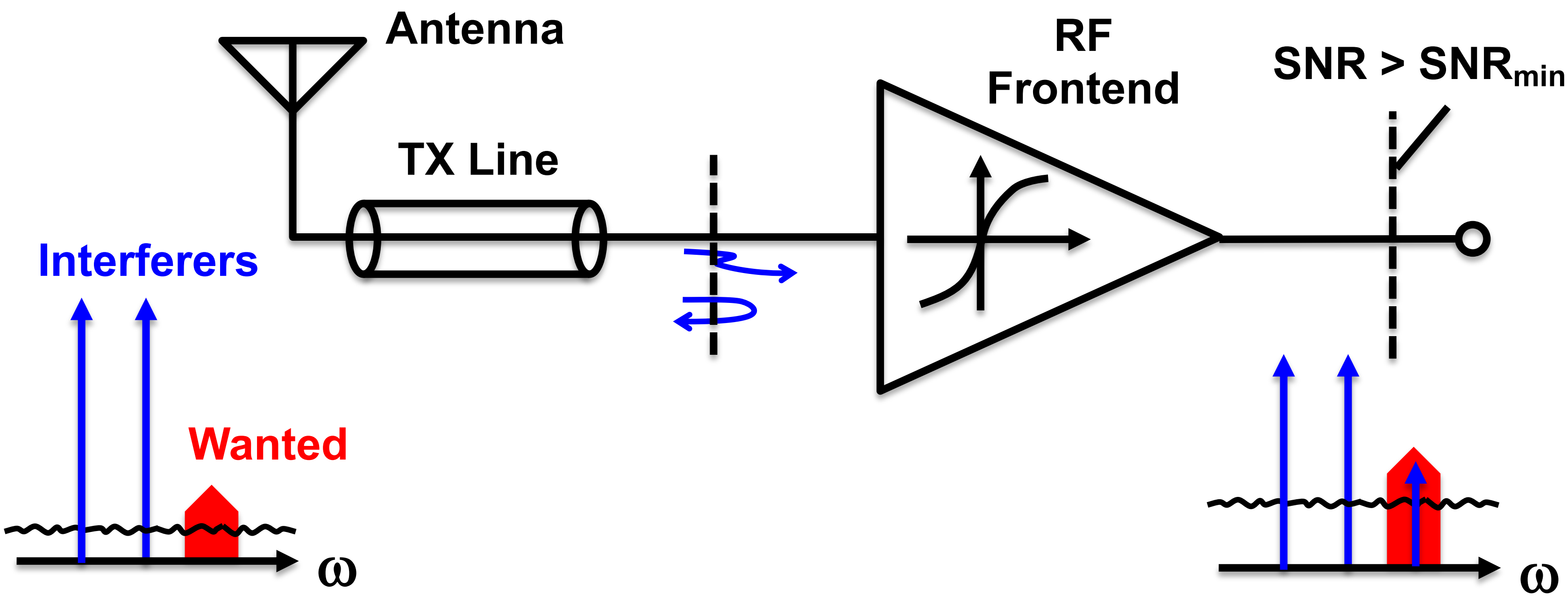
Basics of RF Systems

Prof. Salvatore Levantino

Politecnico di Milano

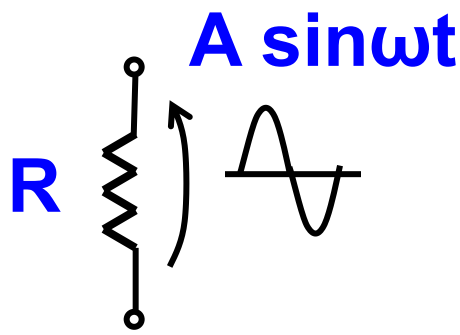
RF Receivers



- **Max. tolerable signal** limited by nonlinearity
- **Min. detectable signal** limited by impedance matching, noise nonlinearity

Amplitude and Power

- **Amplitude A [V]: $20\log_{10}(A)$**
  - **1V (0dBV)**



- **Power P [W] : $10\log_{10}(P)$**
  - **1W (30dBm) → 10Vp (20dBV)**
  - **10µW (-20dBm) → 31.6mVp (-30dBV)**

if R = 50Ω

Sinusoid with zero-peak amplitude A: $$P = \frac{A^2}{2R}$$

Effects of Non-linearity

Memoryless and Dynamic Systems

$$x \rightarrow \boxed{\text{System}} \rightarrow y$$

- **Memoryless nonlinear systems**

$$\boxed{y = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) + \ldots}$$

with coefficients depending on time if time-variant

- **Dynamic systems**
  - **LTI:** $y(t) = h(t) * x(t)$
  - **LTV:** $y(t) = h(t,\tau) * x(t)$
  - **Nonlinear:** **h(t) approximated with Volterra series**

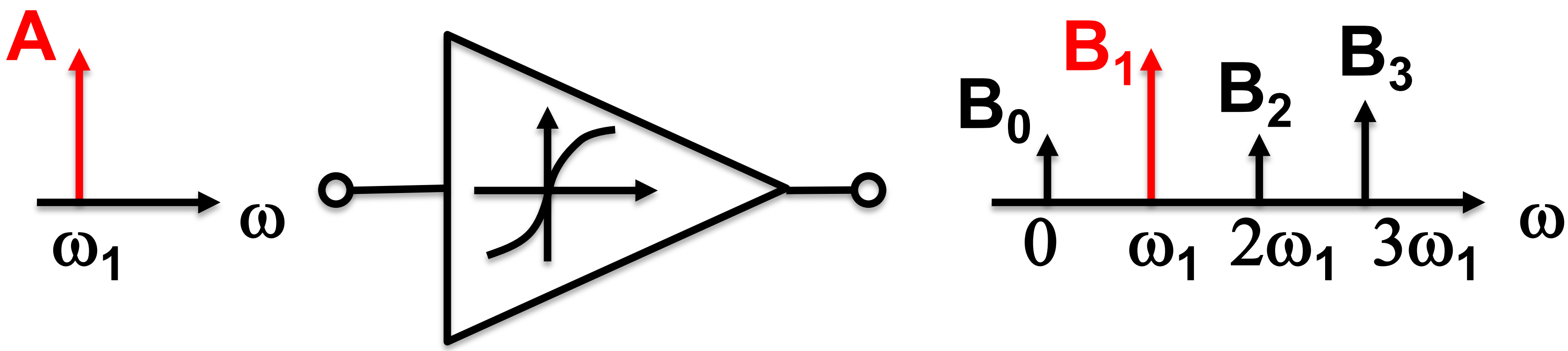
Effects of Nonlinearity

- **Case 1: Single tone at the input**
  - **Harmonic generation**
  - **Gain compression**

- **Case 2: Two tones at the input**
  - **Blocking**
  - **Third-order intermodulation**

Harmonic Generation

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

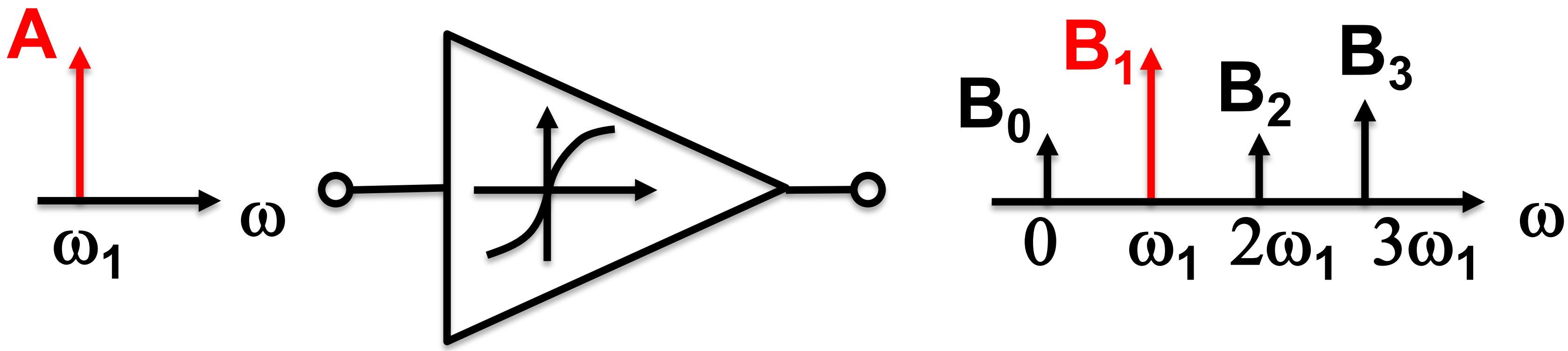


$$B_0 = \alpha_2 A^2/2 \qquad B_2 = \alpha_2 A^2/2$$

$$B_1 = \alpha_1 A + 3\alpha_3 A^3/4 \qquad B_3 = \alpha_3 A^3/4$$

- $B_{2n} = 0$ for fully-differential. Mismatches…
- B_n approx. prop. to A^n

Gain Compression

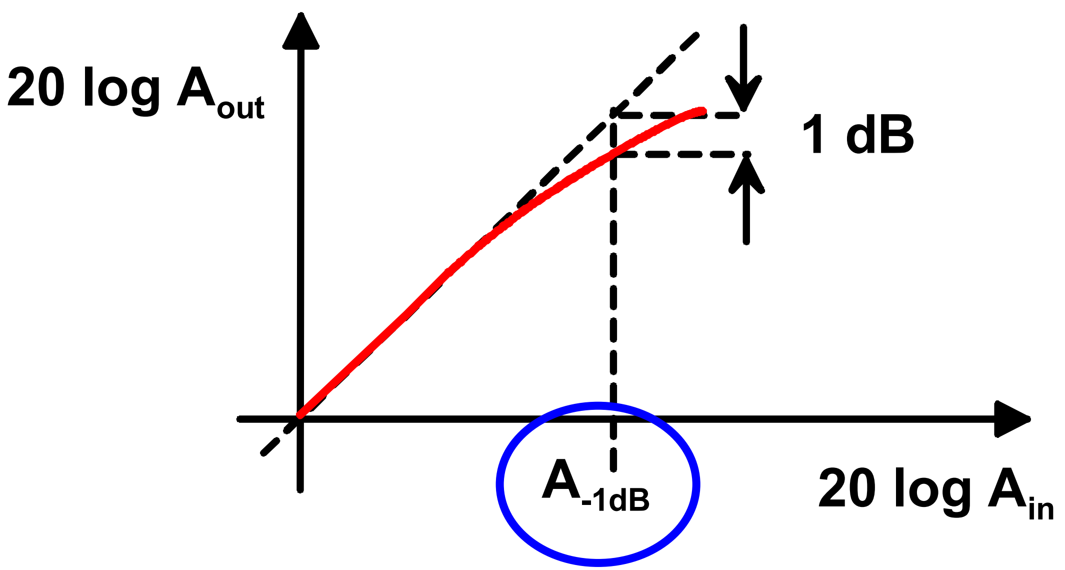


$$B_1 = \underbrace{\left(\alpha_1 + 3\alpha_3 A^2/4\right)}_{}A$$

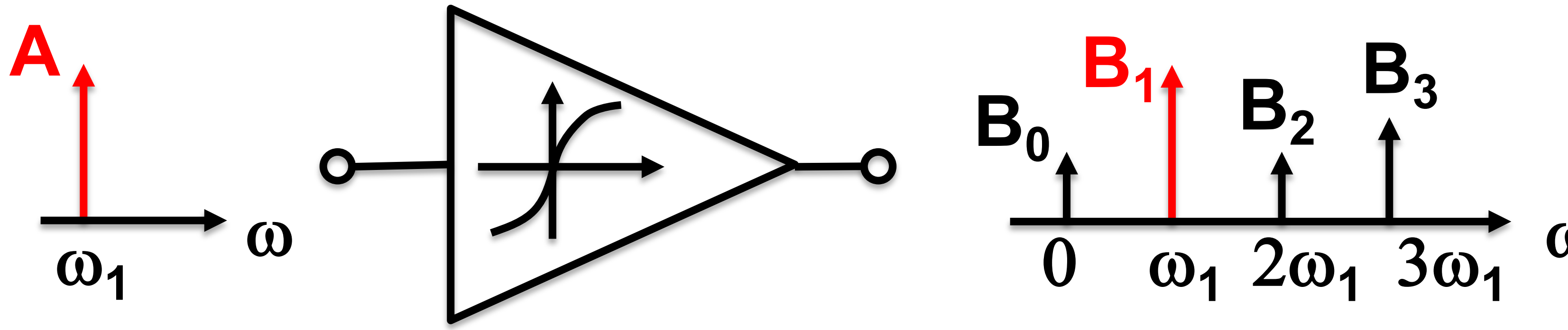
For $\alpha_3 < 0$, decreasing function of A

Definition of "1-dB Compression Point"

- A_{-1dB} is the input amplitude at which the output is 1 dB less than the ideal one
- Quantifies the gain compression
- Measures the input full-scale range



1-dB Compression Point



$$B_1 = \left(a_1 + \frac{3a_3A^2}{4}\right)\cdot A \rightarrow \frac{a_1 A_{-1dB}}{a_1 A_{-1dB} + \frac{3}{4} a_3 A_{-1dB}^3} = 10^{\frac{1}{20}}$$

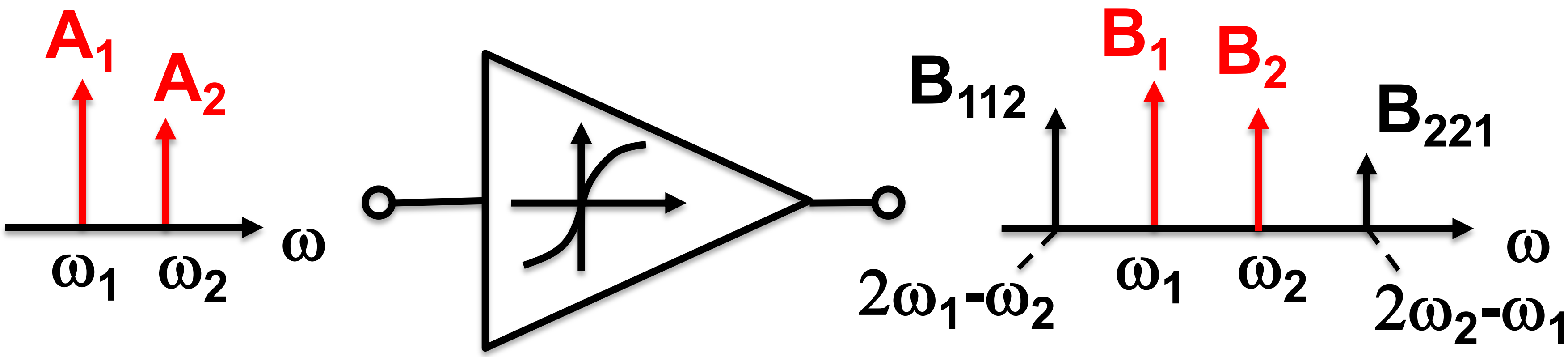
$$\rightarrow A_{-1dB} = \sqrt{\underbrace{\left(1 - 10^{-\frac{1}{20}}\right)}_{\sim 0.11} \cdot \frac{4}{3}\frac{|a_1|}{|a_3|}}$$

$$\rightarrow 20\log_{10}(A_{-1dB}) = -9.6\ \mathrm{dB} + 10\log_{10}\left(\frac{4}{3}\frac{|a_1|}{|a_3|}\right)$$

Effects of Nonlinearity

- Case 1: Single tone at the input
  - Harmonic generation
  - Gain compression
- **Case 2: Two tones at the input**
  - **Blocking**
  - **Third-order intermodulation**

Intermodulation



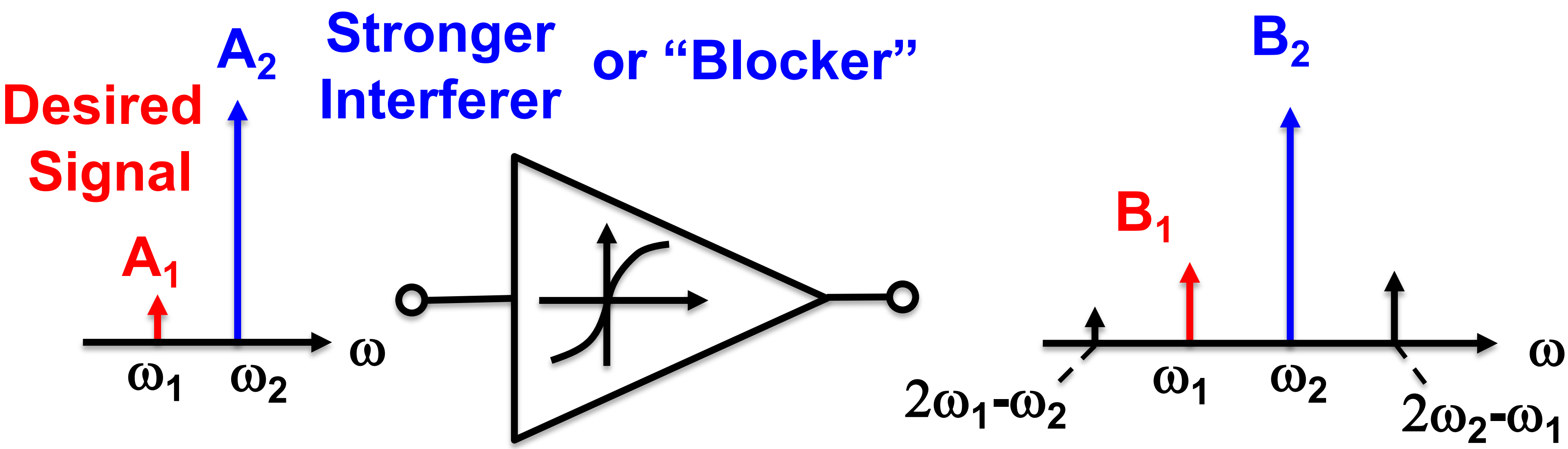
$$B_1 = \alpha_1 A_1 + 3\alpha_3 A_1^3/4 + 3\alpha_3 A_1 A_2^2/2$$

$$B_2 = \alpha_1 A_2 + 3\alpha_3 A_2^3/4 + 3\alpha_3 A_2 A_1^2/2$$

$$B_{112} = 3\alpha_3 A_1^2 A_2/4$$

$$B_{221} = 3\alpha_3 A_2^2 A_1/4$$

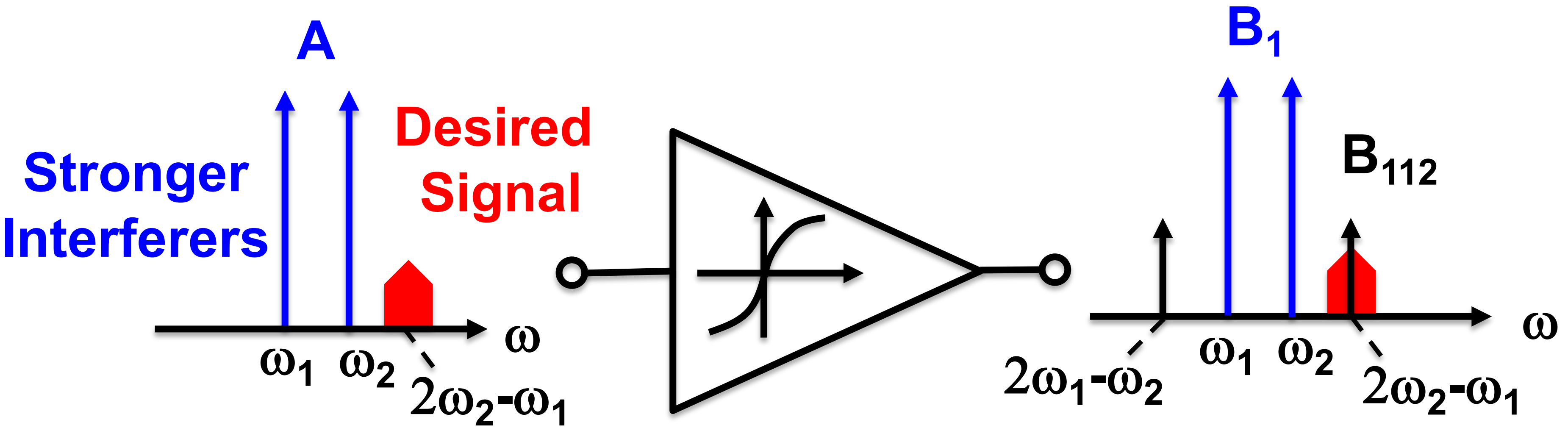
Desensitization and Blocking



$$B_1 = \alpha_1 A_1 + 3\alpha_3 A_1^3/4 + 3\alpha_3 A_1 A_2^2/2 \approx A_1\left(\alpha_1 + \underbrace{3\alpha_3 A_2^2/2}\right)$$

- For $\alpha_3 < 0$, decreasing function of A_2
- Signal is "blocked" when gain is zero

Intermodulation (IM)

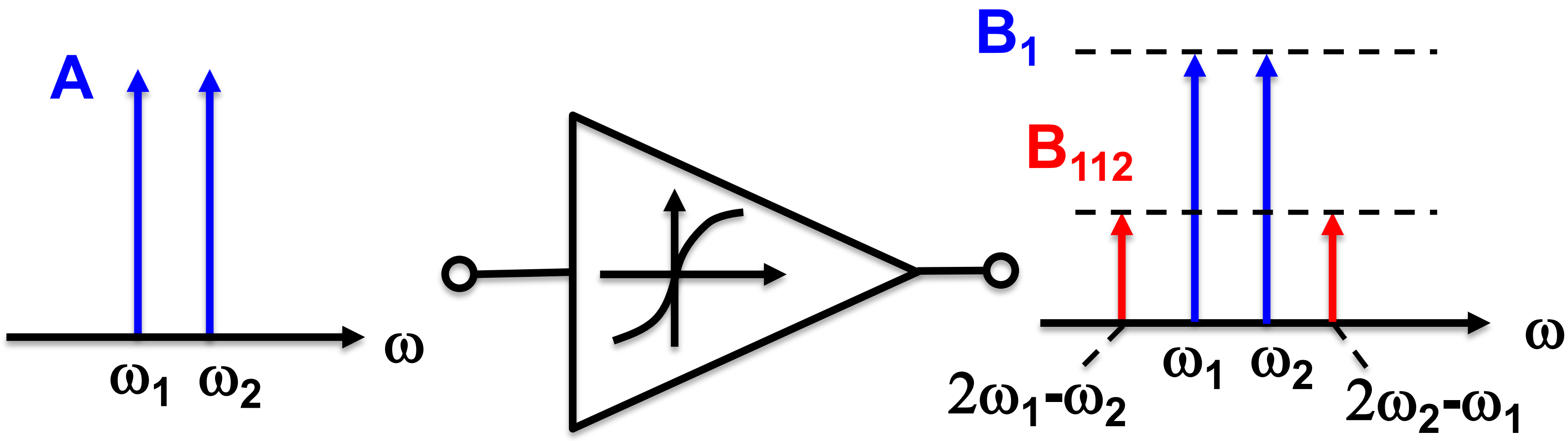


$$B_1 = \alpha_1 A + 3\alpha_3 A^3/4 + 3\alpha_3 A^3/2 \approx \alpha_1 A$$

$$B_{112} = 3\alpha_3 A^3/4$$

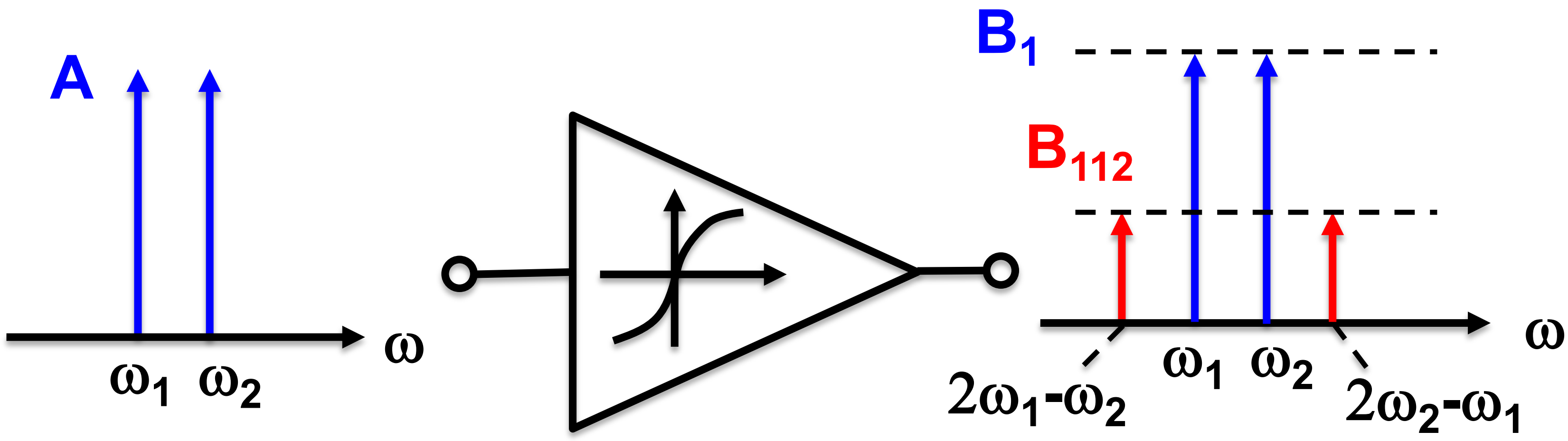
- **The third-order inter-modulation (IM3) product corrupts the desired signal**

Third-Order Intercept Point (IP3)



- **The input-referred intercept point (A_{IIP3}) is the input amplitude at which the IM3 products have the same amplitude as the fundamental tones**

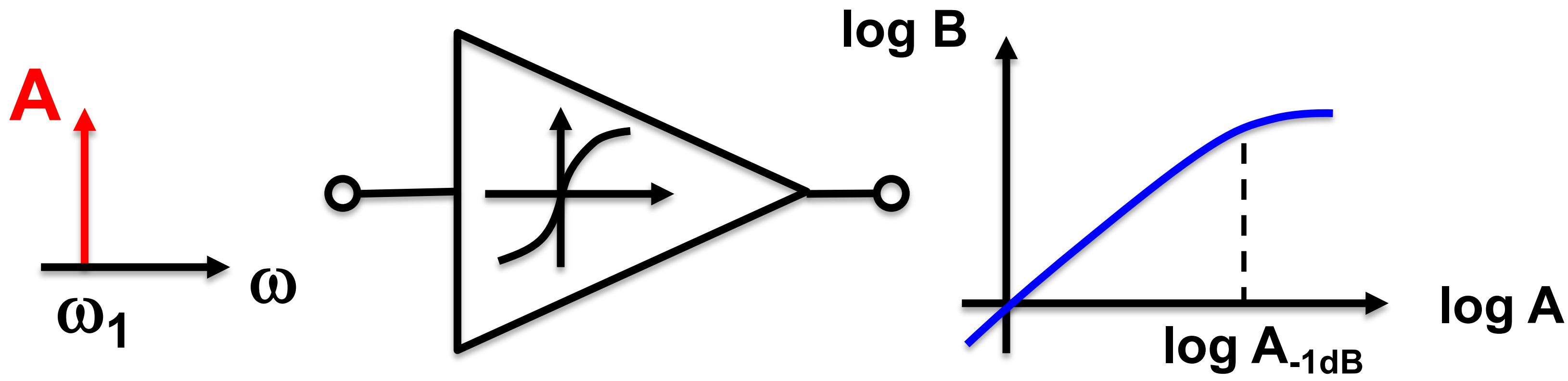
IIP3 and Memory-less Model



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

$$\begin{cases} B_1 = \left(\alpha_1 + 9\alpha_3 A^2/4\right)A \\ \\ B_{112} = 3\alpha_3 A^3/4 \end{cases} \Rightarrow \quad A_{IIP_3} \approx \sqrt{\frac{4}{3}\cdot\frac{|\alpha_1|}{|\alpha_3|}}$$

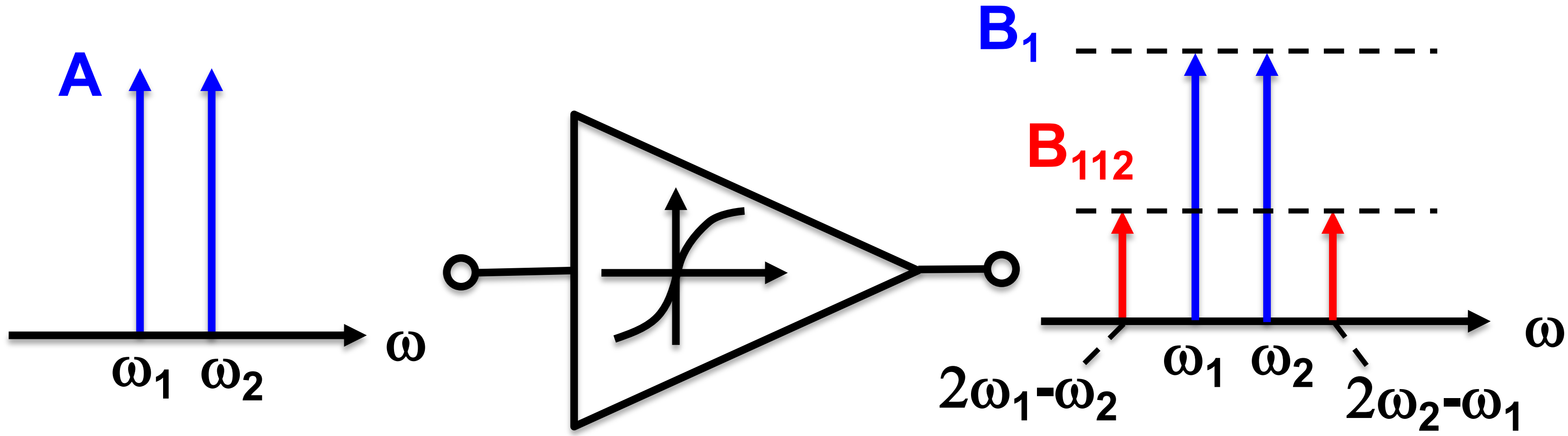
1-dB Compression Point and IIP3

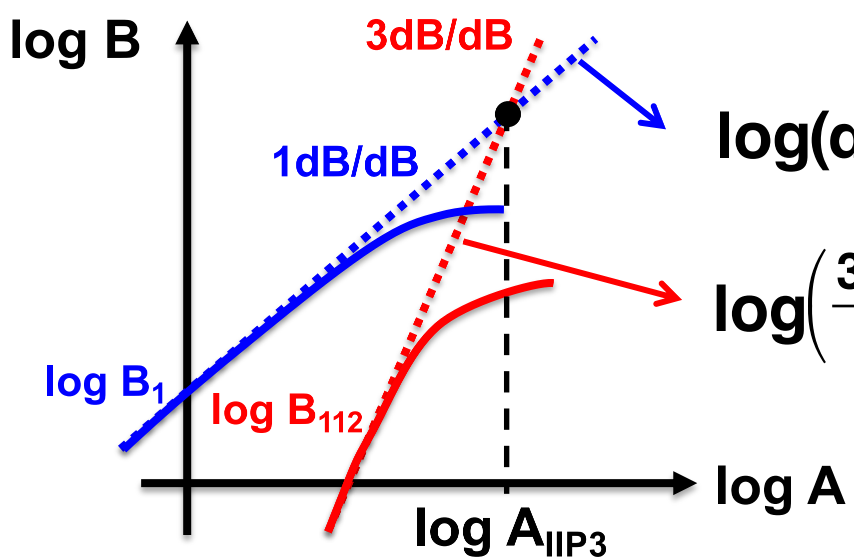


$$20\log_{10}(A_{-1dB}) = -\,9.6\ \text{dB} + \underbrace{10\log_{10}\left(\frac{4}{3}\frac{|a_1|}{|a_3|}\right)}_{20\log_{10}(A_{IIP3})}$$

$$\rightarrow \quad A_{IIP3} = A_{-1dB} + 9.6\ \text{dB}$$

Two-Tone Test and IIP3

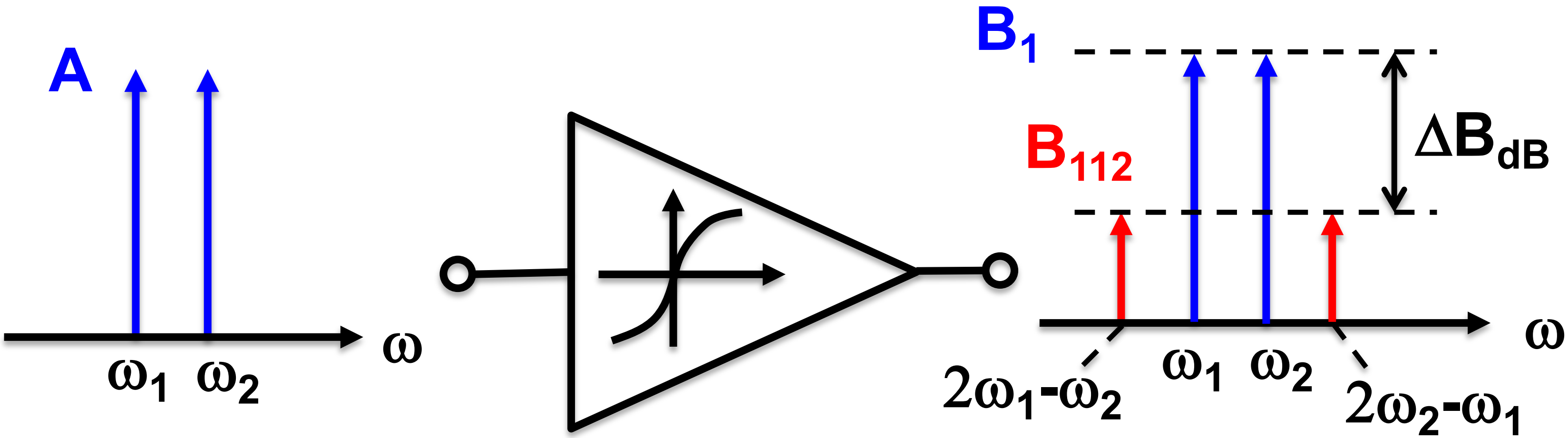


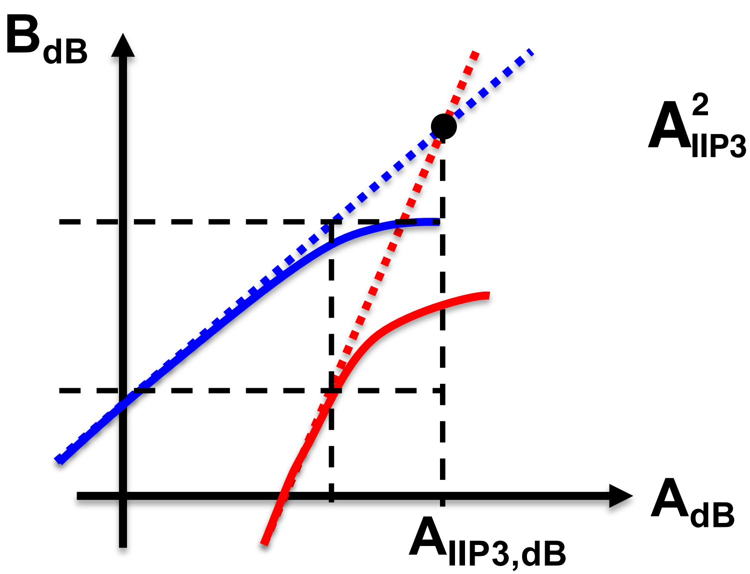


$$\log(a_1 A) = \log(a_1) + \log(A)$$

$$\log\left(\frac{3a_3}{4}A^3\right) = \log\left(\frac{3a_3}{4}\right) + 3\cdot\log(A)$$

Two-Tone Test



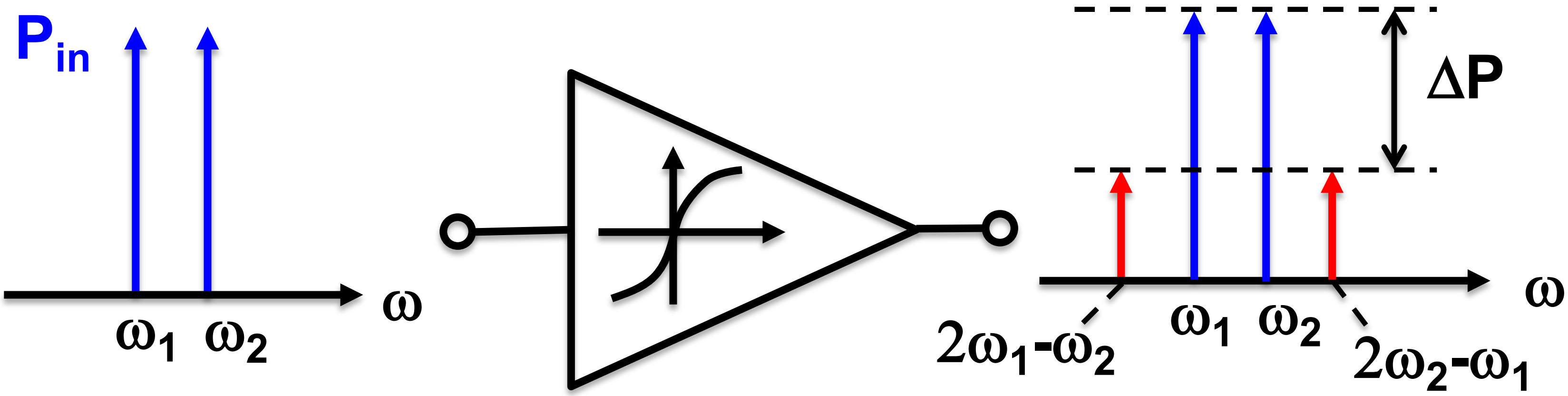


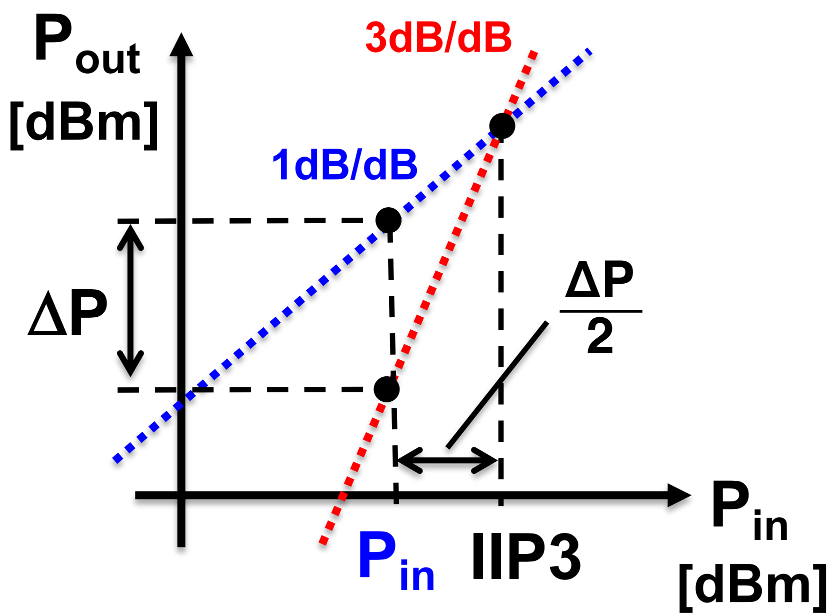
$$A_{IIP3}^2 = \frac{4}{3} \cdot \left|\frac{a_1}{a_3}\right| = \left|\frac{a_1 A}{\frac{3}{4} a_3 A^3}\right| \cdot A^2 = \frac{B_1}{B_{112}} \cdot A^2$$

$$\Downarrow$$

$$A_{IIP3,dB} = \frac{1}{2} \cdot \underbrace{(B_{1,dB} - B_{112,dB})}_{\Delta B_{dB}} + A_{dB}$$

How to measure IIP3



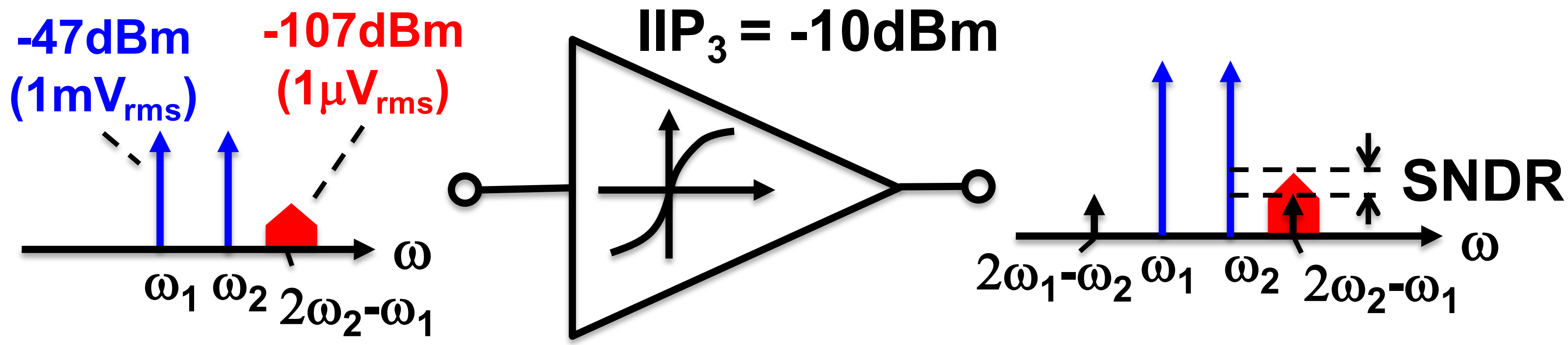


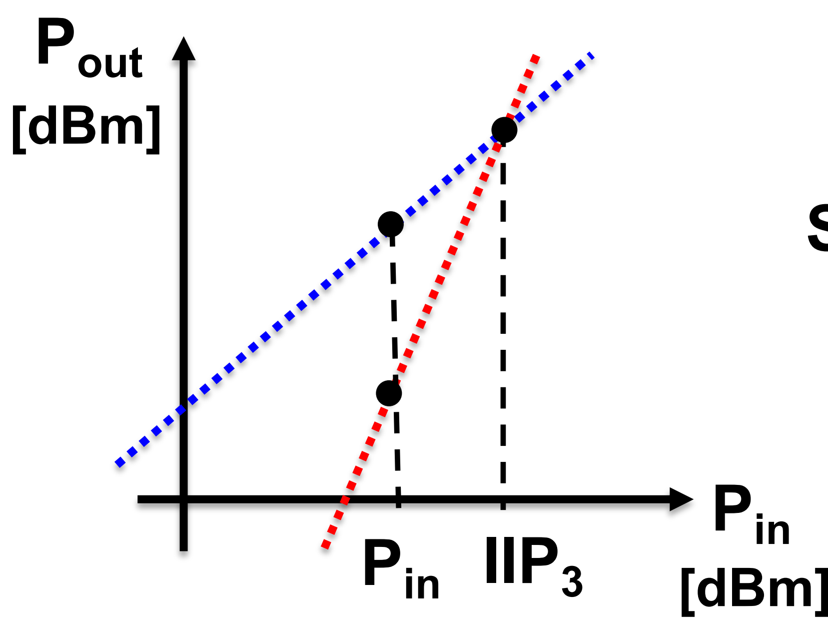
$$A_{IIP3,dB} = \frac{1}{2} \cdot (B_{1,dB} - B_{112,dB}) + A_{dB}$$

$$\downarrow$$

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

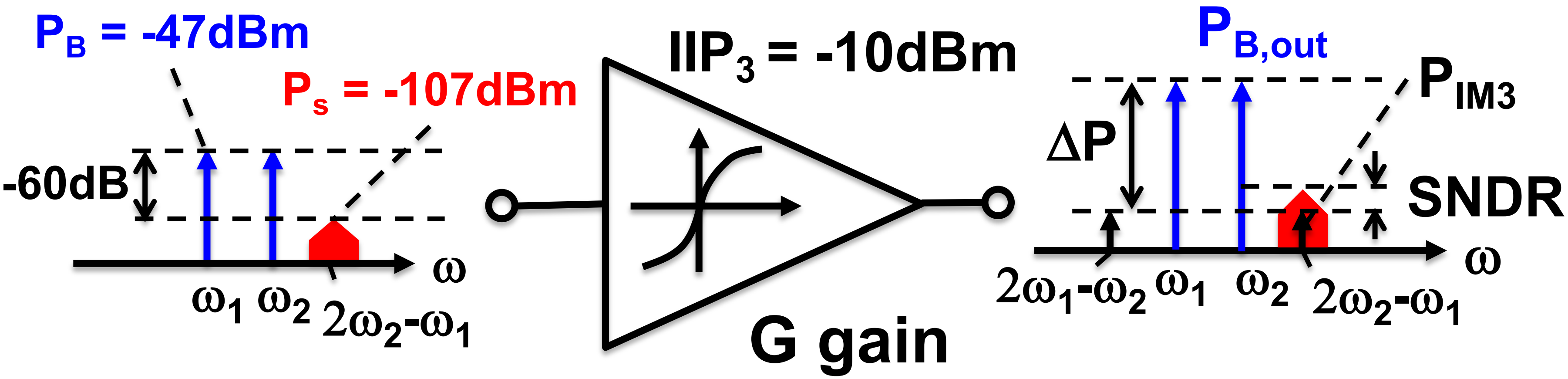
Exercise: Compute SNDR at the Output





SNDR = ?

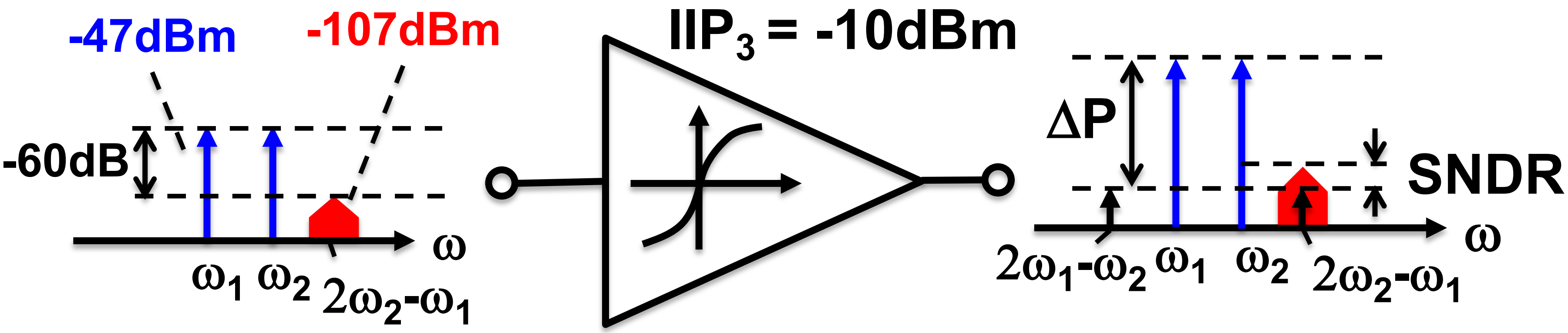
Exercise: Solution in Formulas

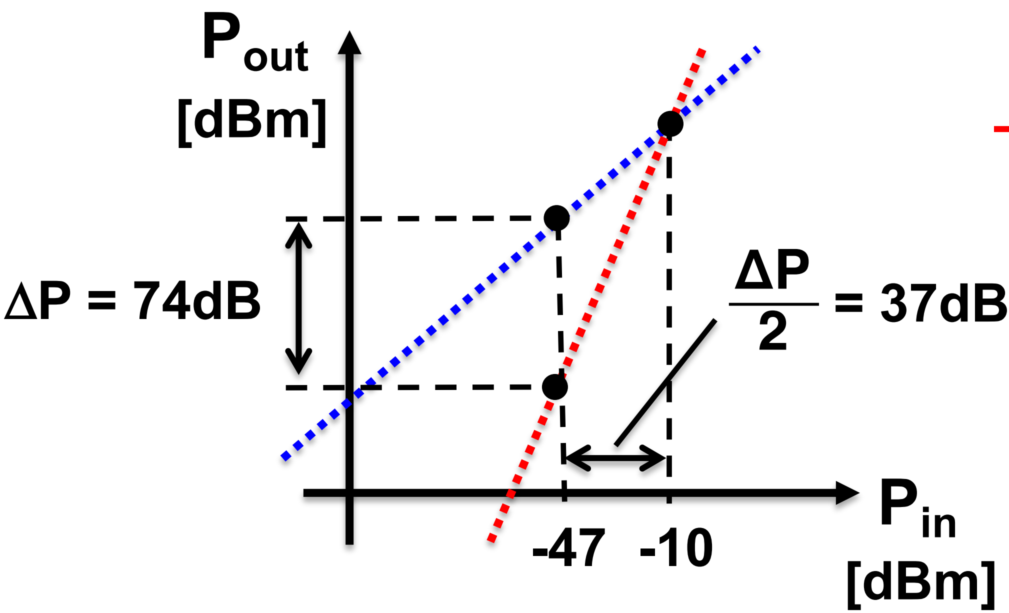


$$IIP3 = P_B + \Delta P/2 = P_B + P_{B,out}/2 - P_{IM3}/2$$

$$SNDR = P_{S,out} - P_{IM3} = P_S + G - P_{IM3} =$$
$$= P_S + G - (2P_B + P_{B,out} - 2IIP3) =$$
$$= P_S + \cancel{G} - 2P_B - P_B - \cancel{G} + 2IIP3 =$$
$$= P_S - 3P_B + 2IIP3 = -107 + 3*47 - 20 = 14dB$$

Exercise: Quicker Solution





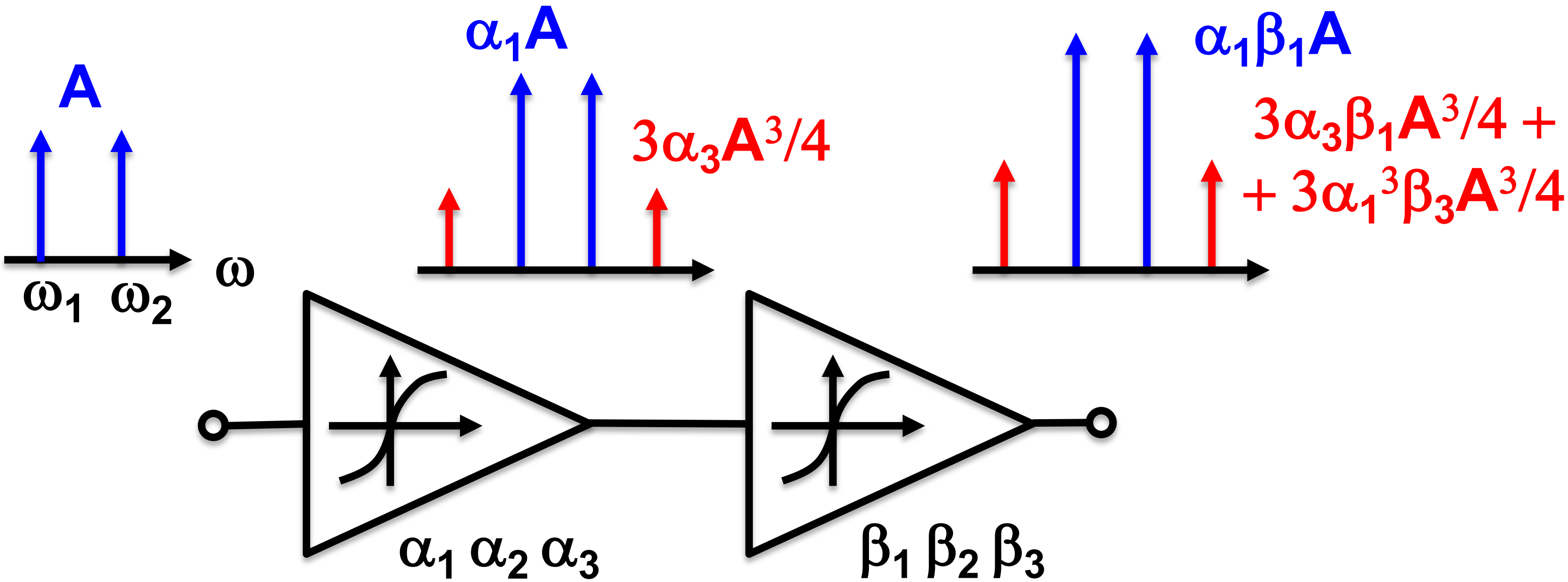
$$\rightarrow \text{SNDR} = \overbrace{-107}^{P_S} - \overbrace{(-47-74)}^{P_B-\Delta P}$$

$$= 14 \text{ dB}$$

IIP3 of Cascaded Amplifiers

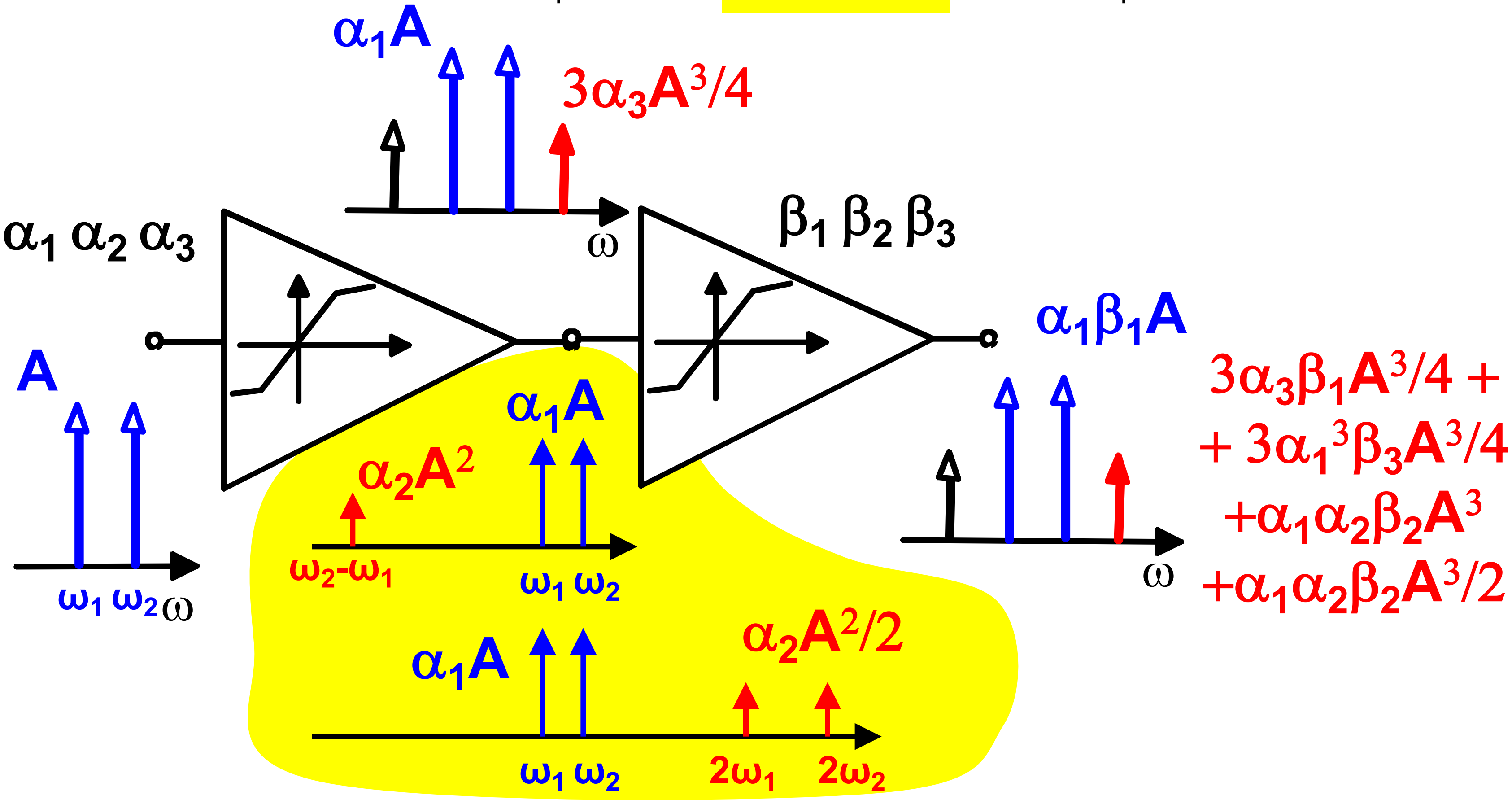
$$y_2 = \beta_1\left[\alpha_1 x + \alpha_2 x^2 + \alpha_3 x^3\right] + \beta_2\left[\alpha_1 x + \alpha_2 x^2 + \alpha_3 x^3\right]^2 + \beta_3\left[\alpha_1 x + \alpha_2 x^2 + \alpha_3 x^3\right]^3$$

$$A_{IIP3}^2 = \frac{4}{3}\left|\frac{\alpha_1\beta_1}{\alpha_3\beta_1 + 2\alpha_1\alpha_2\beta_2 + \alpha_1^3\beta_3}\right|$$



IIP3 of Cascaded Amplifiers: Insight

$$A_{IIP3}^2 = \frac{4}{3}\left|\frac{\alpha_1\beta_1}{\alpha_3\beta_1 + \boxed{2\alpha_1\alpha_2\beta_2} + \alpha_1^3\beta_3}\right|$$



Formula of IIP3 of Cascaded Amplifiers

$$A_{IIP3}^2 = \frac{4}{3}\left|\frac{\alpha_1\beta_1}{\alpha_3\beta_1 + 2\alpha_1\alpha_2\beta_2 + \alpha_1^3\beta_3}\right|$$

$$\downarrow$$

$$\frac{1}{A_{IIP_3}^2} = \left|\frac{1}{A_{IIP_3,1}^2} + \frac{3\alpha_2\beta_2}{2\beta_1} + \frac{\alpha_1^2}{A_{IIP_3,2}^2}\right|$$

$$\downarrow$$

$$\frac{1}{A_{IIP_3}^2} \approx \frac{1}{A_{IIP_3,1}^2} + \frac{\alpha_1^2}{A_{IIP_3,2}^2} + \frac{\alpha_1^2\beta_1^2}{A_{IIP_3,3}^2} + \ldots$$

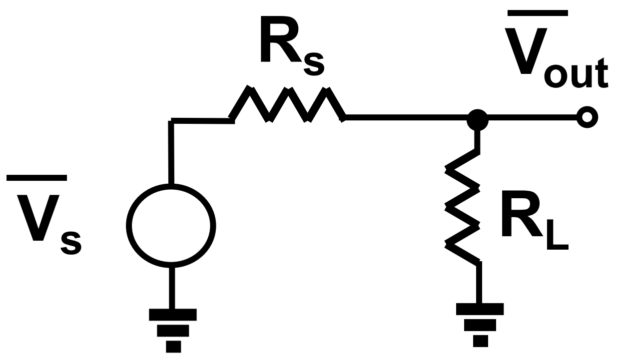
Highlights

- **Nonlinearity causes:**
  - **Harmonic generation**
  - **Gain Compression (P_{1dB})**
  - **Desensitization and blocking**
  - **Intermodulation (IP)**
- **Nonlinear cascaded stages**
  - **Nonlinearity of latter stages is more critical**

Basic Concepts in RF:
Impedance Matching

Impedance Matching: Resistive Case

- **Maximum power transfer** to the load is obtained matching the load resistance to the source resistance



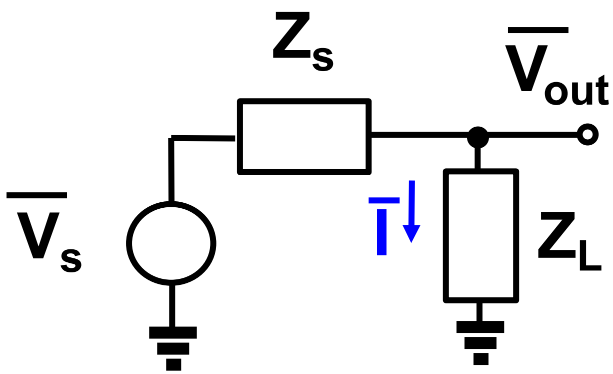
$$P_L = \frac{|\overline{V}_{out}|^2}{2R_L}$$

$$P_{L,max} = \frac{|\overline{V}_s|^2}{8R_L} \quad \text{for } R_L = R_s$$

Available Power

Impedance Matching: Reactive Case

- **Maximum power transfer to the load is obtained with conjugate matching of load impedance to the source impedance**



$Z_s = R_s + jX_s$

$Z_L = R_L + jX_L$

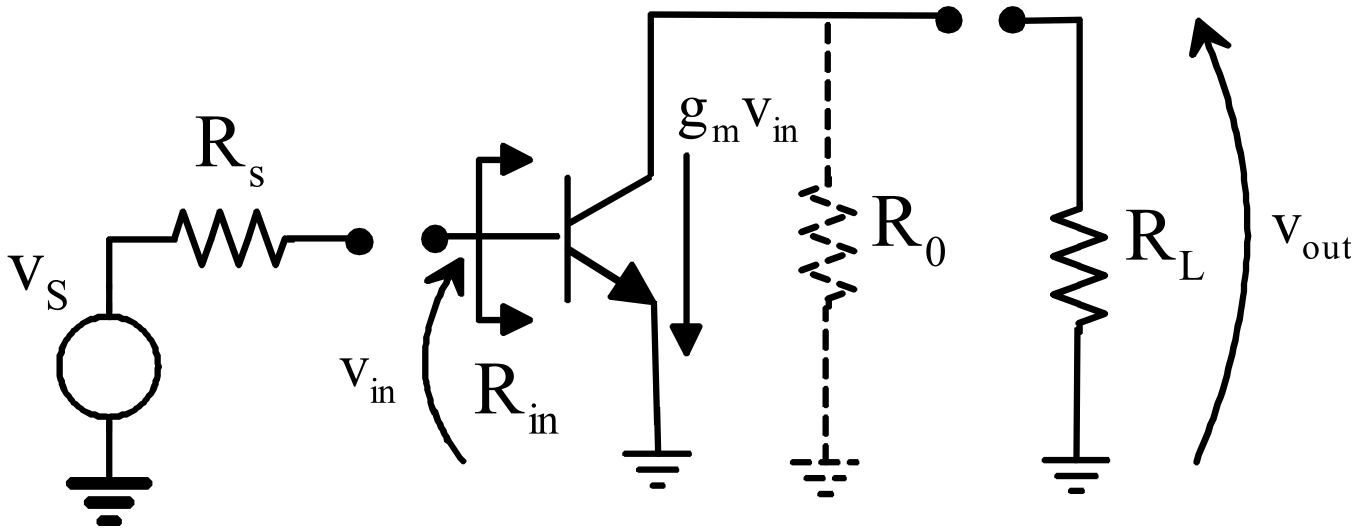
$$P_L = \frac{|\overline{I}|^2 R_L}{2} = \frac{1}{2}\frac{|\overline{V}_S|^2}{|Z_S + Z_L|^2} R_L$$

$$P_{L,max} = \frac{|\overline{V}_s|^2}{8R_L} \quad \text{for } Z_L = Z_s^*$$

$R_L = R_s$

resonance ← $\boxed{X_L = -X_s}$

Voltage Amplifier

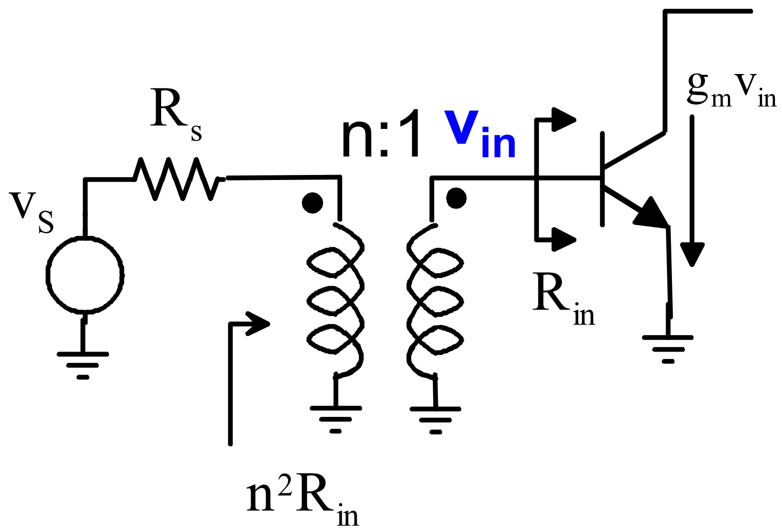


Unloaded Voltage Gain (V_{out}/V_s): $A_0 = \alpha A_v$

$$v_{out} = v_s \cdot \boxed{\frac{R_{in}}{(R_s + R_{in})} \cdot \boxed{g_m R_0}} \cdot \frac{R_L}{(R_0 + R_L)}$$

Unloaded Voltage Gain (V_{out}/V_{in}): A_v

Impedance Matching



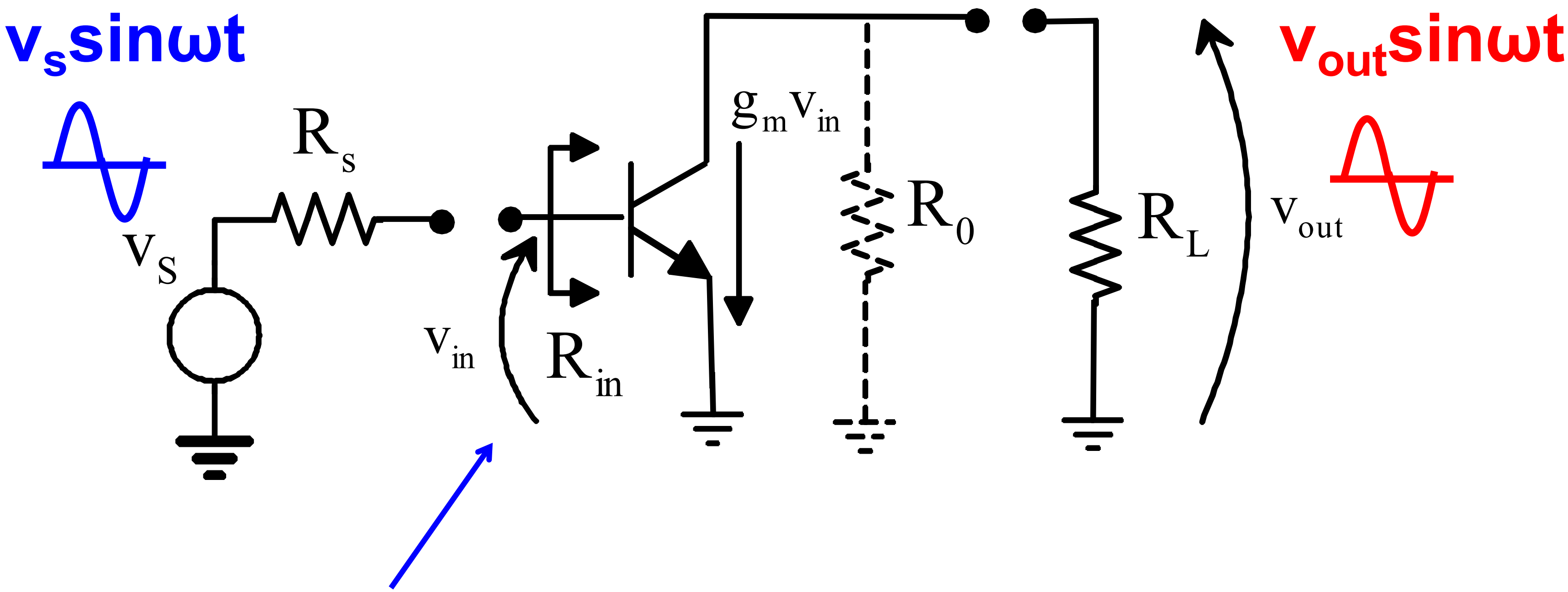
$$\begin{cases} v_1 = n v_2 \\ i_1 = \dfrac{i_2}{n} \end{cases} \Leftrightarrow \begin{cases} i_1 v_1 = i_2 v_2 \\ \dfrac{v_1}{i_1} = n^2 \dfrac{v_2}{i_2} \end{cases}$$

$$v_{in} = v_s \cdot \frac{n^2 R_{in}}{\left(R_s + n^2 R_{in}\right)} \cdot \frac{1}{n}$$

Maximum voltage gain if

$$n = \sqrt{\frac{R_s}{R_{in}}} \Leftrightarrow n^2 R_{in} = R_s$$

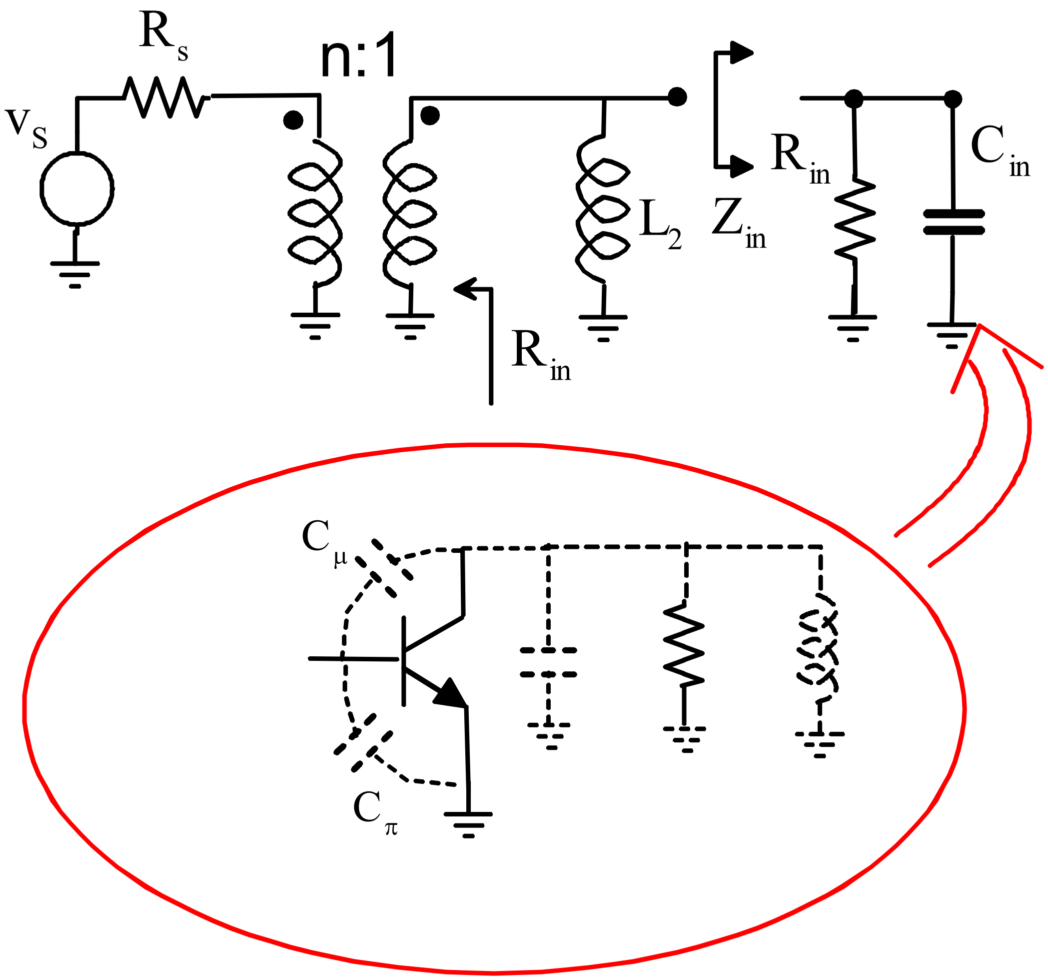
Theoreom of Maximum Power Transfer



$Z_{in} = Z_s^*$

Conjugate Matching for given source impedance

Resonant Matching



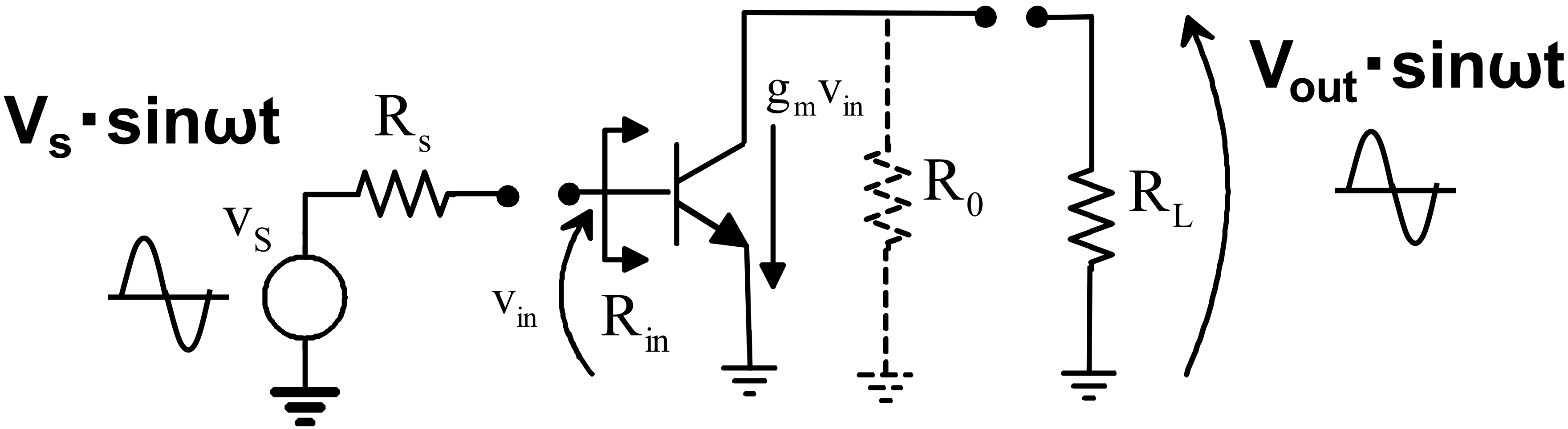
$$\omega_0 = \frac{1}{\sqrt{L_2 C_{in}}}$$

$$Q_{in} = \omega_0 \frac{R_{in}}{2} C_{in}$$

Definition of Power Gains

- ***Operating*** **Power Gain:** $$G_P = \frac{P_{out}}{P_{in}}$$
- ***Transducer*** **Power Gain:** $$G_T = \frac{P_{out}}{P_{in,av}}$$
- ***Available*** **Power Gain:** $$G_A = \frac{P_{out,av}}{P_{in,av}}$$

Power Transfer



Maximum or available power gain

$$P_{out} = \underbrace{\boxed{\frac{v_s^2}{8R_s}}}_{P_{in,av}} \cdot \underbrace{\frac{4R_sR_{in}}{\left(R_s + R_{in}\right)^2} \cdot \overbrace{\boxed{\frac{R_{in} g_m^2 R_0}{4}}}^{G_A} \cdot \frac{4R_0R_L}{\left(R_0 + R_L\right)^2}}_{G_T}$$

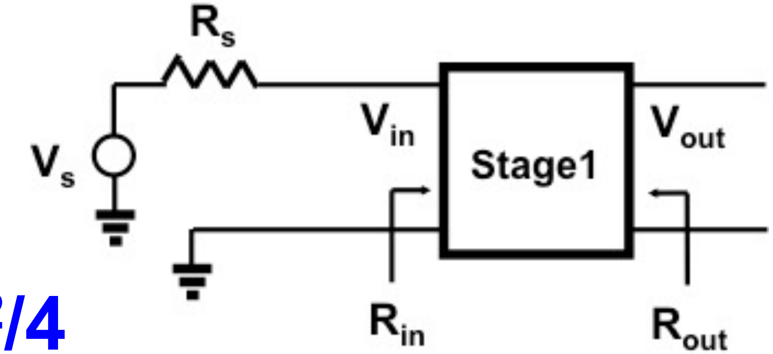
Transducer Power Gain

Power Gains as a Function of Voltage Gain A_0

$$G_T = \frac{P_{out}}{P_{in,av}} = \frac{\dfrac{V_s^2 A_0^2}{2R_L}\left(\dfrac{R_L}{R_L + R_{out}}\right)^2}{\dfrac{V_s^2}{8R_s}} = A_0^2 \frac{4R_s R_L}{\left(R_L + R_{out}\right)^2}$$

$$G_A = \frac{P_{out,av}}{P_{in,av}} = \frac{\dfrac{V_s^2 A_0^2}{8R_{out}}}{\dfrac{V_s^2}{8R_s}} = A_0^2 \frac{R_s}{R_{out}}$$

Unloaded Voltage Gain (V_{out}/V_s): $A_0 = \alpha A_v$



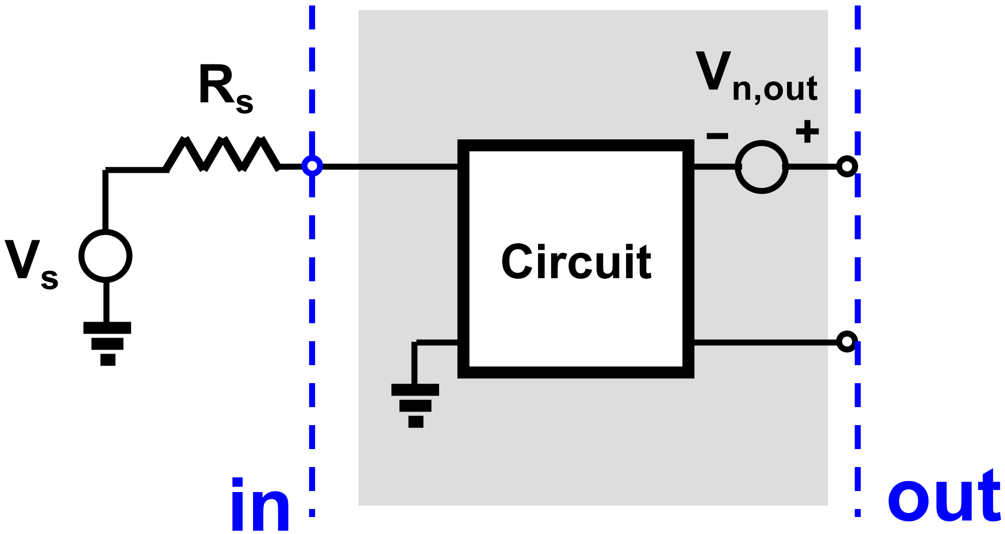
If R_s=R_{out}, then $G_A = A_0^2 = A_v^2/4$

Highlights

- **Impedance matching** improves voltage/power gain
- **Power gain** is <u>not</u> in general the square of voltage gain
- **Available power gain G_A** is the square of the unloaded voltage gain A_0 only if $R_s = R_{out}$
- **Reactive matching** is narrowband

Basic Concepts in RF:
Noise Figure

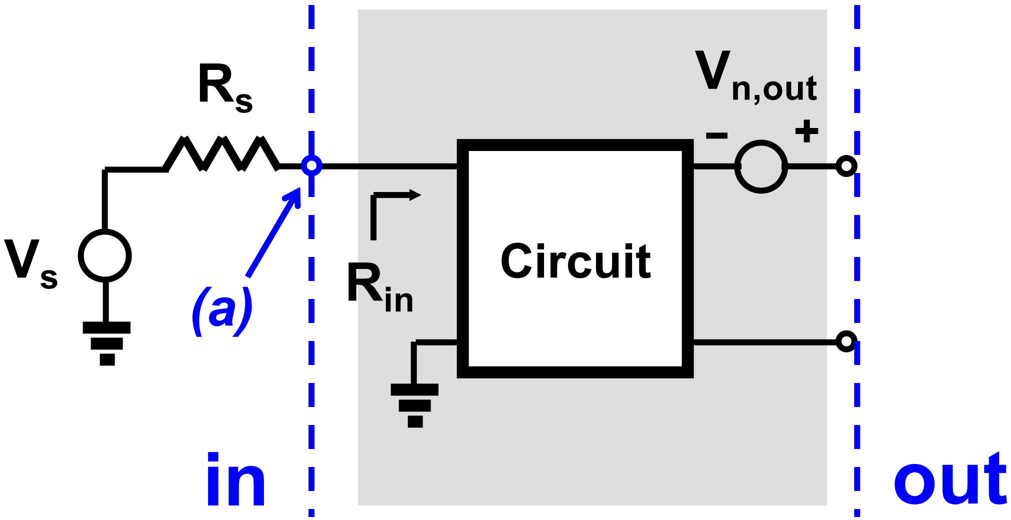
Impact of Thermal Noise



$$NF \triangleq \frac{SNR_{in}}{SNR_{out}}$$

- **In RF receivers, the input signal is corrupted by the thermal noise of the radiation resistance of the antenna ($4kTR_s$)**
- **The receiver adds other noise ($S_{Vn,out}$)**
- **Definition of Noise Figure (NF)**

Noise Figure from Output Noise

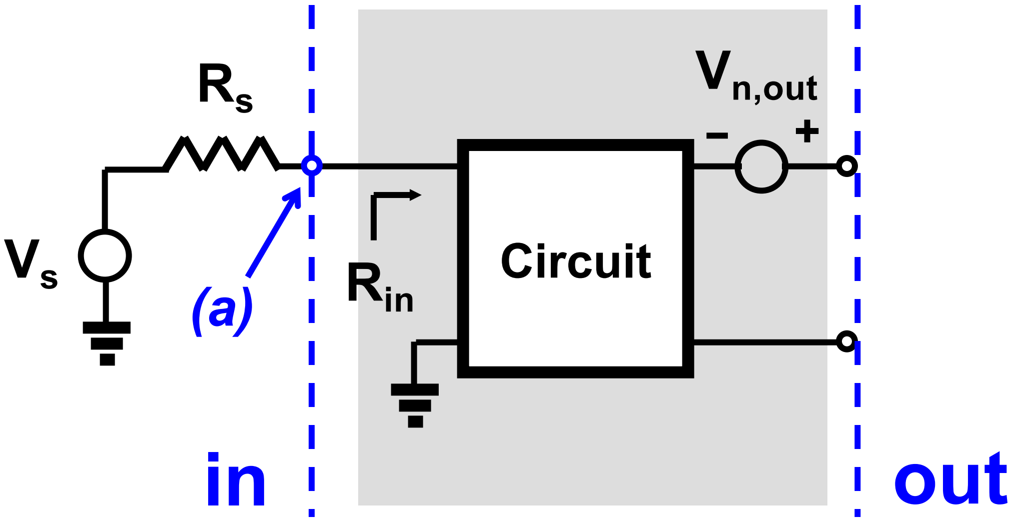


$$\boxed{NF \triangleq \frac{SNR_{in}}{SNR_{out}}}$$

$$NF = \frac{\dfrac{\cancel{\alpha^2} \cdot \cancel{V^2_{s,eff}}}{\cancel{\alpha^2} \cdot 4kTR_s}}{\dfrac{\alpha^2 A_v^2 \cdot \cancel{V^2_{s,eff}}}{\alpha^2 A_v^2 \cdot 4kTR_s + \overline{V^2_{n,out}}}} = \frac{\alpha^2 \cdot 4kTR_s + \dfrac{\overline{V^2_{n,out}}}{A_v^2}}{\alpha^2 \cdot 4kTR_s}$$

$$\frac{R_{in}}{R_s+R_{in}}$$

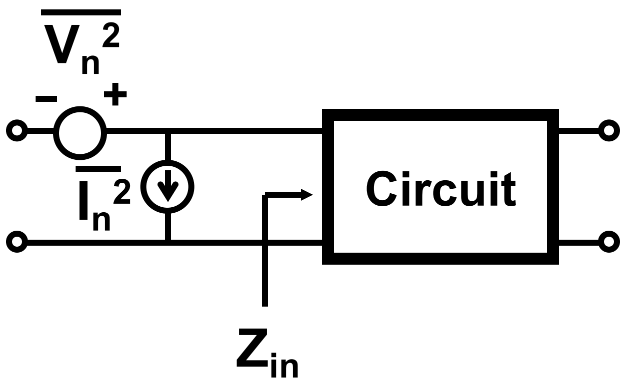
Meaning of Noise Figure

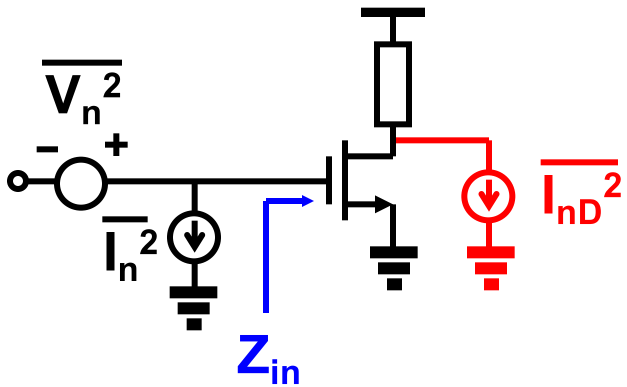


$$NF \triangleq \frac{SNR_{in}}{SNR_{out}}$$

$$NF = \frac{\text{Total Voltage Noise at } (a)}{\text{Voltage Noise at } (a) \text{ from } R_s}$$

Input-Referred Noise of a Two-port Network





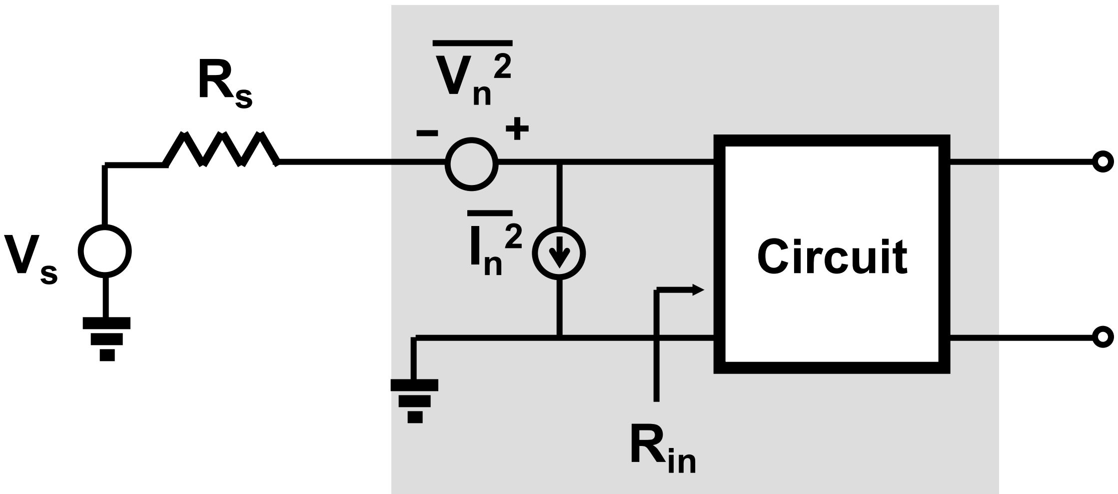
- **Two noise generators for a two-port network**
- **Each generator must produce the same output noise of the original noise source. E.g.**

$$\overline{V_n^2} = \frac{\overline{I_{nD}^2}}{g_m^2} = \frac{8kT}{3g_m} \qquad \overline{I_n^2} = \frac{\overline{I_{nD}^2}}{g_m^2 \left|Z_{in}\right|^2} = \frac{8kT}{3g_m \left|Z_{in}\right|}$$

$\Delta f = 1\text{Hz}$

correlation

Noise Figure from Input-Referred Noise

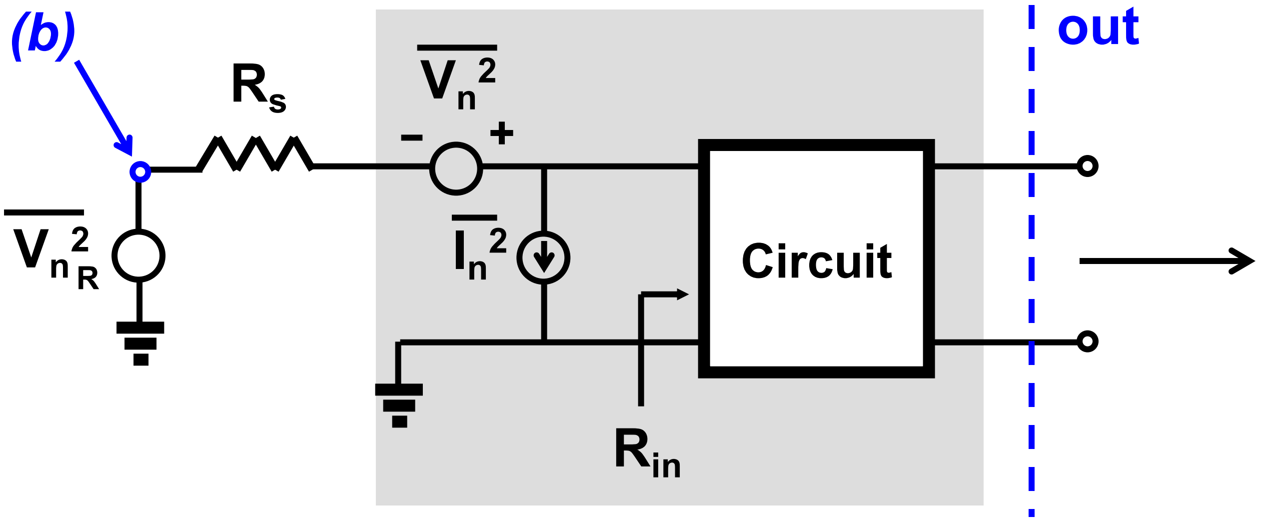


$$NF = \frac{4kTR_s + \overline{\left(V_n + I_n R_s\right)^2}}{4kTR_s} = 1 + \frac{\overline{\left(V_n + I_n R_s\right)^2}}{4kTR_s}$$

If uncorrelated:

$$\boxed{NF = 1 + \frac{\overline{V_n^2}}{4kTR_S} + \frac{\overline{I_n^2}}{4kT/R_S}}$$

Practical Calculation of Noise Figure



Total output noise (including source and circuit)

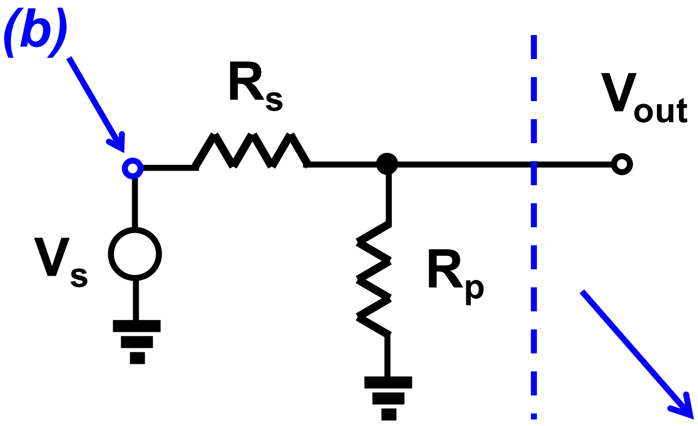
Useful for calculation/simulation of NF:

$$\boxed{NF = \frac{\overline{V^2_{n,out,TOT}}}{A_0^2} \cdot \frac{1}{4kTR_s}}$$

$$A_0 = \frac{V_{out}}{V_s} = \alpha \cdot A_V$$

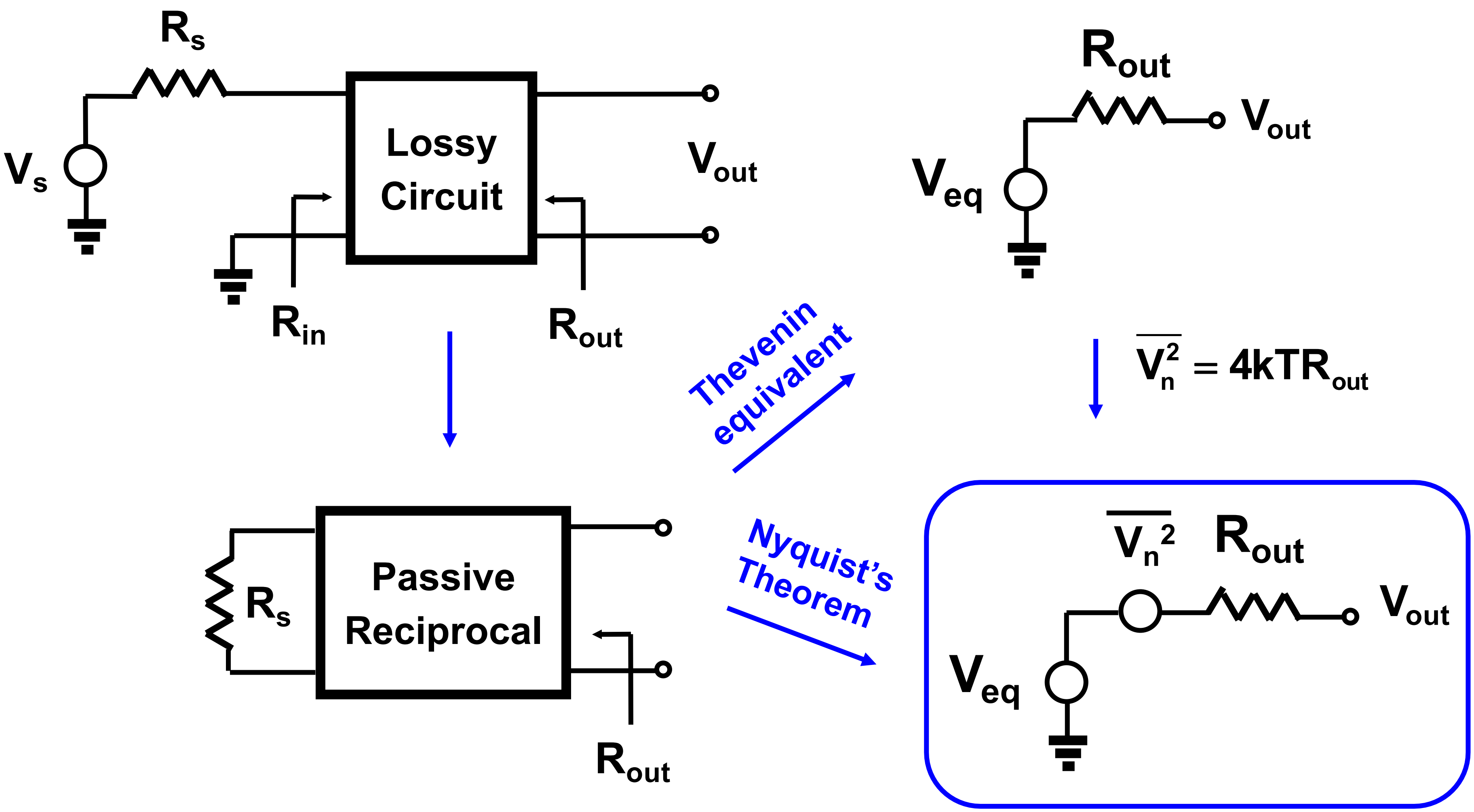
Unloaded voltage gain

Example: NF of Voltage Divider

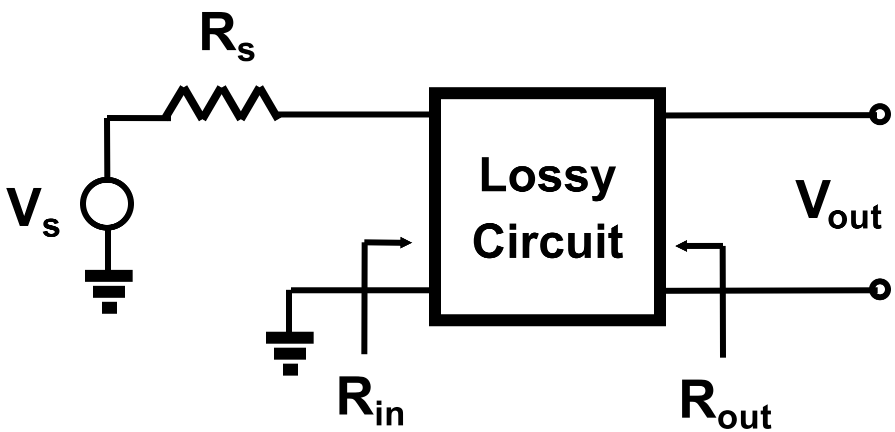


$$NF = \frac{\overbrace{4kT\left(R_s // R_p\right)}^{\overline{V^2_{n,out}}}}{\underbrace{\left(\frac{R_p}{R_p + R_s}\right)^2}_{A_0}} \cdot \frac{1}{4kTR_s} = 1 + \frac{R_s}{R_p}$$

NF of Lossy Circuits



NF of Lossy Circuits



Available Power Loss

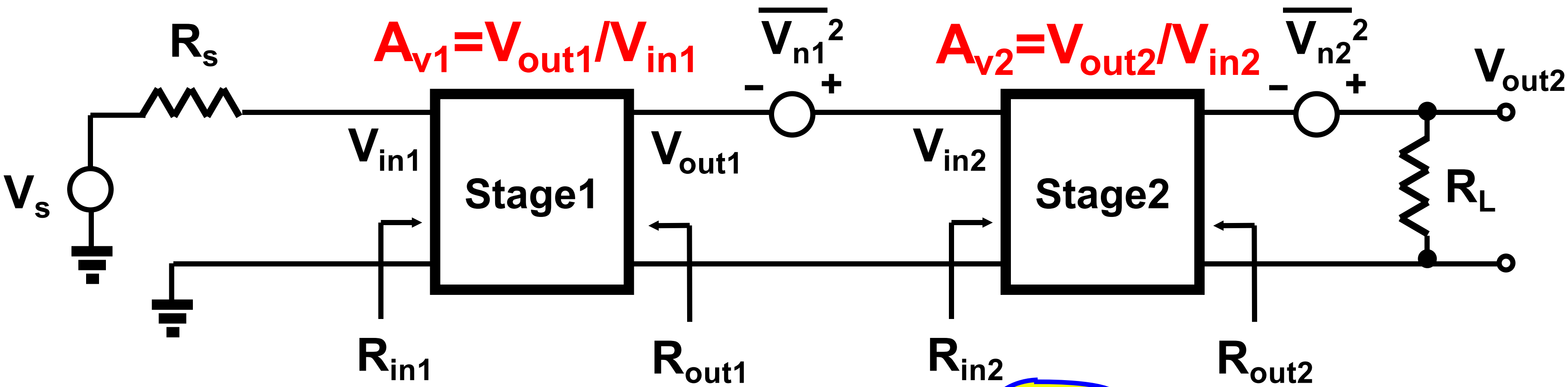
$$L = \frac{P_{in,av}}{P_{out,av}} = \frac{V_s^2 / 8R_s}{V_{eq}^2 / 8R_{out}}$$

$$NF = \frac{\overbrace{4kTR_{out}}^{\overline{V^2_{n,out}}}}{\left(\frac{V_{eq}}{V_s}\right)^2} \frac{1}{4kTR_s} = \frac{V_s^2}{V_{eq}^2}\frac{R_{out}}{R_s} = L$$

$\frac{V_{eq}}{V_s}$ = Gain A = V_{out}/V_s

Cascading NF

Unloaded Gain

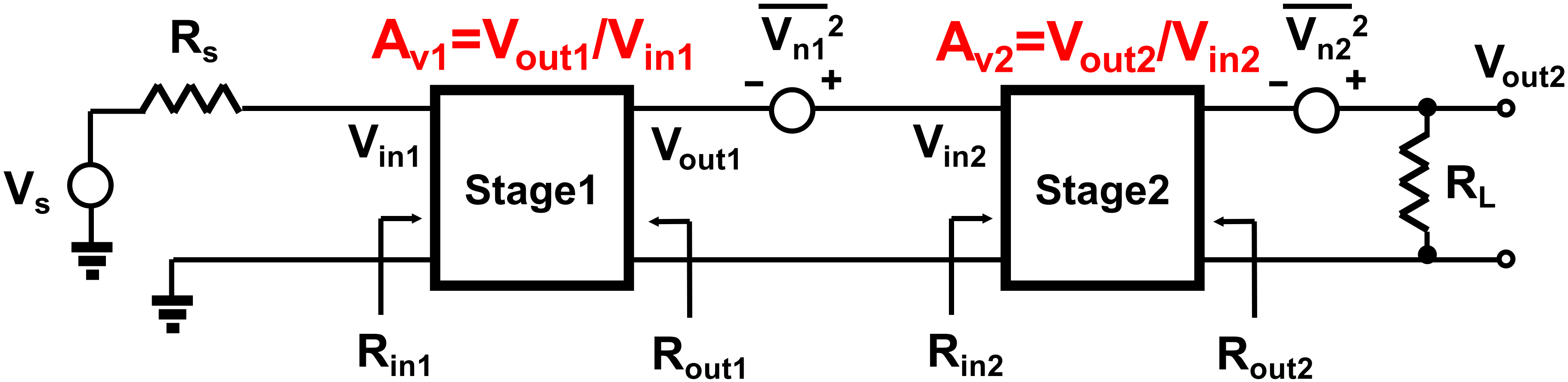


$$NF = \underbrace{1+\frac{\overline{V_{n1}^2}}{\underbrace{\left(\frac{R_{in1}}{R_{in1}+R_s}\right)^2 A_{v1}^2}_{(A_{01})^2}}\frac{1}{4kTR_s}}_{NF_1} + \frac{\overline{V_{n2}^2}}{\left(\frac{R_{in1}}{R_{in1}+R_s}\right)^2 A_{v1}^2 \left(\frac{R_{in2}}{R_{in2}+R_{out1}}\right)^2 A_{v2}^2}\frac{1}{4kTR_s}$$

$$NF_2\big|_{R_{out1}} = 1+\frac{\overline{V_{n2}^2}}{\left(\frac{R_{in2}}{R_{in2}+R_{out1}}\right)^2 A_{v2}^2}\frac{1}{4kTR_{out1}}$$

Cascading NF

Unloaded Gain



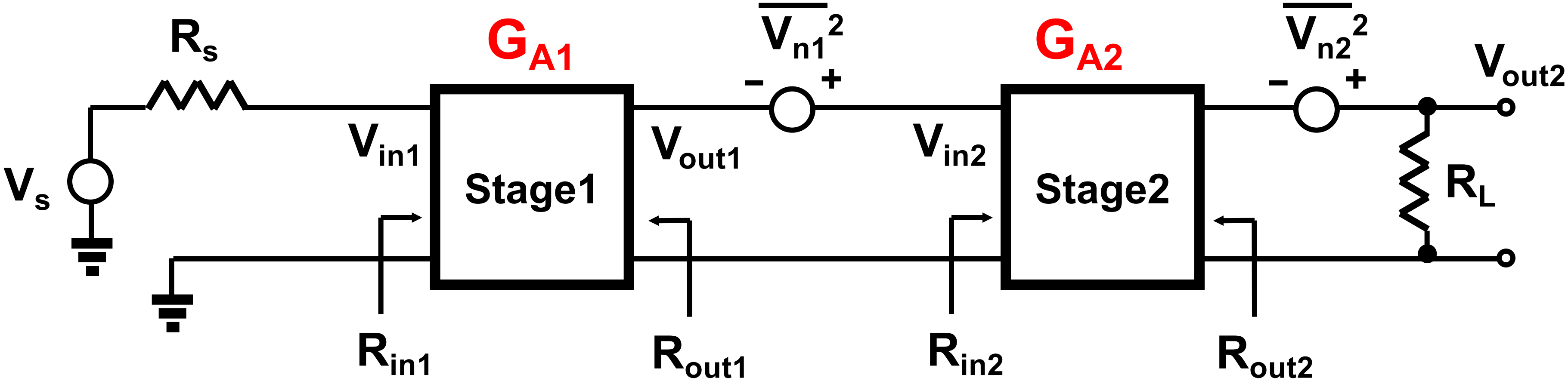
$$NF = NF_1 + \frac{NF_2\big|_{R_{out1}} - 1}{\underbrace{\left(\frac{R_{in1}}{R_{in1}+R_s}\right)^2 A_{v1}^2}_{(A_{01})^2} \frac{R_s}{R_{out1}}}$$

Voltage Gain

V_{out1}/V_s: A_{01}

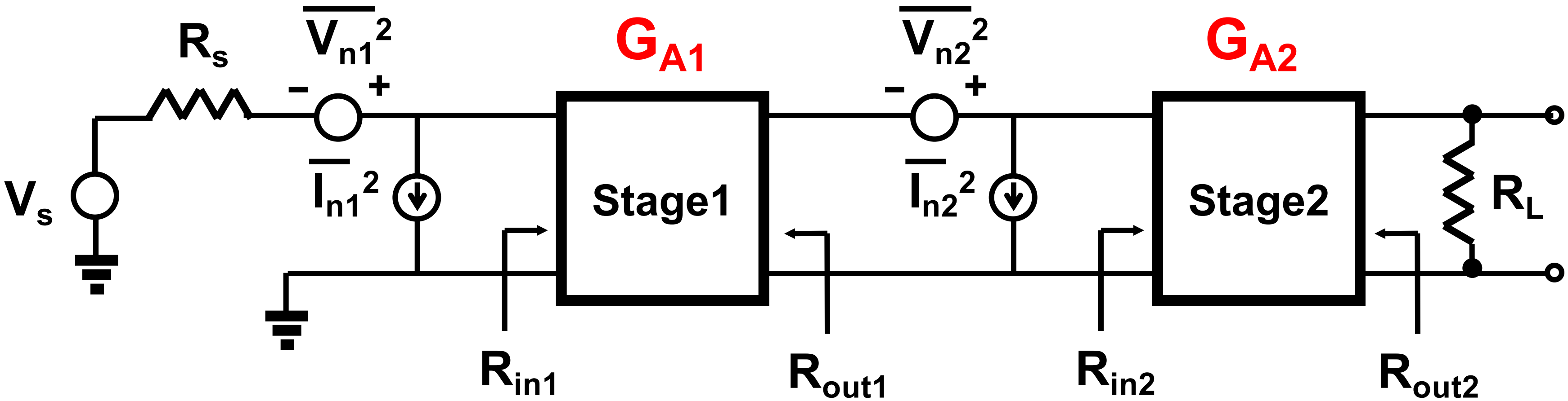
Available Power Gains

Available Power Gain



$$G_{A1} = \frac{P_{out,av}}{P_{in,av}} = \frac{V_s^2 \left(\frac{R_{in1}}{R_{in1} + R_s} \right)^2 A_{v1}^2 \cdot \frac{1}{8R_{out1}}}{\frac{V_s^2}{8R_s}} = A_{01}^2 \frac{R_s}{R_{out1}}$$

Friis Equation



Referred to R_{out1}

Referred to R_{out2}

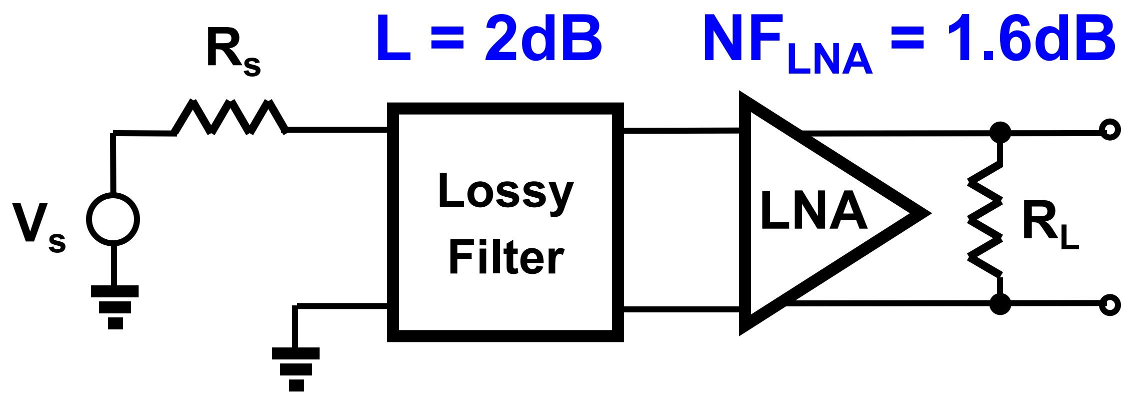
$$NF = NF_{1,Rs} + \frac{(NF_{2,Rout1} - 1)}{G_{A1}} + \frac{(NF_{3,Rout2} - 1)}{G_{A1}G_{A2}} + \ldots$$

Referred to R_s

Available Power Gains

This sum is <u>not</u> in dB!

Effect of Lossy Filter and Example



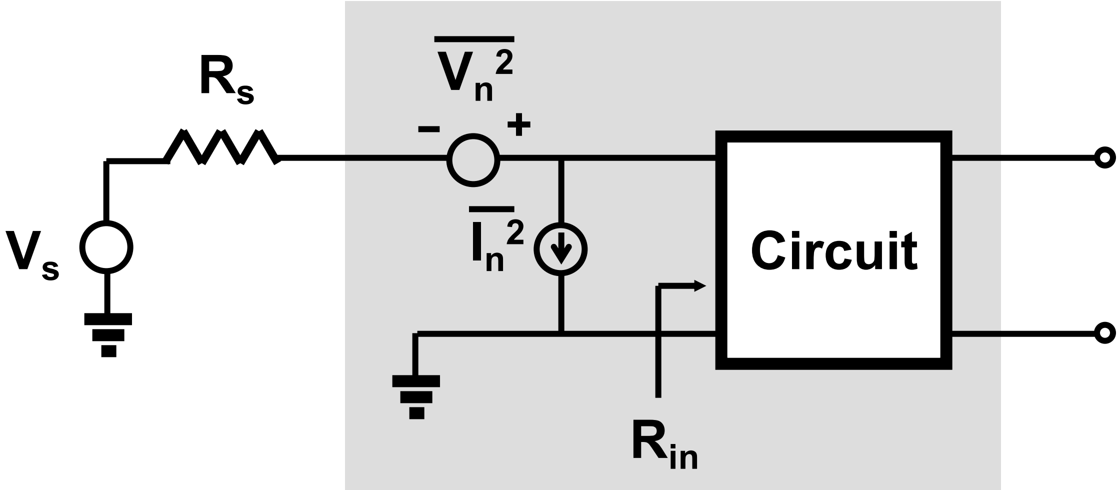
NF = 3.6dB

L

$$NF = NF_{filt} + \frac{\left(NF_{LNA} - 1\right)}{1/L} = L \cdot NF_{LNA}$$

- First stage are most critical for noise
- The noise figure is amplified by losses

Matching for Minimum Noise (Noise Matching)



$$NF = 1 + \frac{\overline{\left(V_n + I_n R_s\right)^2}}{4kTR_s} \approx 1 + \frac{\overline{V_n^2}}{4kTR_S} + \frac{\overline{I_n^2}}{4kT/R_S}$$

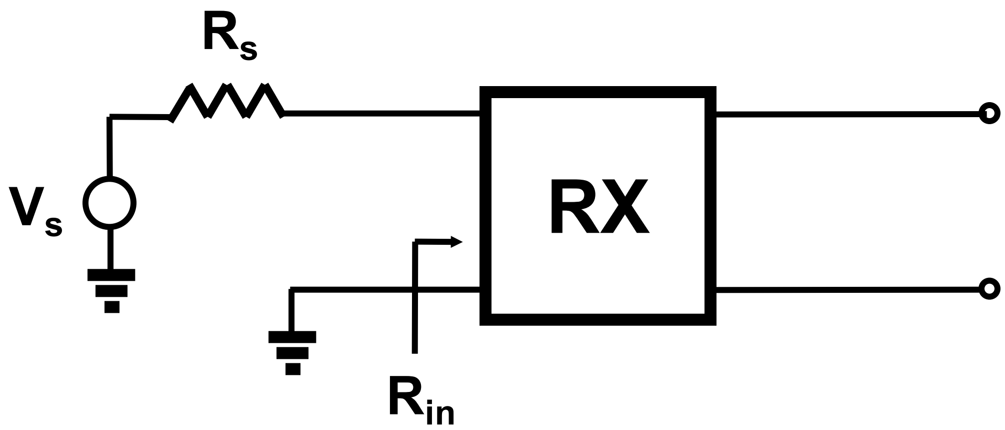
$$\frac{\partial NF}{\partial R_s} = 0 \longrightarrow R_{s,opt} = \sqrt{\frac{\overline{V_n^2}}{\overline{I_n^2}}}$$

Highlights

- **Two input-referred generators needed to model noise of a two-port network**
- **Noise Figure:**
  - **is the ratio between total noise and source noise**
  - **is a single parameter, referred to a specific source resistance**
- **Cascaded stage: first stages more critical**
- **Lossy filters degrade the noise figure**
- **Minimum noise figure is obtained with optimum source resistance (Noise matching)**

Basic Concepts in RF:
Sensitivity and Dynamic Range

Available Noise Power



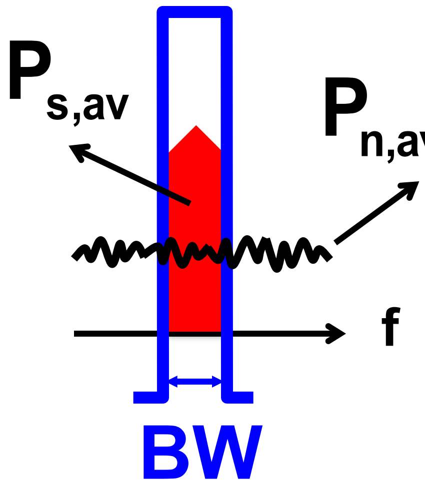
[V²/Hz] **[W/Hz]**

$$\frac{\overline{V_{n,s}^2}}{\Delta f} = 4kTR_s \rightarrow \frac{P_{n,av}}{\Delta f} = kT$$

$$\downarrow$$

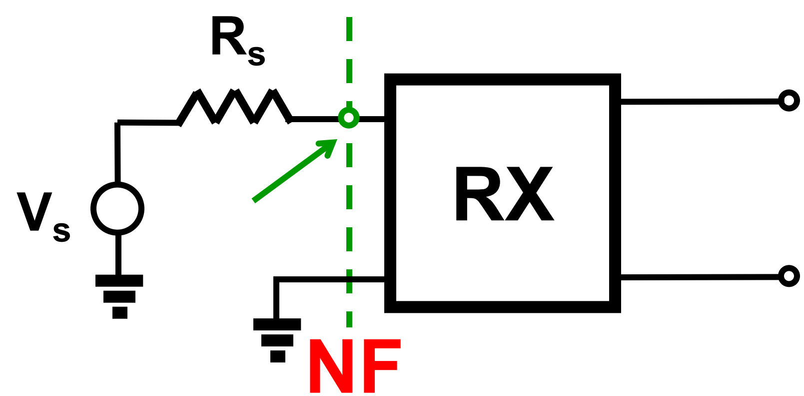
-174 dBm/Hz at room temperature (25 degrees Celsius)

Sensitivity



$$P_{n,av} = kT \cdot NF \cdot BW$$

$$SNR = \frac{P_{s,av}}{P_{n,av}}$$



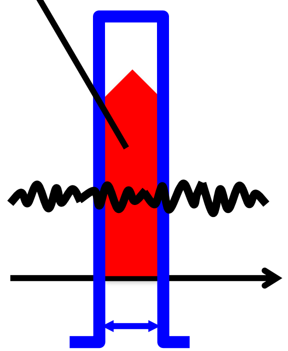
- ***Sensitivity*** **is the minimum detectable signal**

$$P_{s,min}\Big|_{dBm} = \overbrace{kT\Big|_{dBm} + NF\Big|_{dB} + 10\log(BW)}^{P_{n,av}} + \overbrace{SNR\Big|_{dB}}^{\text{Minimum SNR}}$$

Example: NF of a GSM Receiver

Sensitivity

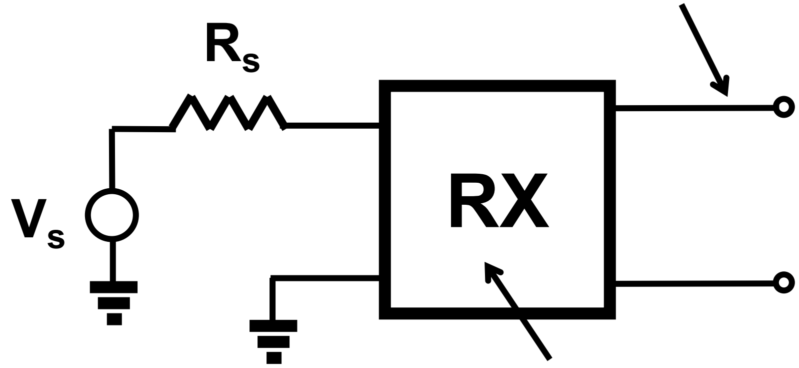
$P_{s,min}$ **= -100 dBm**



Noise BW
200 kHz

Signal-to-Noise Ratio

SNR = 12 dB

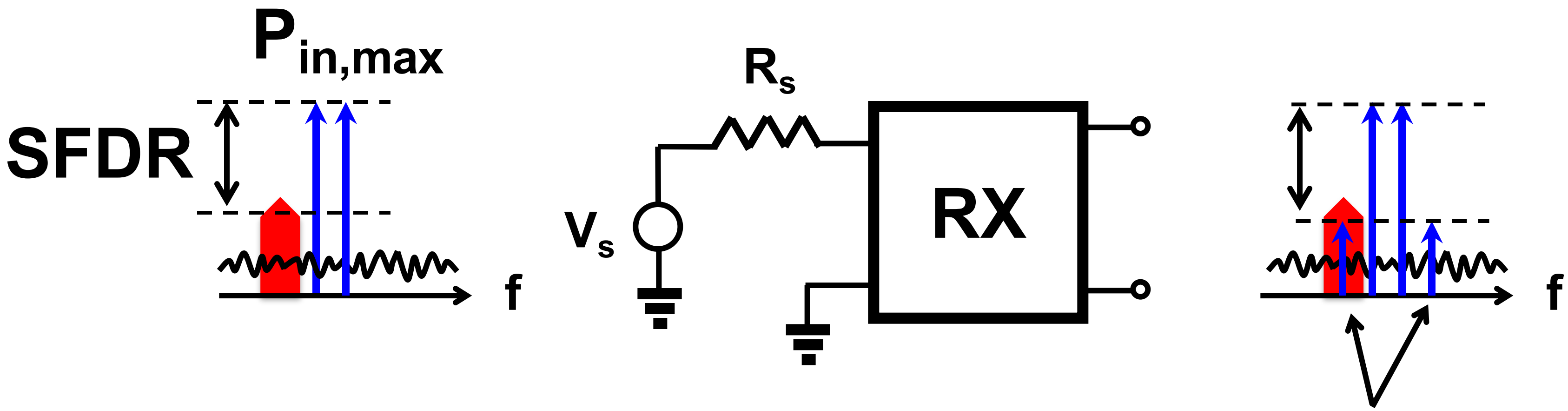


Noise Figure NF

$$NF_{dB} = -kT - 10\log(BW) - SNR_{min} + P_{s,min}$$

$$= 174 - 53 - 12 - 100 = 9\text{ dB}$$

Dynamic Range

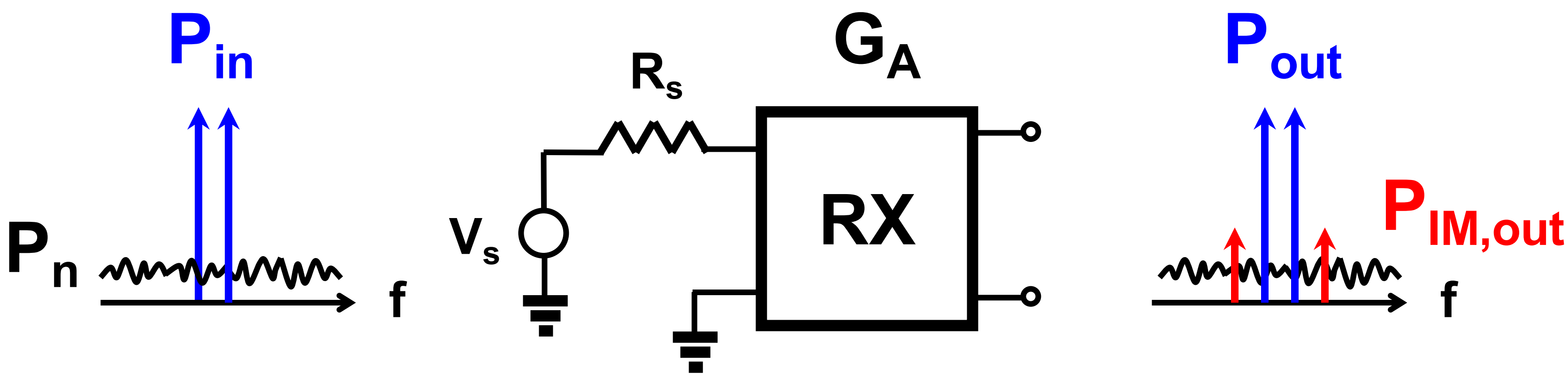


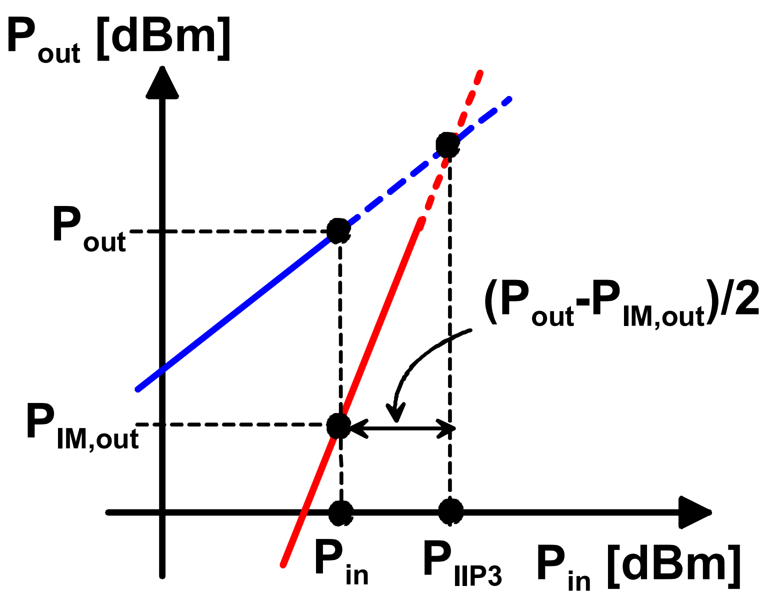
Third-order nonlinearity gives rise to **IM3 products**

- **Upper end:** IM3 products equal to noise
- **Lower end:** sensitivity level

→ The available full-scale range is the Spurious-Free Dynamic Range (SFDR)

Dynamic Range (cont'd)





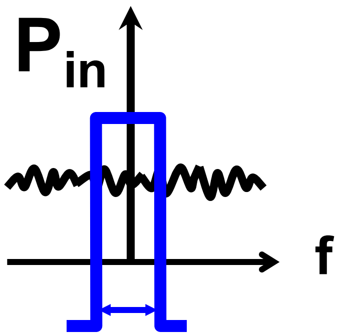
$$P_{IIP_3} = P_{in} + \frac{\left(P_{out} - P_{IM,out}\right)}{2} =$$

$$= P_{in} + \frac{\left(P_{in} + \cancel{G_A} - P_{IM,in} - \cancel{G_A}\right)}{2}$$

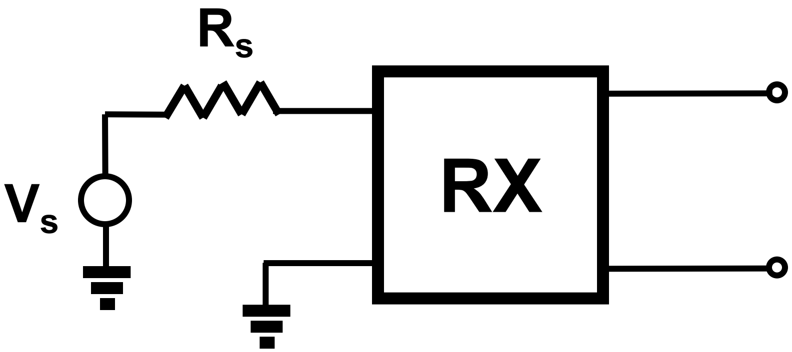
$$\boxed{P_{in,max} = \frac{2P_{IIP_3} + P_n}{3}}$$

in dBm!

Example: SFDR of a GSM Receiver



SNR = 12 dB



NF = 9 dB → P_n = -112 dBm → $P_{in,min}$ = -100 dBm

IIP3 = -15 dBm → $P_{in,max} = \frac{2IIP_3 + P_n}{3}$ = -47.3 dBm

→ SFDR = $P_{in,max}$ - $P_{in,min}$ = 52.7 dB

Highlights

- **RX Sensitivity is the power of the minimum detectable signal (with minimum SNR)**
- **RX Spurious-Free Dynamic Range is the ratio between maximum signal producing IM products equal to noise and sensitivity**