-ohm load for GSM 1.8GHz application.

1. What should be the value of Rs when a matching network is inserted to ensure Rin = Rs for maximum power transfer at the frequency of interest?

2. Suggest a circuit you have to put in the matching network shown below.

$$Power = \frac{{V_{rms}}^2}{R_s} = \frac{0.5^2}{R_s} = 1 \Longrightarrow R_s = 0.5^2 = 0.25$$

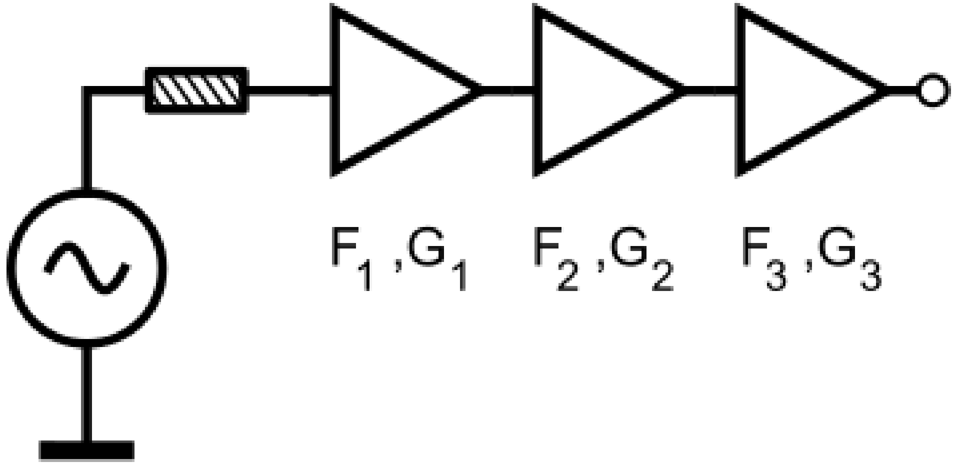




Friis Formula

Friis's formula is used to calculate the total noise factor of a cascade of stages, each with its own noise factor and gain where F_i and G_i are the noise factor and available power gain.

Note that both magnitudes are expressed as ratios, not in decibels.

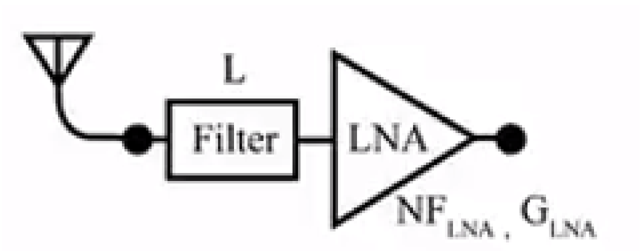


$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \ldots + \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}}$$

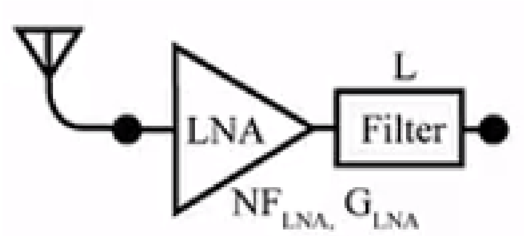
Noise Figure of Cascaded Stages

Example:
$L = 1\text{ dB} = 1.25$
$G_{LNA} = 10\text{ dB} = 10$
$NF_{LNA} = 3\text{ dB} = 2$

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1}$$



$$\begin{aligned} NF_{tot} &= L + (NF_{LNA} - 1) \cdot L \\ &= 1.25 + 1\text{x}1.25 = 2.5 = 4\text{dB} \end{aligned}$$

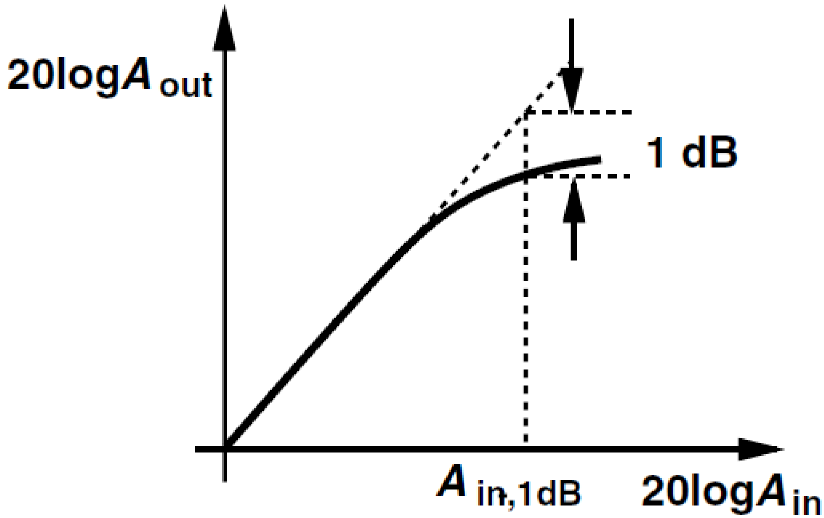


$$\begin{aligned} NF_{tot} &= NF_{LNA} + (L - 1) / G_{LNA} \\ &= 2 + 0.25/10 = 2.025 = 3dB \end{aligned}$$

1. Place those components with lowest NF and highest gain at earlier stages
2. Avoid lossy components at the input

Gain Compression

$$y(t) = \frac{\alpha_2 A^2}{2} + \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right)\cos\omega t + \frac{\alpha_2 A^2}{2}\cos 2\omega t + \frac{\alpha_3 A^3}{4}\cos 3\omega t$$



$$20\log\left|\alpha_1 + \frac{3}{4}\alpha_3 A_{in,1dB}^2\right| = 20\log|\alpha_1| - 1\text{ dB}$$

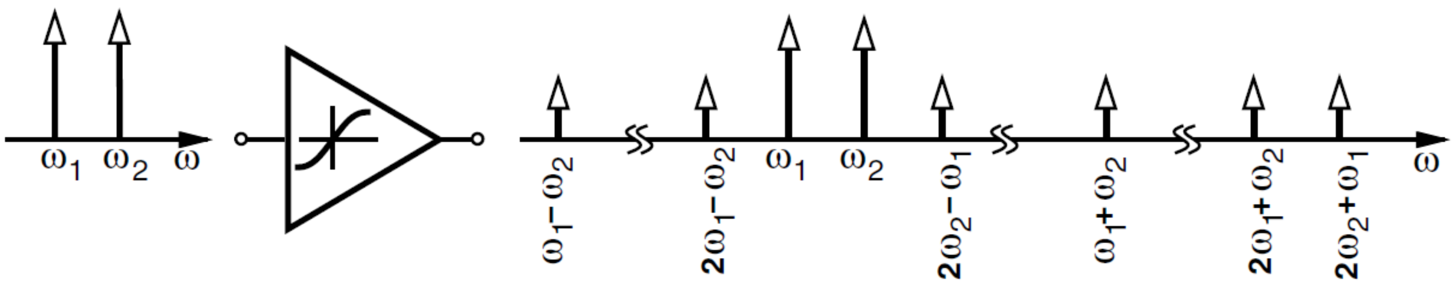
$$A_{in,1dB} = \sqrt{0.145\left|\frac{\alpha_1}{\alpha_3}\right|}$$

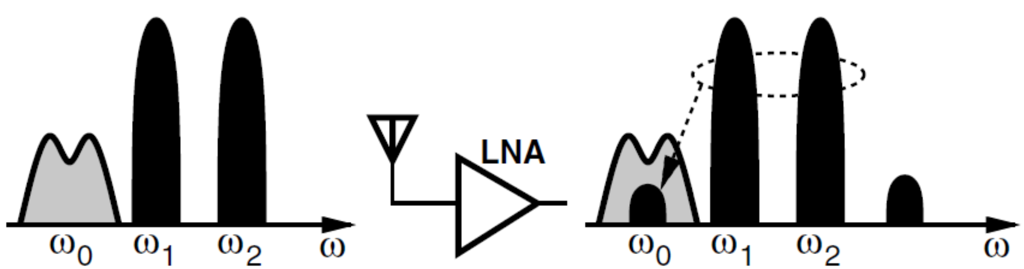
Intermodulation

$$y(t) \approx \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

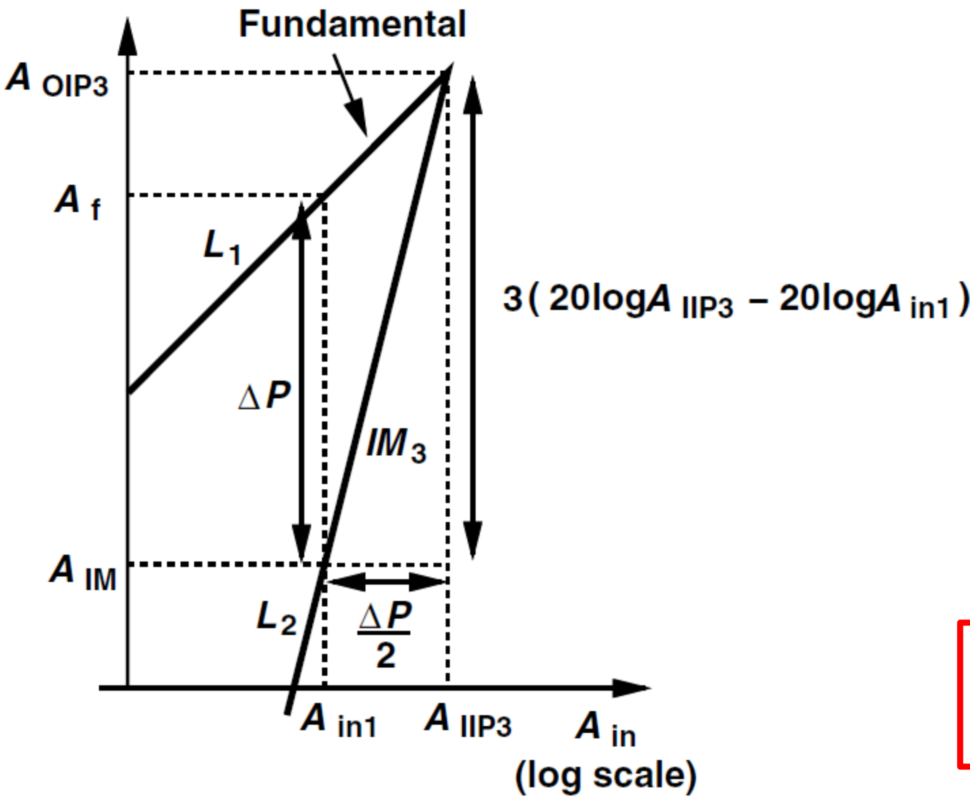
$$x(t) = A_1 \cos \omega_1 t + A_2 \cos \omega_2 t$$

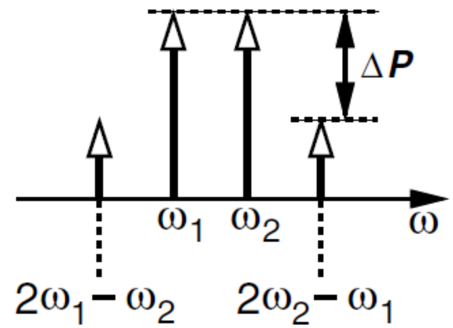
$$y(t) = \alpha_1 (A_1 \cos \omega_1 t + A_2 \cos \omega_2 t) + \alpha_2 (A_1 \cos \omega_1 t + A_2 \cos \omega_2 t)^2 + \alpha_3 (A_1 \cos \omega_1 t + A_2 \cos \omega_2 t)^3.$$





IP3

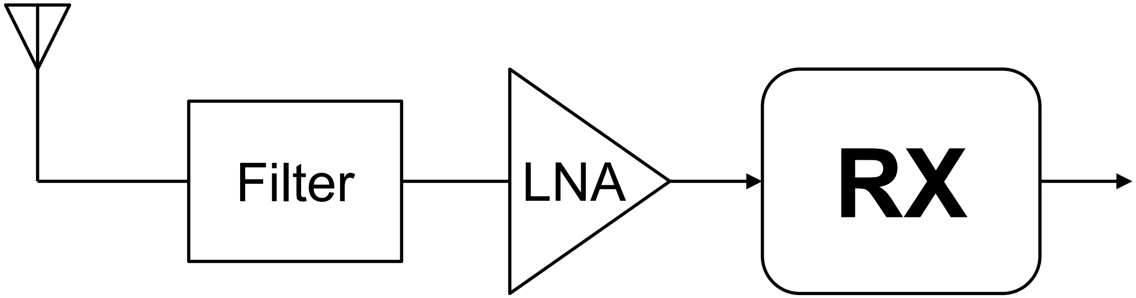




$$IIP_3\big|_{dBm} = \frac{\Delta P\big|_{dB}}{2} + P_{in}\big|_{dBm}$$

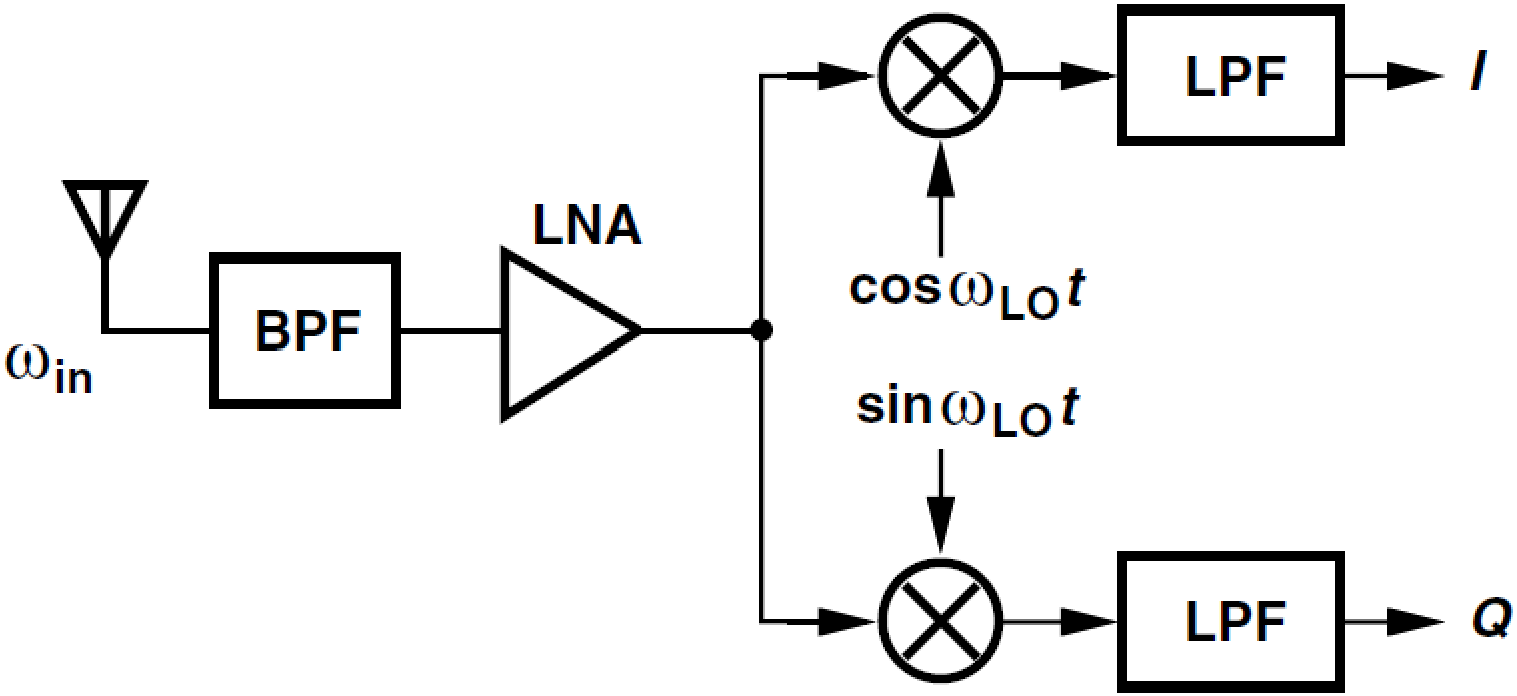
For a given input level (well below $P1dB$), the IIP3 can be calculated by halving the difference between the output fundamental and IM levels and adding the result to the input level,
where all values are expressed as logarithmic quantities.

Receiver Architecture Types



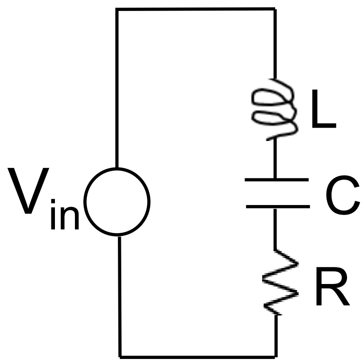
- Heterodyne
- Super-Heterodyne
- Homodyne (Direct conversion or Zero IF)

Direct Conversion Receiver



- Absence of an image greatly simplifies the design process
- Channel selection is performed by on-chip low-pass filter
- Mixing spurs are considerably reduced in number

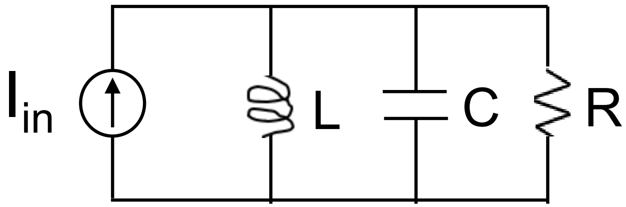
Series & Parallel Resonance



$$Z(\omega_0) = R$$

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR}$$

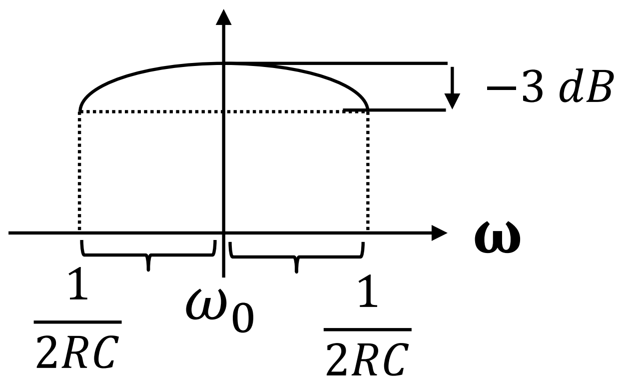
$$|V_L| = |V_C| = Q \cdot |V_{in}|$$



$$Q = \frac{R}{\omega_0 L} = \omega_0 RC$$

$$|I_L| = |I_C| = Q \cdot |I_{in}|$$

BW & Q relationship



$$Total\ BW = \frac{1}{RC}$$

$$\frac{\omega_0}{BW} = \frac{RC}{\sqrt{LC}} = \frac{R}{\sqrt{L/C}} = Q$$

Series-Parallel Transformation

R_p is always larger than R_s

$$R_p = R_s(1 + Q^2) \Longrightarrow Q = \sqrt{\frac{R_p}{R_s} - 1}$$

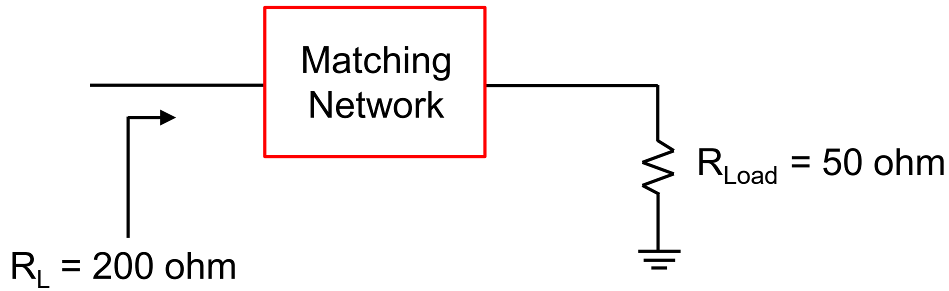
$$X_p = X_s \frac{1+Q^2}{Q^2} \approx X_s$$

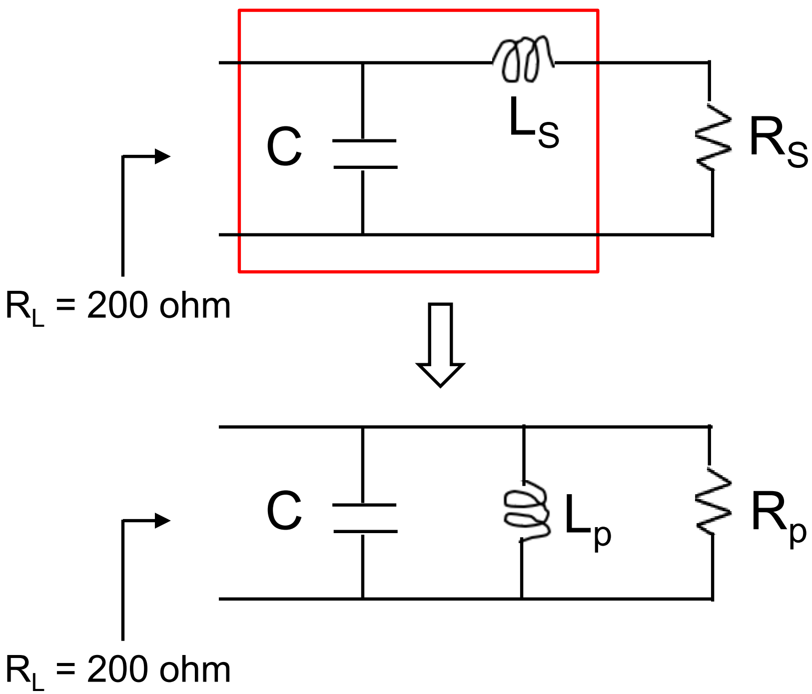
$$L_p = L_s \frac{1+Q^2}{Q^2} \approx L_s$$

$$C_p = C_s \frac{Q^2}{1+Q^2} \approx C_s$$

L-Match: Upward Impedance Transform

Low-pass L-match



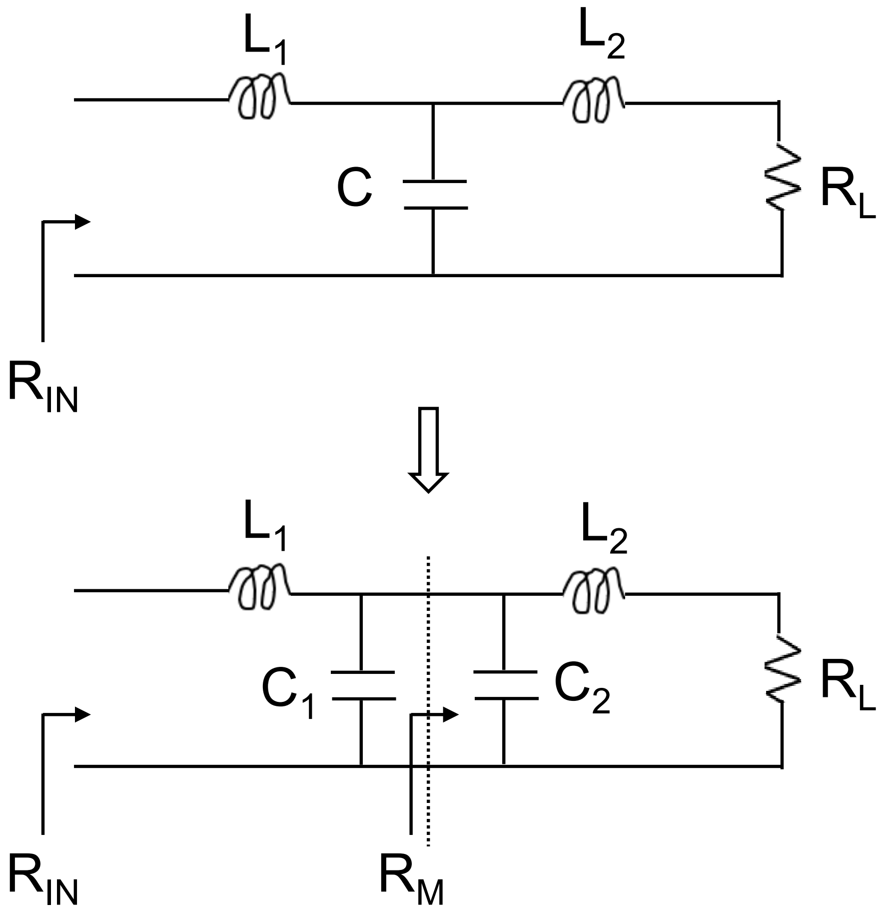


$$R_p = R_s(1 + Q^2)$$

$$L_p = L_s \frac{1 + Q^2}{Q^2}$$

T-Match

To design for a different Q, i.e. different Bandwidth for a given ω_0
We need another degree of freedom



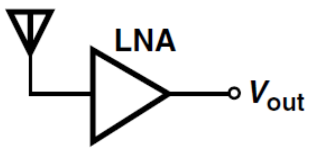
$$Q = Q_L + Q_R$$

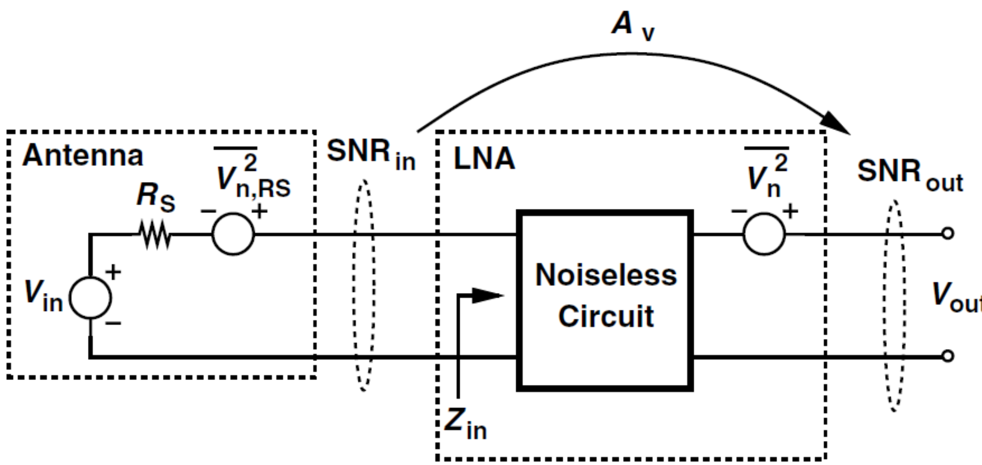
$$= \sqrt{\frac{R_M}{R_{IN}} - 1} + \sqrt{\frac{R_M}{R_L} - 1}$$

$R_M > R_L$

$R_M > R_{IN}$

Noise Figure





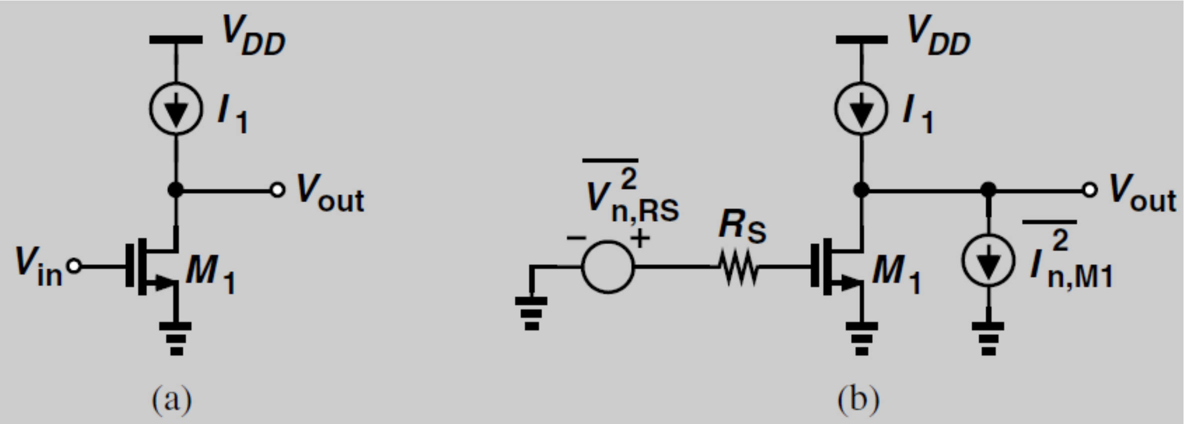
$$\mathrm{NF} = \frac{SNR_{in}}{SNR_{out}} \qquad SNR_{in} = \frac{|\alpha|^2 V_{in}^2}{|\alpha|^2 \overline{V_{RS}^2}} \qquad SNR_{out} = \frac{V_{in}^2 |\alpha|^2 A_v^2}{\overline{V_{RS}^2} |\alpha|^2 A_v^2 + \overline{V_n^2}}$$

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

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

Noise Figure Calculation Example

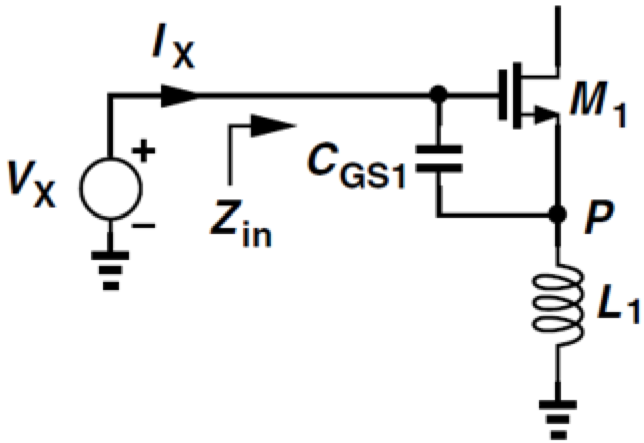
Determine the noise figure of the common-source stage shown below with a source impedance R_S. Neglect the capacitances and flicker noise of M1 and assume I_1 is ideal.



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

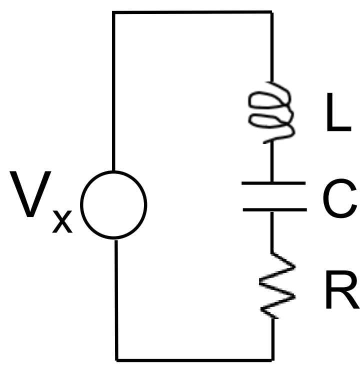
$$= \frac{(4kT\gamma g_m)r_o^2 + 4kTR_s(g_m r_o)^2}{4kTR_s(g_m r_o)^2} \quad = 1 + \frac{\gamma}{g_m R_s}$$

Series Resonance in LNA



$$\frac{V_X}{I_X} = \boxed{\frac{1}{C_{GS1}s} + L_1 s} + \boxed{\frac{g_m L_1}{C_{GS1}}}$$

Resonate　　　　$50\ \Omega$

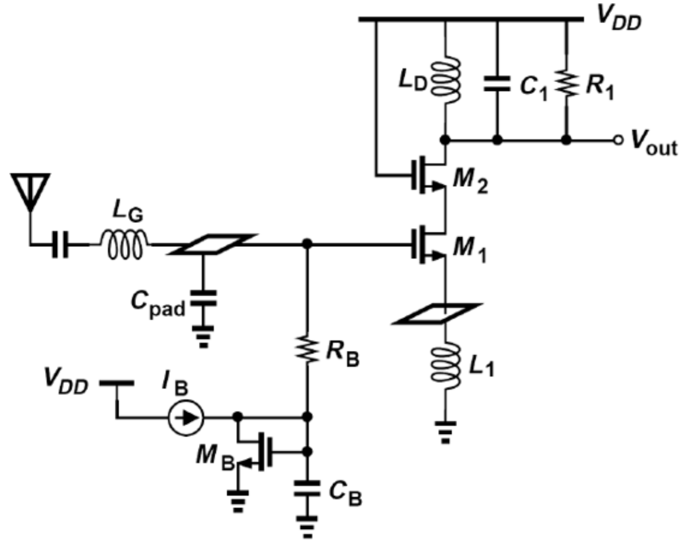


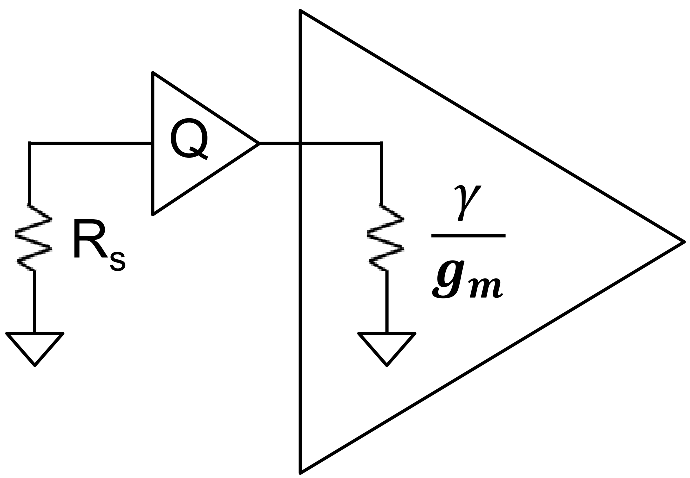
$$Z(\omega_0) = R$$

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 C R}$$

$$|V_L| = |V_C| = Q \cdot |V_x|$$

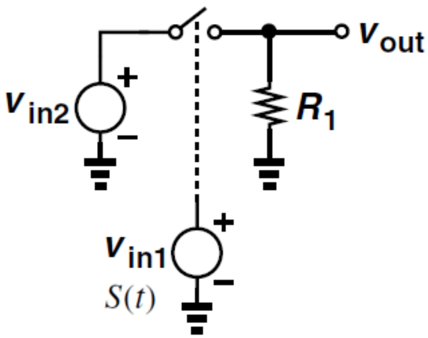
Noise Figure of CS LNA with Inductive Degeneration



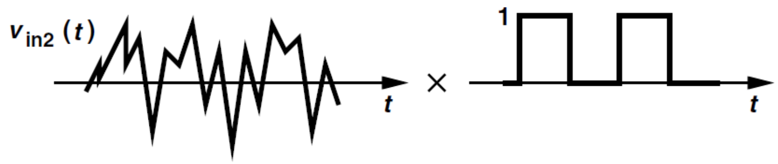


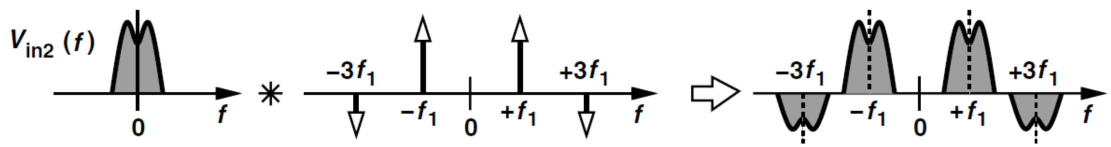
$$NF = 1 + \frac{\gamma}{Q^2 g_m R_S}$$

RF Mixer



$$v_{out}(t) = v_{in2}(t) \cdot S(t)$$





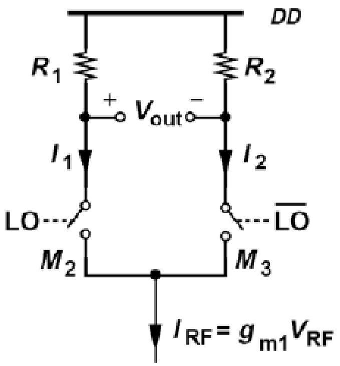
$$T_1 = 2\pi/\omega_1$$

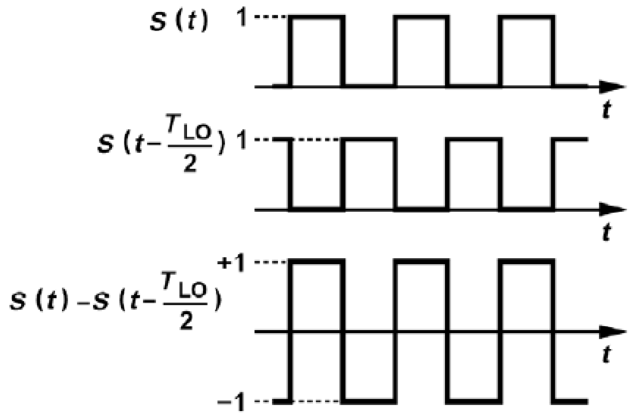
$$V_{out}(f) = V_{in2}(f) * \sum_{n=-\infty}^{+\infty} \frac{\sin(n\pi/2)}{n\pi}\delta\left(f - \frac{n}{T_1}\right) = \sum_{n=-\infty}^{+\infty} \frac{\sin(n\pi/2)}{n\pi} V_{in2}\left(f - \frac{n}{T_1}\right)$$

What is the amplitude when n=1? $\Rightarrow$ $\frac{1}{\pi}$

Conversion Gain

With abrupt LO switching, the circuit reduces to that shown in figure below (left).





$$I_1 = I_{RF} \cdot S(t)$$

$$I_2 = I_{RF} \cdot S\left(t - \frac{T_{LO}}{2}\right)$$

We have for $R_1 = R_2 = R_D$ $V_{out}(t) = I_{RF} R_D \left[S\left(t - \frac{T_{LO}}{2}\right) - S(t) \right]$

The waveform exhibits a fundamental amplitude equal to 4/π, yielding an output given by

$$V_{out}(t) = I_{RF}(t) R_D \cdot \frac{4}{\pi} \cos \omega_{LO} t + \cdots$$

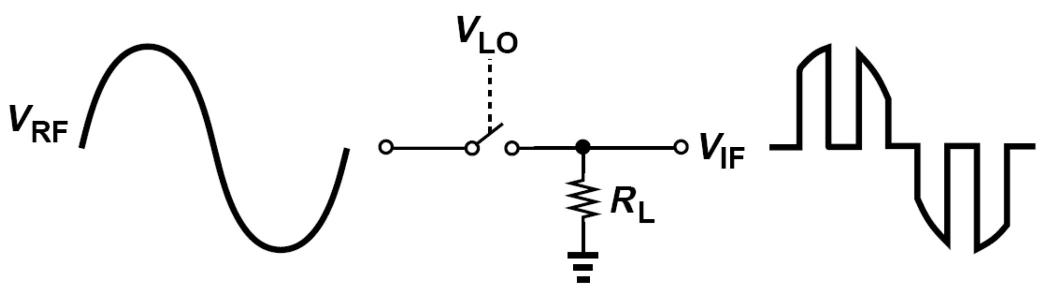
If $I_{RF}(t) = g_{m1} * V_{RF} * \cos(\omega_{RF} t)$, then

$$V_{IF}(t) = \frac{2}{\pi} g_{m1} R_D V_{RF} \cos(\omega_{RF} - \omega_{LO}) t$$

$$\boxed{\frac{V_{IF,p}}{V_{RF,p}} = \frac{2}{\pi} g_{m1} R_D}$$

Conversion Gain of Passive Mixer

- The conversion gain is $1/\pi$ for abrupt LO switching.
- We call this topology a "return-to-zero" (RZ) mixer because the output falls to zero when the switch turns off.

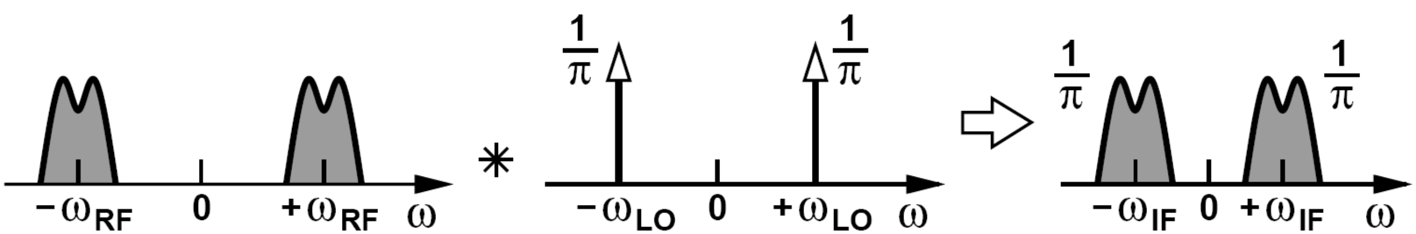


(a)

log(1 / 3.14) * 20 =

-9.93859296146

Conversion Gain -10dB



Conversion Gain of Single-Balanced Topology

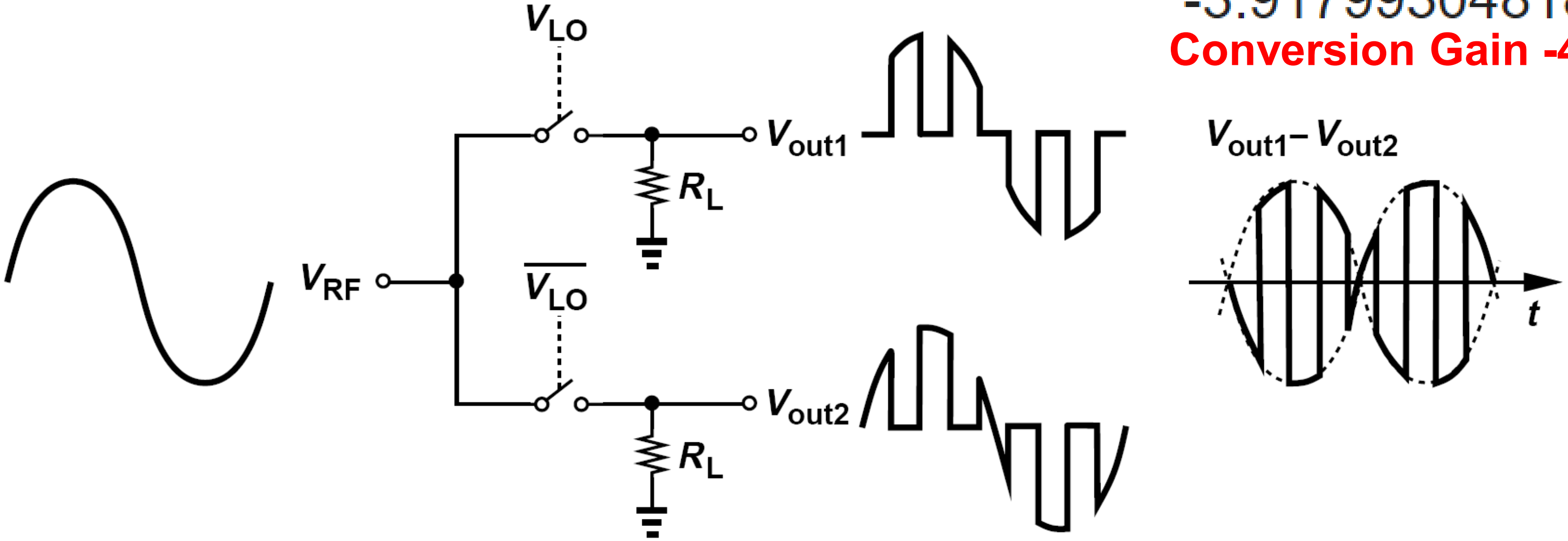
Determine the conversion gain of the single-balanced topology.

Solution:

log(2 / 3.14) * 20 =

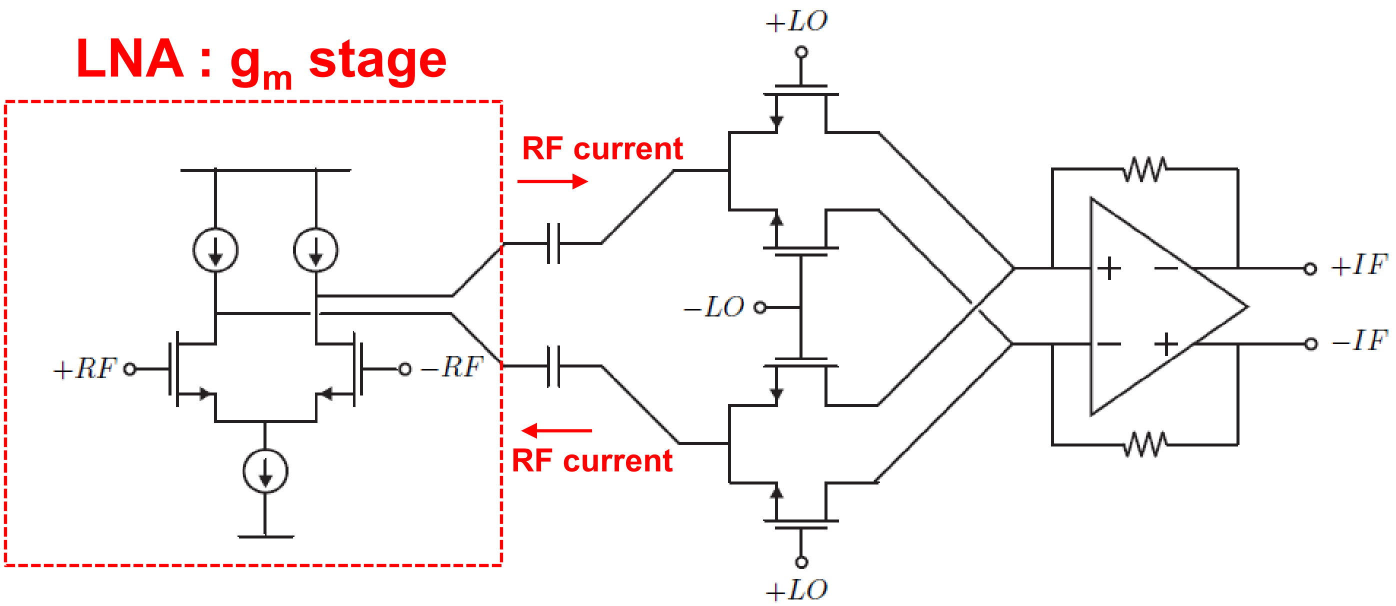
-3.91799304818

Conversion Gain -4dB



- **The second output is similar to the first but shifted by 180º.**
- **Differential output contains twice the amplitude of each single-ended output.**
- **Conversion gain is therefore equal to 2/π (≈ -4 dB).**
- **Superior to the single-ended topology**

Passive MOS Commutator



- The input stage is a G_m stage similar to a Gilbert cell mixer. The Gilbert Quad, though, has no DC current and switches on/off similar to a passive mixer.
- The output signal drives the virtual ground of a differential op-amp. The current signal is converted into a voltage output by the op-amp.

Exercises

We would like to use the matching network shown in Fig. 1 to transform $R_L = 50\Omega$ up to $R_{in} = 100\Omega$. The matching network should be designed for operation at a frequency of 1 GHz, and should have an overall quality factor of $Q = 100$. **In all series-parallel transformation, you may use the high Q approximation ($Q^2 >> 1$).**

Choose appropriate values for C_1, L_1, and L_2.

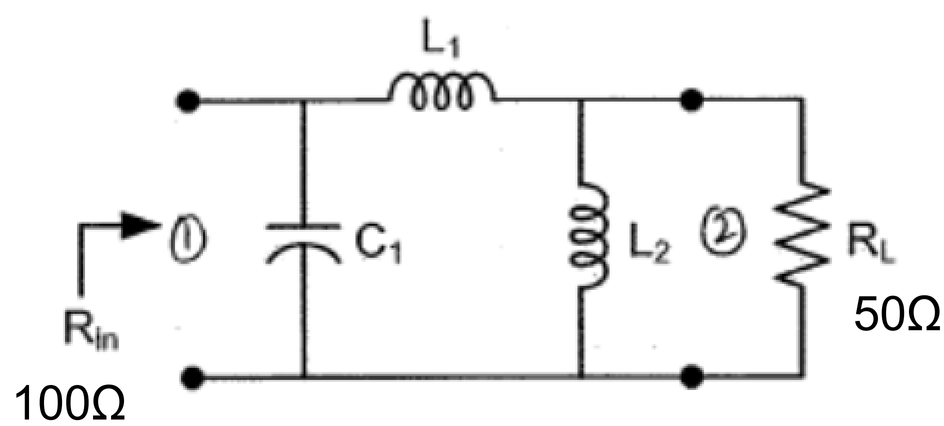
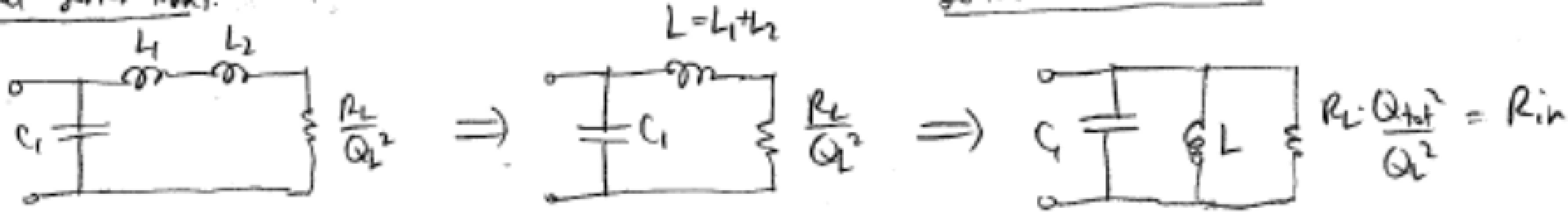


Fig. 1

Parallel - Series trans. Series - Parallel trans.



Now, $R_{in} = R_L \cdot \frac{Q_{tot}^2}{Q_L^2} \Rightarrow Q_R^2 = \frac{R_L}{R_{in}} \cdot Q_{tot}^2 = \frac{50}{100}(100)^2 \Rightarrow \boxed{Q_R \approx 71.}$

Also, $Q_{tot} = \frac{R_{in}}{\omega_0 L} \Rightarrow L = \frac{R_{in}}{Q_{tot} \cdot \omega_0} = \frac{100}{100 \cdot 2\pi \cdot 1E9} = 1.59E{-10} = L = L_1 + L_2$

To find L_1 & L_2, use Q_R: $Q_R = \frac{R_L}{\omega_0 L_2} \Rightarrow L_2 = \frac{R_L}{Q_R \cdot \omega_0} = \frac{50}{71 \cdot 2\pi \cdot 1E9} = \boxed{1.13E{-10} = L_2}$

$L_1 = L - L_2 = 1.59E{-10} - 1.13E{-10} = \boxed{4.6E{-11} = L_1}$

Use ω_0 to find C_1: $\omega_0 = \frac{1}{\sqrt{LC_1}} \Rightarrow C_1 = \frac{1}{\omega_0^2 L} = \frac{1}{(2\pi \cdot 1E9)^2 \cdot 1.59E{-10}} = \boxed{1.59E{-10} = C_1}$

You are analyzing an RF front end that has an IIP3 of 10 dBm, and a total gain of 30 dB.

(a) Label the IP3 point on the plot provided in Fig. 3.

(b) If the **input-referred** noise floor is -110 dB, use Fig. 3 to graphically determine the spurious-free dynamic range.

(c) Why is extrapolation used to measure the IP3, instead of just increasing the input power until the power in the third order IM component is equal to the power in the fundamental?

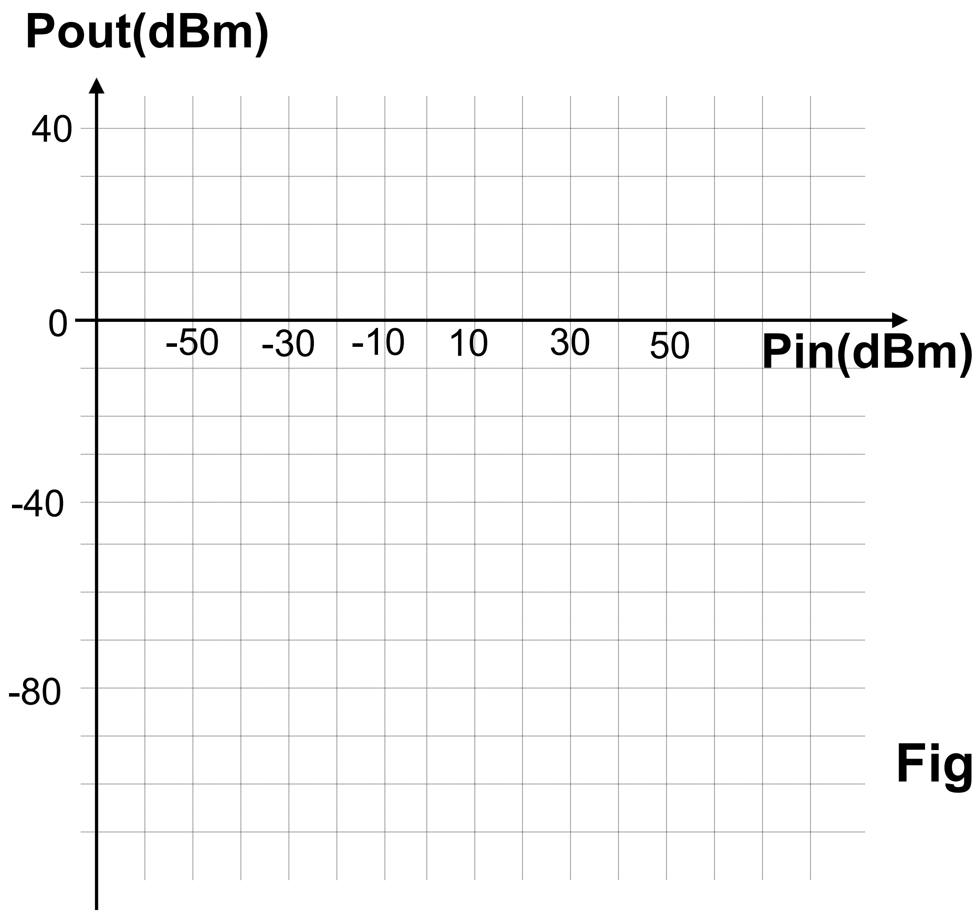


Fig. 3