RF power amplifiers – Class A to class C

Microwave Electronics

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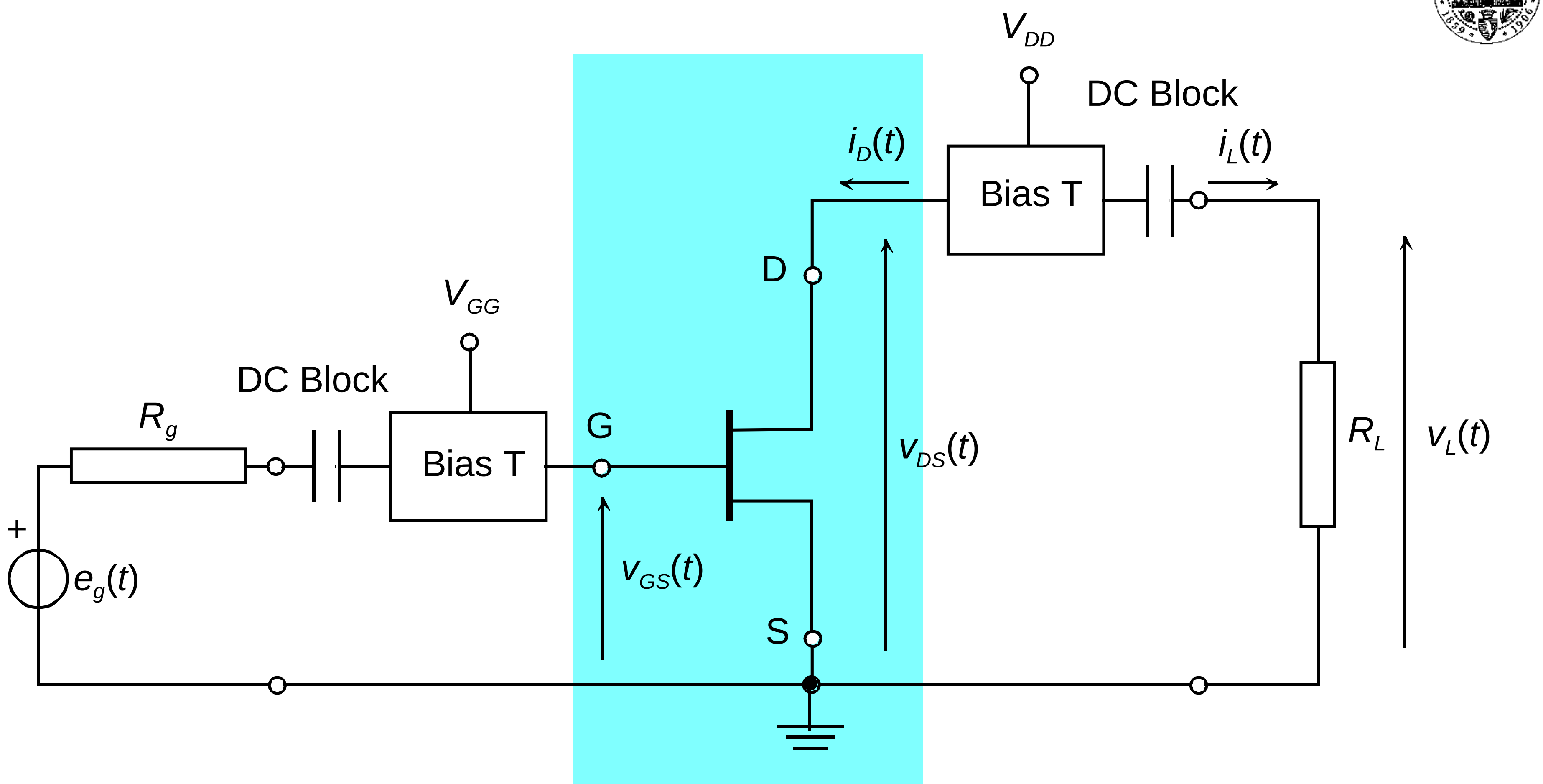
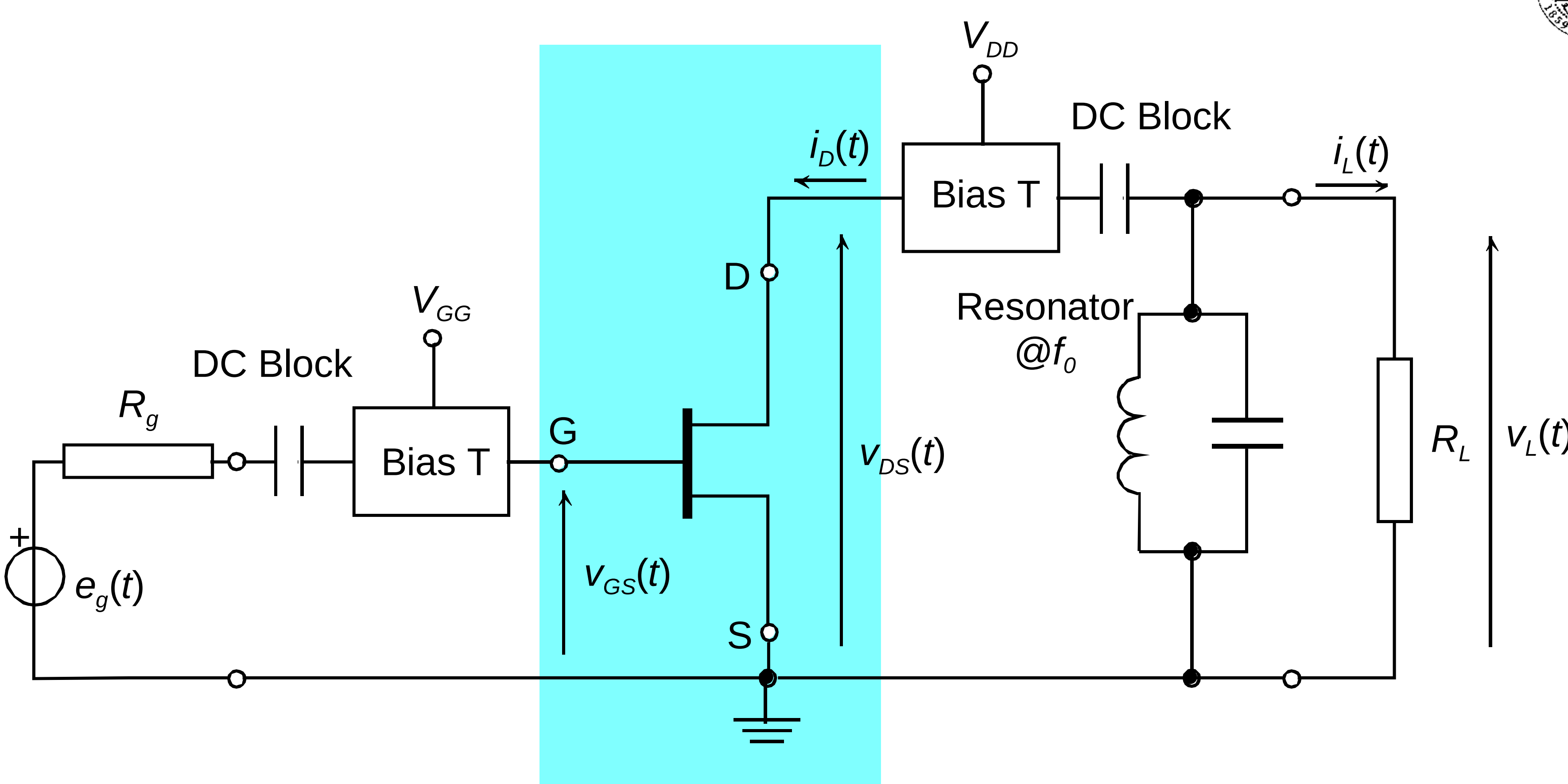
RF amplifiers

- Receiver chain:
  - Low-noise amplifiers → optimized with respect to noise figure & gain
  - High gain amplifiers → optimized with respect to gain
- Transmitter chain:
  - High gain amplifiers
  - Power amplifiers → optimized vs. output power, linearity, efficiency

PA with “resistive” load



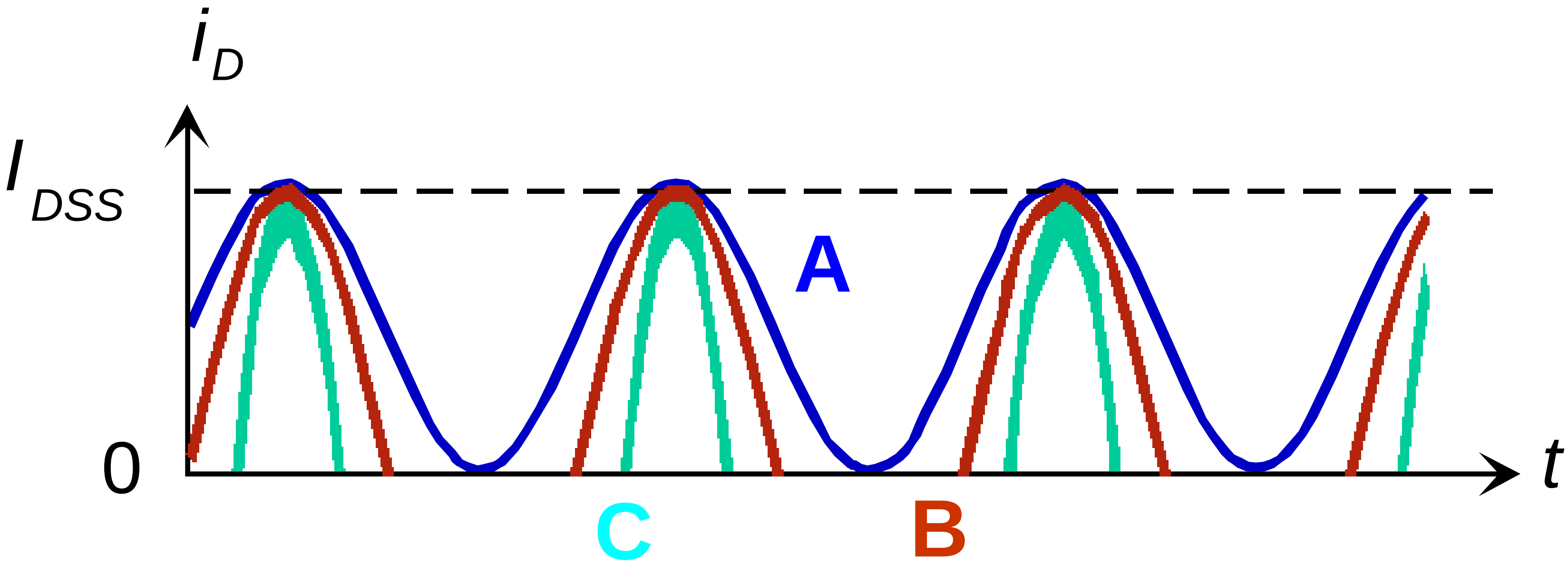
PA with “tuned” load



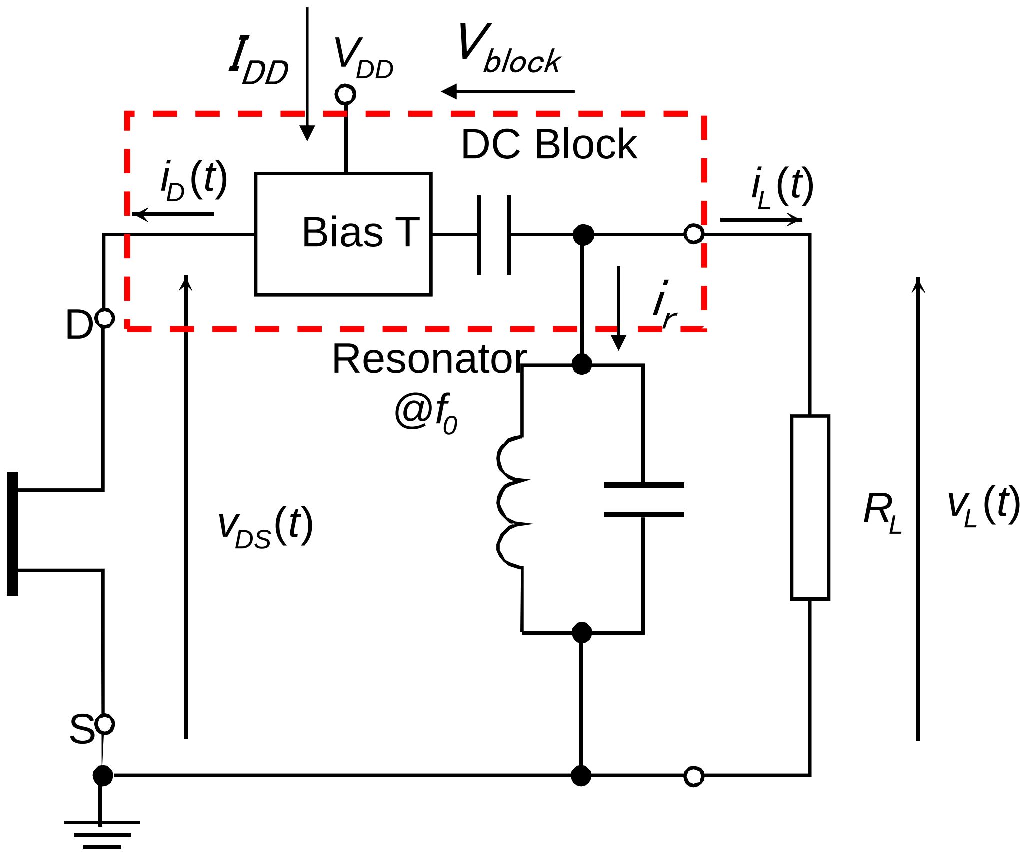
PA – Classes (traditional)

- Suppose to apply a sinusoidal input signal of period T to the power amplifier; cases:
  - Class A (quasi-linear): the active device is always ON
  - Class AB: the active device is ON for more than 50% of the time
  - Class B: the active device is ON for exactly 50% of the time
  - Class C: the active device is ON for less than 50% of the time

From class A to class C: device current



Tuned PA output loop equations



Time domain:

$$v_L(t) + V_{block} = v_{DS}(t)$$

$$i_L(t) + i_D(t) + i_r(t) = I_{DD}$$

Frequency domain

$$V_{DS}(DC) = V_{block}(DC) = V_{DD}$$

$$V_{DS}(f_0) = V_L(f_0)$$

$$V_{DS}(nf_0) = V_L(nf_0) = 0$$

$$I_D(DC) = I_{DD} \qquad I_L(DC) = I_r(DC) = 0$$

$$I_L(f_0) = -I_D(f_0)$$

$$I_L(nf_0) = 0, \quad I_r(nf_0) = -I_D(nf_0)$$

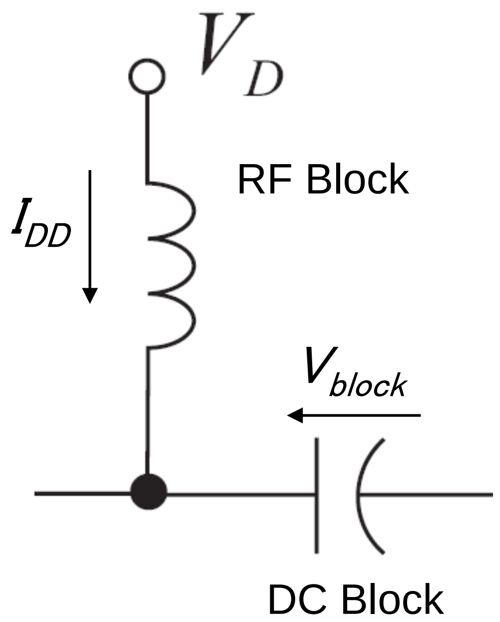
Load line (generally a curve)

$$V_{DS}(f_0) = V_L(f_0) = R_L I_L(f_0) = -R_L I_D(f_0)$$

$$v_{DS}(t) = V_{DD} - R_L I_D(f_0)\cos\omega_0 t$$

$$i_D(t) = I_{DD} + I_D(f_0)\cos\omega_0 t + I_D(2f_0)\cos 2\omega_0 t + \ldots$$

Bias T voltages & currents



- Ideally the RF block is a very large inductor → only the DC component of the current can pass, the block blocks all frequencies above DC
- The DC block is a very large capacitor → only the DC component of voltage exists, all other frequencies above DC are shorted

Load line & output device $I_D(V_{DS})$

Load line + device characteristics

$$v_{DS}(t) = V_{DD} - R_L I_D(f_0)\cos\omega_0 t$$

$$i_D(t) = I_{DD} + I_D(f_0)\cos\omega_0 t + I_D(2f_0)\cos 2\omega_0 t + \ldots$$

$$i_D(t) = I(v_{DS}(t), v_{GS}(t))$$

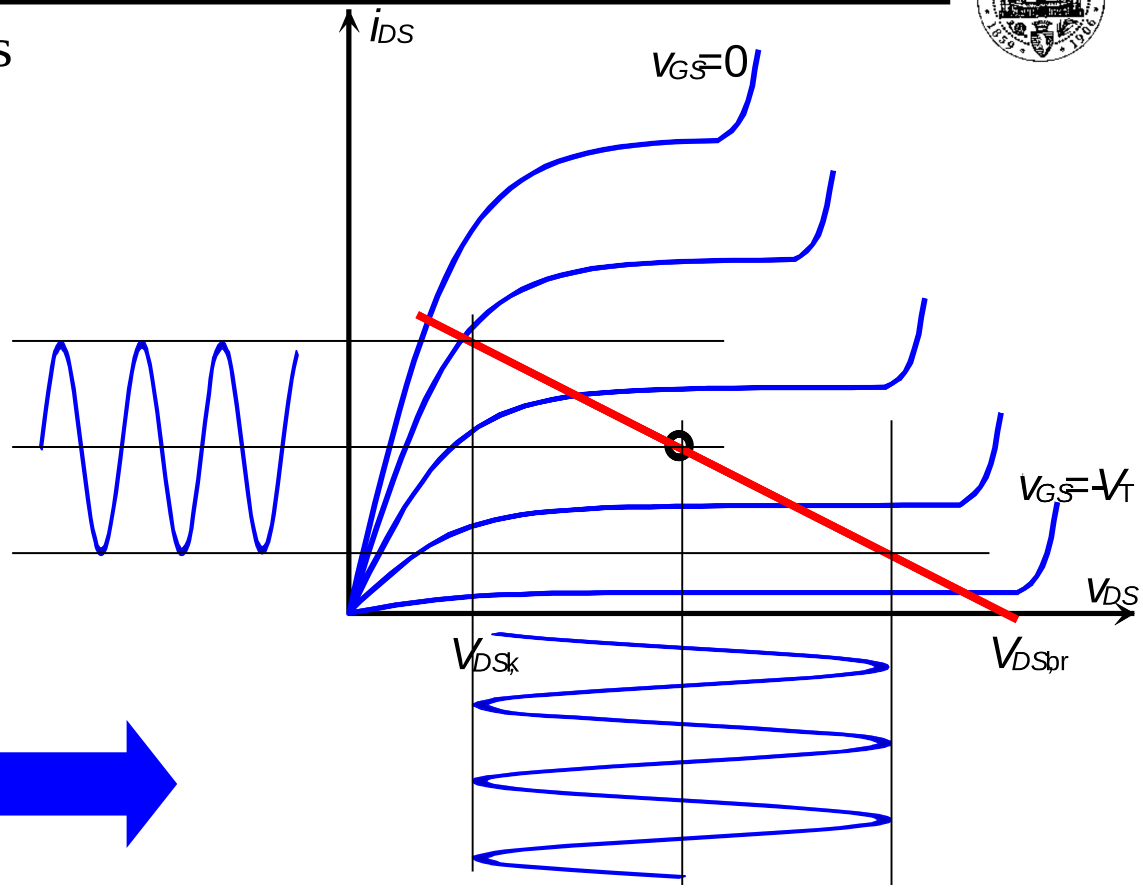
No harmonics (e.g. class A before saturation)

$$v_{DS}(t) = V_{DD} - R_L I_D(f_0)\cos\omega_0 t$$

$$i_D(t) = I_{DD} + I_D(f_0)\cos\omega_0 t$$

$$\rightarrow (i_D - I_{DD}) = -(v_{DS} - V_{DD})/R_L$$

$$i_D(t) = I(v_{DS}(t), v_{GS}(t))$$



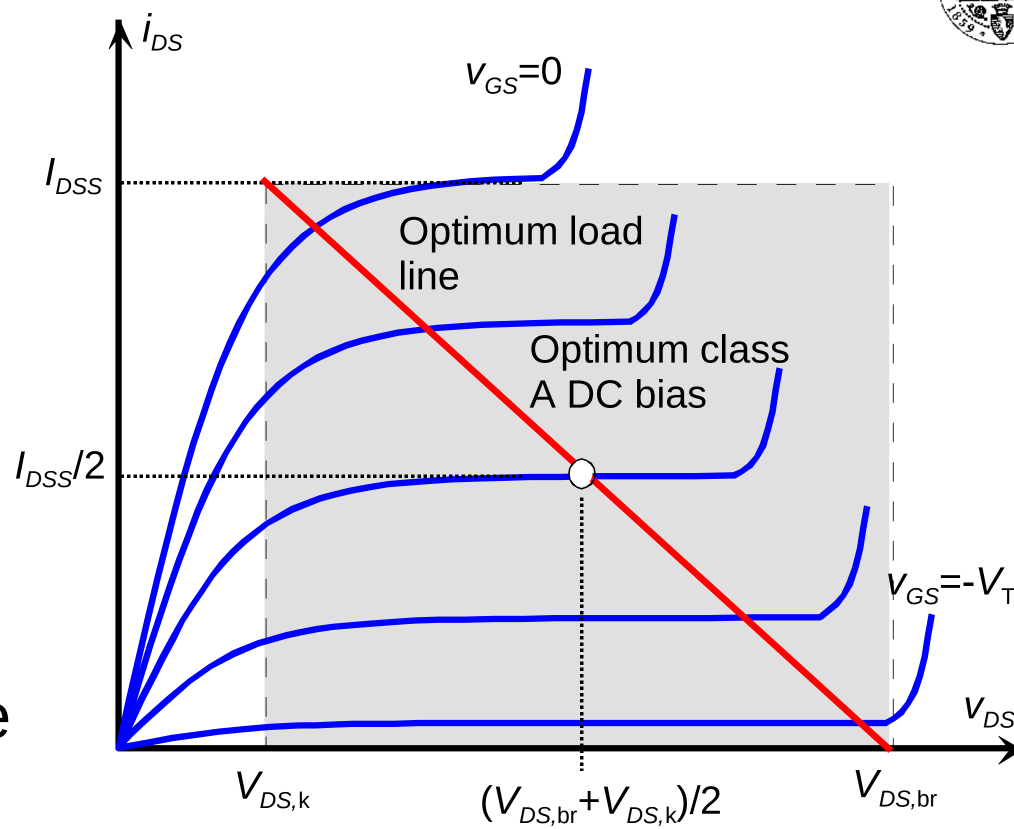
Class A amplifier analysis

- PA dynamics limited by
  - current saturation
  - triode (linear) region
  - cutoff
  - breakdown
- Optimum DC bias point:

$$I_{D,DC} = I_{DSS} / 2$$

$$V_{DS,DC} \approx V_{DS,br} / 2$$

- Maximum (peak) AC voltage and current amplitude



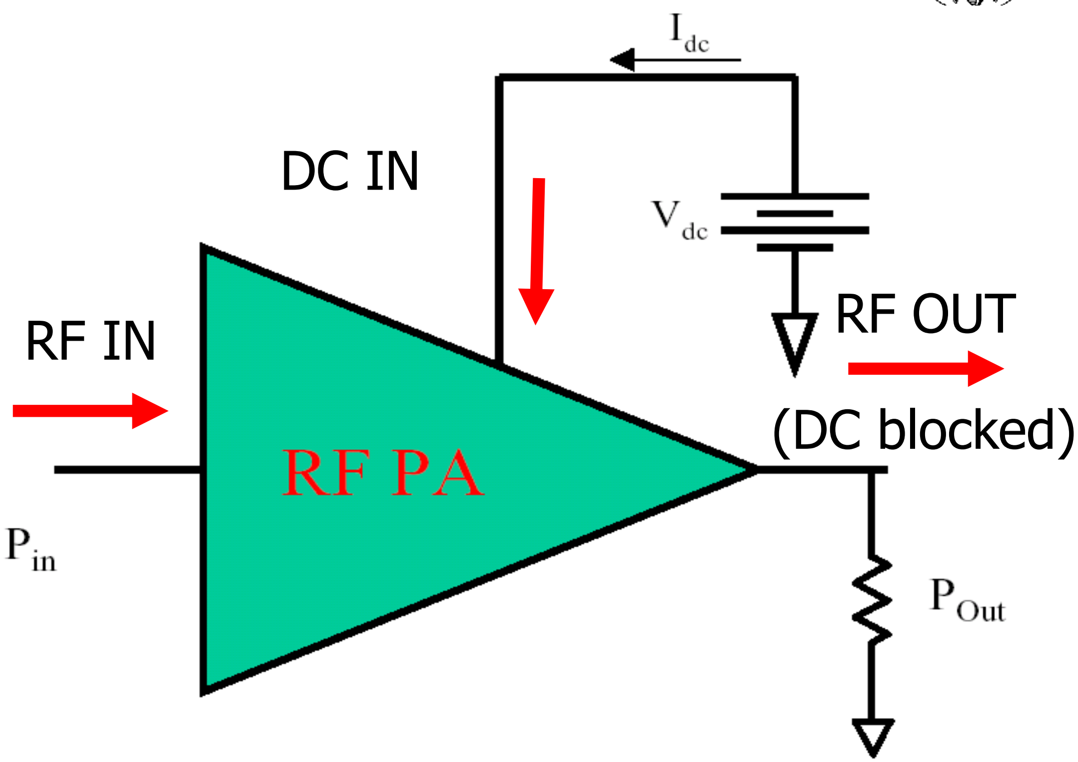
$$v_{DS,M} = \frac{V_{DS,br} - V_{DS,k}}{2} \approx \frac{V_{DS,br}}{2} \qquad i_{D,M} = \frac{I_{DSS}}{2}$$

Power amplifier gain

- Power amplifier power gain:
  - Transducer: $$G_{tr} = \frac{P_{out}}{P_{disp,in}}$$
  - Operational: $$G_{op} = \frac{P_{out}}{P_{in}}$$
  - Available power ????

PA Efficiency & PAE

- Total DC power from bias $P_{DC} = V_{DC} I_{DC}$ → no DC power to load!
- Only in class A amplifiers = to DC power without applied signal!
- Efficiency:
- Power-added efficiency *(PAE):*



$$\eta = \frac{P_{out}(f_0)}{P_{DC}}$$

$$\mathrm{PAE} = \frac{P_{out}(f_0) - P_{in}(f_0)}{P_{DC}} = \eta\left(1 - \frac{1}{G_{op}}\right)$$

Class A power, efficiency, waveforms

- Optimum load resistance

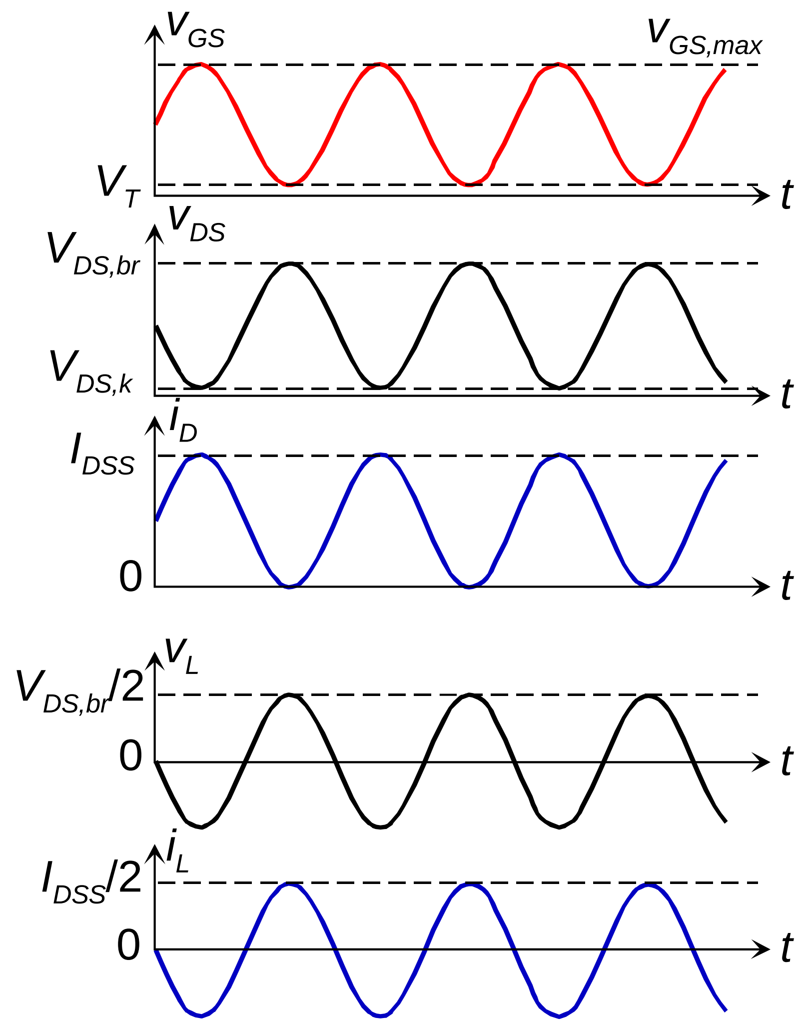
$$R_{Lo} = \frac{V_{DS,br}}{I_{DSS}}$$

- Average RF power to load

$$P_{RF,M} = \frac{1}{2} v_{L,M} i_{L,M} \cos\theta = $$
$$= \frac{1}{2} v_{DS,M} i_{D,M} \approx \frac{V_{DS,br} I_{DSS}}{8}$$

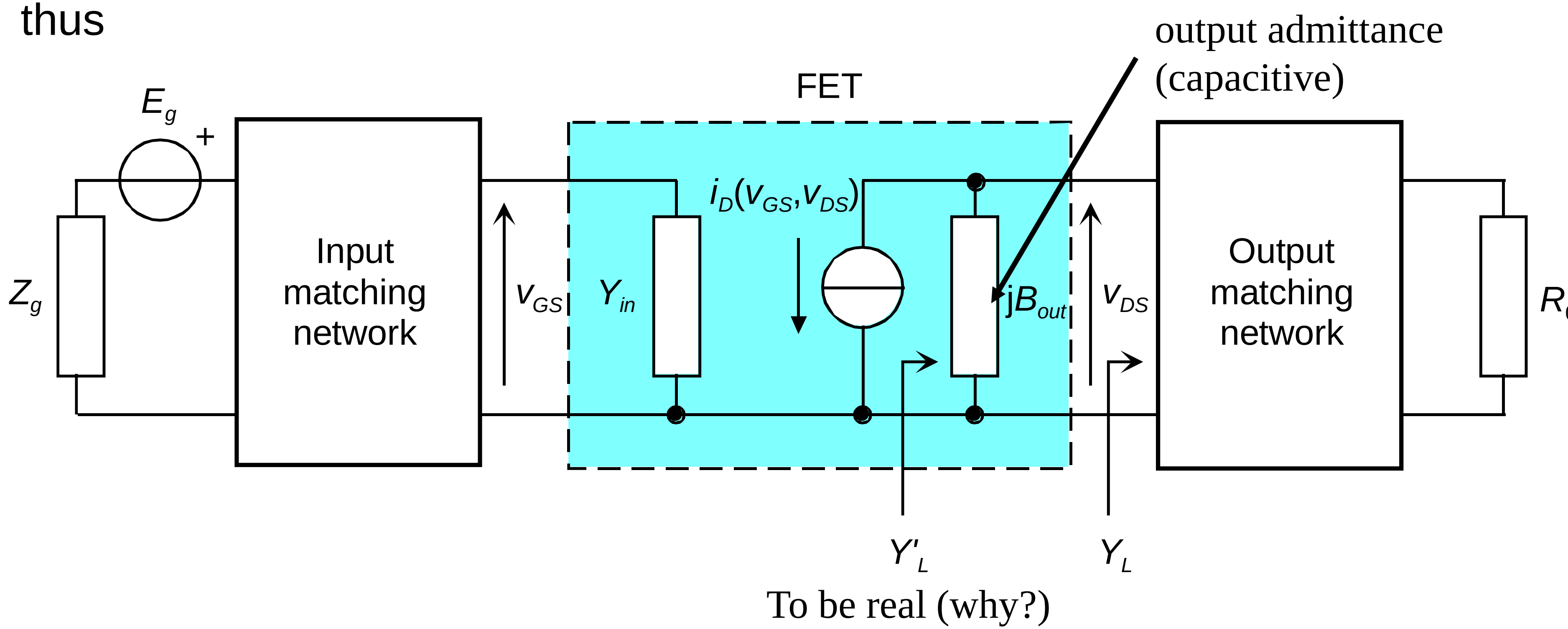
- DC power & efficiency

$$P_{DC} = \frac{V_{DS,br} I_{DSS}}{4} \qquad \eta_A = \frac{P_{RF,M}}{P_{DC}} = 0.5$$



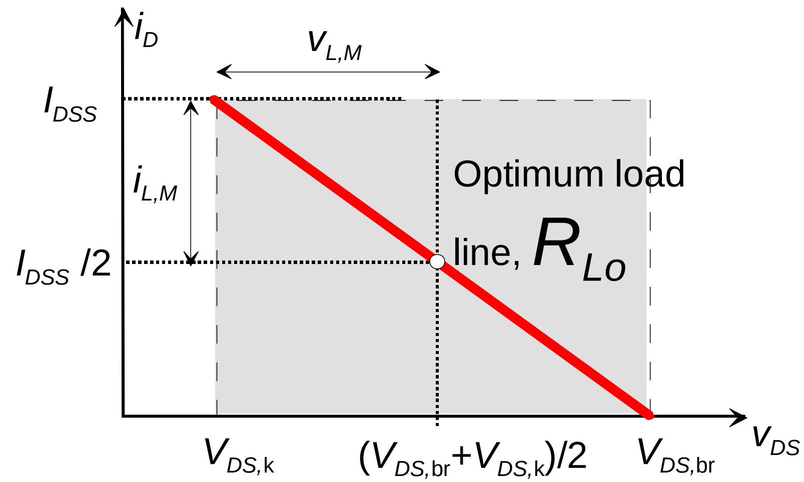
Class A design

- Optimum A bias point
- IMN: input matching (input admittance → generator) $Y'_L = 1/R_{Lo}$
- OMN: transform load into Y_L → $Y_L = 1/R_{Lo} - \mathrm{j}B_{out}$
- thus

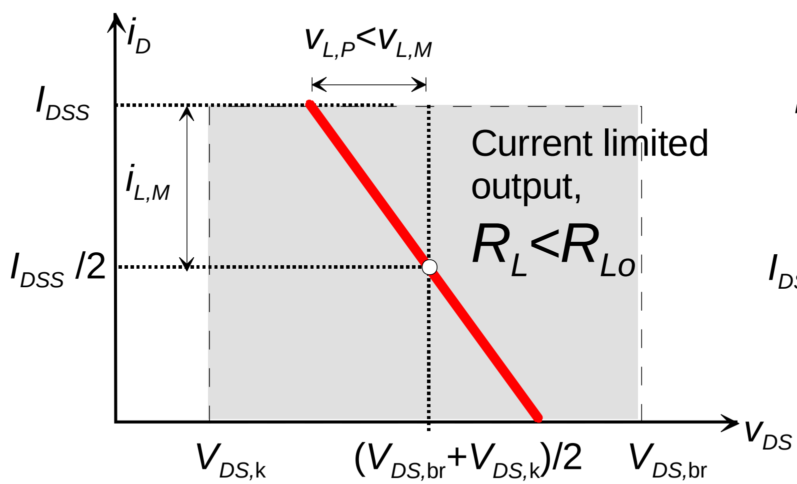


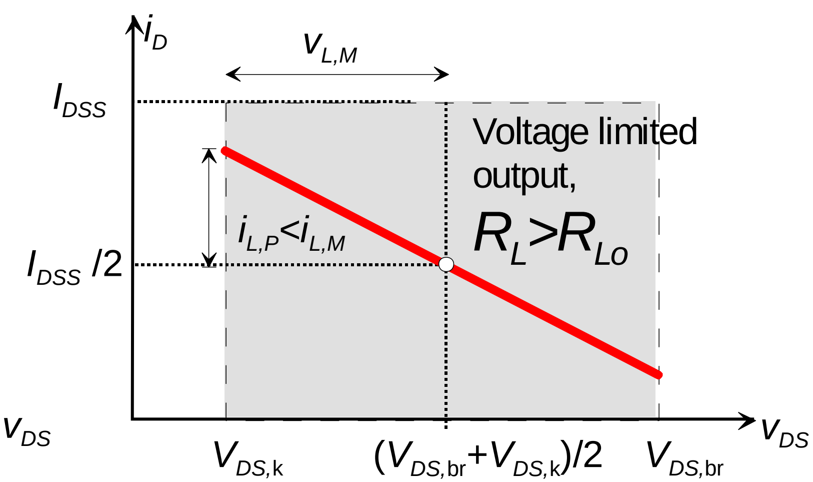
Deviation from optimum load

$$P_{RF} = \frac{1}{2} i_{L,M}^2 R'_L$$
$$= P_{RF,M} \frac{R'_L}{R_{Lo}}$$

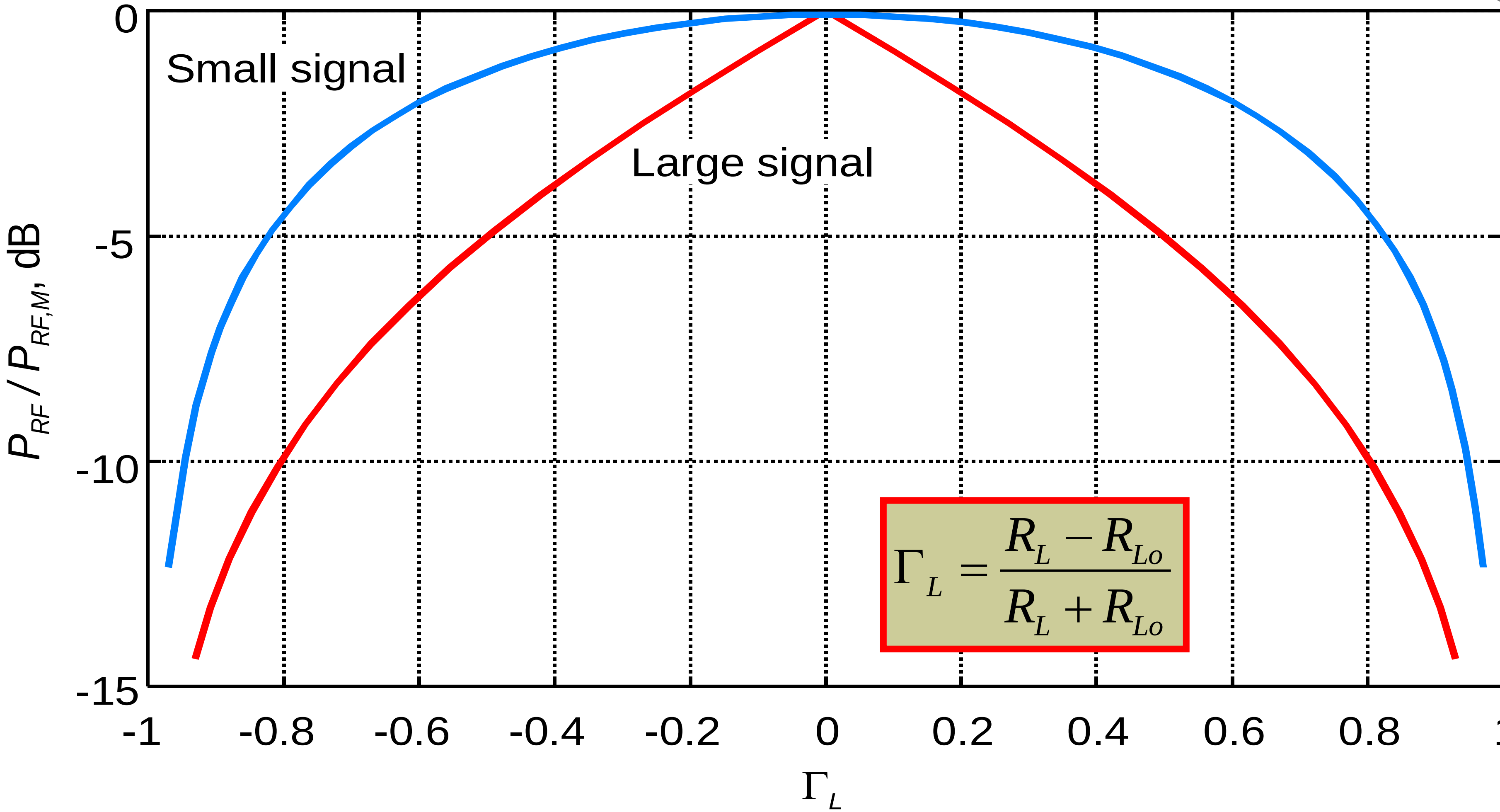


$$P_{RF} = \frac{1}{2} v_{L,M}^2 \frac{1}{R'_L}$$
$$= P_{RF,M} \frac{R_{Lo}}{R'_L}$$

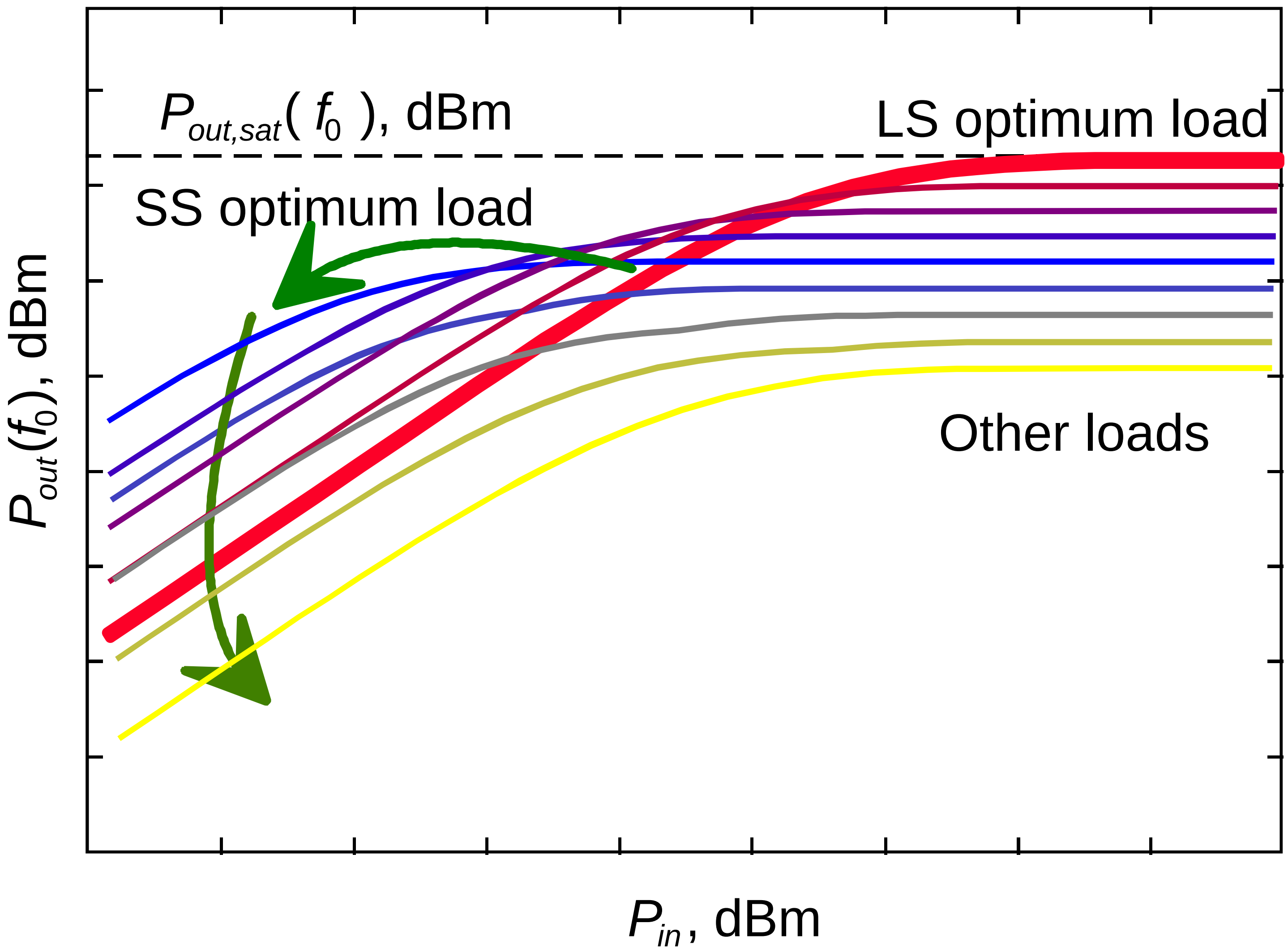




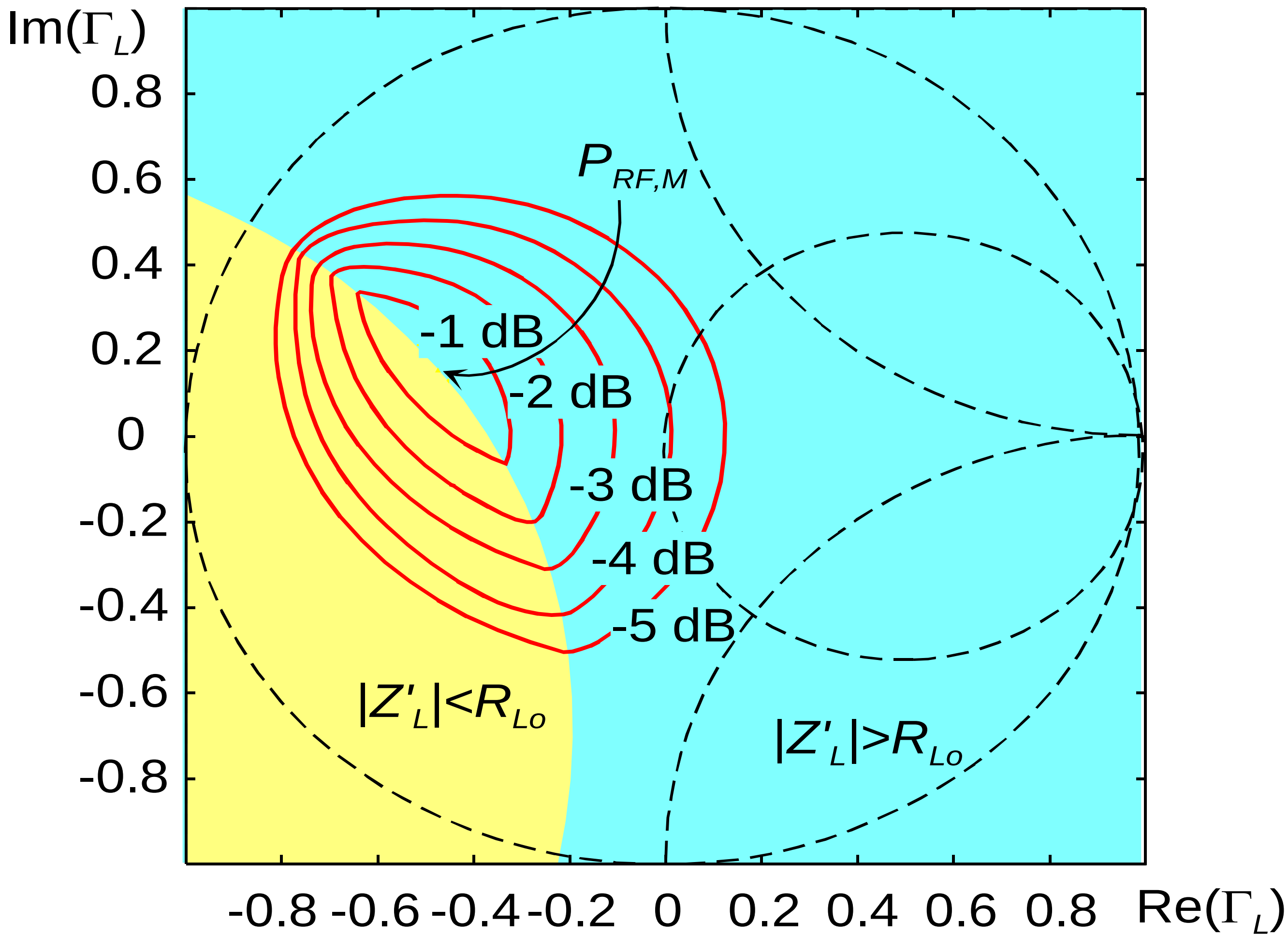
Power vs. optimum, res. load



Deviations on Pin-Pout



Class A Load-Pull (Cripps)

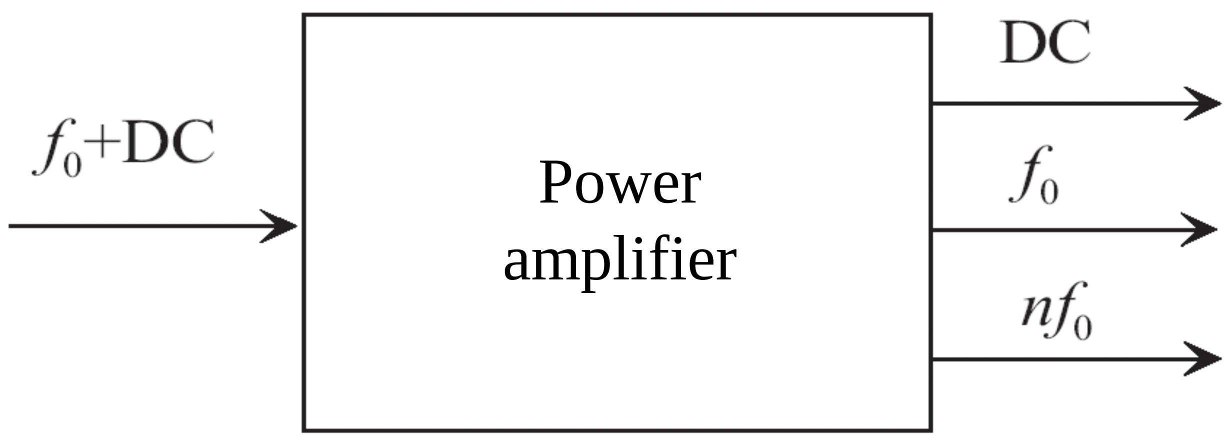


Load pull design

- The load-pull procedure can be carried out experimentally by changing the load seen by the device with a mechanical or electronic tuner; in this way the optimum load impedance can be detected, also for other parameters (IMPs, efficiency etc.)
- Also a source-pull approach is feasible, but less effective at least in FETs (low sensitivity with respect to source impedance)

Power amplifier performances I

- Power amplifier: *quasi-linear system (class A)*
- Single-frequency input + DC (bias): output @ fundamental + DC + harmonics



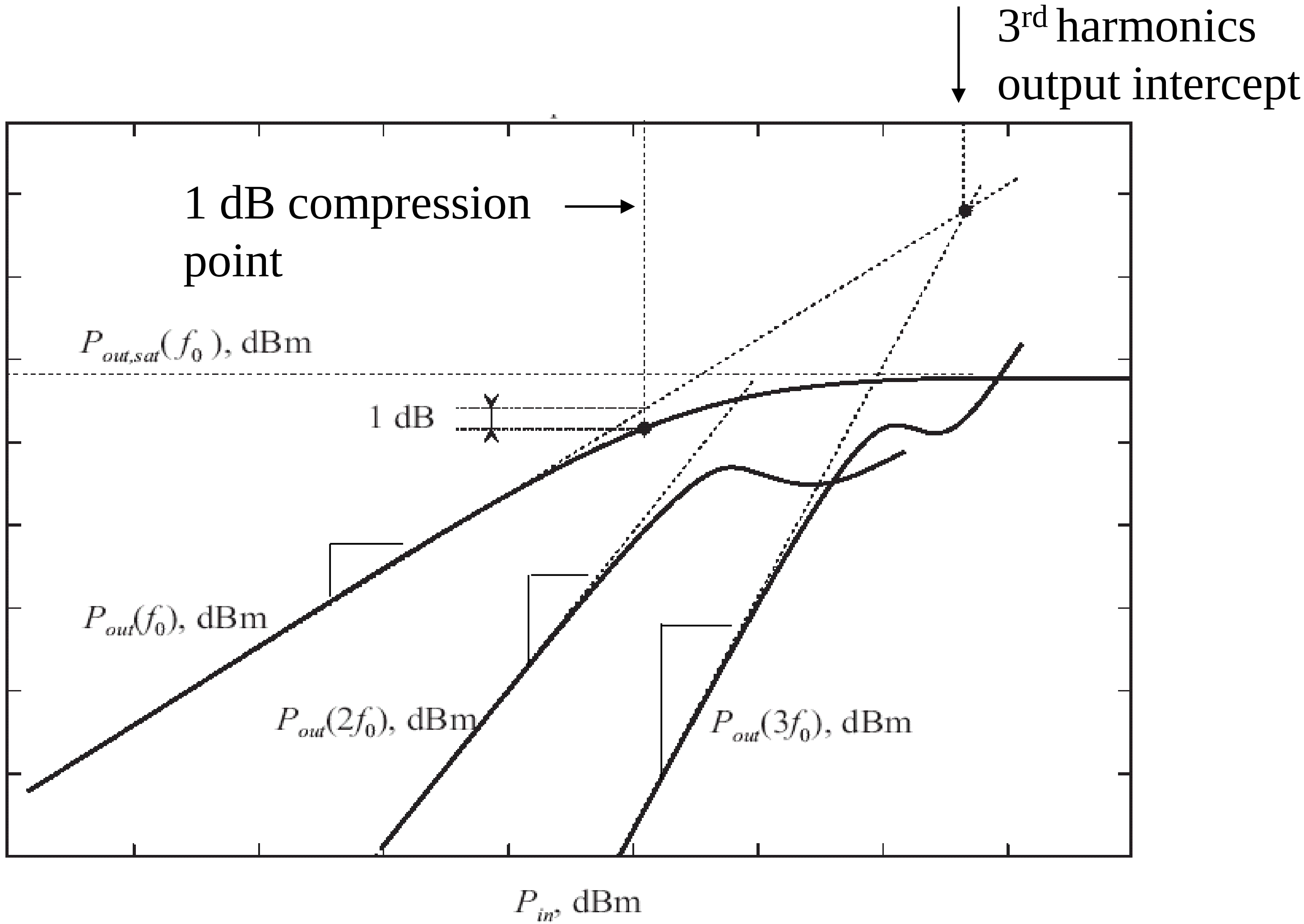
Power amplifier performances II

- Power amplifier power gain:
  - Transducer: $G_{tr} = \dfrac{P_{out}}{P_{av,in}}$
  - Operational: $G_{op} = \dfrac{P_{out}}{P_{in}}$
  - Conversion (fundamental → harmonics & DC; defined in small-signal):

$$P_{out}\left(nf_0\right) = K_n P_{in}^n\left(f_0\right)$$

Single-tone Pin-Pout

Output saturation power



3rd, 5th… harmonics intercept

- Output power @ nth harmonic = linear output power at fundamental

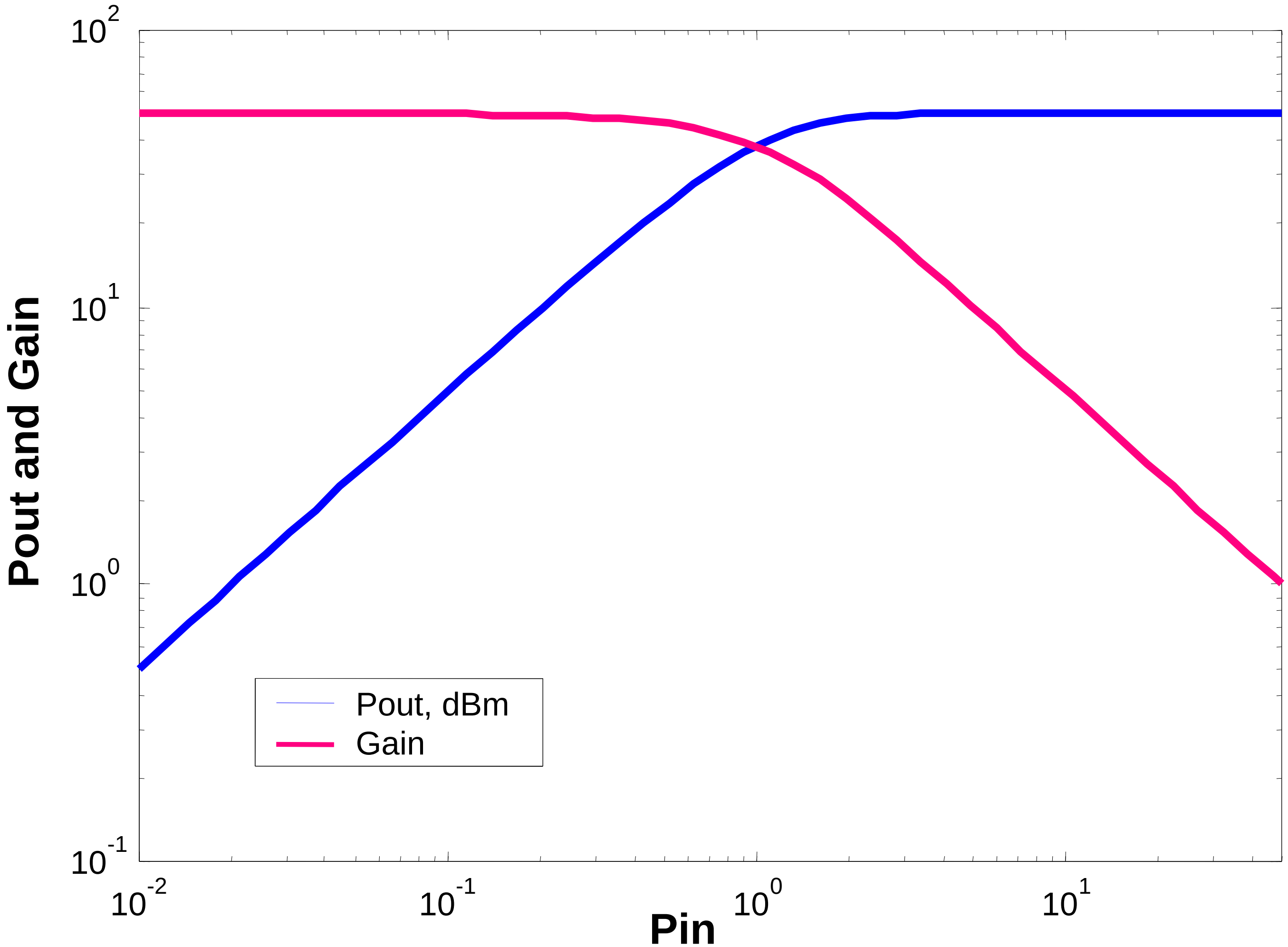
$$G_{op,SS}P_{in,n} = K_n P_{in,n}^n$$

- Corresponding input intercept power:

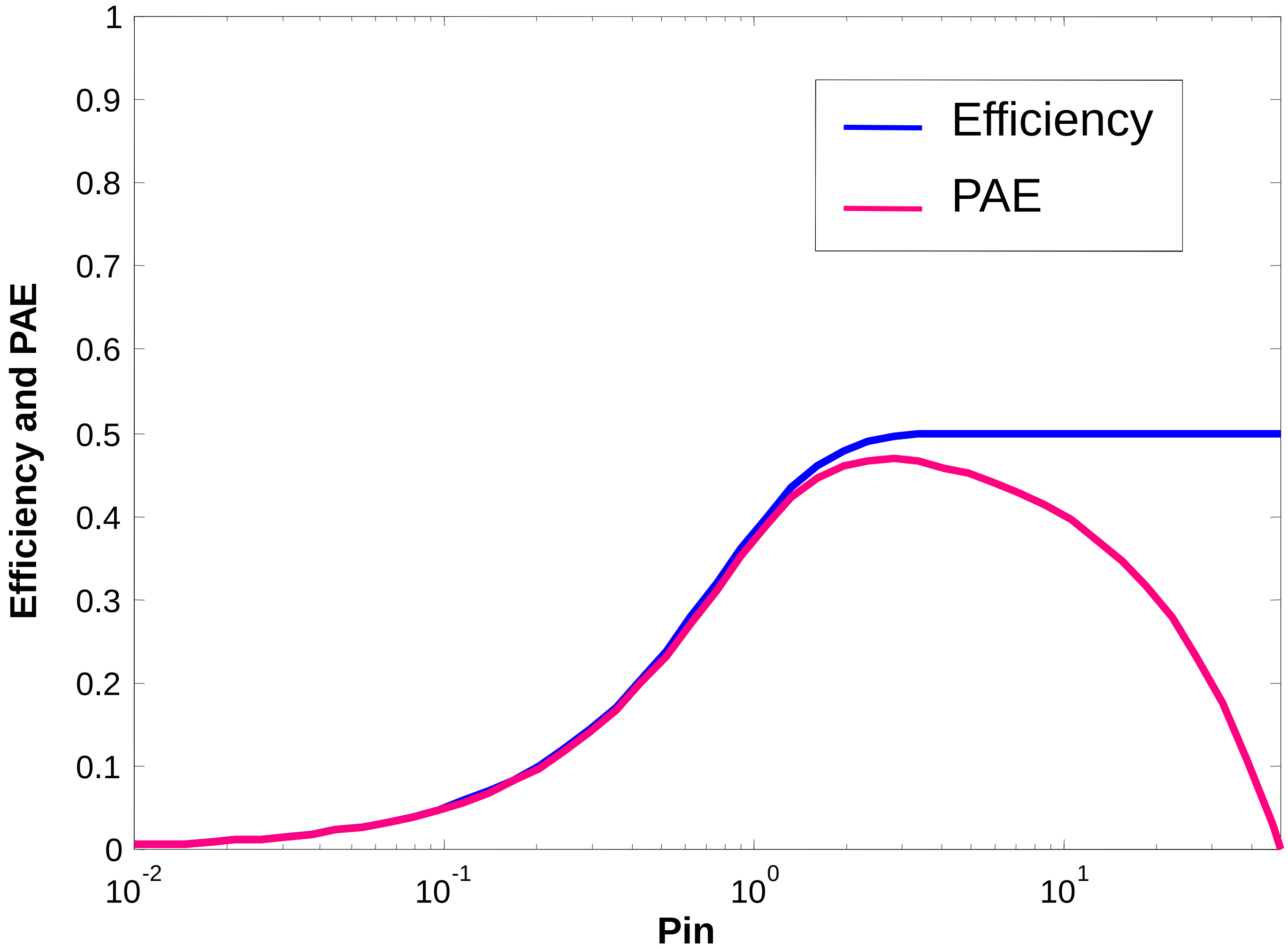
$$P_{in,n} = \left(\frac{G_{op,SS}}{K_n}\right)^{\frac{1}{n-1}}$$

- Sometimes defined with reference to output power.

Pout and gain vs. Pin

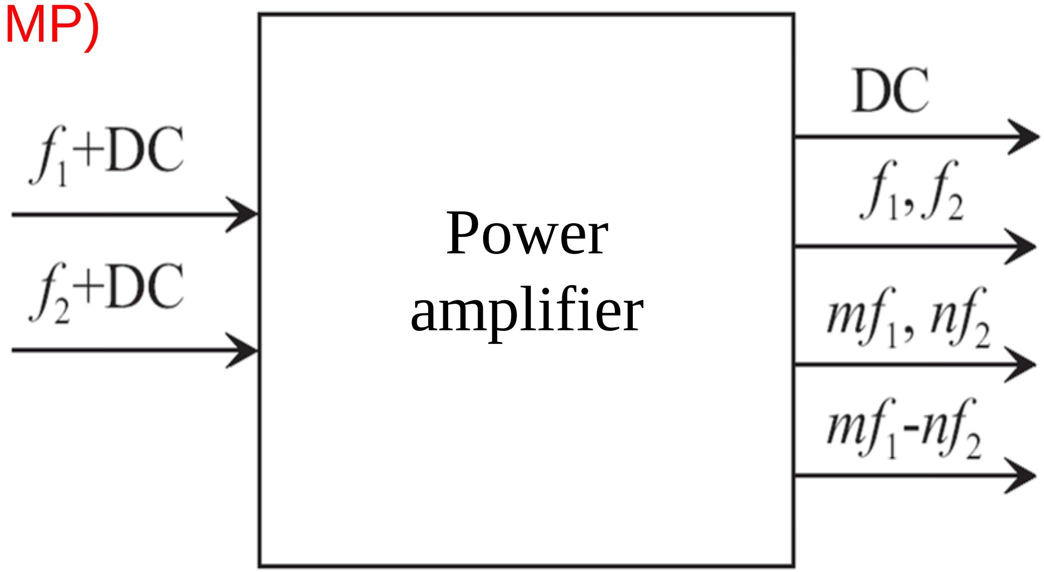


Efficiency & PAE vs. Pin

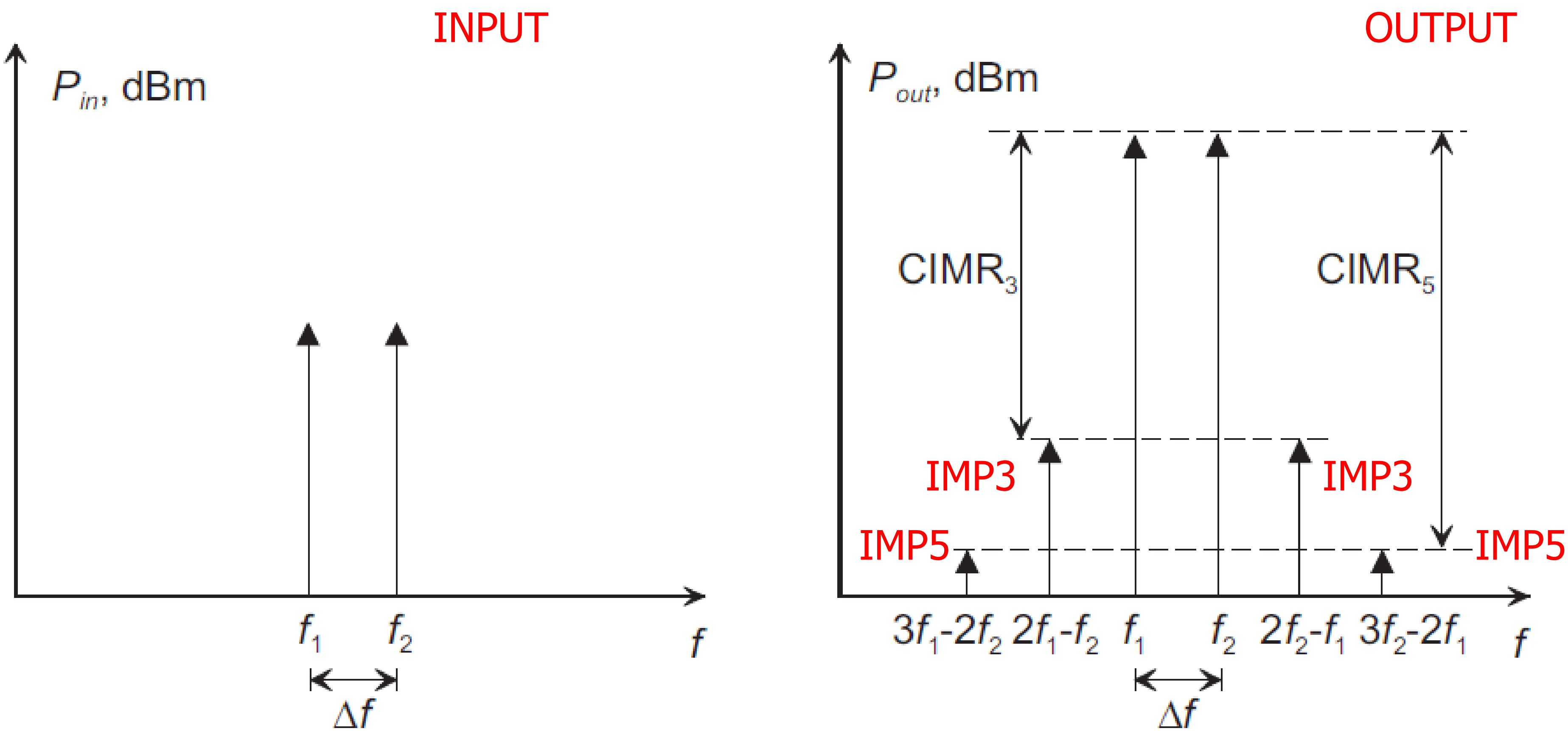


Two-tone PA operation I

- Rationale: two-tone operation **simulates** narrowband operation on a continuous band f_1 - f_2
- PA output:
  - fundamentals + DC
  - harmonics of two tones
  - Intermodulation products (IMP)



Two-tone PA operation II



3rd order IMPs

- Intermodulation products mf_1+/-nf_2 falling close to the input tones→ within the same bandwidth (potentially) → interferers to nearby channel

$$f_a = 2f_1 - f_2 = f_1 - \Delta f$$

$$f_b = 2f_2 - f_1 = f_2 + \Delta f$$

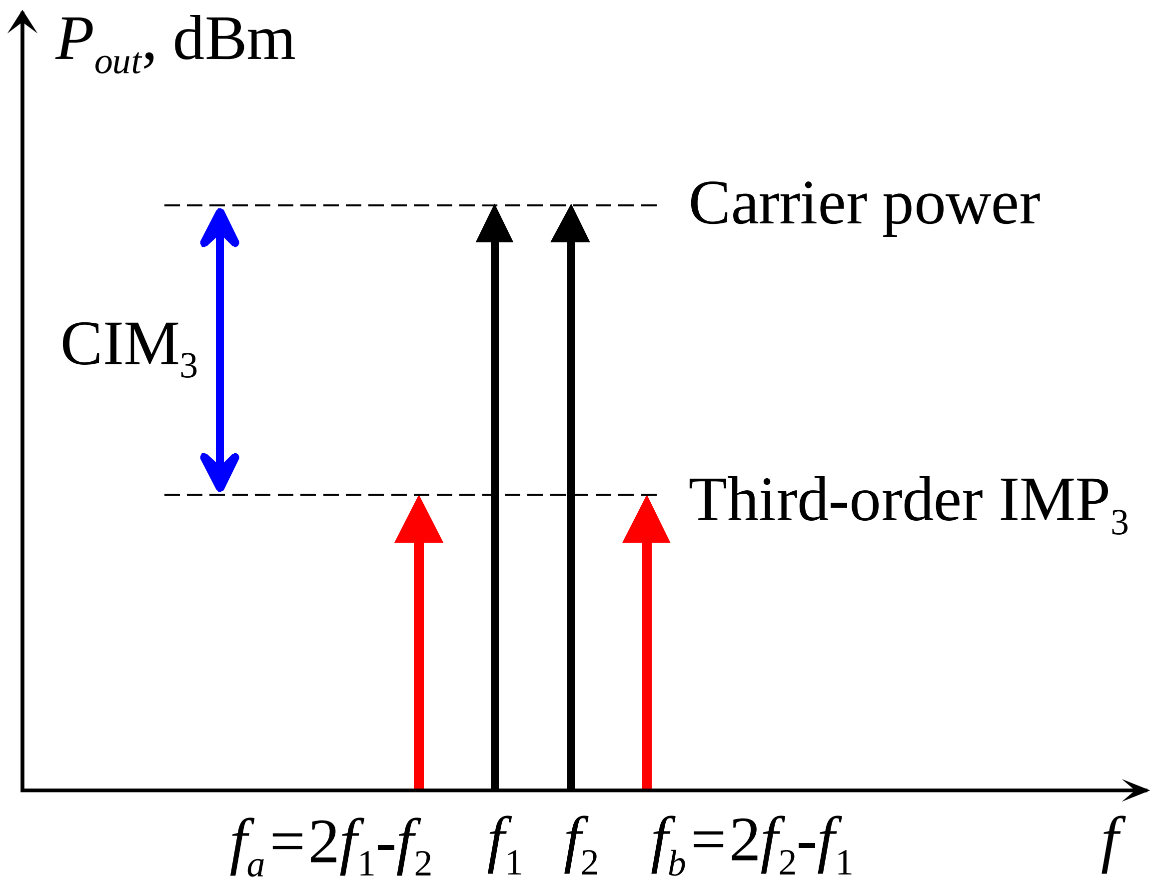
with

$$f_2 = f_1 + \Delta f$$

Two-tone Intermodulation Test

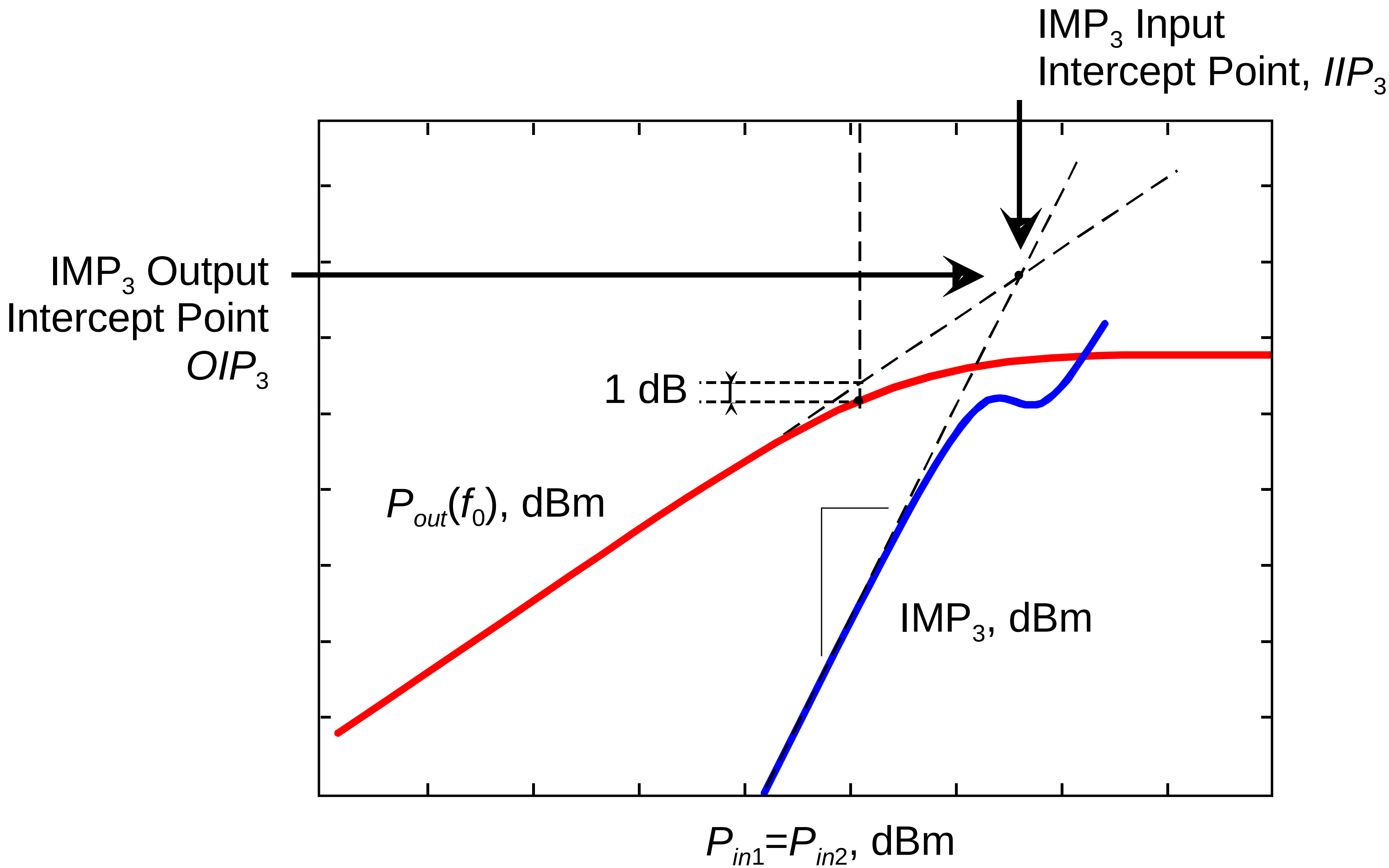
- Standard procedure for intermodulation experimental evaluation of power amplifier
- Input signal: two tones with same power, small spacing (e.g. 10 MHz at RF)
- Output: fundamental tones + intermodulation products of different order
- If the PA is a narrowband system the two output IMPs have the same power

Carrier-to-IM3 Ratio (CIM3)



$$\mathrm{CIM}_3 = \frac{P_{out}(f_0)}{P_{\mathrm{int},3}}$$

3rd order IMP intercept – IP_3



IP_3 from SS measurements I

- The third-order intercept cannot be measured directly, but can be extrapolated from low-power measurements; in fact:

$$\underbrace{P_{\mathrm{IM3},out}}_{\substack{\text{IM3 power}\\ \text{for an arbitrary}\\ \text{input power } P_{in}}} = \underbrace{GP_{in}}_{\substack{\text{output power}\\ \text{in linearity}}} \times \left(\frac{P_{in}}{IIP_3}\right)^2 \Rightarrow IIP_3 = \frac{\left(P_{in}\right)^{3/2} G^{1/2}}{\left(P_{\mathrm{IM3},out}\right)^{1/2}}$$

IMP3 input intercept point

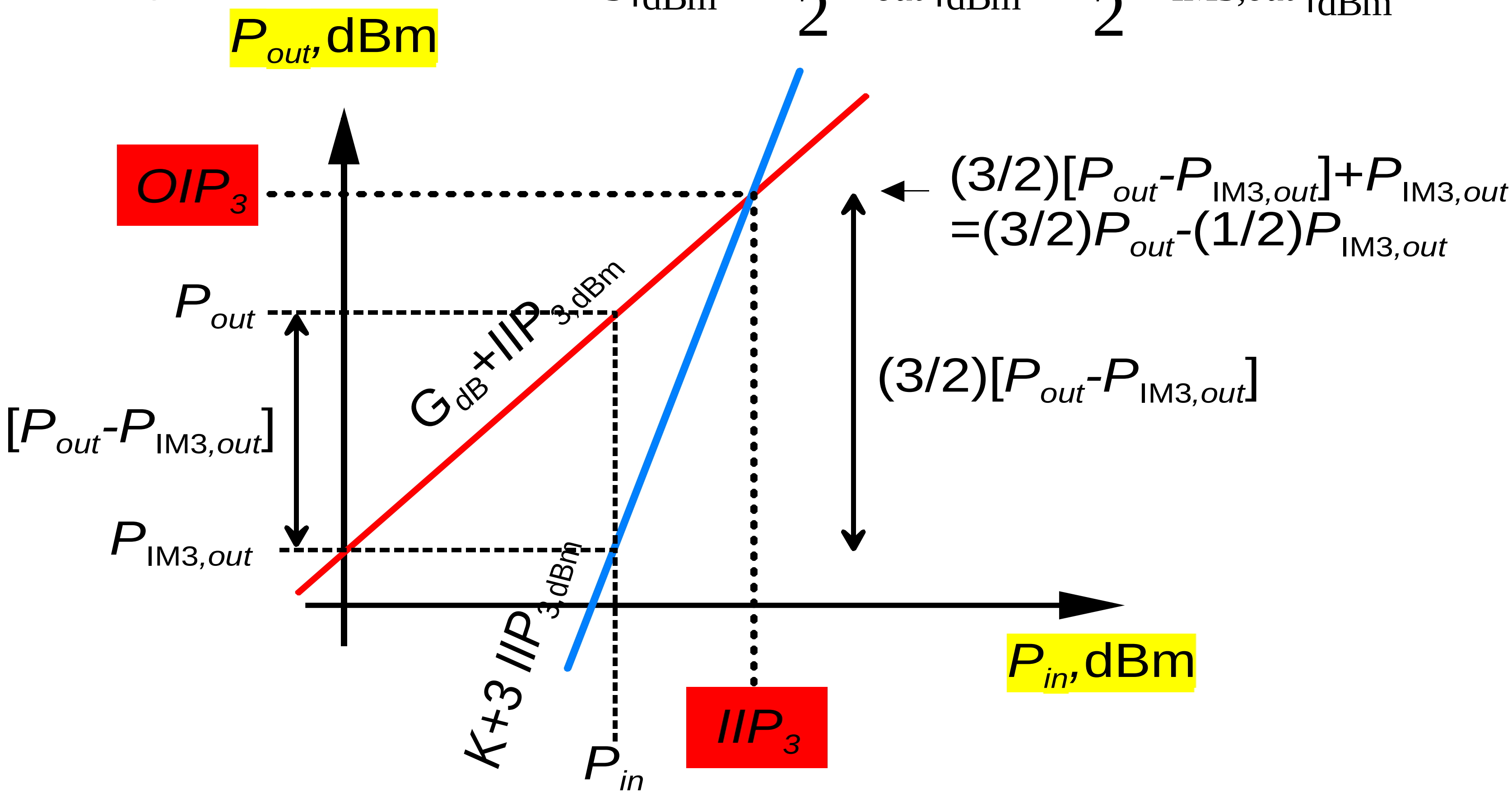
- output IP_3:

$$OIP_3 = G \times IIP_3 = \frac{\left(P_{in}\right)^{3/2} G^{3/2}}{\left(P_{\mathrm{IM3},out}\right)^{1/2}} = \frac{\left(P_{out}\right)^{3/2}}{\left(P_{\mathrm{IM3},out}\right)^{1/2}}$$

IP_3 from SS measurements II

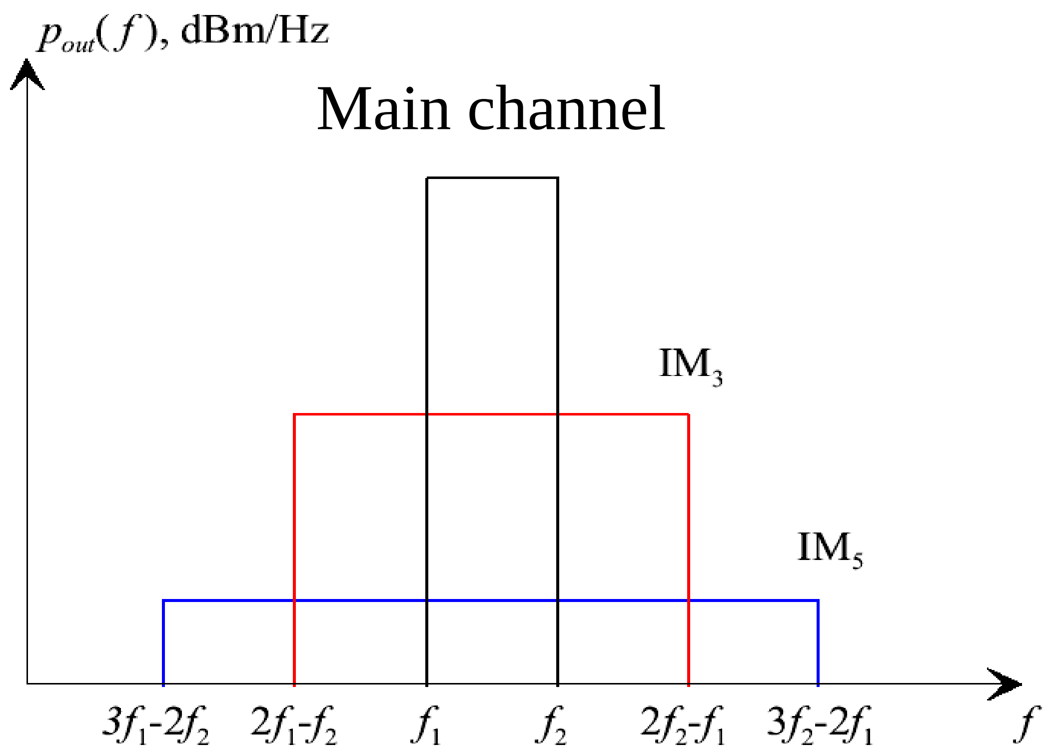
- Log scale:

$$OIP_3\Big|_{\mathrm{dBm}} = \frac{3}{2} P_{out}\Big|_{\mathrm{dBm}} - \frac{1}{2} P_{\mathrm{IM3},out}\Big|_{\mathrm{dBm}}$$

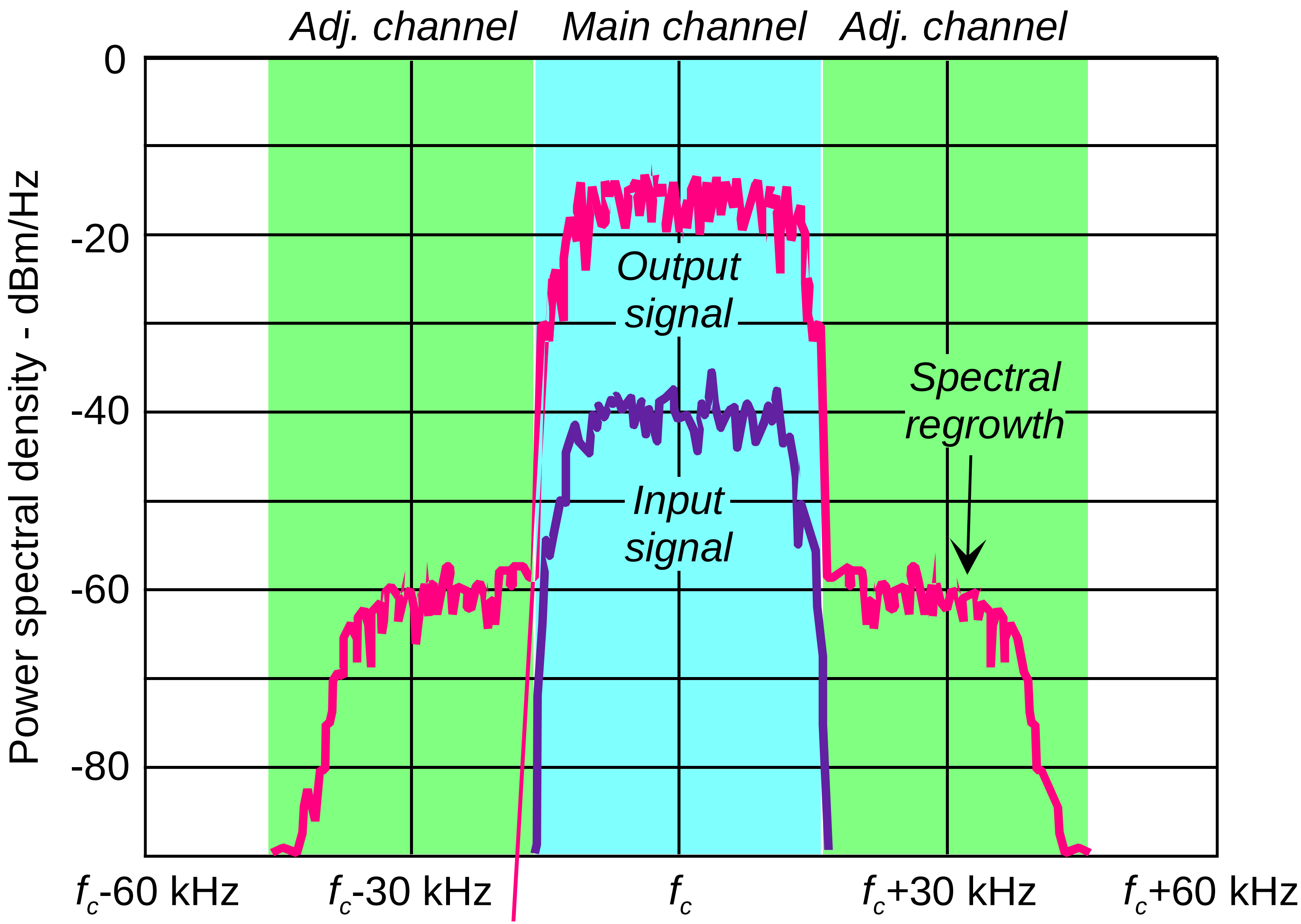


Intermodulation in a real channel

- Two-tone excitation → IMP3, IMP5 etc. as single tones
- Narrowband (continuous) excitation → IMP3, IMP5 etc. as (wider) band signals entering nearby channels



“Spectral Regrowth”



Adjacent Channel Power Ratio

- The ACPR is a quantitative measure of spectral regrowth as an interference to a nearby channel
- ACPR definition (MC→ Main Channel; C_k → k-th adjacent channel):

$$\mathrm{ACPR}_k = \frac{\int_{MC} p_{out}(f)\mathrm{d}f}{\int_{C_k} p_{out}(f)\mathrm{d}f}$$

- ACPR sensitive to the signal format:
  - Constant envelope (e.g. analog FM) → less sensitive
  - Variable envelope (e.g. multilevel digital, see later) → more sensitive

Dynamic range - qualitative definition

- For an amplifier (power, small signal, low noise…) the dynamic range (also called Spurious Free Dynamic Range, SFDR) is the input power range providing operation “within specs”
- SFDR limits:
  - Lower limit: related to noise → **minimum input power able to provide at the amplifier output the required signal over noise ratio (SNR)**
  - Upper limit: related to distortion → **maximum input power providing acceptable distortion at amplifier output**