Phase Noise in RF and Microwave Amplifiers

Enrico Rubiola and Rodolphe Boudot

IFCS, Newport, CA, 1–4 June 2010

Outline

- Noise types (white and flicker)
- Amplifier networks
- Experiments
- Conclusions

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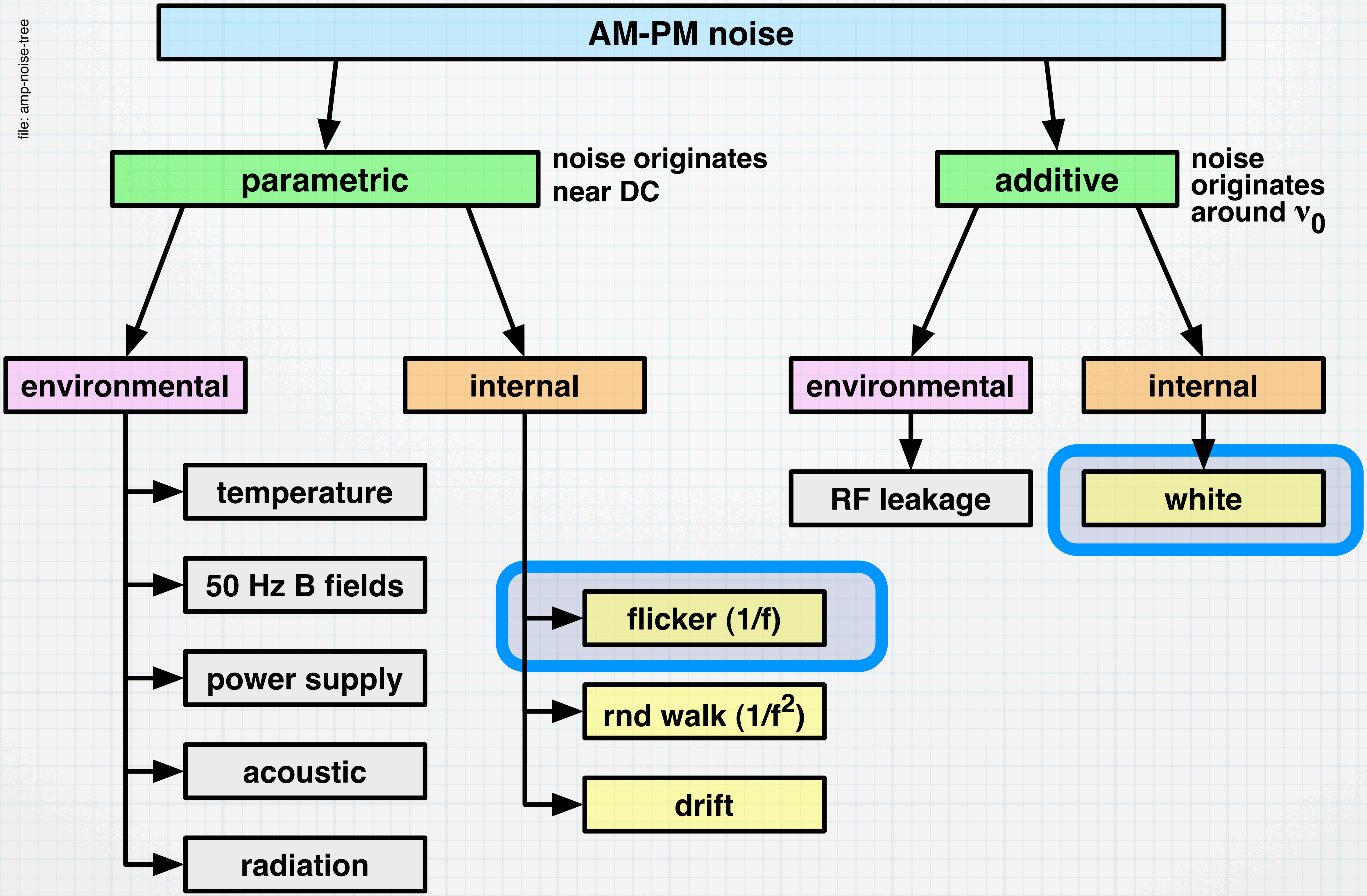
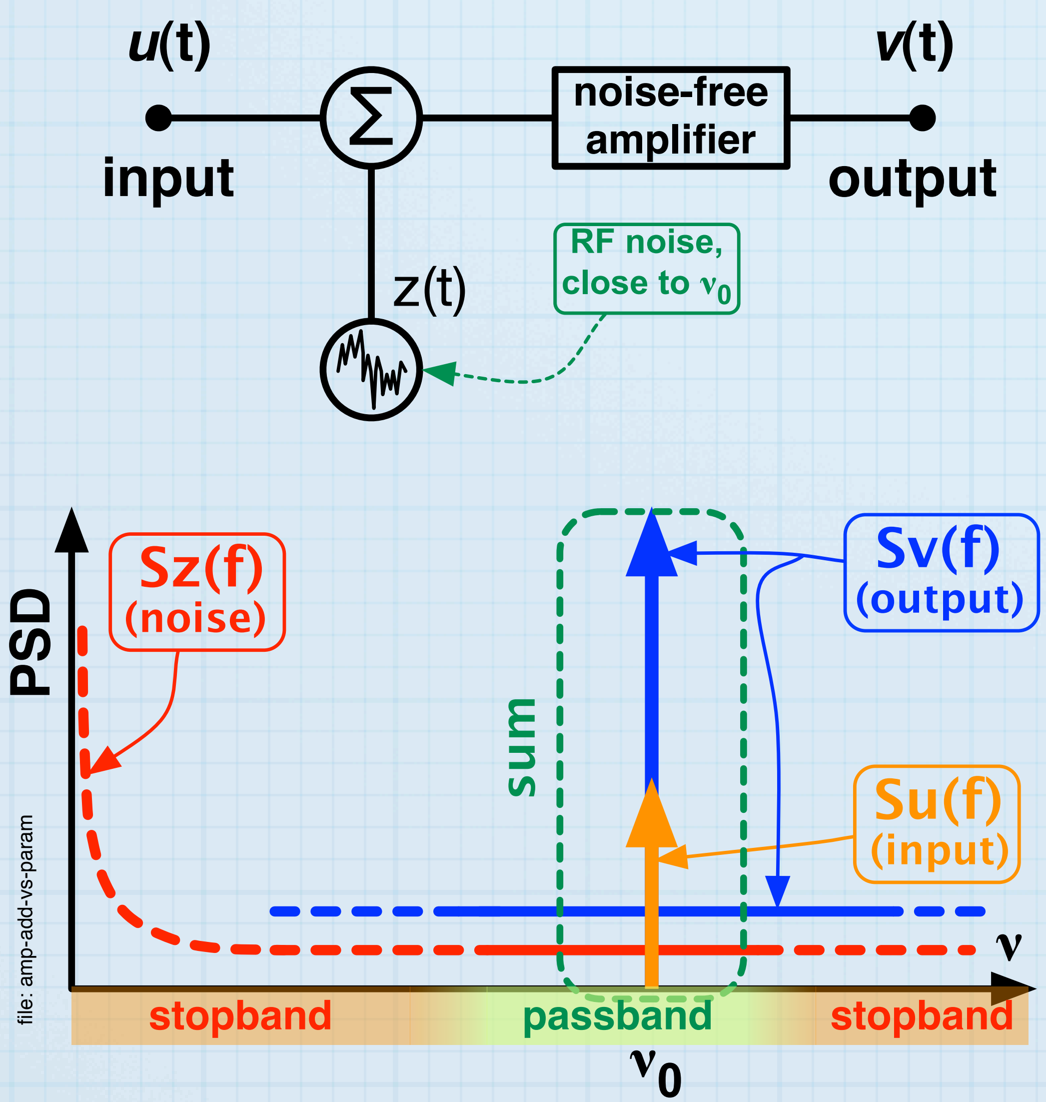
AM-PM noise types



file: amp-noise-tree

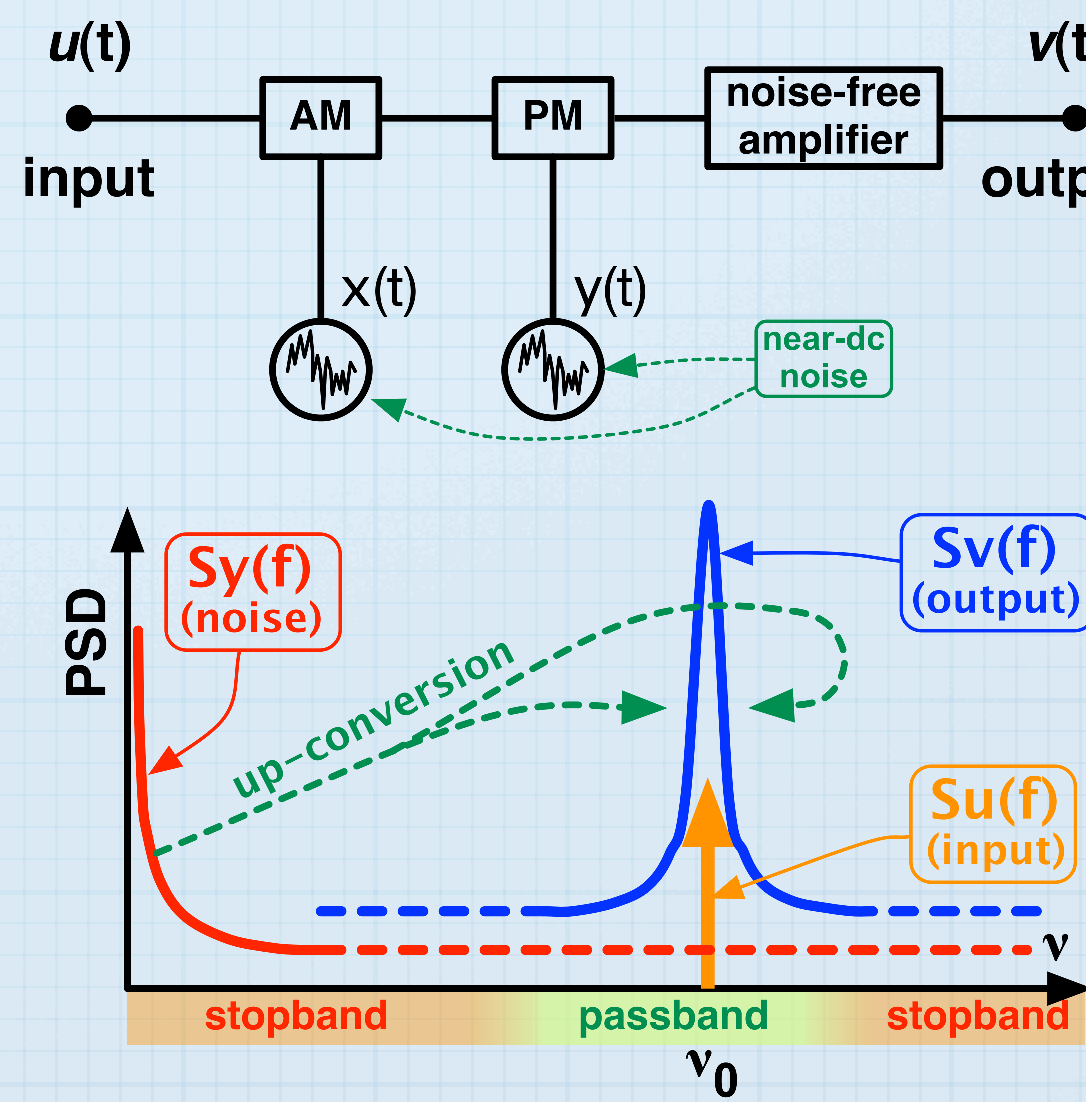
The difference between additive and parametric noise

additive noise



the noise sidebands are **independent of the carrier**

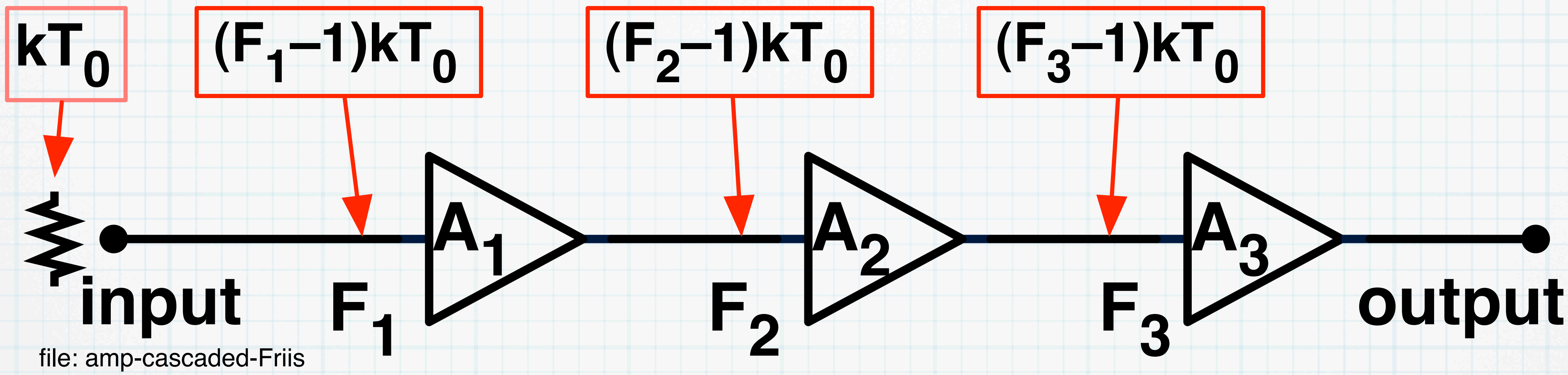
parametric noise



the noise sidebands are **proportional to the carrier**

White noise in cascaded amplifiers

White noise is chiefly the noise of the first stage



$$N_e = F_1 kT_0 + \frac{(F_2-1)kT_0}{A_1^2} + \frac{(F_3-1)kT_0}{A_2^2A_1^2} + \ldots$$

$$F = F_1 + \frac{(F_2-1)}{A_1^2} + \frac{(F_3-1)}{A_2^2A_1^2} + \ldots$$

Friis formulae

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

Noise is chiefly that of the 1st stage

$$b_0 = \frac{FkT_0}{P_0}$$

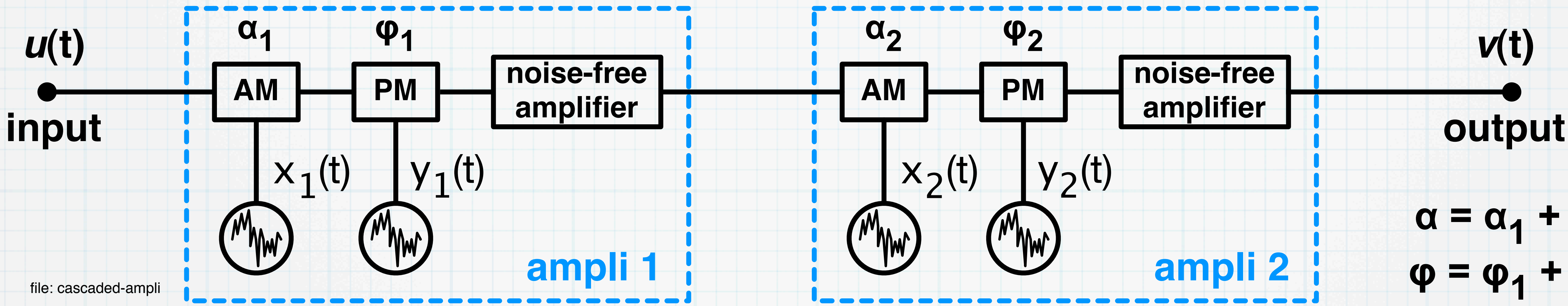
white phase noise

$$b_0 = \frac{F_1kT_0}{P_0} + \frac{(F_2-1)kT_0}{A_1^2P_0} + \frac{(F_3-1)kT_0}{A_2^2A_1^2P_0} + \ldots$$

Friis formula for phase noise

Parametric noise in cascaded amplifiers

There is a nonlinear model that gives exactly the same results, see Chap. 2 of
E. Rubiola, *Phase Noise and Frequency Stability in Oscillators*, Cambridge 2008, ISBN 978-0521-88677-2



$\alpha = \alpha_1 + \alpha_2$

$\varphi = \varphi_1 + \varphi_2$

Flicker: the two amplifiers are independent

$$\mathbb{E}\{\alpha^2\} = \mathbb{E}\{\alpha_1^2\} + \mathbb{E}\{\alpha_2^2\} \qquad S_\alpha = S_{\alpha\,1} + S_{\alpha\,2}$$

$$\mathbb{E}\{\varphi^2\} = \mathbb{E}\{\varphi_1^2\} + \mathbb{E}\{\varphi_2^2\} \qquad S_\alpha = S_{\varphi\,1} + S_{\varphi\,2}$$

Environment: a single process drives the two amplifiers

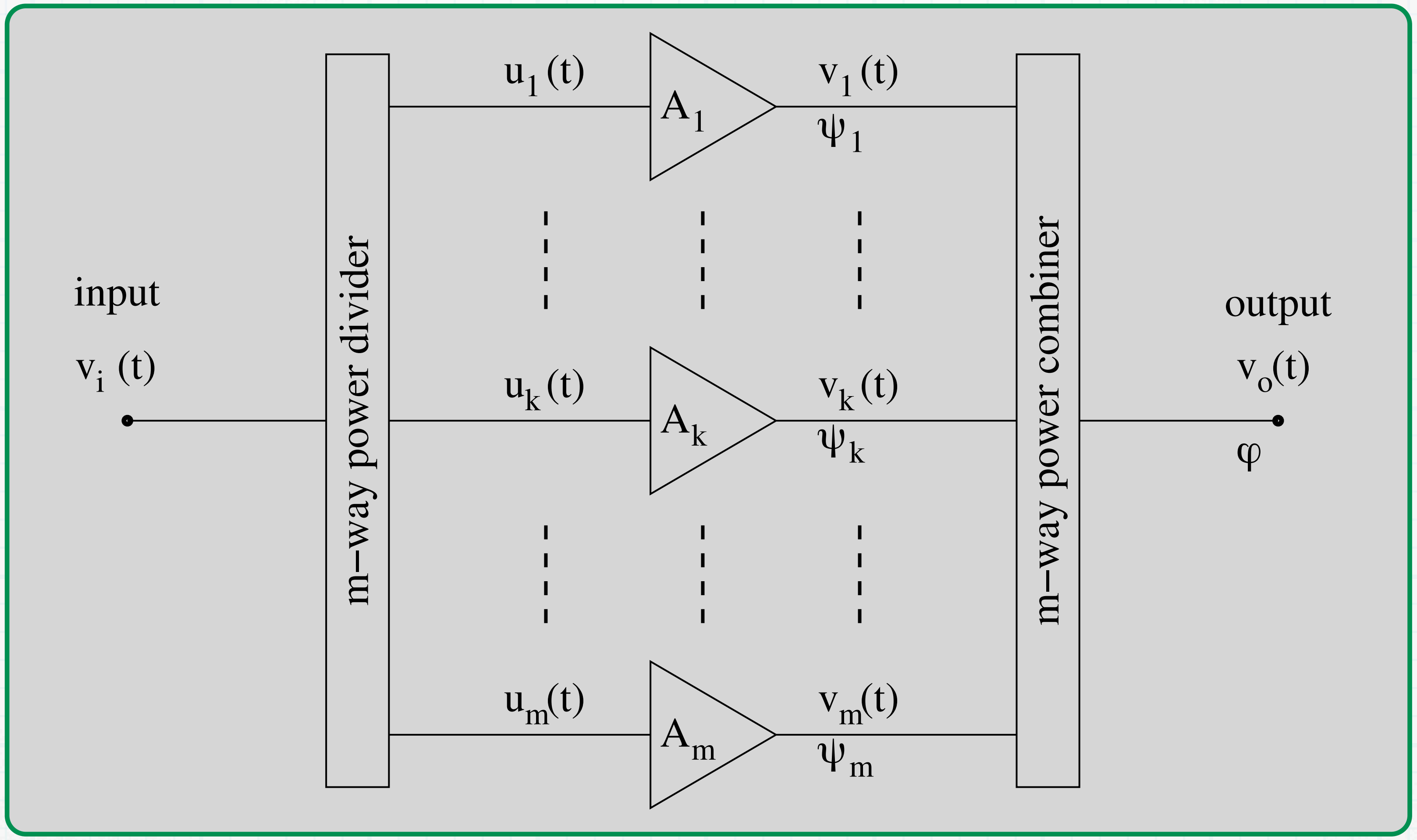
$$\alpha = \alpha_1 + \alpha_2 \qquad \mathbb{E}\{\alpha^2\} = \mathbb{E}\{(\alpha_1 + \alpha_2)^2\}$$

$$\varphi = \varphi_1 + \varphi_2 \qquad \mathbb{E}\{\varphi^2\} = \mathbb{E}\{(\varphi_1 + \varphi_2)^2\}$$

Yet there can be a time constant, not necessarily the same for the two devices

Flicker noise in parallel amplifiers

E. Rubiola, *Phase Noise and Frequency Stability in Oscillators*, Cambridge 2008, ISBN 978-0521-88677-2



- 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
- Only the flicker noise can be reduced in this way

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

Volume law

The analysis of the parallel amplifier suggests that:

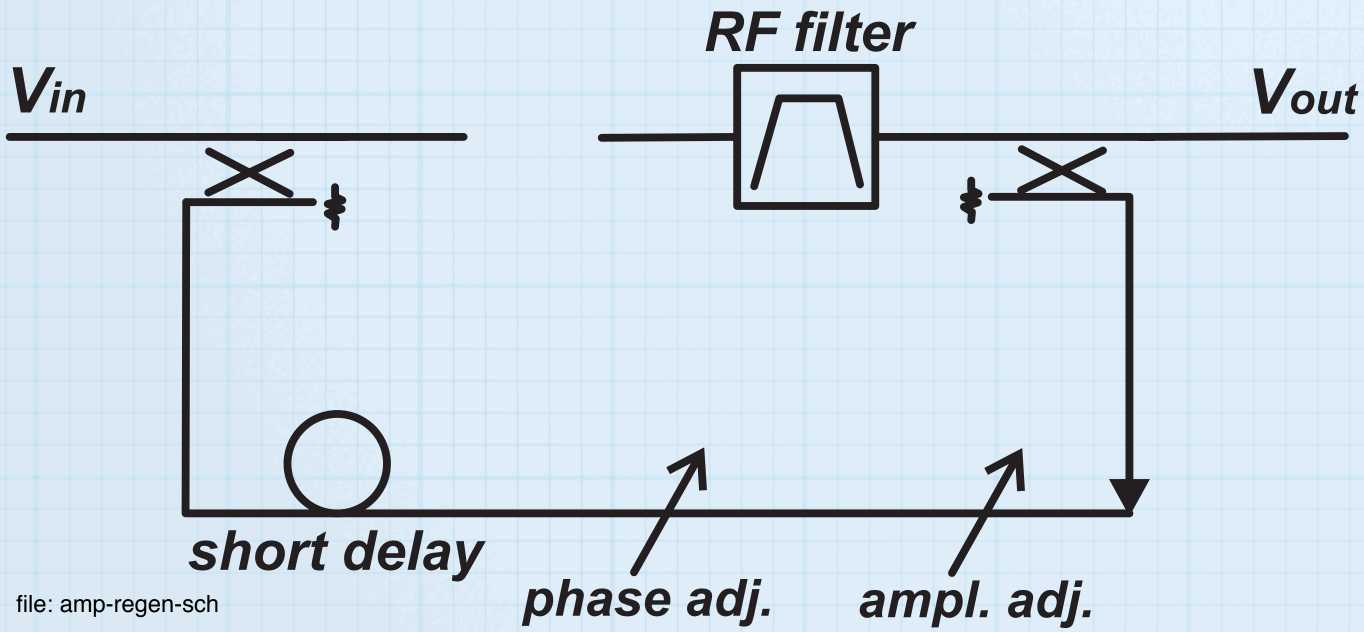
For a given technology, the flicker coefficient b_{-1} should be proportional to the inverse of the volume of the active region

Gedankenexperiment

- Flicker is of microscopic origin because it has Gaussian PDF (central limit theorem)
- Join the m branches of a parallel device forming a compound
- Phase flicker is proportional to the inverse size of the amplifier active region

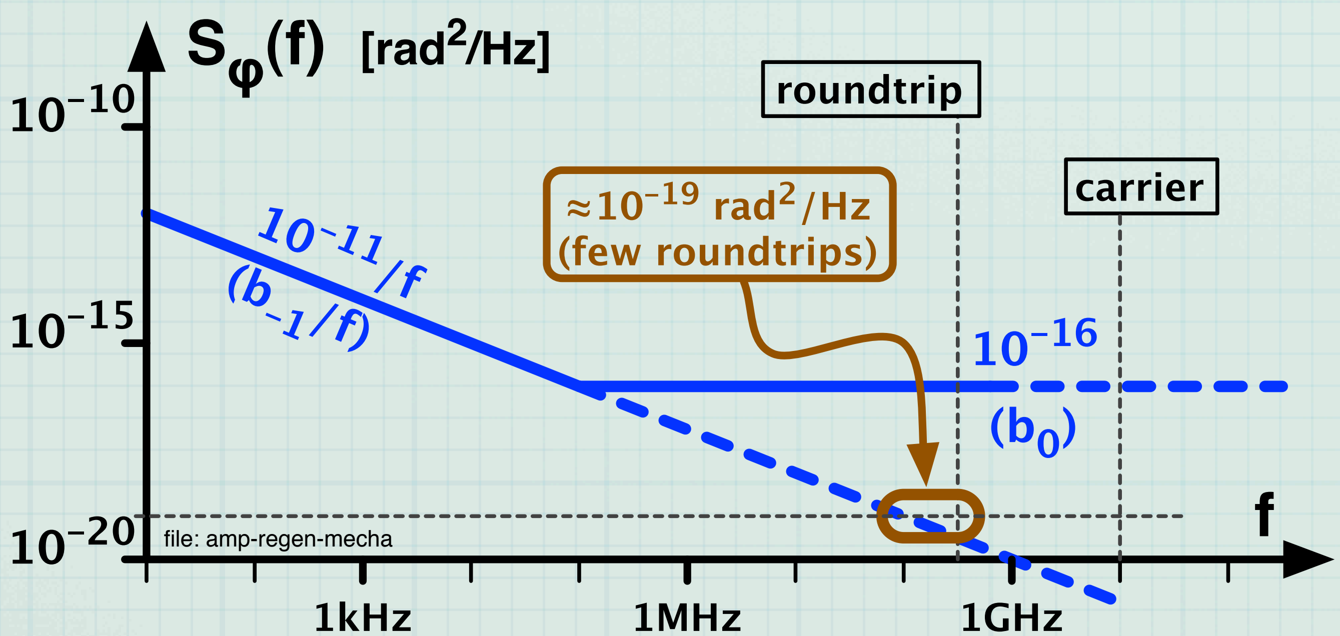
Parametric noise in regenerative amplifiers

R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitt. IEEE Transact. MTT



$$A = \frac{A_0}{1 - A_0\beta}$$

$$A = A_0^m \quad \Rightarrow \quad \beta = \frac{A_0^{m-1} - 1}{A_0^m}$$



- Short roundtrip time, vs. flicker time frame
- Quasi-static analysis holds

$$A \to \frac{A_0\, e^{j\psi}}{1 - A_0\beta\, e^{j\psi}}$$

$$A = \frac{A_0}{1 - A_0\beta}\left[1 + j\,\frac{1}{1 - A_0\beta}\,\psi\right] .$$

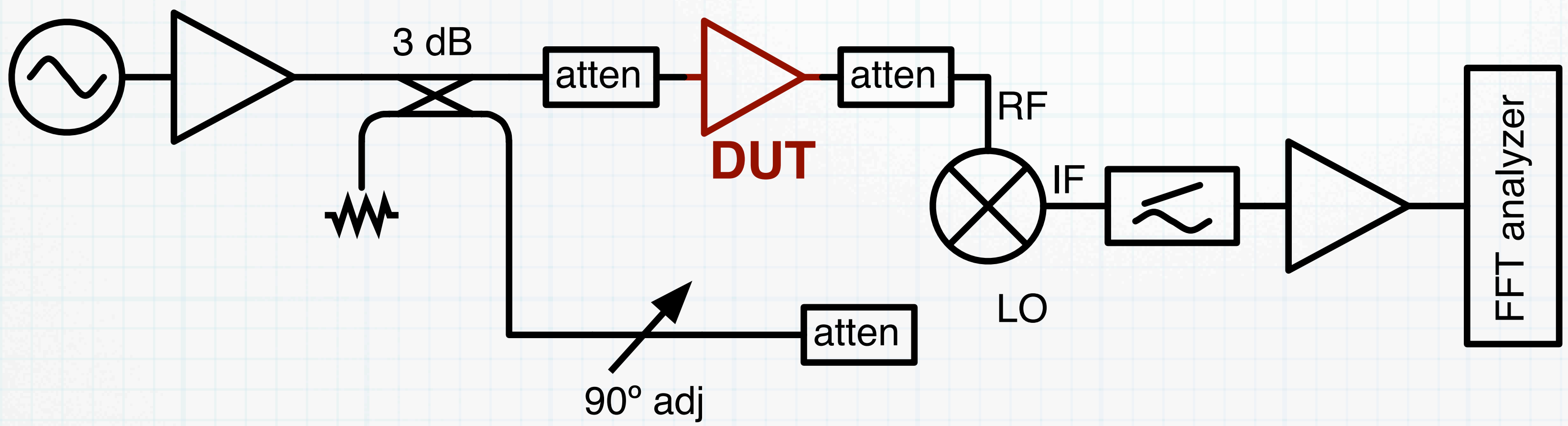
$$\varphi(t) = \frac{1}{1 - A_0\beta}\,\psi(t)$$

$$(b_{-1})_{\mathrm{RA}} = \left[\frac{1}{1 - A_0\beta}\right]^2 (b_{-1})_{\mathrm{ampli}}$$

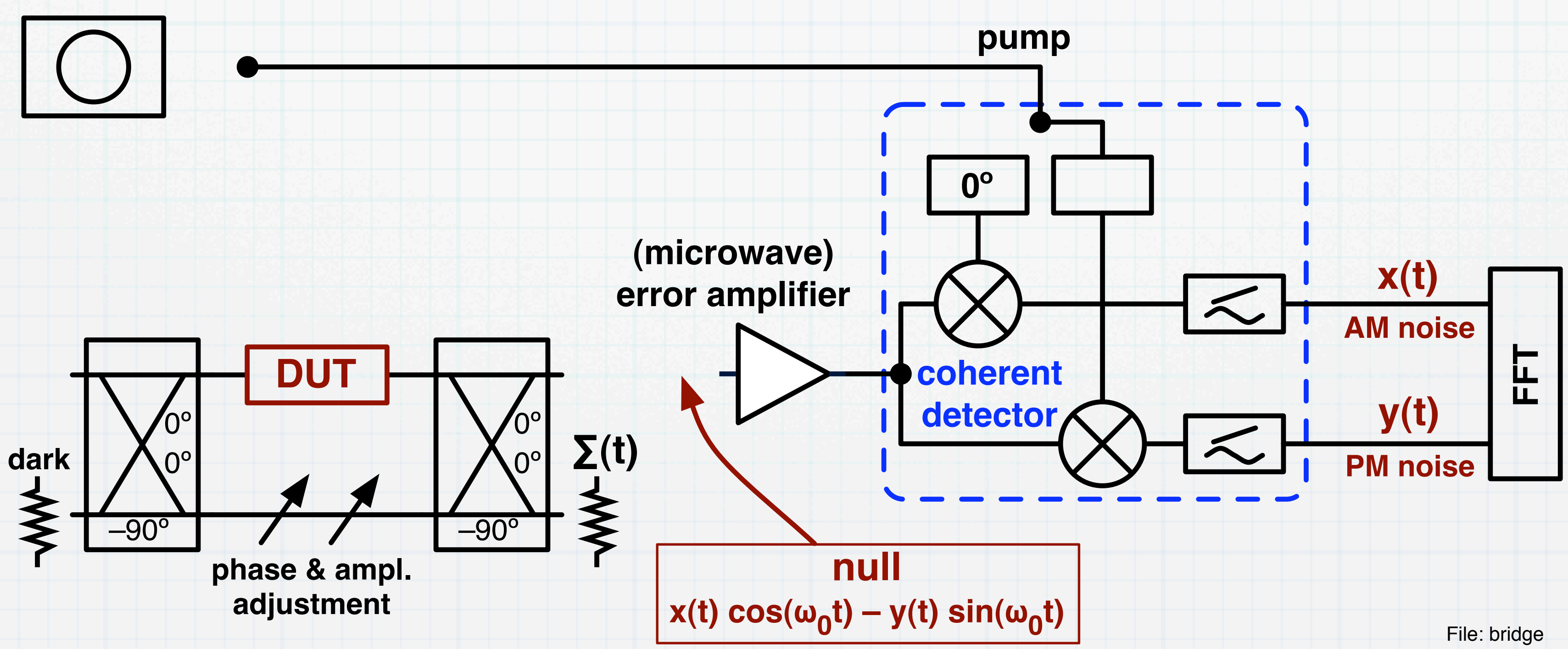
$$(b_{-1})_{\mathrm{RA}} = m^2 (b_{-1})_{\mathrm{ampli}}$$

Measurement methods

Saturated mixer (common laboratory practice)



Bridge (interferometer)



E. Rubiola, V. Giordano, Rev. Sci. Instrum. 73(6) pp.2445-2457, June 2002

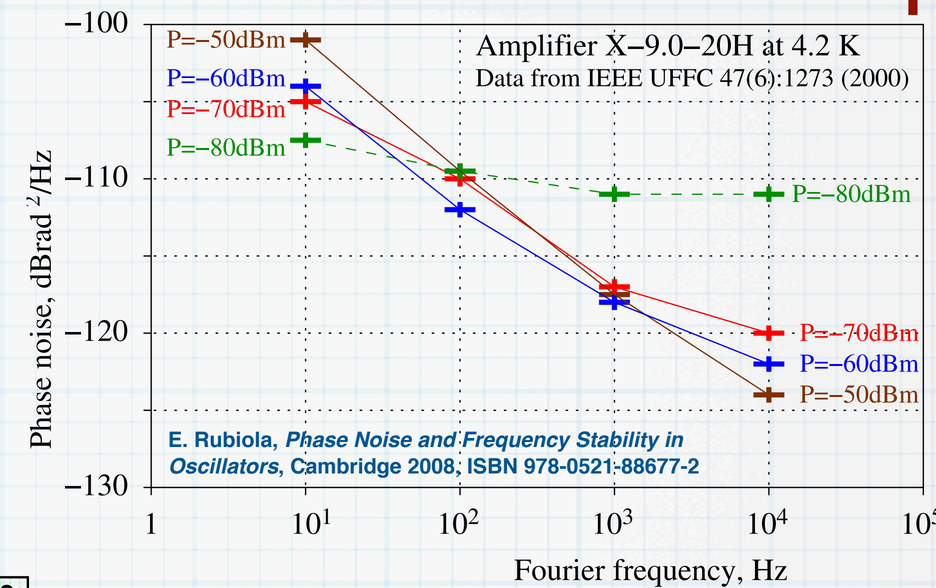
Flicker noise of some amplifiers

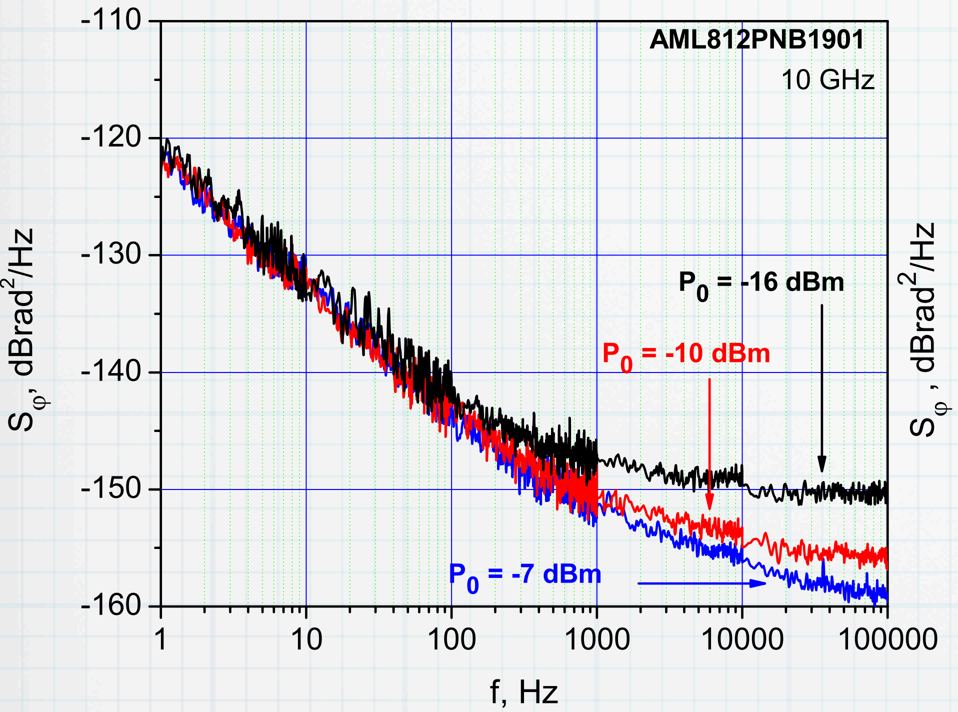
R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitt. IEEE Transact. MTT

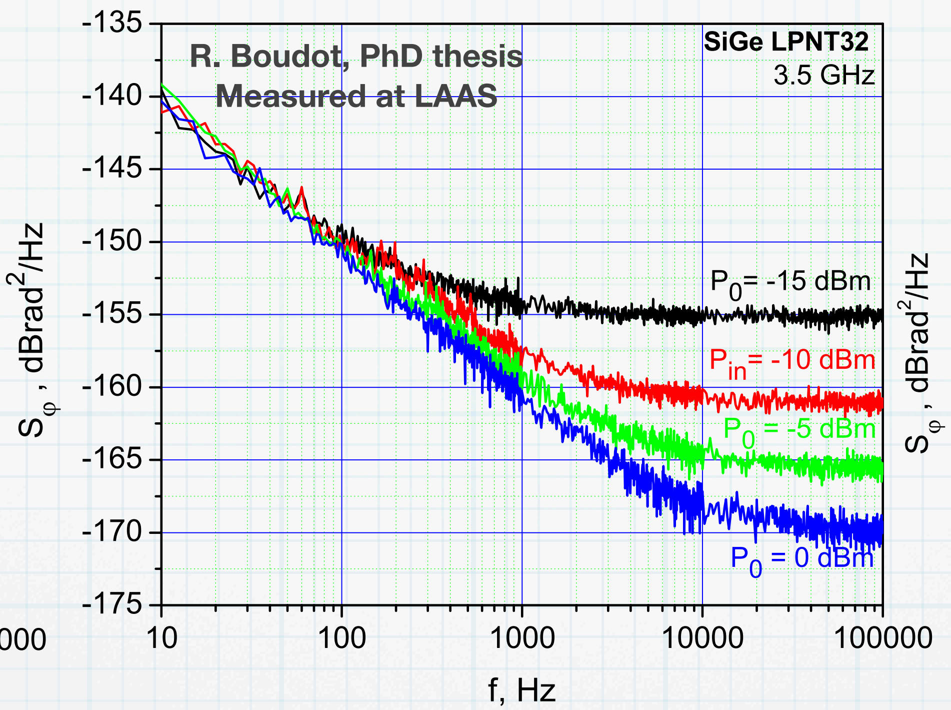
Amplifier	Frequency (GHz)	Gain (dB)	$P_{1\,\mathrm{dB}}$ (dBm)	F (dB)	DC bias	b_{-1} (meas.) (dBrad^2/Hz)
AML812PNB1901	8 – 12	22	17	7	15 V, 425 mA	−122
AML412L2001	4 – 12	20	10	2.5	15 V, 100 mA	−112.5
AML612L2201	6 – 12	22	10	2	15 V, 100 mA	−115.5
AML812PNB2401	8 – 12	24	26	7	15 V, 1.1A	−119
AFS6	8 – 12	44	16	1.2	15 V, 171 mA	−105
JS2	8 – 12	17.5	13.5	1.3	15 V, 92 mA	−106
SiGe LPNT32	3.5	13	11	1	2 V, 10 mA	−130
Avantek UTC573	0.01 – 0.5	14.5	13	3.5	15 V, 100 mA	−141.5
Avantek UTO512	0.005–0.5	21	8	2.5	15 V, 23 mA	−137

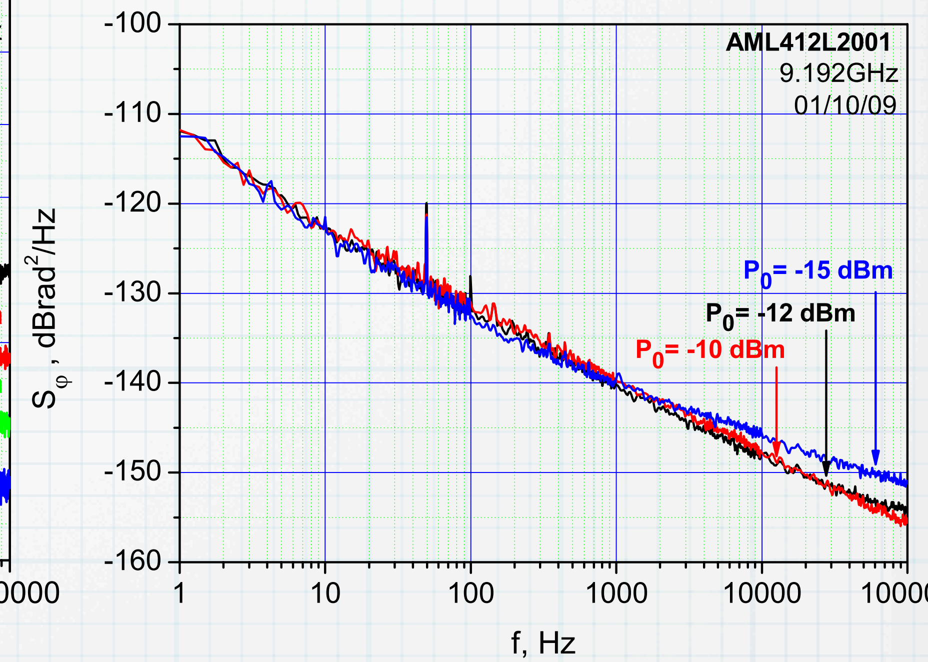
Phase noise vs. power

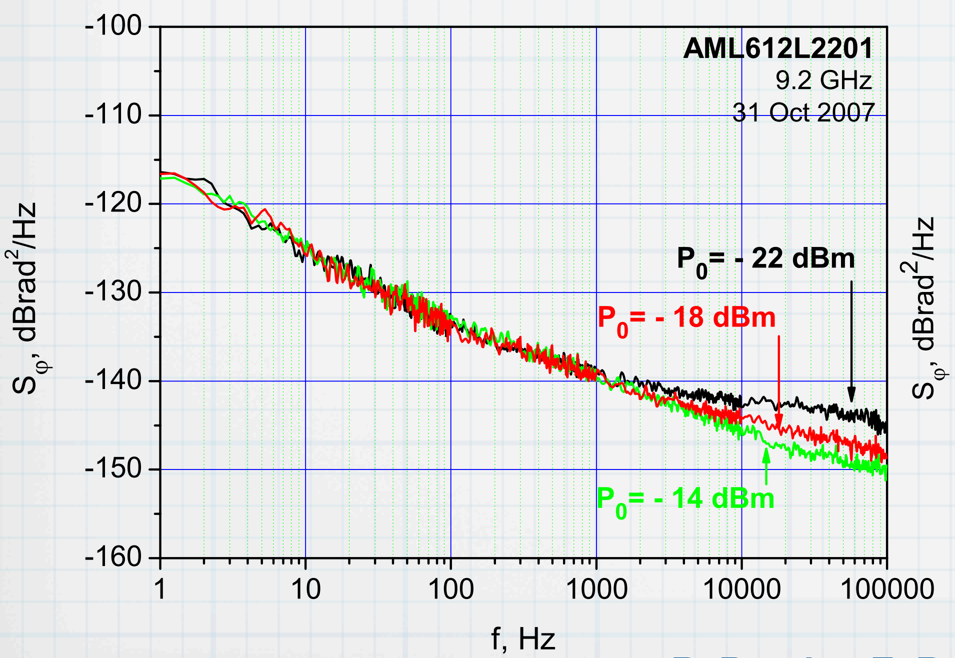
- The 1/f phase noise b_{-1} is about independent of power
- The white noise b_0 scales as the inverse of the power
- The corner frequency is misleading because it depends on power

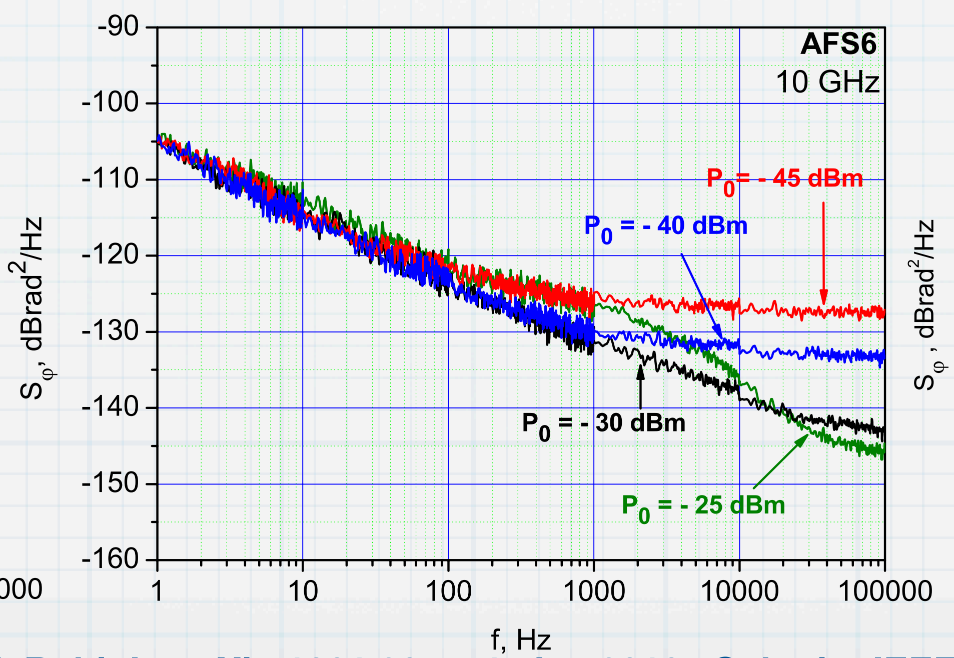


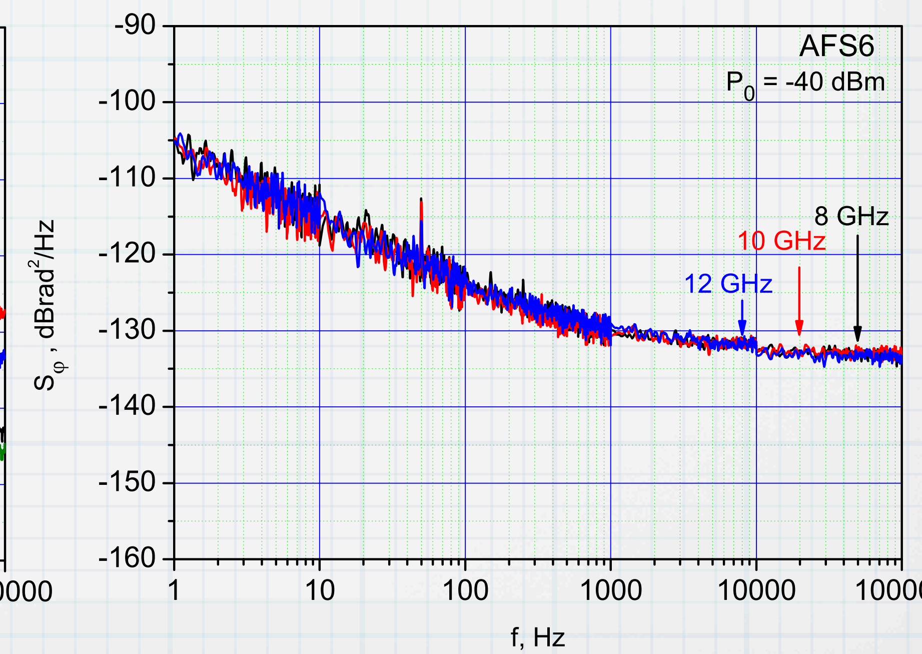












R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitt. IEEE Transact. MTT

Phase noise in cascaded amplifiers

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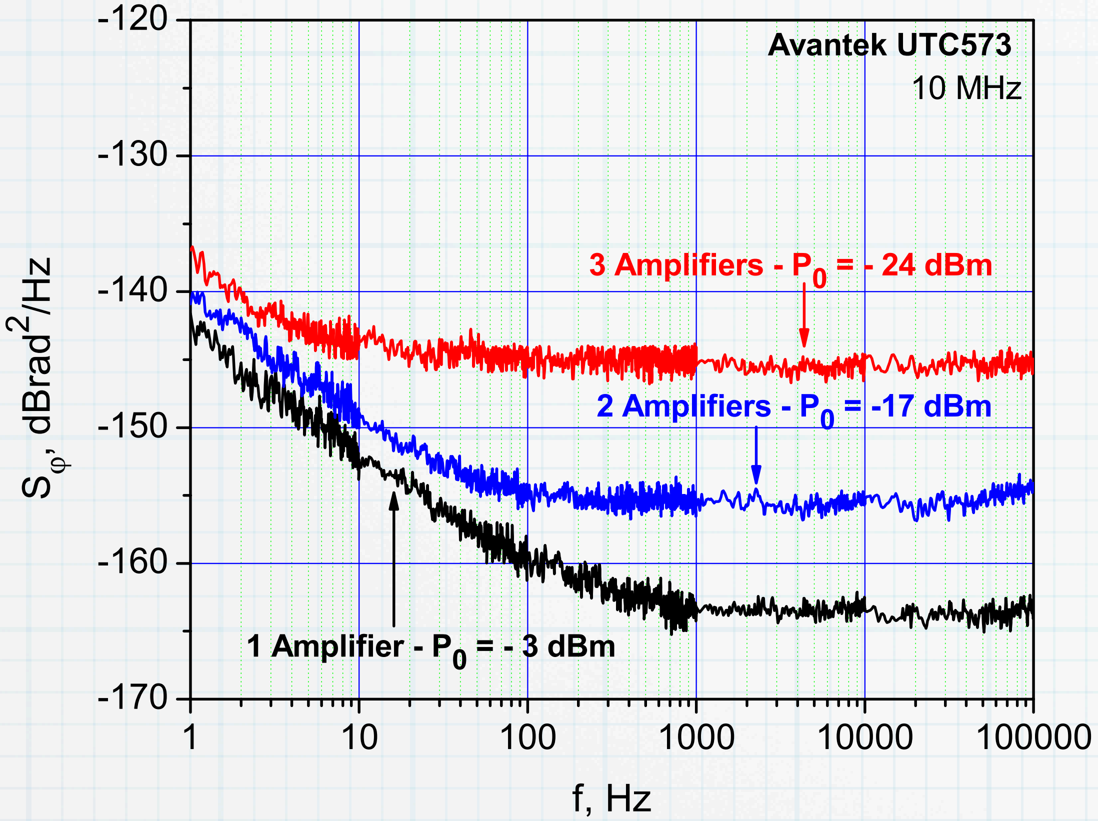
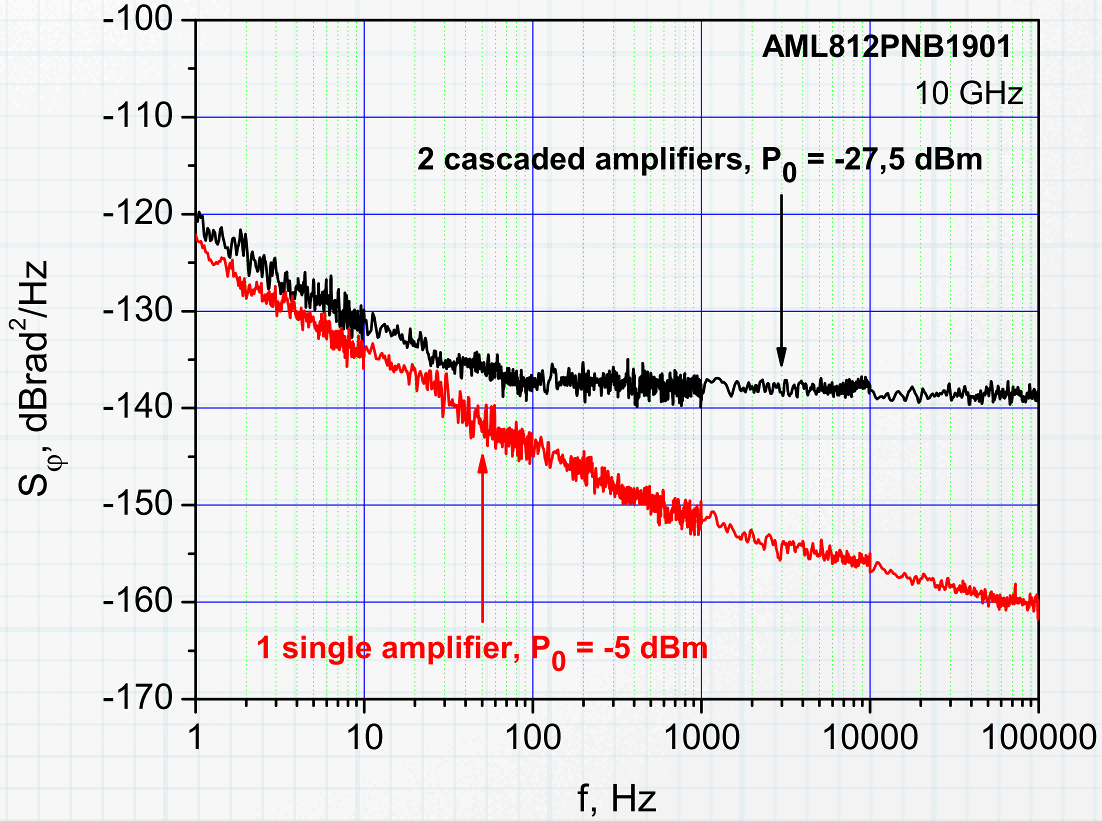
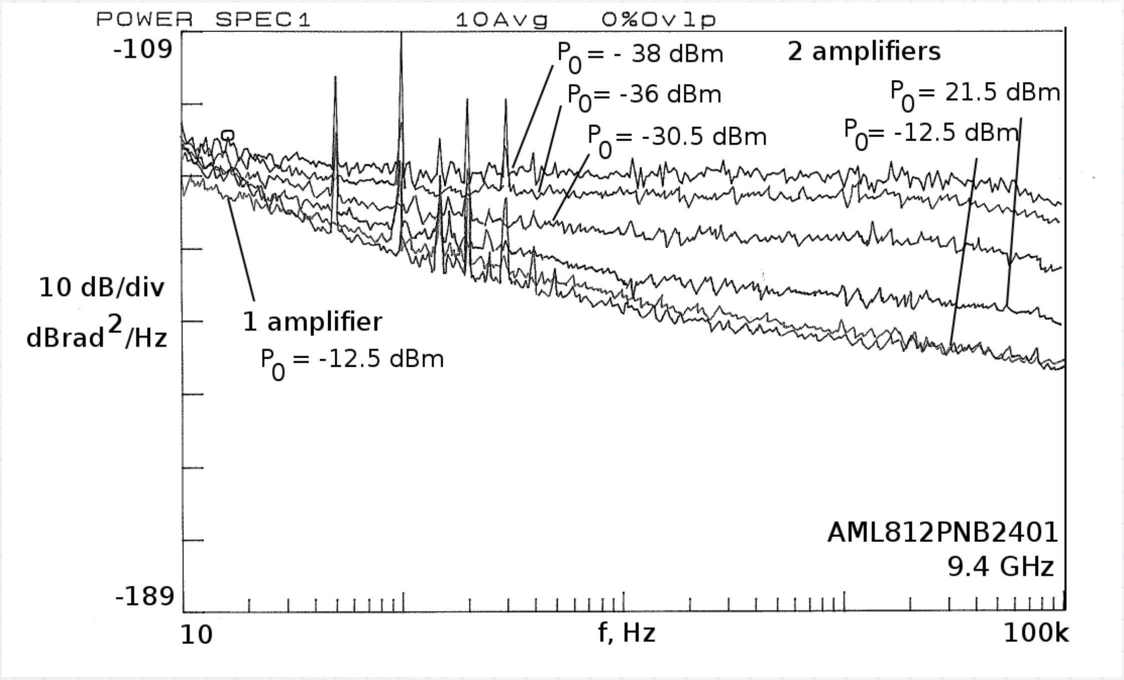






The expected flicker of a cascade increases by:

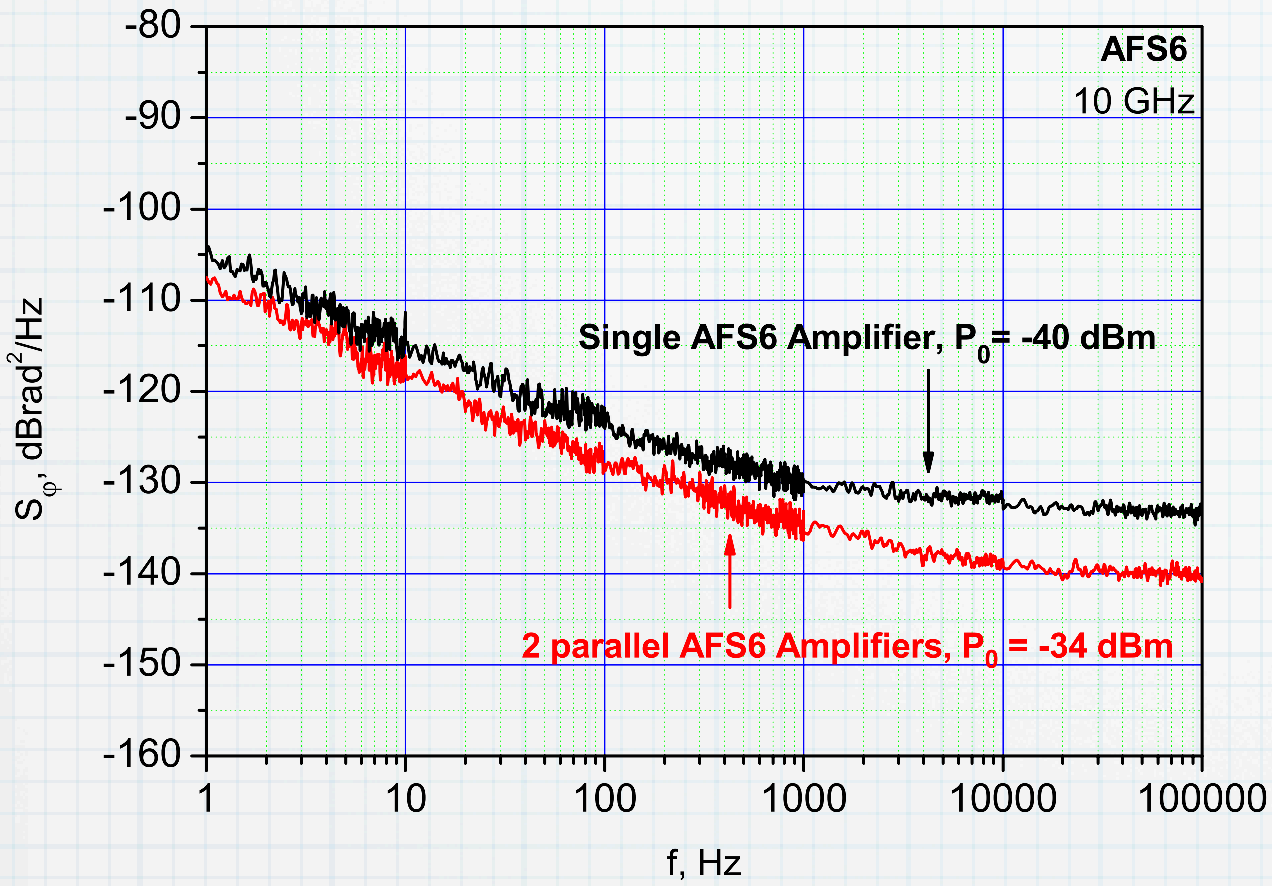
3 dB, with 2 amplifiers

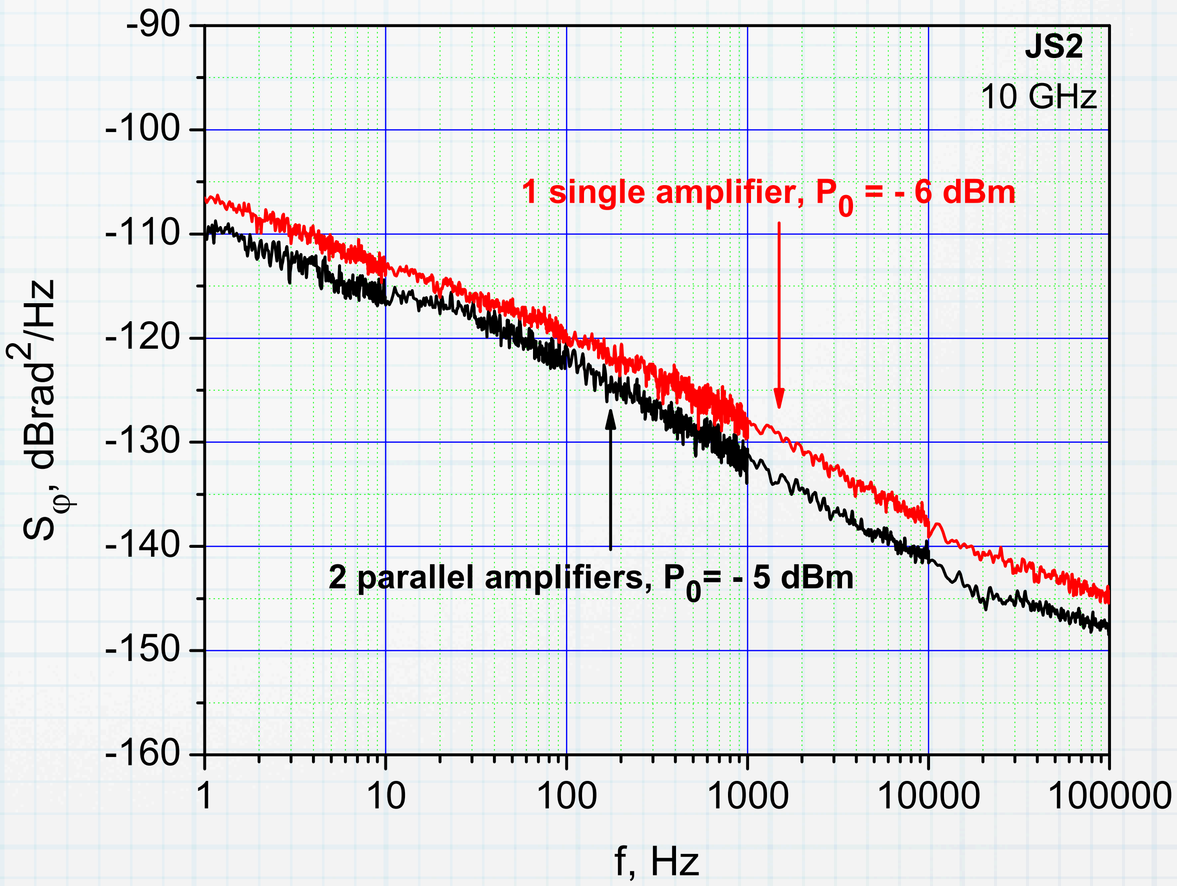
4.8 dB, with 3 amplifiers

White noise is limited by the (small) input power

Phase noise in parallel amplifiers

R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitt. IEEE Transact. MTT

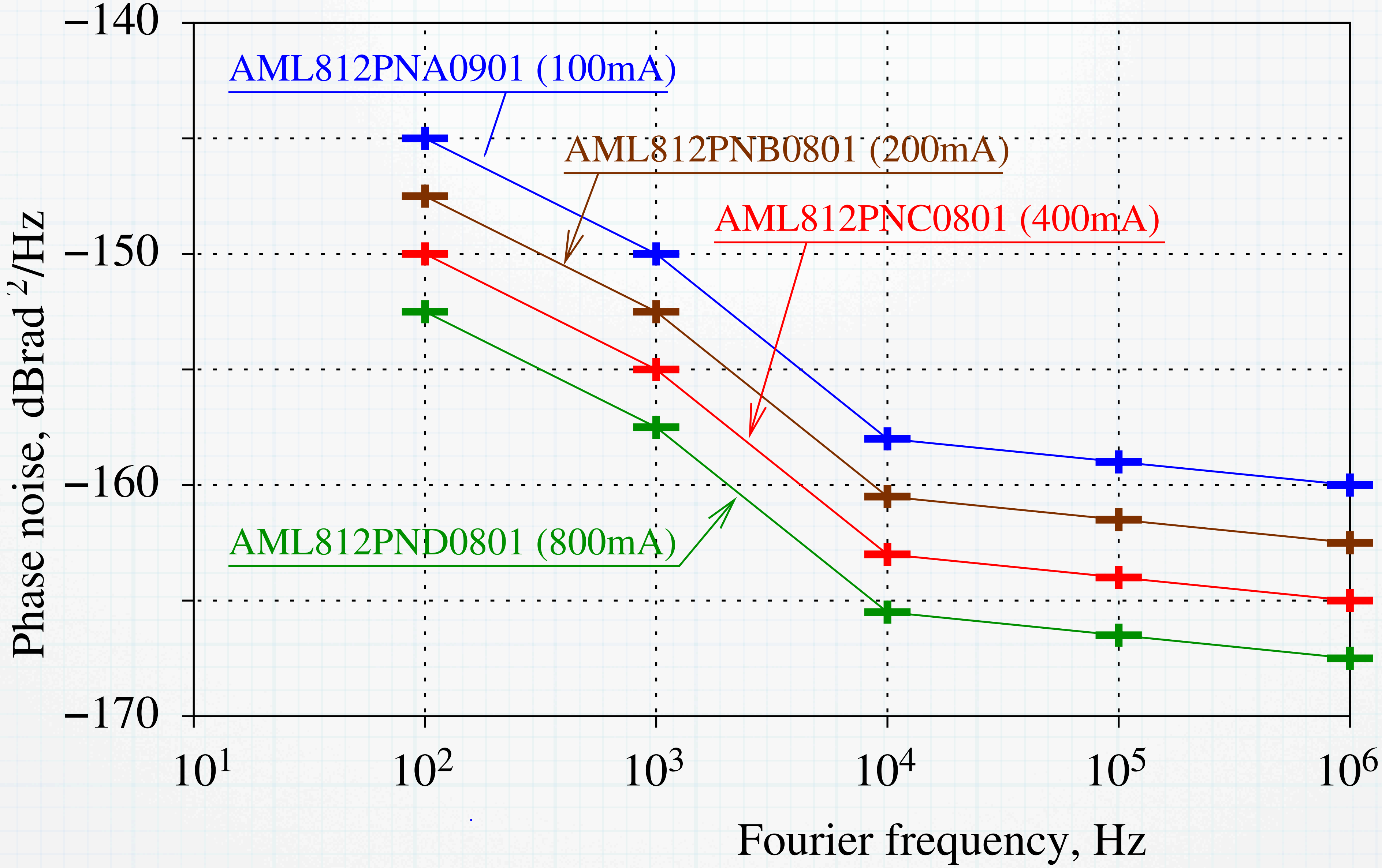




Connecting two amplifier in parallel, a 3 dB reduction of flicker is expected

Flicker noise in parallel amplifiers

E. Rubiola, *Phase Noise and Frequency Stability in Oscillators*, Cambridge 2008, ISBN 978-0521-88677-2



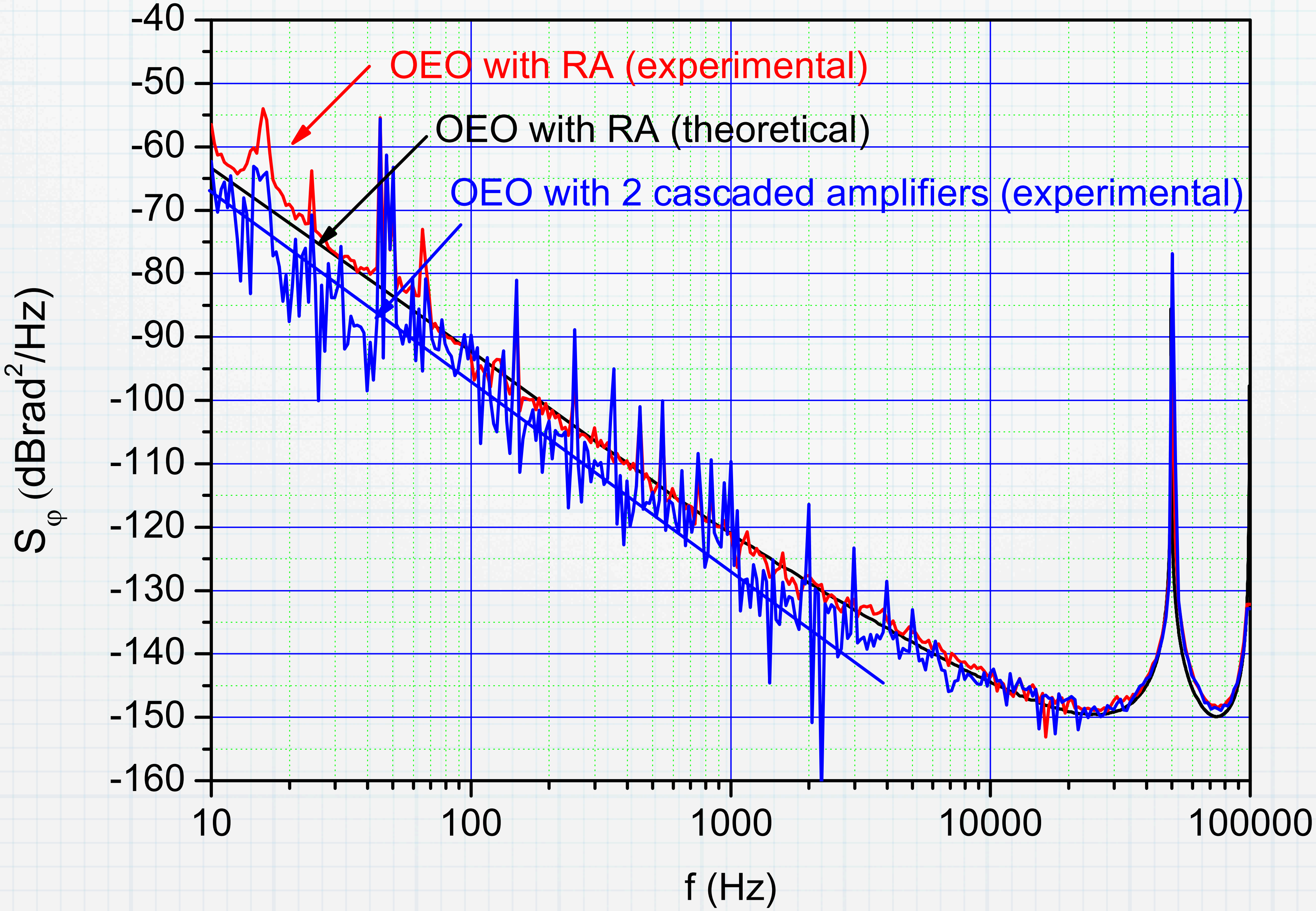
Specification of low phase-noise amplifiers (AML web page)

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			

Phase noise of a regenerative amplifier

R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitt. IEEE Transact. MTT

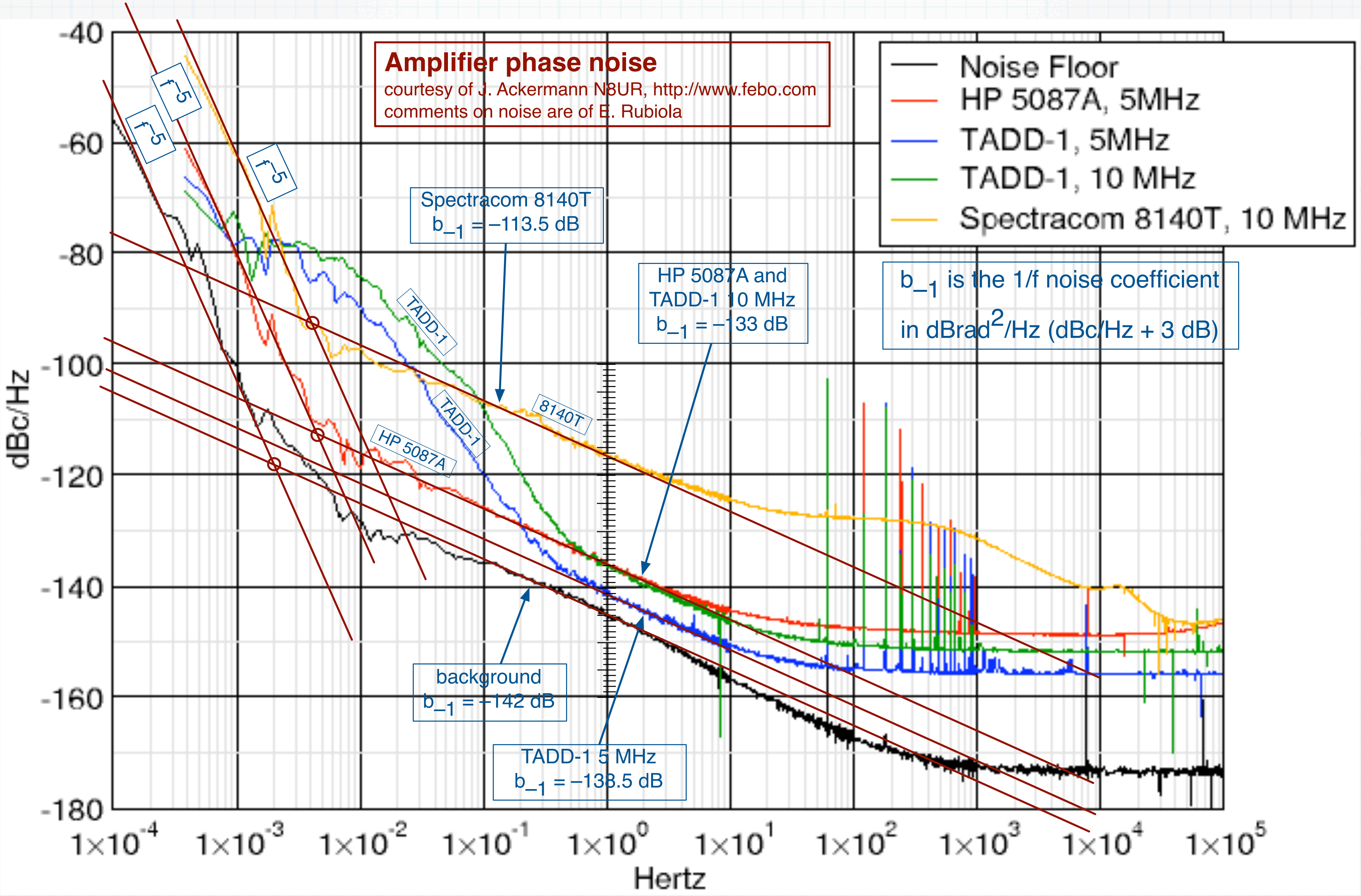
Indirect measurement: The RA replaces the two-stage sustaining amplifier in a Opto-Electronic oscillator



- **A RA is set for the gain of two cascaded amplifiers**
- **As expected, the RA flicker is 3 dB higher than the two amplifiers**
- **Indirect measurement through the frequency flicker**

Environmental effects in RF amplifiers

E. Rubiola, *Phase Noise and Frequency Stability in Oscillators*, Cambridge 2008, ISBN 978-0521-88677-2

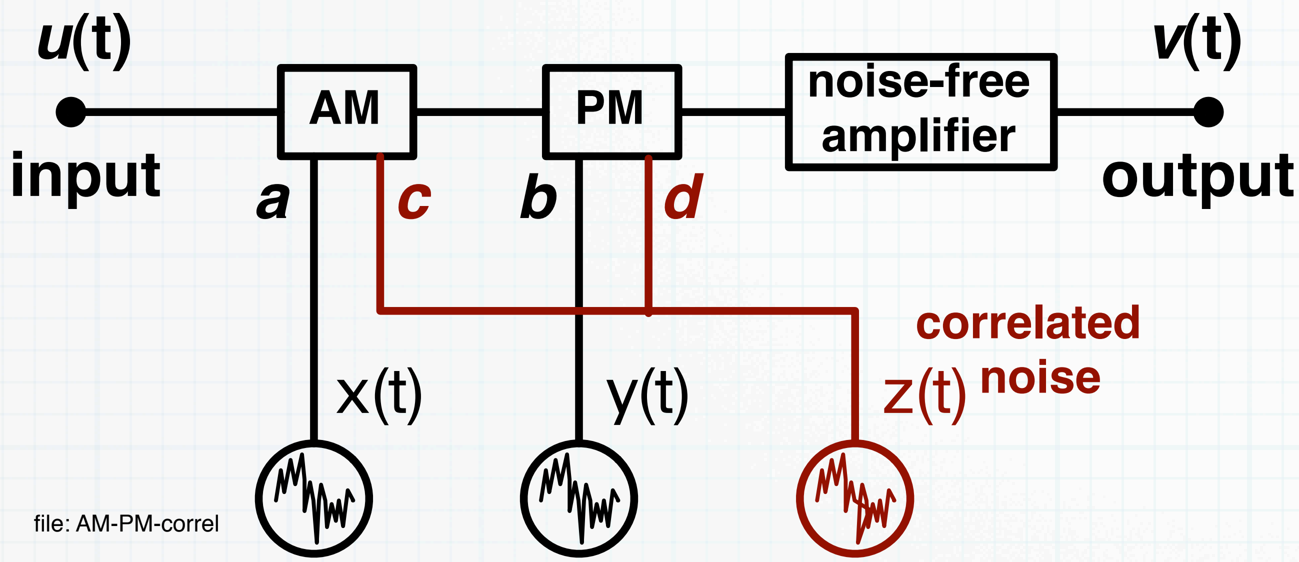


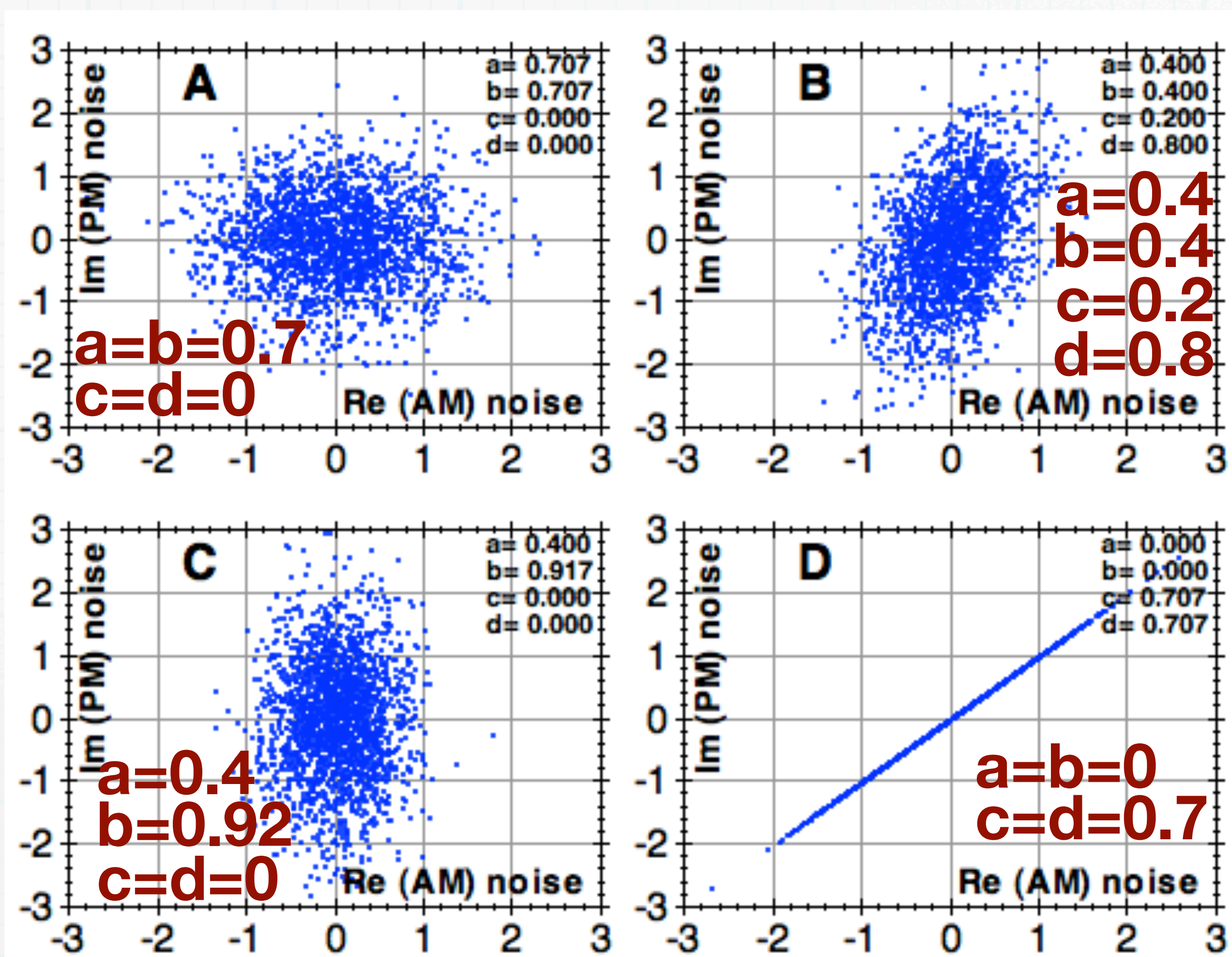
It is experimentally observed that the temperature fluctuations cause a spectrum $S_\alpha(f)$ or $S_\varphi(f)$ of the $1/f^5$ type

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

Correlation between AM and PM noise

R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitt. IEEE Transact. MTT





$$a^2 + b^2 + c^2 + d^2 = 1$$

The need for this model comes from the physics of popular amplifiers

- Bipolar transistor. The fluctuation of the carriers in the base region acts on the base thickness, thus on the gain, and on the capacitance of the reverse-biased base-collector junction.
- Field-effect transistor. The fluctuation of the carriers in the channel acts on the drain-source current, and also on the gate-channel capacitance because the distance between the `electrodes' is affected by the channel thickness.
- Laser amplifier. The fluctuation of the pump power acts on the density of the excited atoms, and in turn on gain, on maximum power, and on refraction index.

AM and PM fluctuations are correlated because originate from the same near-dc random process

Conclusions

- The model predicts the noise of the amplifier and of networks
- First noise model of the regenerative (positive-feedback) amplifier
- Experimental data validate the model
- Correlation between AM noise and PM noise (needs further work)

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R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitt. IEEE Transact. MTT

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