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The effect of AM noise on correlation PM noise measurements

1/f noise in RF and microwave amplifiers

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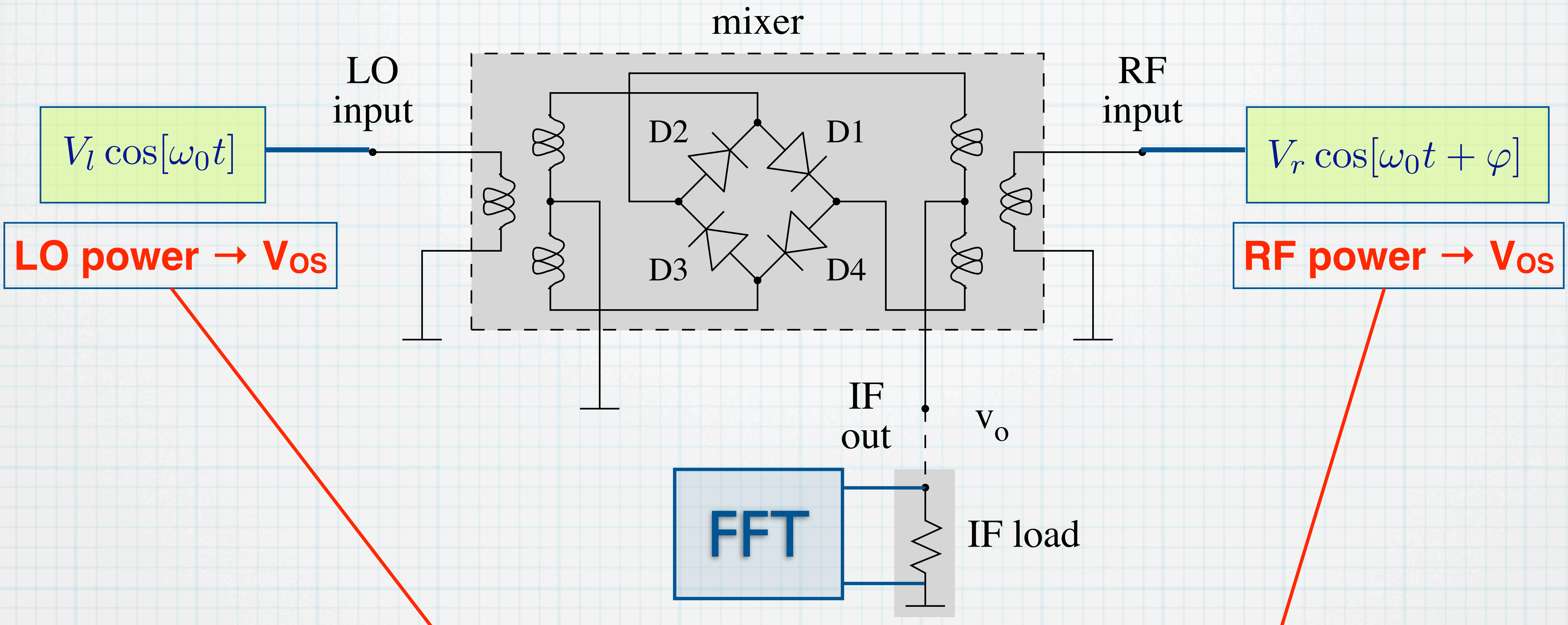
Outline

* Part 1 – The effect of AM noise ...
* Part 2 – Amplifier noise ...

home page http://rubiola.org

1 - The effect of AM noise on correlation phase noise measurements

Effect of AM noise on a saturated mixer



phase detection → $v = k_\varphi \varphi + V_{OS}$

for $|\varphi| \ll 1$

static: P → V_{OS} (offset)

noise: AM noise → DC noise mistaken for phase noise

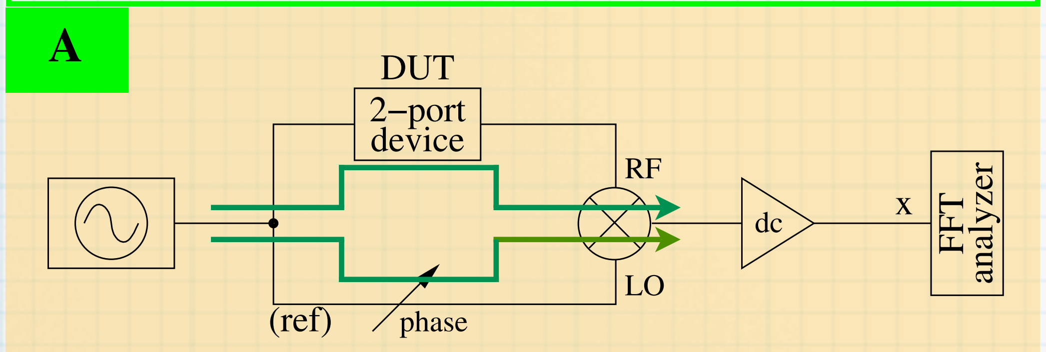
origin: diode and balun asymmetry

RF mixer: balun asymmetry ≈ const. vs. frequency

microwave: balun asymmetry depends on frequency

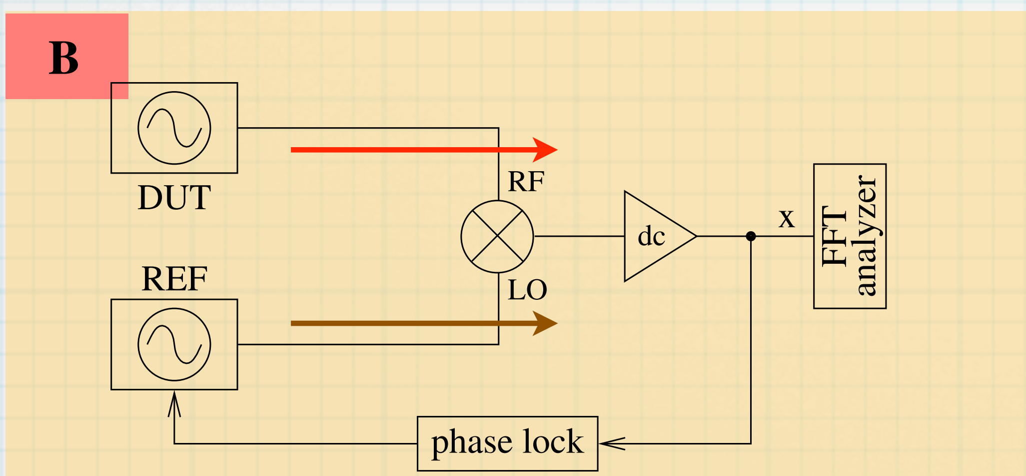
The AM noise propagates through the system

A null of AM sensitivity (sweet point) can be found in some mixers



tip: use a phase offset, or a DC bias at the mixer IF

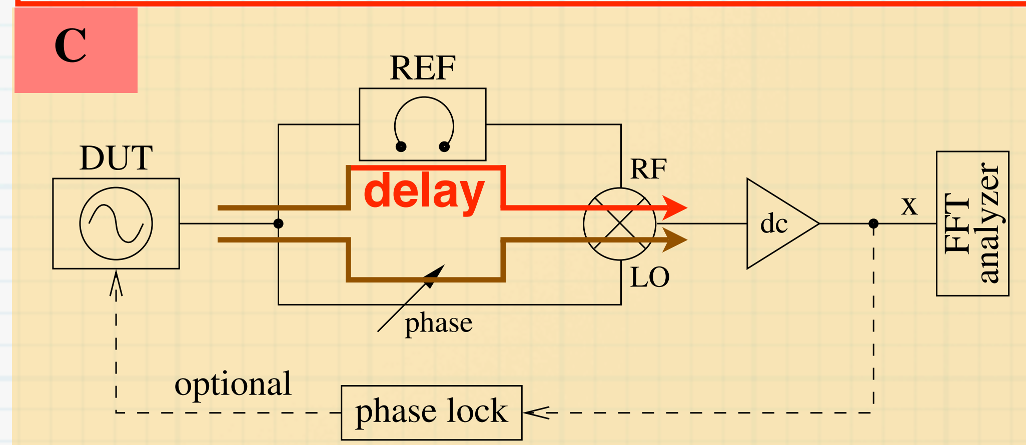
$$v_o(t) = k_\varphi\,\varphi(t) + k_{lr}\,\alpha(t)$$



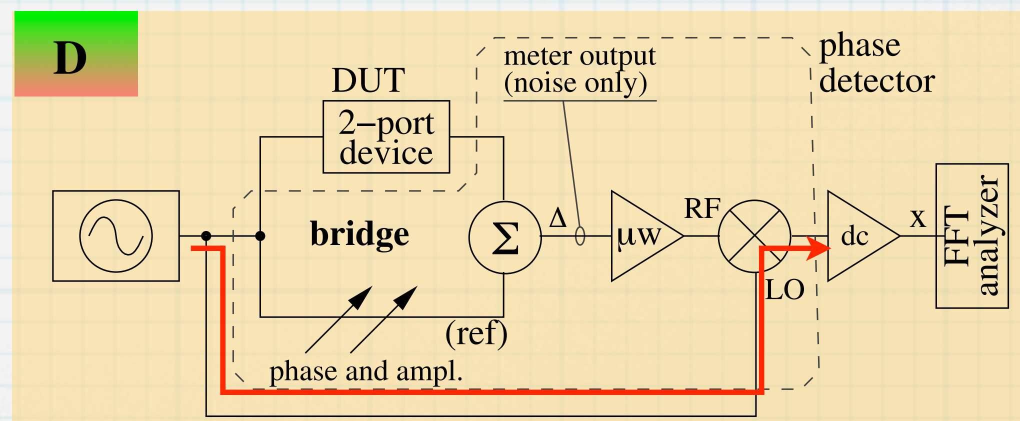
$$v_o(t) = k_\varphi\,\varphi(t) + k_l\,\alpha_l(t) + k_r\,\alpha_r(t)$$

With two separated inputs, the effect of AM noise adds up

A delay de-correlates the two inputs, thus it destroys the sweet point



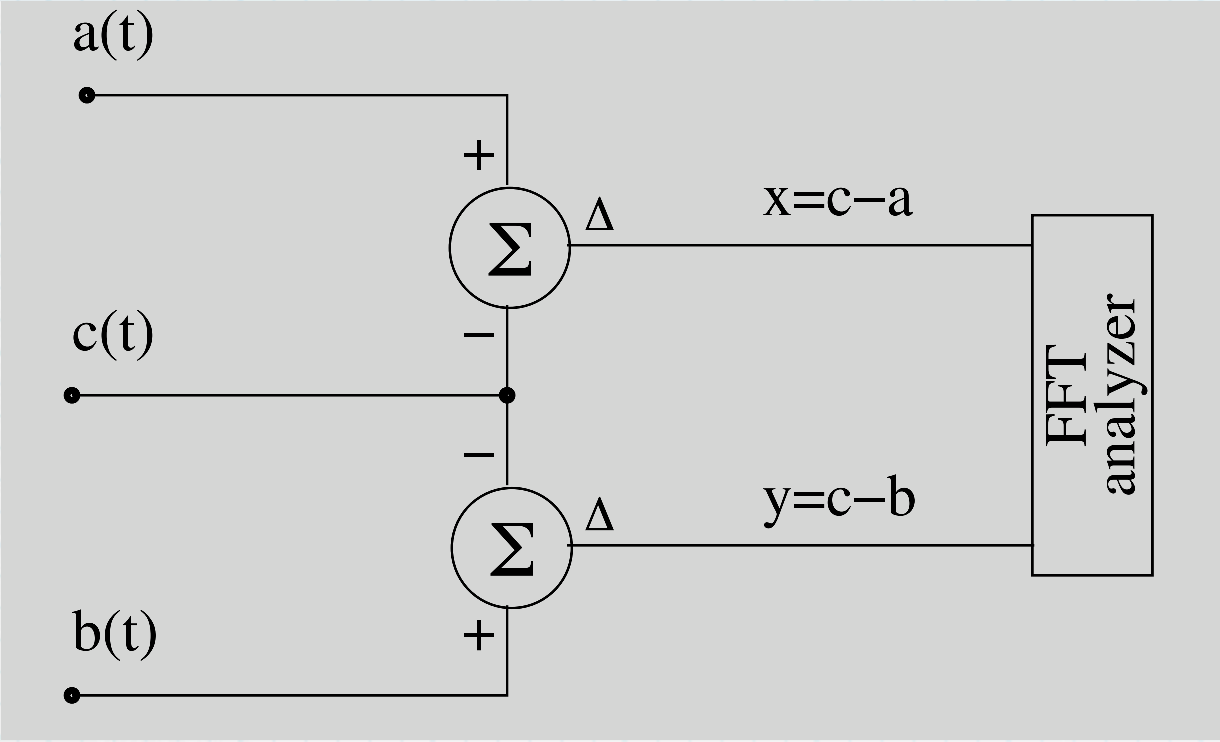
$$v_o(t) = k_\varphi\,\varphi(t) + k_l\,\alpha_l(t) + k_r\,\alpha_r(t)$$



$$v_o(t) = k_\varphi\,\varphi(t) + k_{sd}\,\alpha(t)$$

In a bridge, the AM noise propagates to the output only through the LO.
The effect is strongly reduced by the RF amplification before detecting

Basics of correlation spectrum measurements



phase noise measurements		
DUT noise, normal use	a, b c	instrument noise DUT noise
background, ideal case	a, b c = 0	instrument noise no DUT
background, with AM noise	a, b c ≠ 0	instrument noise AM-to-DC noise

$S_{yx} = \mathbb{E}\left\{YX^*\right\}$ W. K. theorem

$S_{yx} = \langle YX^* \rangle_m$ measured, m samples

a, b and c are incorrelated

expand $X = C - A$ and $Y = C - B$

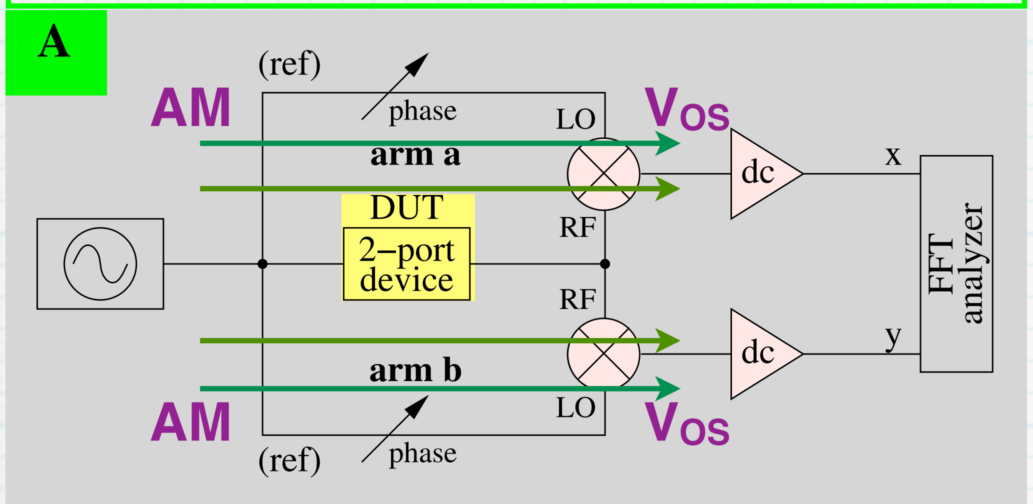
$S_{yx} = S_{cc}$ a, b, c independent

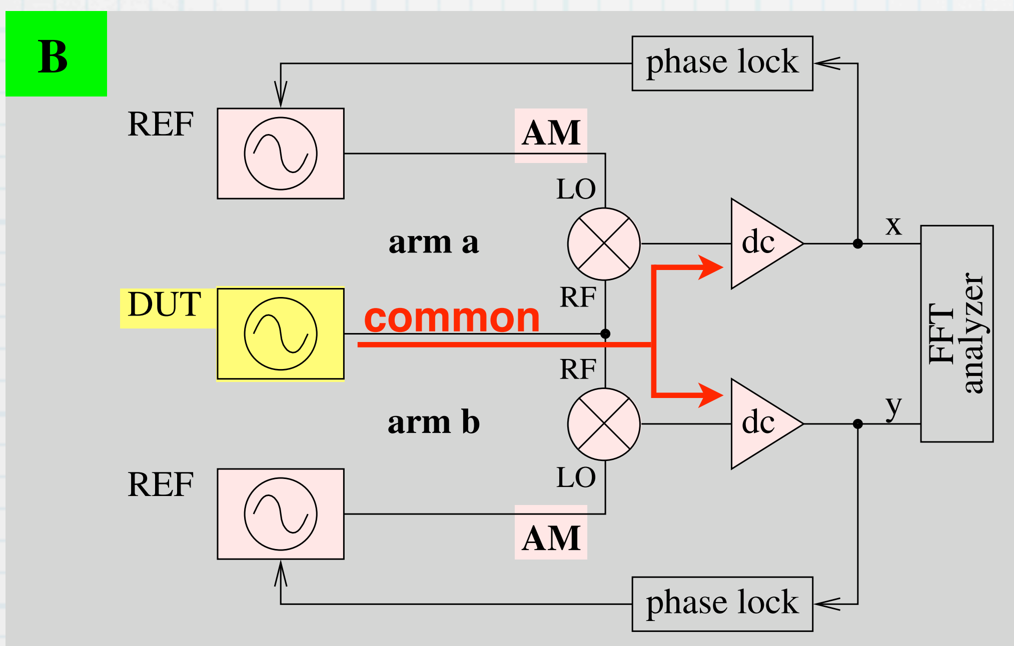
$S_{yx} = S_{cc} + O(\sqrt{1/m})$ measured, m samples

Averaging on a sufficiently large number m of spectra is necessary to reject the single-channel noise

The AM noise in a correlation system

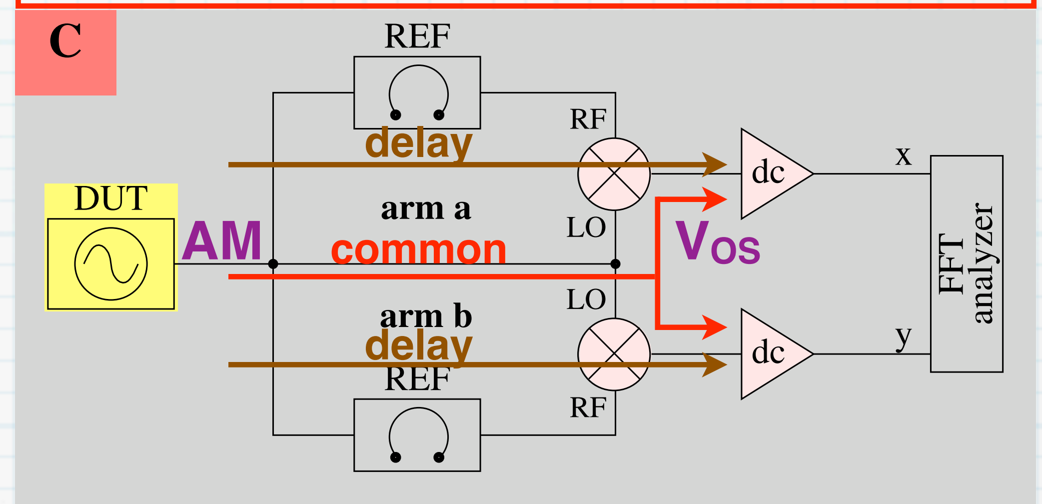
Should set both channels at the sweet point, if exists

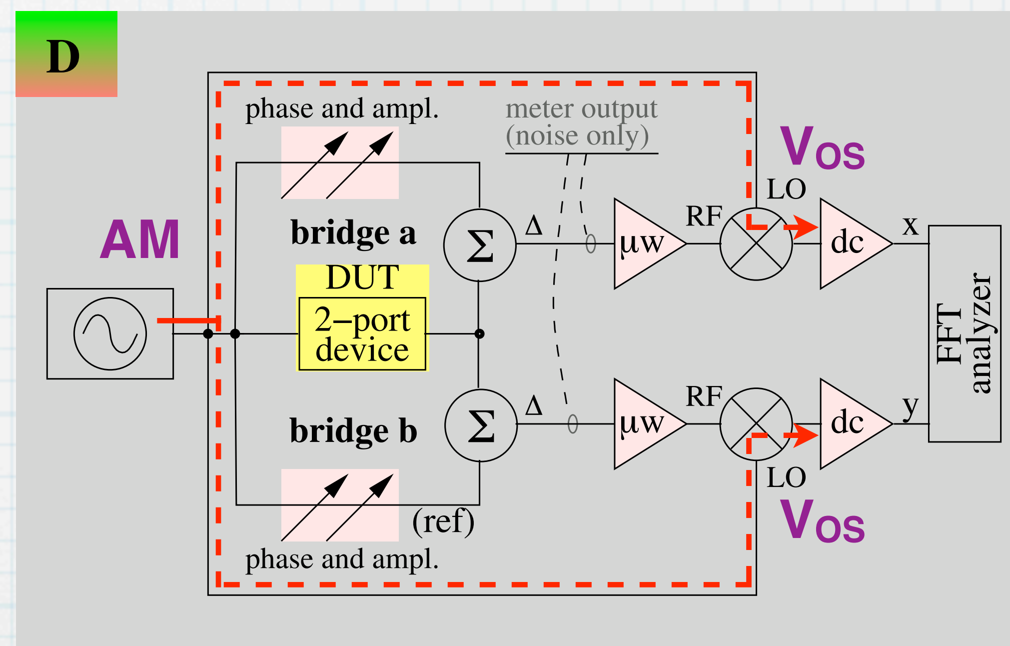




Should set both channels at the sweet point of the RF input, if exists, by offsetting the PLL or by biasing the IF

The delay de-correlates the two inputs, so there is no sweet point



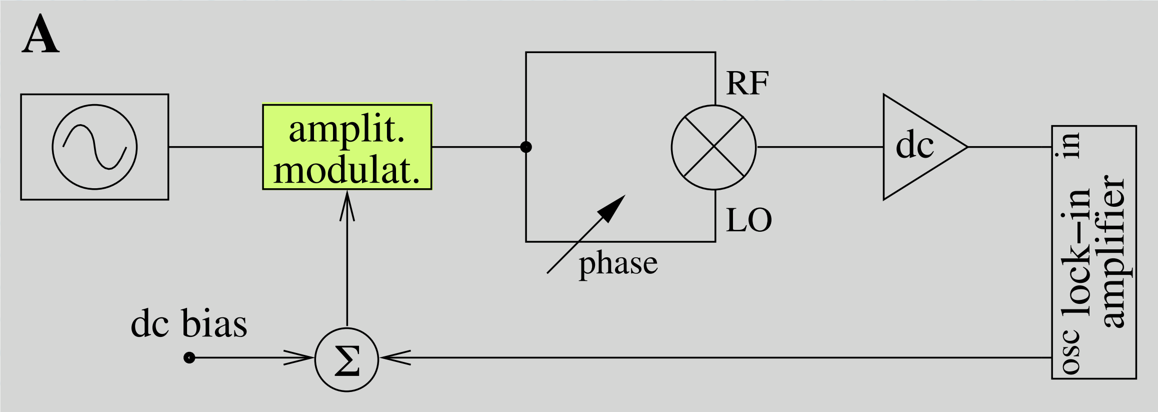


The effect of the AM noise is strongly reduced by the RF amplification

pink: noise rejected by correlation and averaging

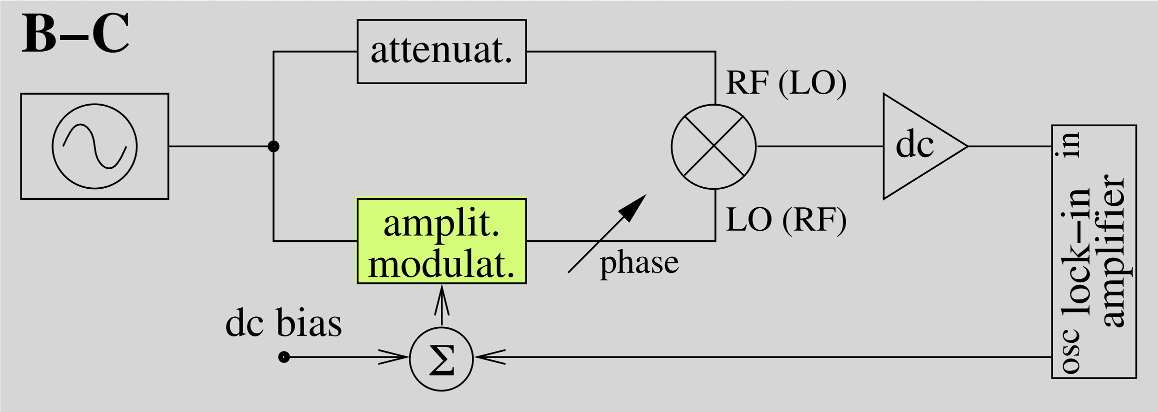
Measurement of the mixer sensitivity to AM

- The measurement schemes follow immediately from the statement of the problem
- A lock-in amplifier is used for highest noise immunity
- Set the amplitude modulator to the minimum of residual PM (at least in the scheme B-C)



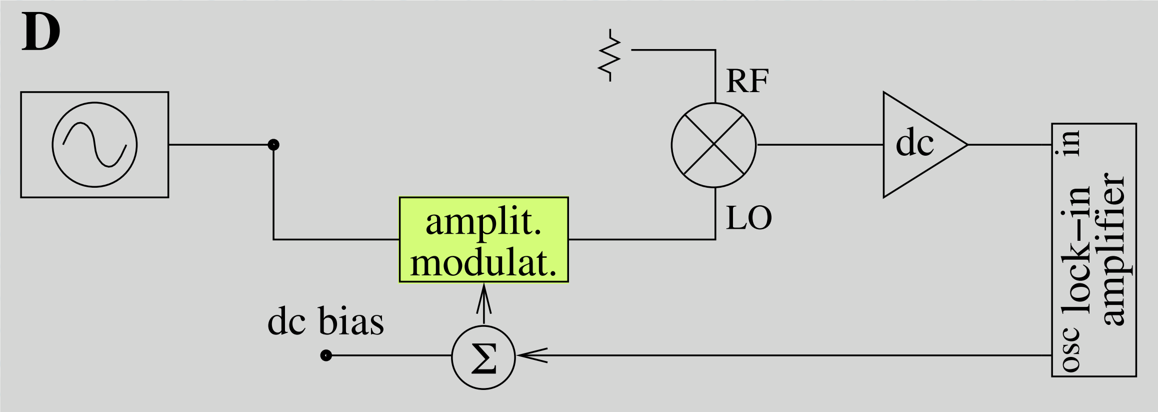
LO & RF → IF: coefficient k_{lr}

$$v_o(t) = k_\varphi\, \varphi(t) + k_{lr}\, \alpha(t)$$



LO or RF → IF: coefficients k_l and k_r

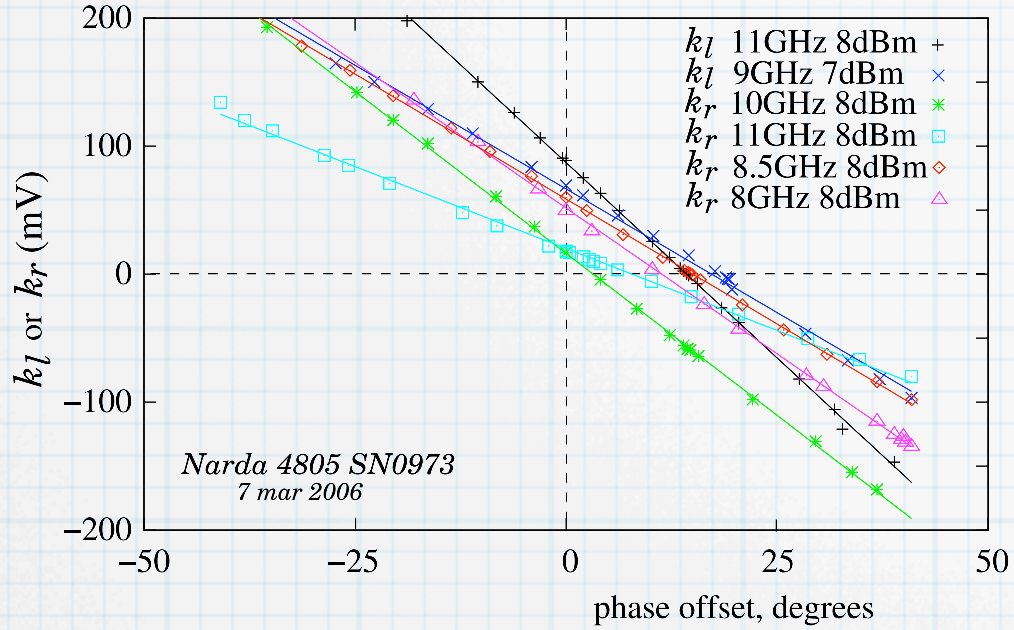
$$v_o(t) = k_\varphi\, \varphi(t) + k_l\, \alpha_l(t) + k_r\, \alpha_r(t)$$



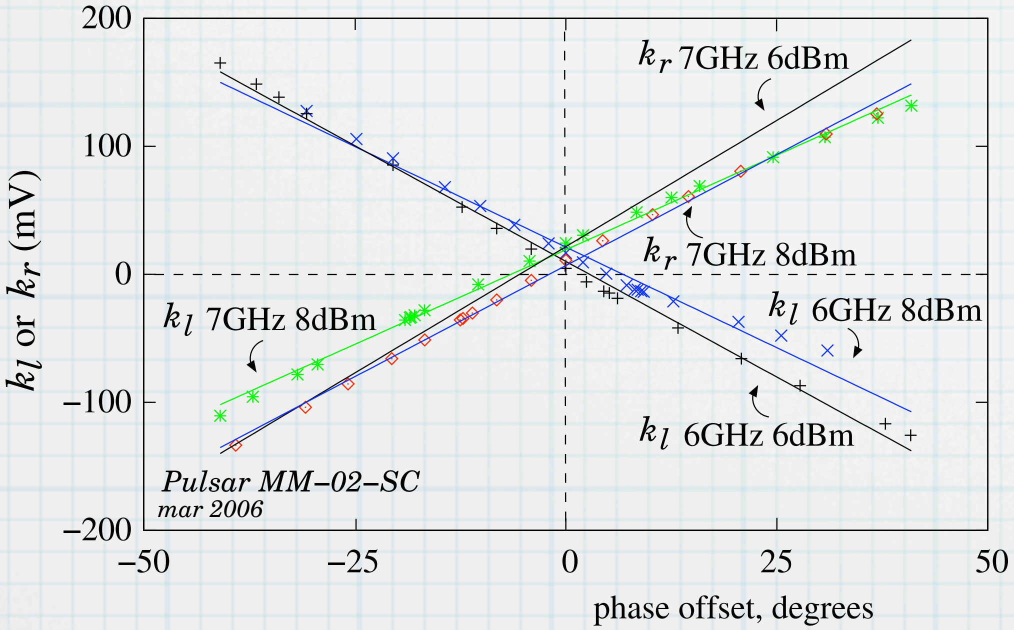
LO → IF in a sync.-detection scheme: coefficient k_{sd}

$$v_o(t) = k_\varphi\, \varphi(t) + k_{sd}\, \alpha(t)$$

Example of results (microwave mixers)

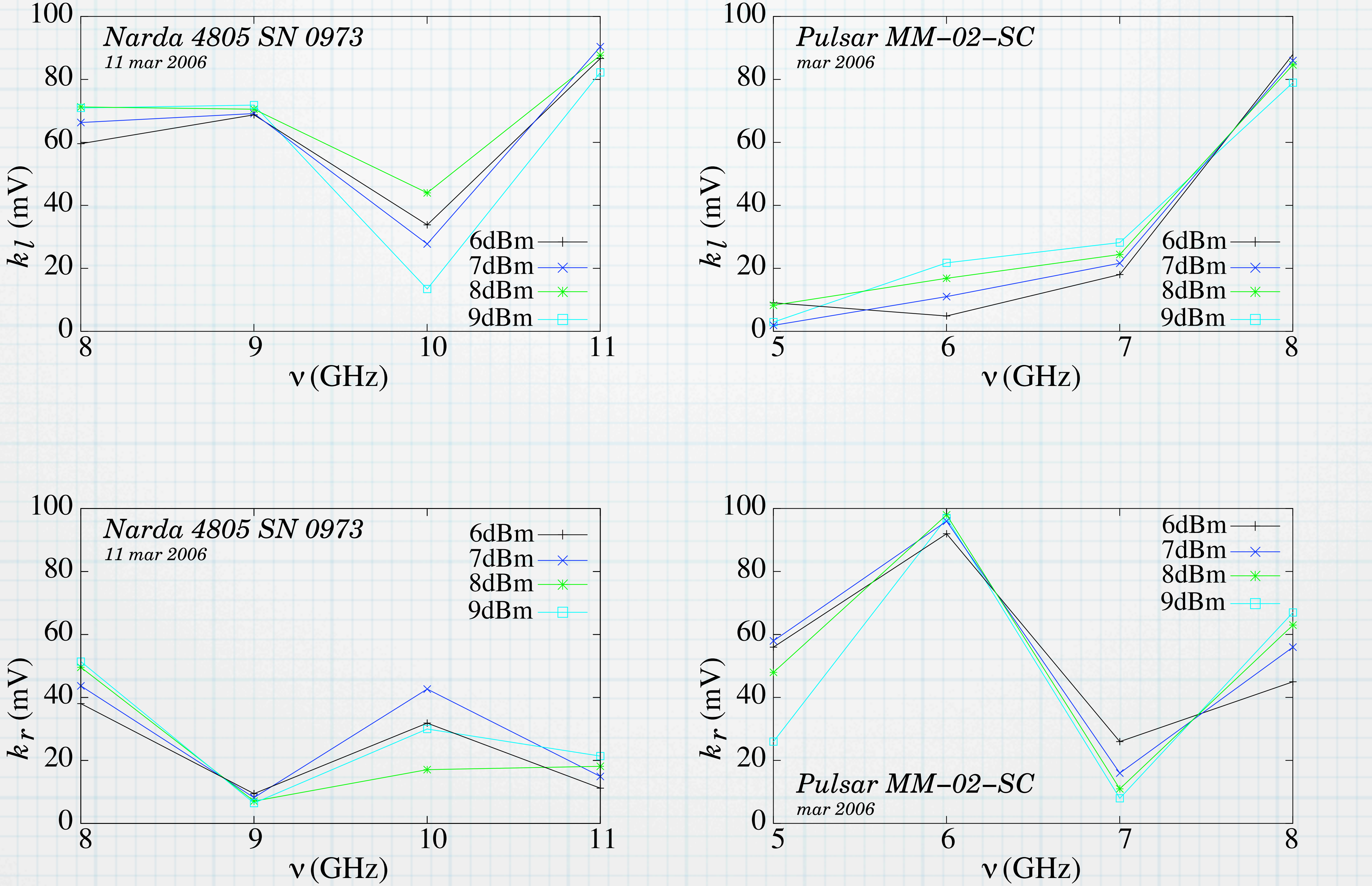


The AM sensitivity depends on frequency. This is ascribed to the microstrip baluns, and to the diode capacitances



The AM sensitivity can have opposite sign at the two inputs

Example of results (microwave mixers)



The effect of power is somewhat weaker than that of frequency

Example of results (microwave mixers)

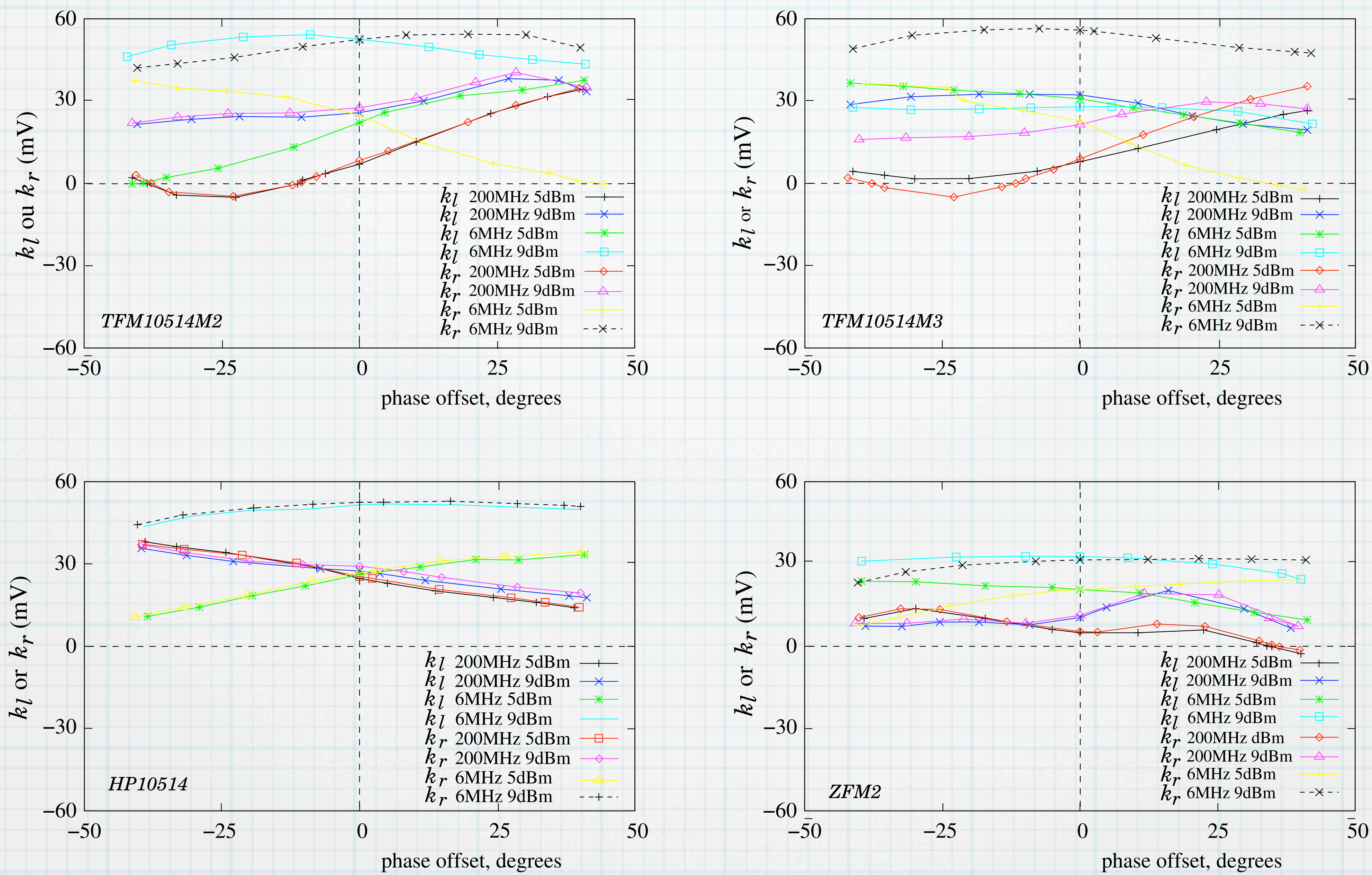
Mixer	k_φ	k_{lr}	k_r	k_l	k_{sd}
Narda 4805 s.no. 0972	272	16	7.9	37	6.5
Narda 4805 s.no. 0973	274	18.3	17.1	44	9.8
NEL 20814	279	51.5	12.1	37.9	2.7
NEL 20814	305	41	1.9	30.2	3.73
unit	mV/rad	mV	mV	mV	mV

Test parameters: $\nu_0 = 10$ GHz, $P = 6.3$ mW (8 dBm)

Some relevant facts

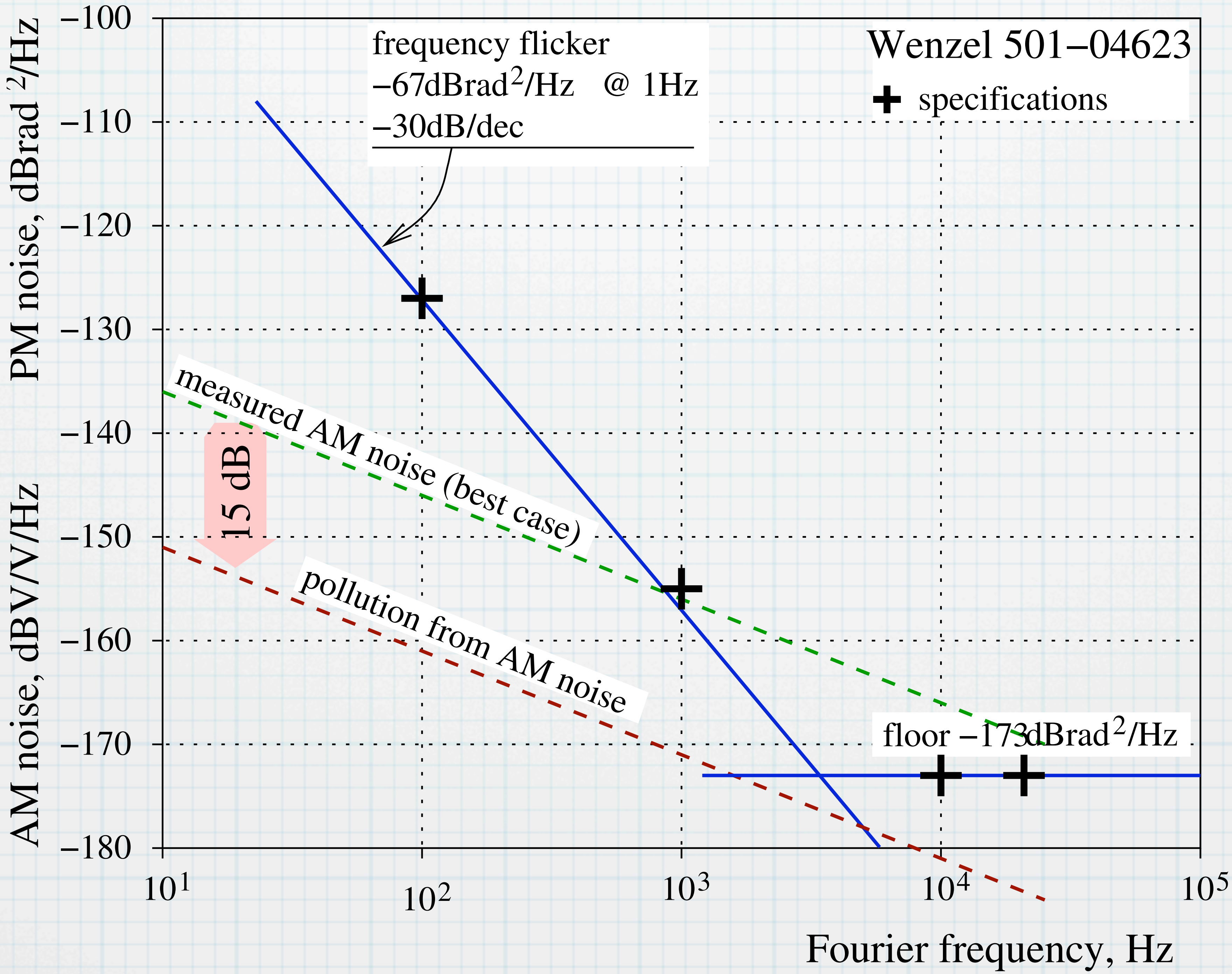
- **The AM noise rejection is of 15–40 dB**
- **Generally, k_{sd} is smaller than the other coefficients**
- **There is no predictable relation between k_φ, k_l, k_r, k_{lr}, and k_{sd}**
- **It is observed that k_{lr}, $\neq k_l + k_r$**

Example of results (VHF mixers)



- **The AM noise rejection is of 15–40 dB**
- **The sweet point is not observed in general**
- **There is no predictable relation between k_φ, k_l, k_r, (k_{lr}, and k_{sd} are not reported)**

Warning: even in single-channel measurements, the pollution from AM noise may be not that small



E. Rubiola, “The measurement of AM noise of oscillators,” arXiv:physics/0512082, dec 2005

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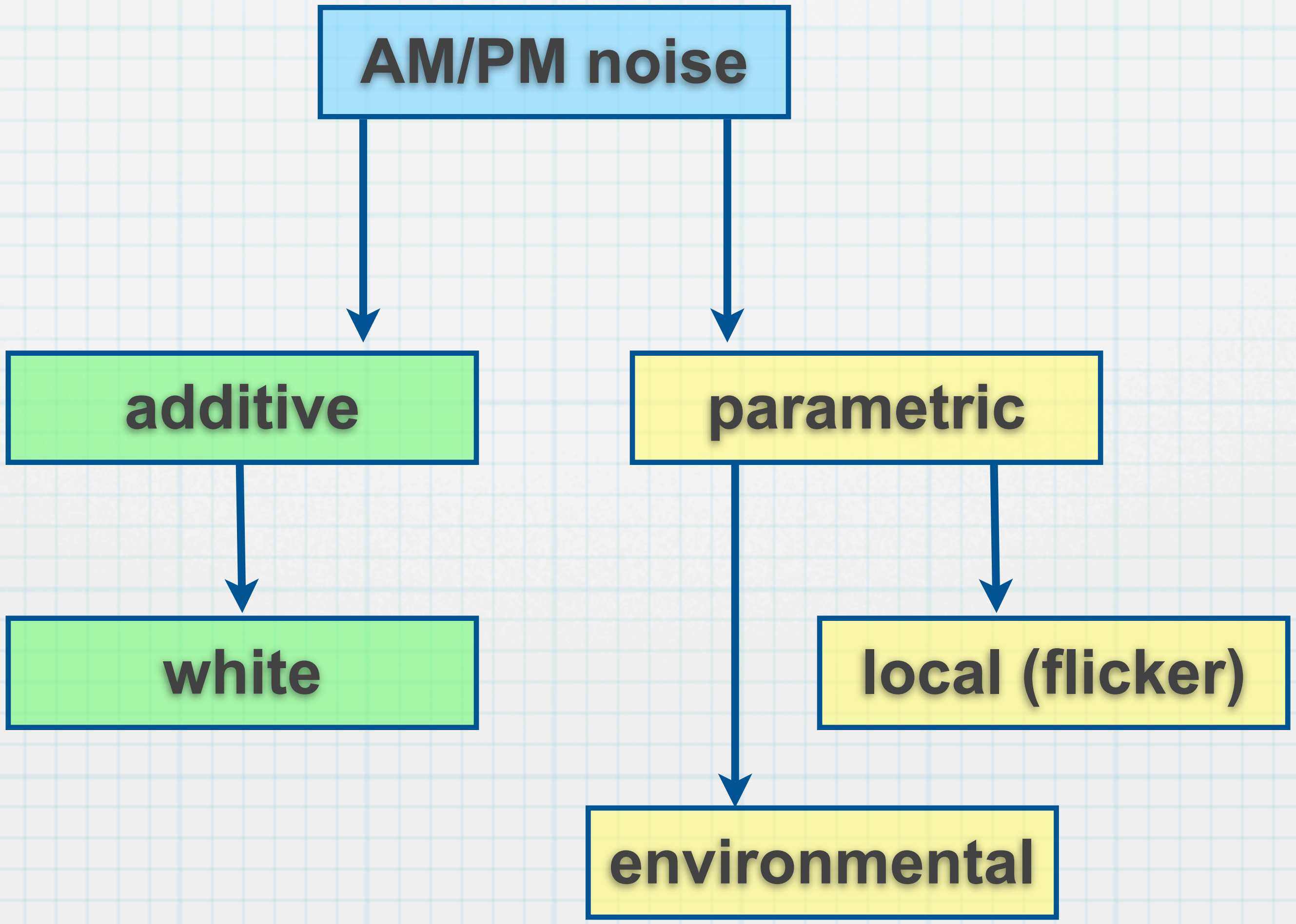
Summary (1)

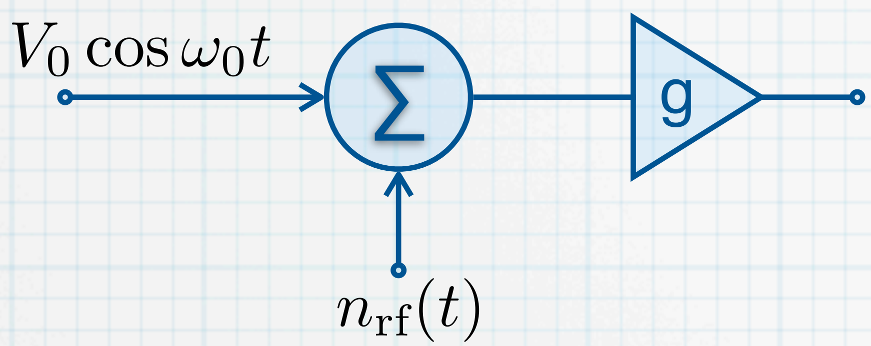
* The AM noise is taken in via the DC-offset sensitivity to the power
* The AM noise rejection is of 15–40 dB
* For a given mixer, there is no predictable relation between the AM noise sensitivity in different configurations
* The sweet point exists only in some configurations
* The sweet point is generally not observed in VHF mixers
* In correlation systems, rejecting the AM noise is possible only in some cases
* The AM noise can even limit the single-channel measurements

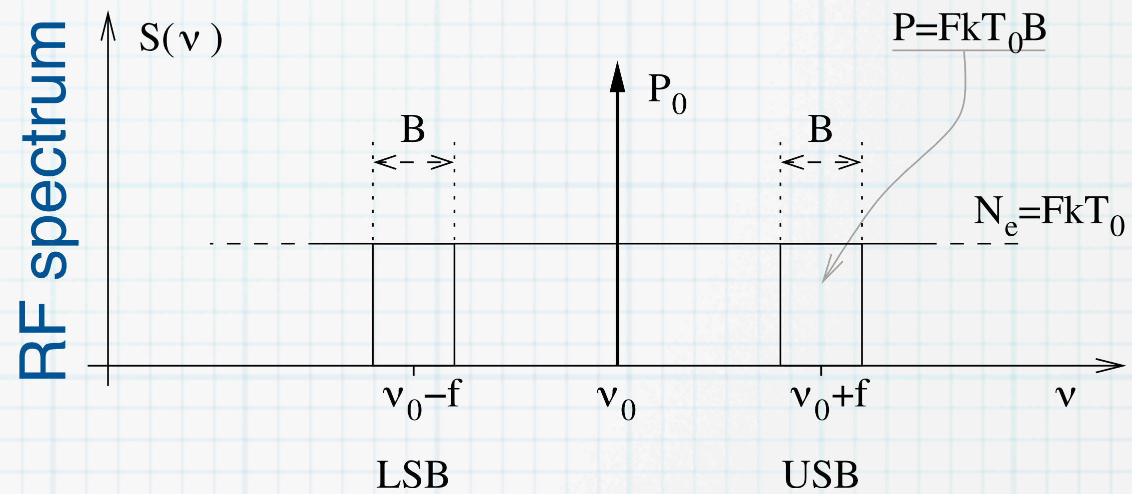
2 – On the 1/f noise in RF and microwave amplifiers



Amplifier white noise

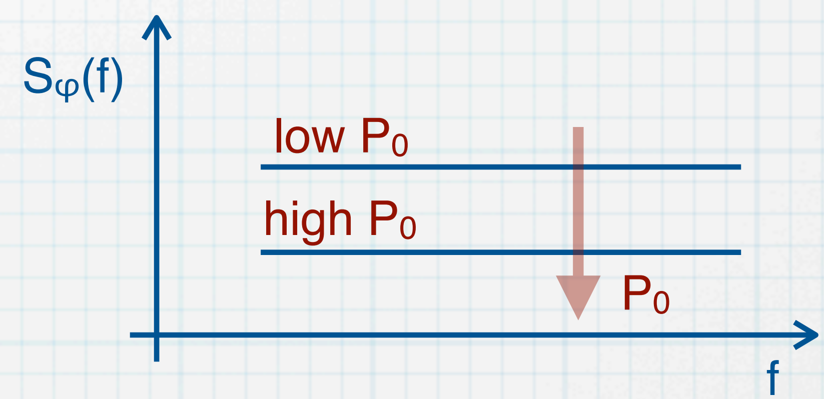
Noise figure F, Input power P_0





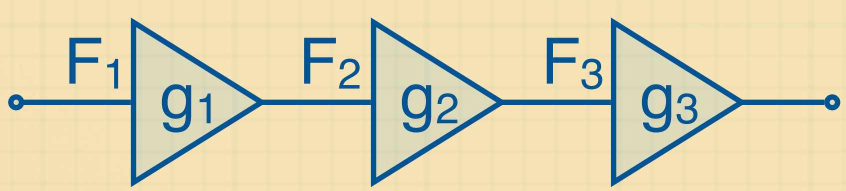
power law $S_\varphi = \sum_{i=-4}^{0} b_i f^i$

white phase noise $b_0 = \dfrac{FkT_0}{P_0}$



Cascaded amplifiers (Friis formula)

The (phase) noise is chiefly that of the 1st stage



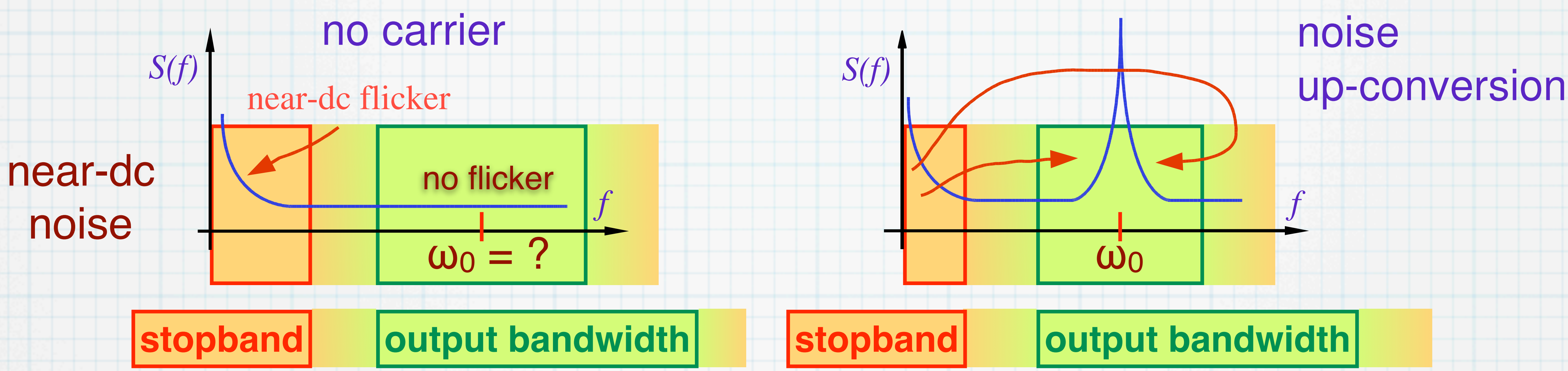
$$N = F_1kT_0 + \frac{(F_2-1)kT_0}{g_1^2} + \ldots$$

H. T. Friis, Proc. IRE **32** p.419-422, jul 1944

The Friis formula applied to phase noise

$$b_0 = \frac{F_1kT_0}{P_0} + \frac{(F_2-1)kT_0}{P_0 g_1^2} + \ldots$$

Amplifier flicker noise



carrier **near-dc noise**

$$v_i(t) = V_i \, e^{j\omega_0 t} + n'(t) + jn''(t)$$

the parametric nature of 1/f noise is hidden in n' and n''

substitute
(careful, this hides the down-conversion)

$$v_o(t) = a_1 v_i(t) + a_2 v_i^2(t) + \ldots$$

non-linear (parametric)amplifier

expand and select the ω_0 terms

$$v_o(t) = V_i \Big\{ a_1 + 2a_2 \big[n'(t) + jn''(t) \big] \Big\} e^{j\omega_0 t}$$

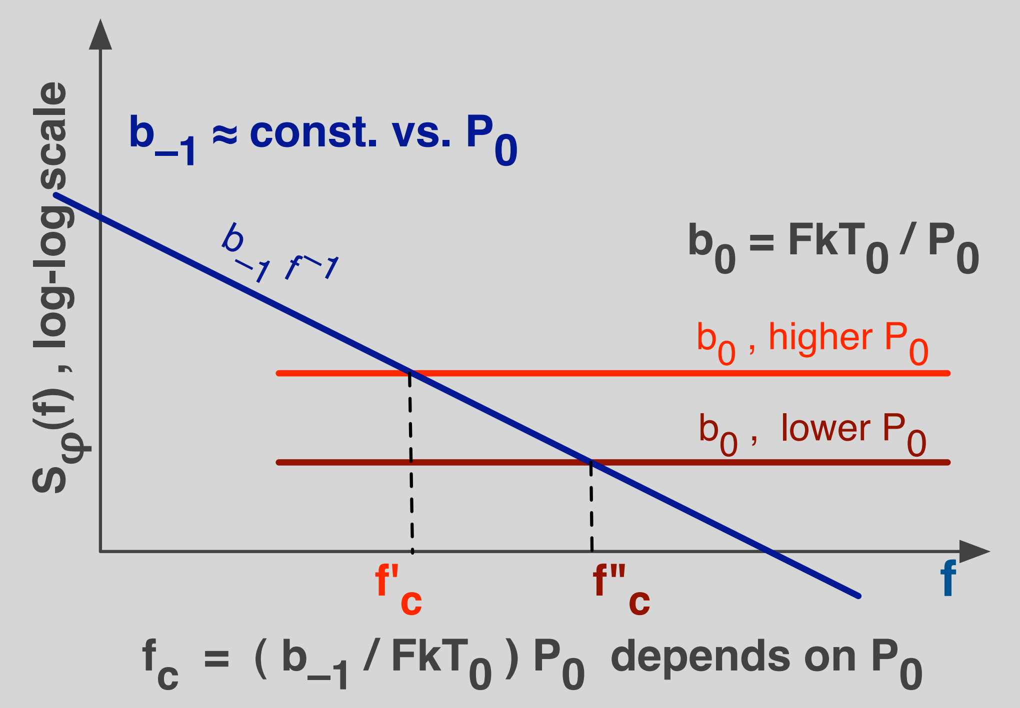
The noise sidebands are proportional to the input carrier

get AM and PM noise

$$\alpha(t) = 2\,\frac{a_2}{a_1}\,n'(t) \qquad \varphi(t) = 2\,\frac{a_2}{a_1}\,n''(t)$$

The AM and the PM noise are independent of V_i , thus of power

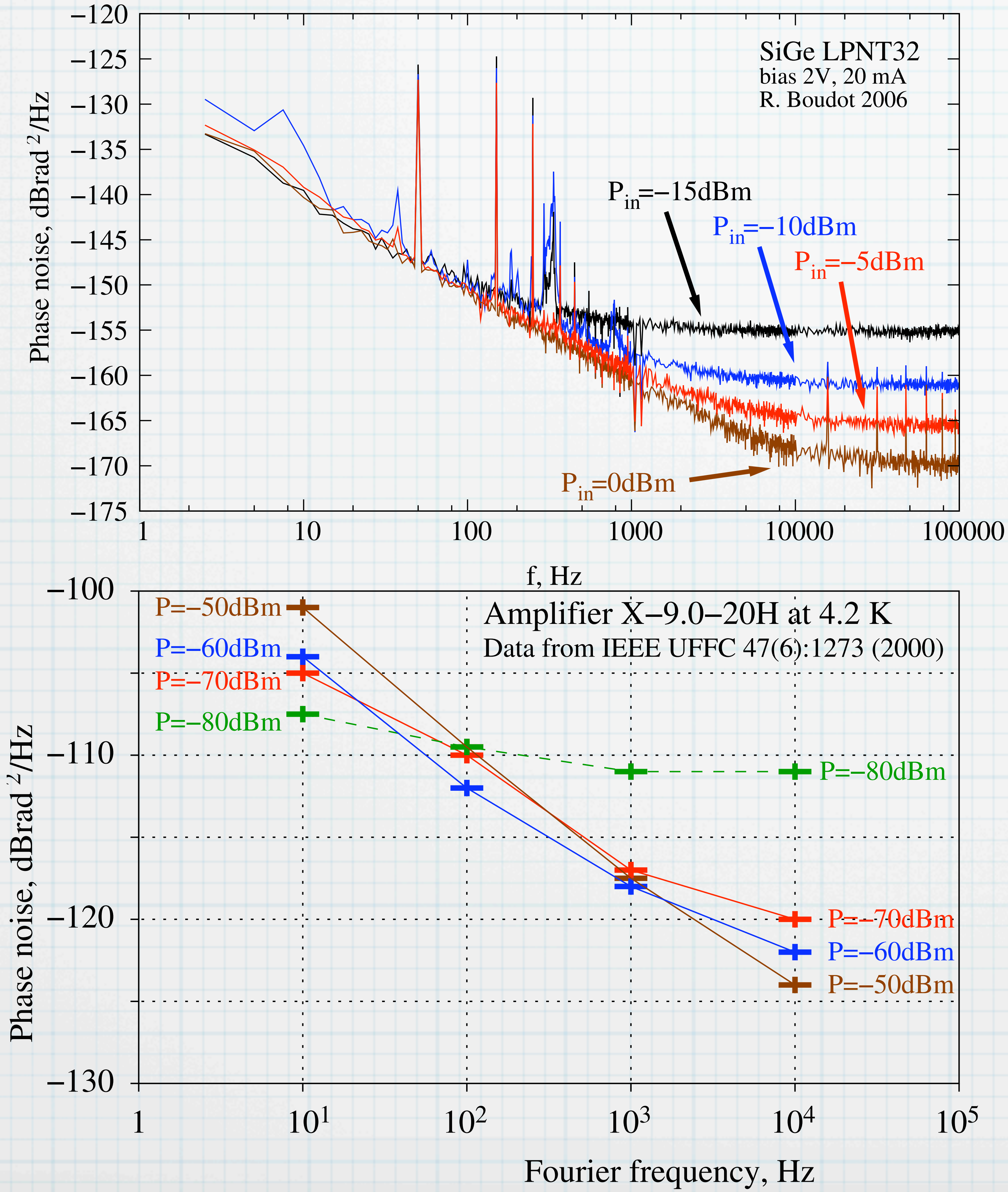
Amplifier flicker noise



typical amplifier phase noise			
RATE	GaSs HBT microwave	SiGe HBT microwave	Si bipolar HF/UHF
fair	−100		−120
good	−110	−120	−130
best	−120	−130	−150
	unit dBrad^2/Hz		

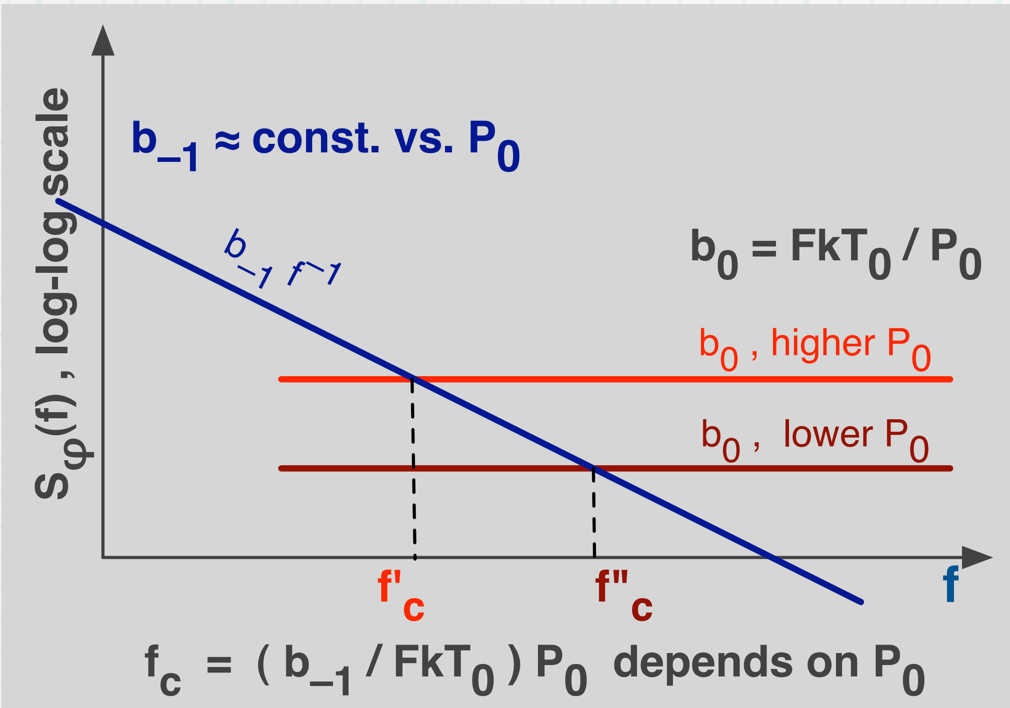
- The phase flicker coefficient b_{-1} is about independent of power.
- Hence, describing the 1/f noise in terms of f_c is misleading because f_c depends on the input power

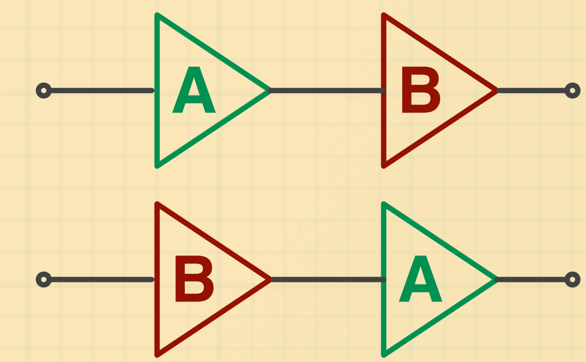
Amplifier flicker noise – experiments



- The 1/f phase noise b_{-1} is about independent of power
- The white noise b_0 scales up/down as $1/P_0$, i.e., the inverse of the carrier power

Flicker noise in cascaded amplifiers





AB and BA have the same 1/f noise

The phase flicker coefficient b_{-1} is about independent of power. Hence:

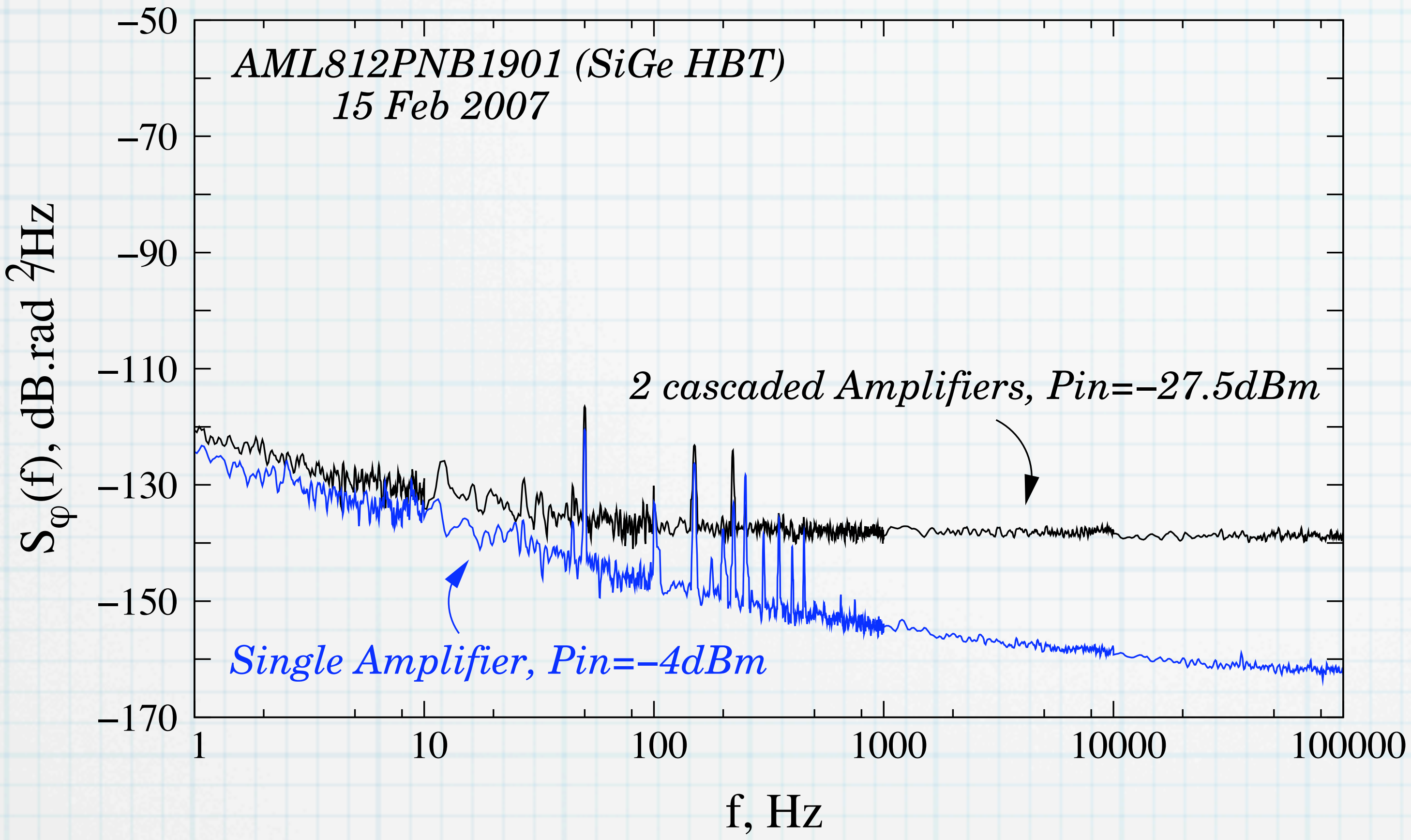
- in a cascade, $(b_{-1})_{tot}$ does not depend of the amplifier order
- in practice, in a cascade each stage contributes about equally

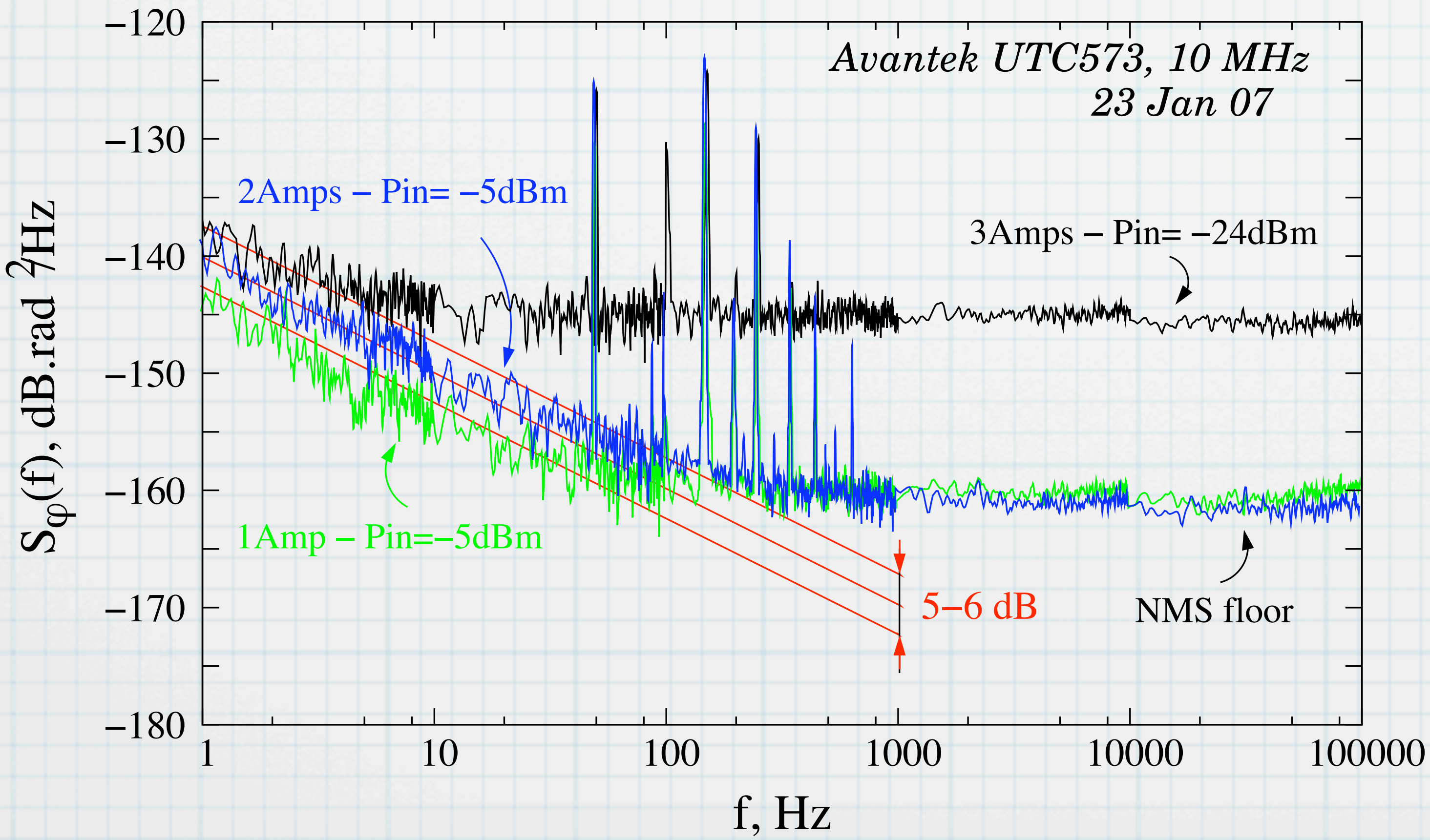
$$(b_{-1})_{\text{tot}} = \sum_{i=1}^{m} (b_{-1})_i$$

m cascaded amplifiers

- b_{-1} is roughly proportional to the gain through the number of stages

Flicker in cascaded amplifiers - experiments



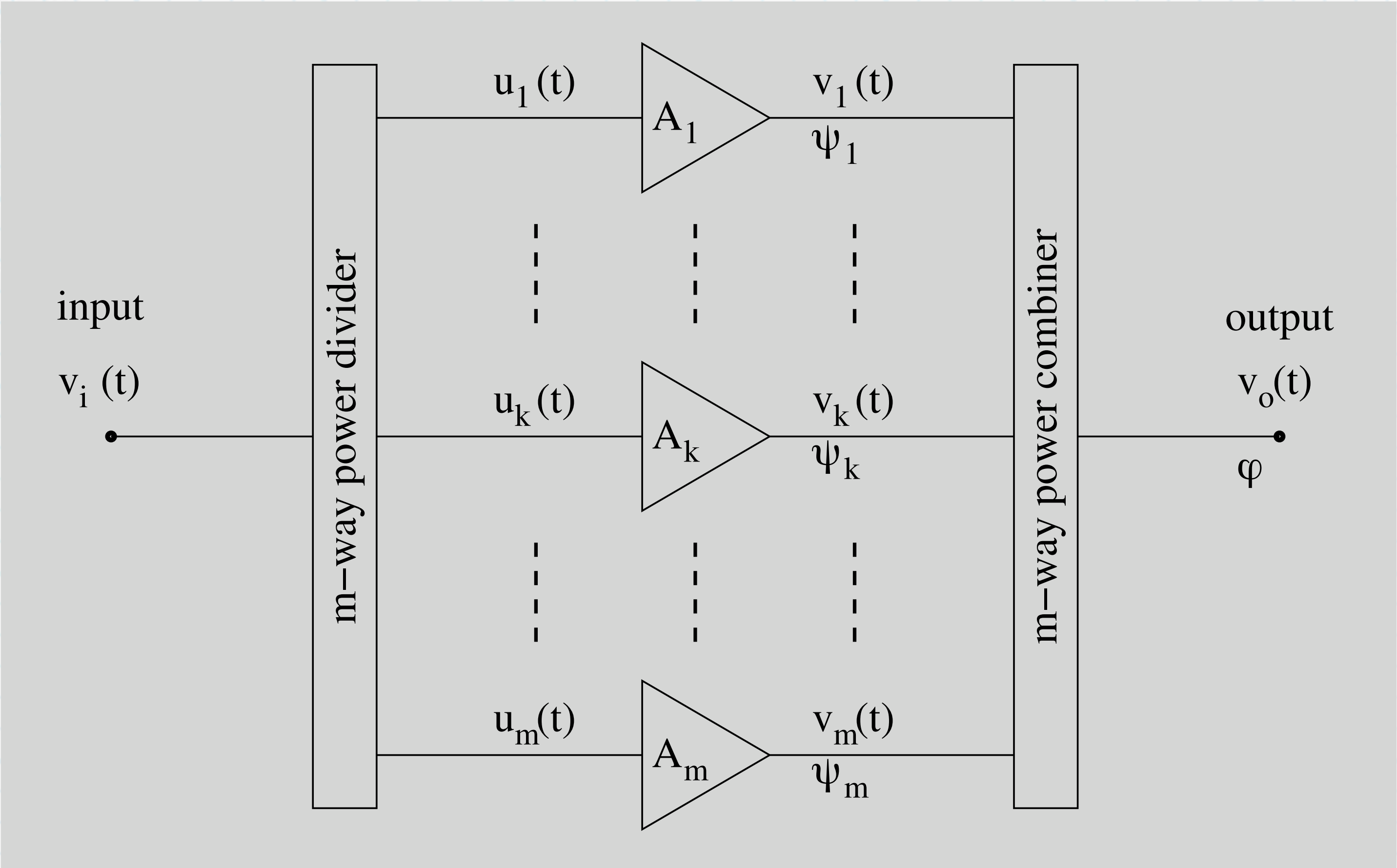


The expected flicker of a cascade increases by:

3 dB, with 2 amplifiers

5 dB, with 3 amplifiers

Flicker noise in parallel amplifiers



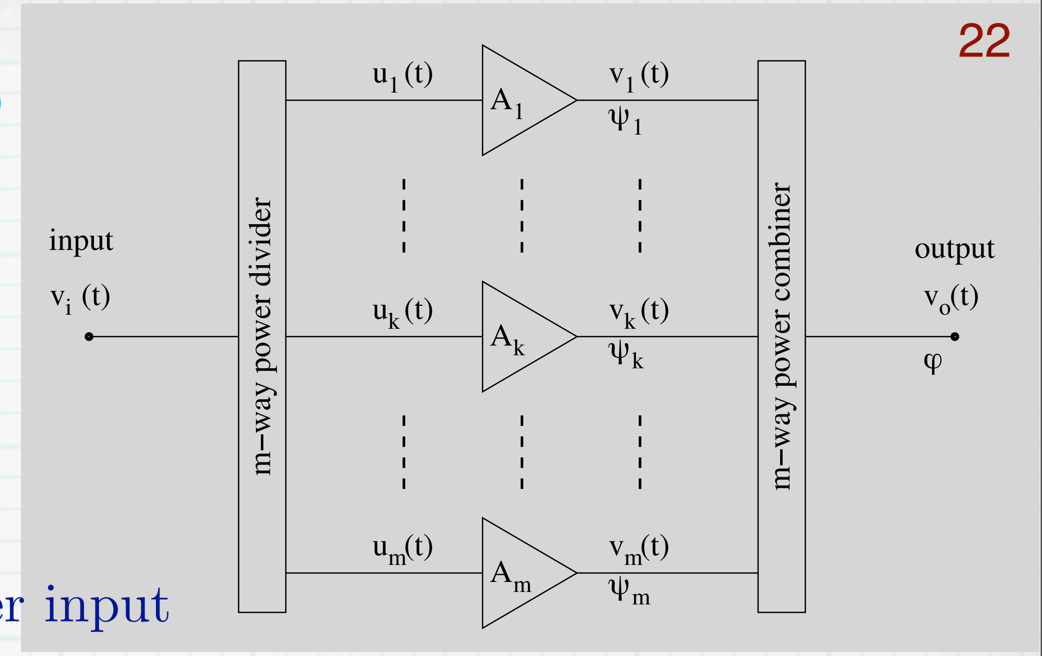
- The phase flicker coefficient b_{-1} is about independent of power
- The flicker of a branch is not increased by splitting the input power
- At the output,
  - the carrier adds up coherently
  - the phase noise adds up statistically
- Hence, the 1/f phase noise is reduced by a factor m

$$b_{-1} = \frac{1}{m}\left[b_{-1}\right]_{\text{branch}}$$

- Only the flicker noise can be reduced in this way

Gedankenexperiment: join the m branches of a parallel amplifier forming a single large active device: the phase flickering is proportional to the inverse physical size of the amplifier active region

Parallel amplifiers, mathematics



$$u_k(t) = \frac{1}{\sqrt{m}} v_i(t)$$ branch-amplifier input

$$v_o(t) = \frac{1}{\sqrt{m}} \sum_{k=1}^{m} v_k(t)$$ main output

$$v_k(t) = \frac{1}{\sqrt{m}} V_i \Big\{ a_1 + 2a_2 \big[n'_k(t) + j n''_k(t) \big] \Big\} e^{j2\pi\nu_0 t}$$ branch → output

$$\psi_k(t) = 2\frac{a_2}{a_1} n''_k(t)$$ branch

$$\varphi_k(t) = \frac{\frac{1}{m} V_i \, 2a_2 n''_k(t) \, e^{j2\pi\nu_0 t}}{a_1 V_i \, e^{j2\pi\nu_0 t}}$$ branch → output

$$= \frac{1}{m} \, 2\frac{a_2}{a_1} \, n''_k(t)$$

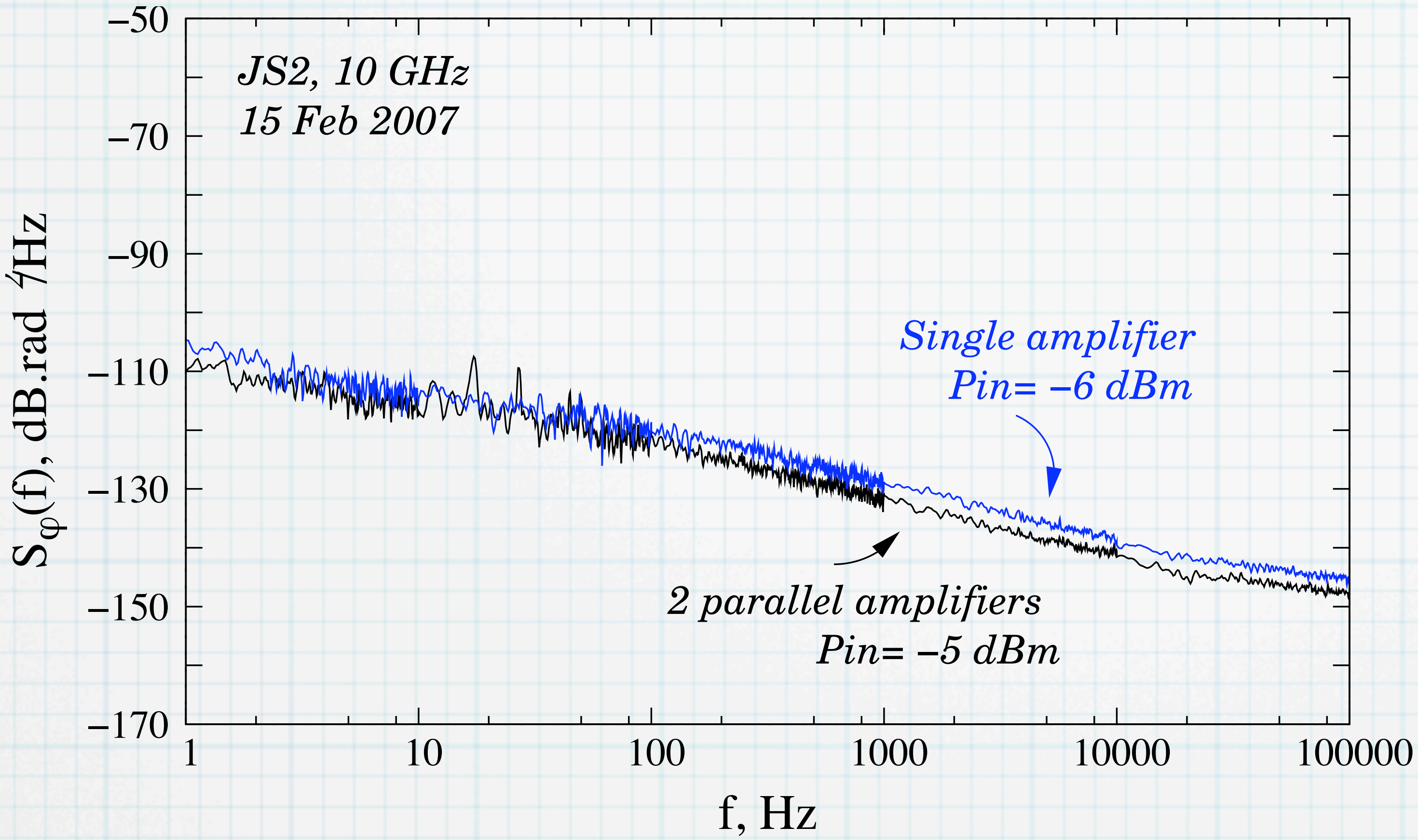
$$S_\varphi(f) = \sum_{k=1}^{m} \frac{1}{m^2} \, 4\frac{a_2^2}{a_1^2} \, S_{n''_k}(f)$$ $\sum$ branches → output

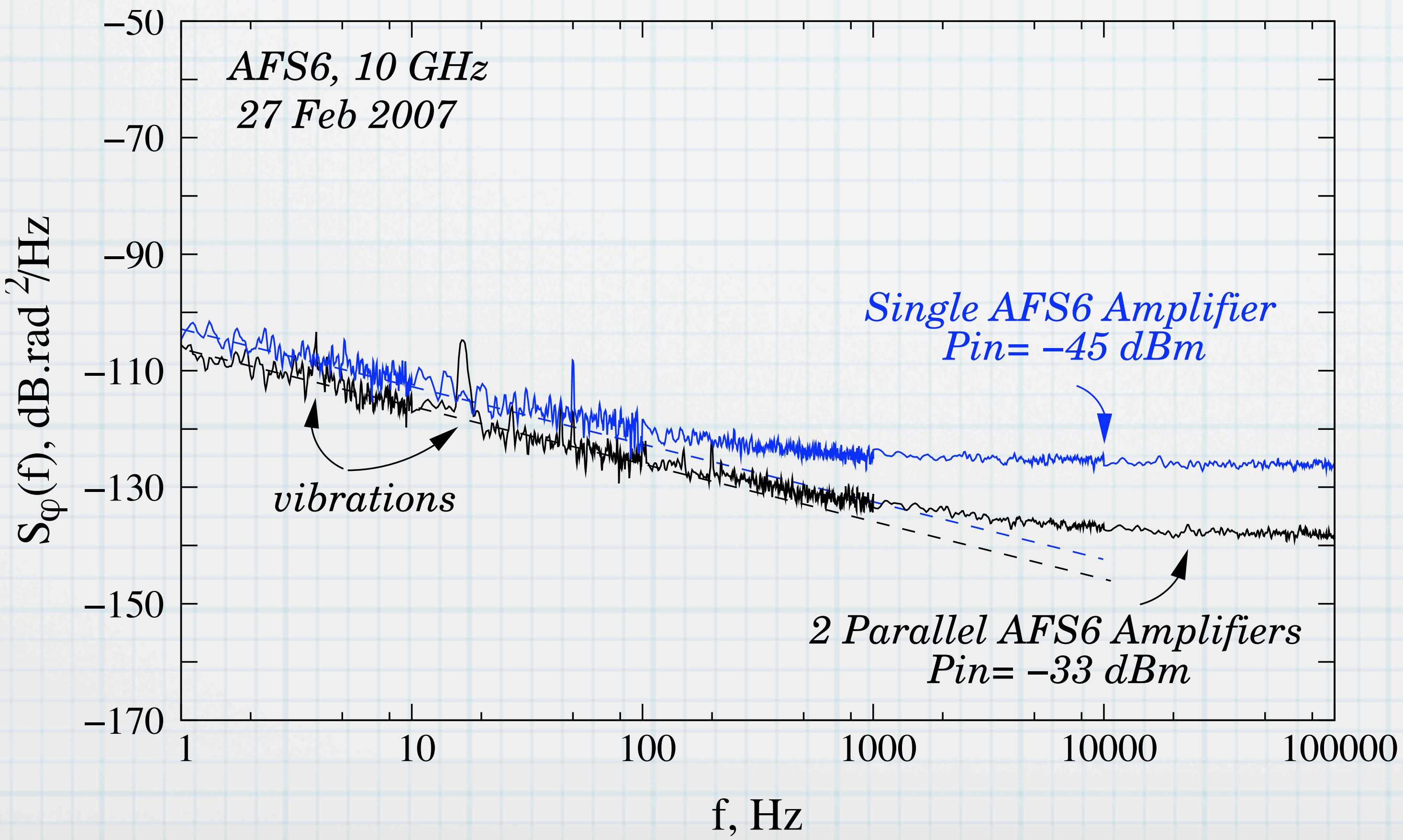
$$S_\varphi(f) = \frac{1}{m} \, 4\frac{a_2^2}{a_1^2} \, S_{n''}(f)$$

$$S_\varphi(f) = \frac{1}{m} S_\psi(f)$$ m equal branches → output

$$b_{-1} = \frac{1}{m} \, \big[b_{-1} \big]_{\text{branch}}$$

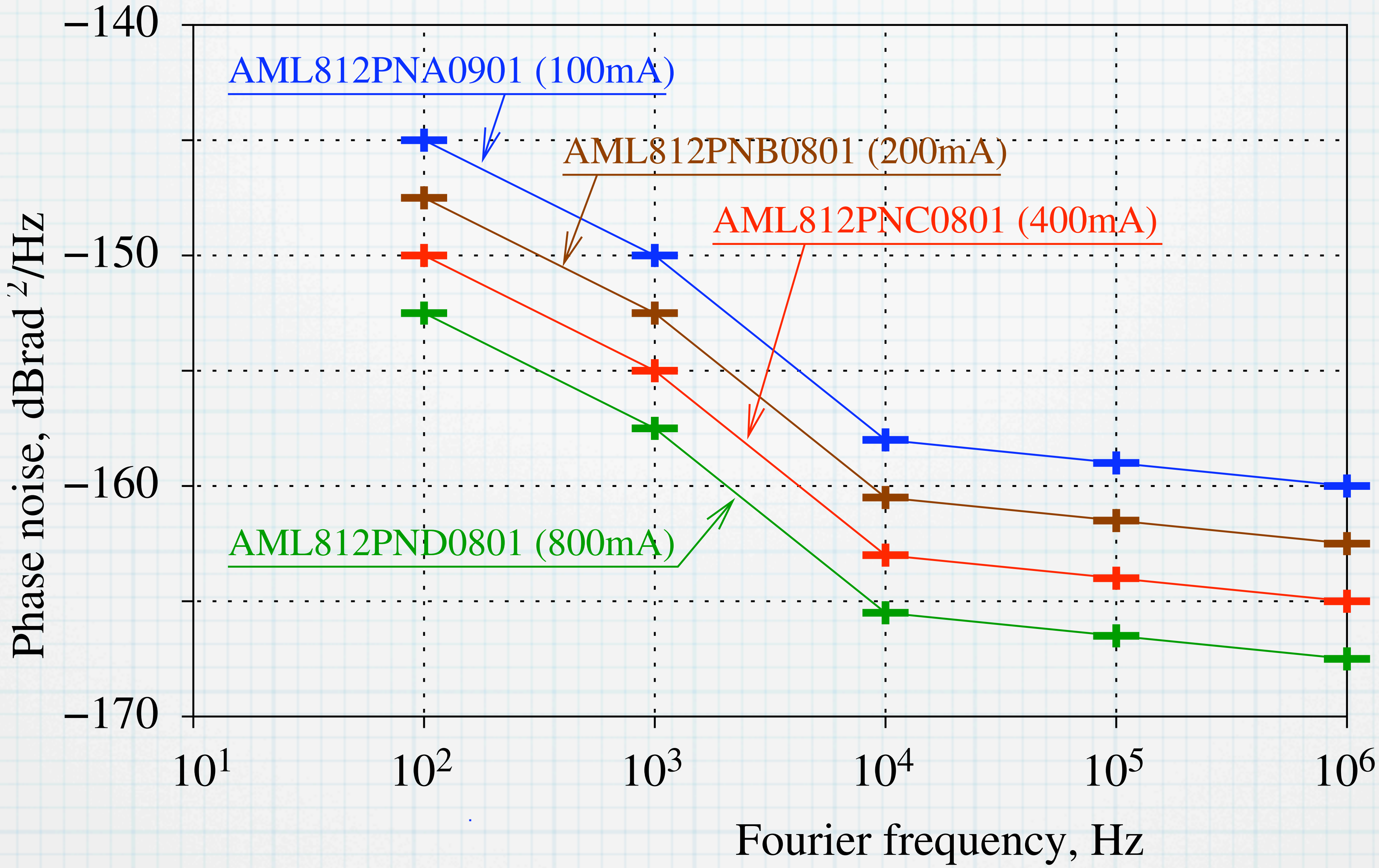
Flicker noise in parallel amplifiers





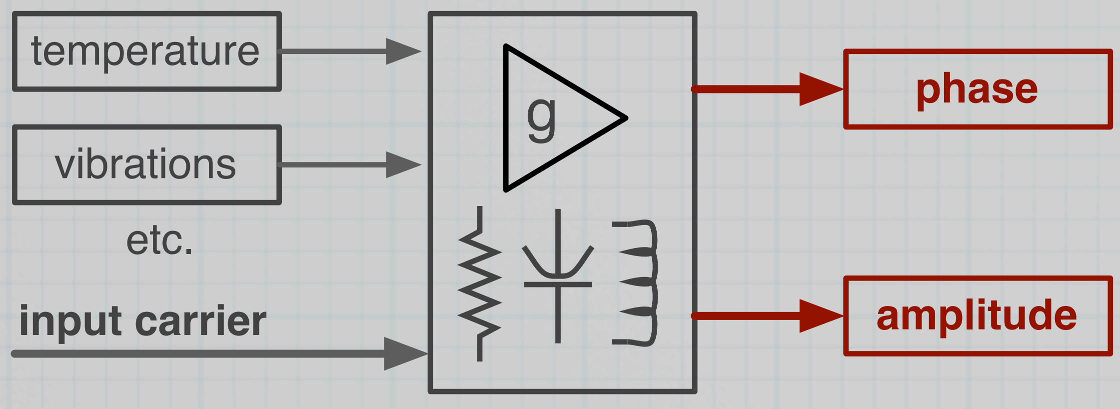
Connecting two amplifiers in parallel, the expected flicker is reduced by 3 dB

Flicker noise in parallel amplifiers

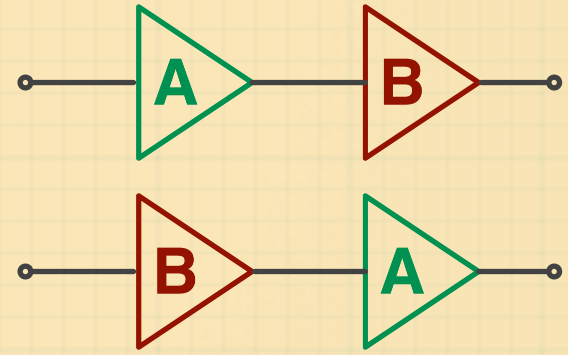


Specification of low phase-noise amplifiers (AML web page)								
amplifier	parameters				phase noise vs. f, Hz			
	gain	F	bias	power	10^2	10^3	10^4	10^5
AML812PNA0901	10	6.0	100	9	−145.0	−150.0	−158.0	−159.0
AML812PNB0801	9	6.5	200	11	−147.5	−152.5	−160.5	−161.5
AML812PNC0801	8	6.5	400	13	−150.0	−155.0	−163.0	−164.0
AML812PND0801	8	6.5	800	15	−152.5	−157.5	−165.5	−166.5
unit	dB	dB	mA	dBm	dBrad^2/Hz			

Environmental (parametric) noise in amplifiers



A time constant can be present



$\varphi = \varphi_A + \varphi_B$ and $\alpha = \alpha_A + \alpha_B$
regardless of the amplifier order

Cascading *m* equal amplifiers, $S_\alpha(f)$ and $S_\varphi(f)$ increase by a factor m^2.

If the amplifier were independent, $S_\alpha(f)$ and $S_\varphi(f)$ would increase only by a factor *m*.

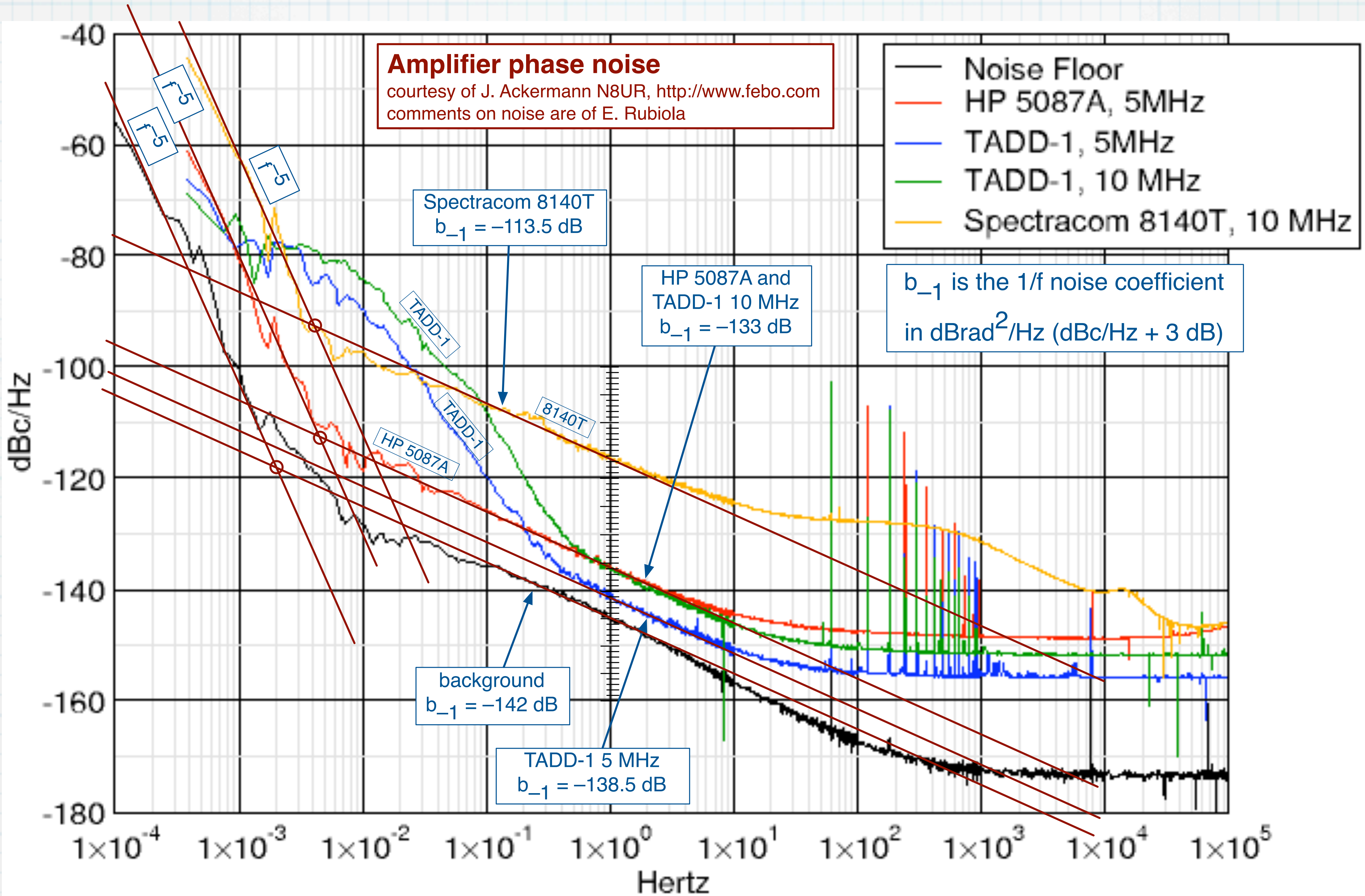
Cascaded amplifiers

let $\quad z(t) = x(t) + y(t)$

Phase noise

$$
\begin{aligned}
S_z(f) &= ZZ^* \\
&= (X+Y)\,(X+Y)^* \\
&= XX^* + YY^* + XY^* + YX^* \\
&= S_x + S_y + \underbrace{S_{xy}}_{>0} + \underbrace{S_{yx}}_{>0}
\end{aligned}
$$

Environmental effects in RF amplifiers



It is experimentally observed that the temperature fluctuations cause a spectrum $S_\alpha(f)$ or $S_\varphi(f)$ of the $1/f^5$ type

Yet, at lower frequencies the spectrum folds back to 1/f

Summary (2)

* Flicker AM/PM noise results from parametric modulation from the near-dc 1/f noise
* The 1/f noise coefficient b_{-1} is about independent of the carrier power
* Describing the 1/f noise in terms of fc is misleading
* Cascading m amplifiers, the 1/f noise increases by a factor m
* Connecting m amplifiers in parallel, the 1/f noise drops by a factor m
* Thermal fluctuations induce $1/f^5$ PM noise, which folds back to 1/f at lower frequencies

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