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UNIVERSITÉ DE FRANCHE-COMTÉ

Phase noise metrology

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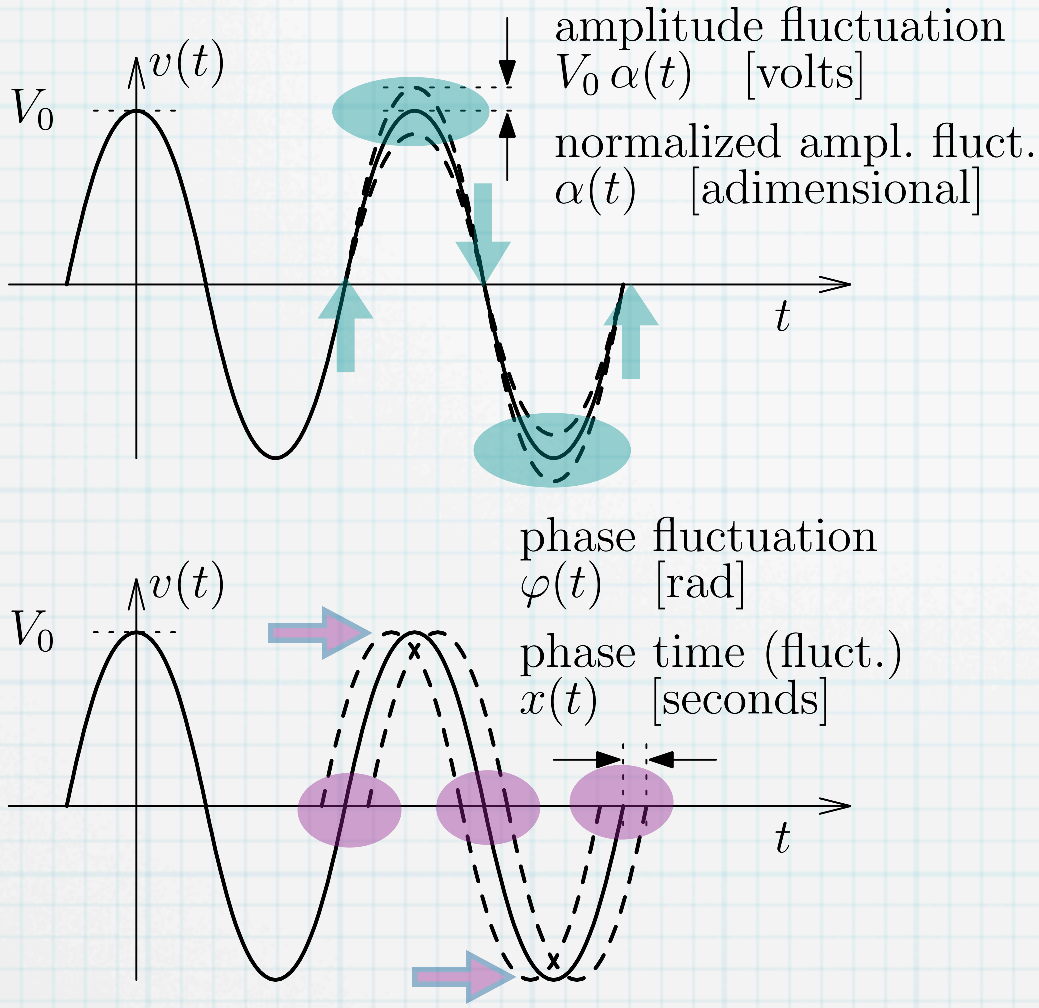
* Phase noise & friends
* Double-balanced mixer
* Bridge techniques
* Advanced techniques
* AM noise
* Systems

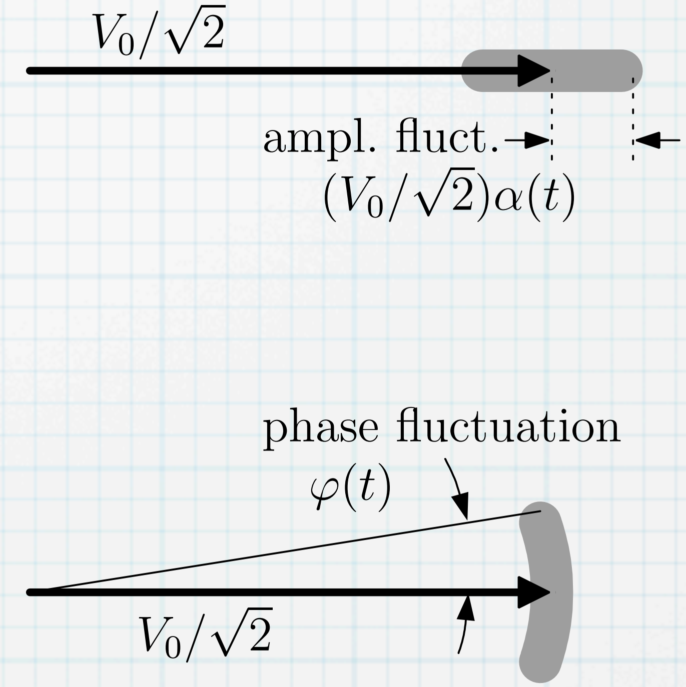
home page http://rubiola.org

Clock signal affected by noise

Time Domain



Phasor Representation



polar coordinates $\quad v(t) = V_0\,[1+\alpha(t)]\cos\,[\omega_0 t + \varphi(t)]$

Cartesian coordinates $\quad v(t) = V_0 \cos \omega_0 t + n_c(t)\cos\omega_0 t - n_s(t)\sin\omega_0 t$

under low noise approximation

$$|n_c(t)| \ll V_0 \quad \text{and} \quad |n_s(t)| \ll V_0$$

It holds that

$$\alpha(t) = \frac{n_c(t)}{V_0} \quad \text{and} \quad \varphi(t) = \frac{n_s(t)}{V_0}$$

Phase noise & friends

random phase fluctuation

$$S_\varphi(f) = \text{PSD of } \varphi(t)$$

power spectral density

it is measured as

$$S_\varphi(f) = \mathbb{E}\left\{\Phi(f)\Phi^*(f)\right\}$$

$$S_\varphi(f) \approx \langle \Phi(f)\Phi^*(f)\rangle_m$$

$$\mathcal{L}(f) = \frac{1}{2} S_\varphi(f) \quad \text{dBc}$$

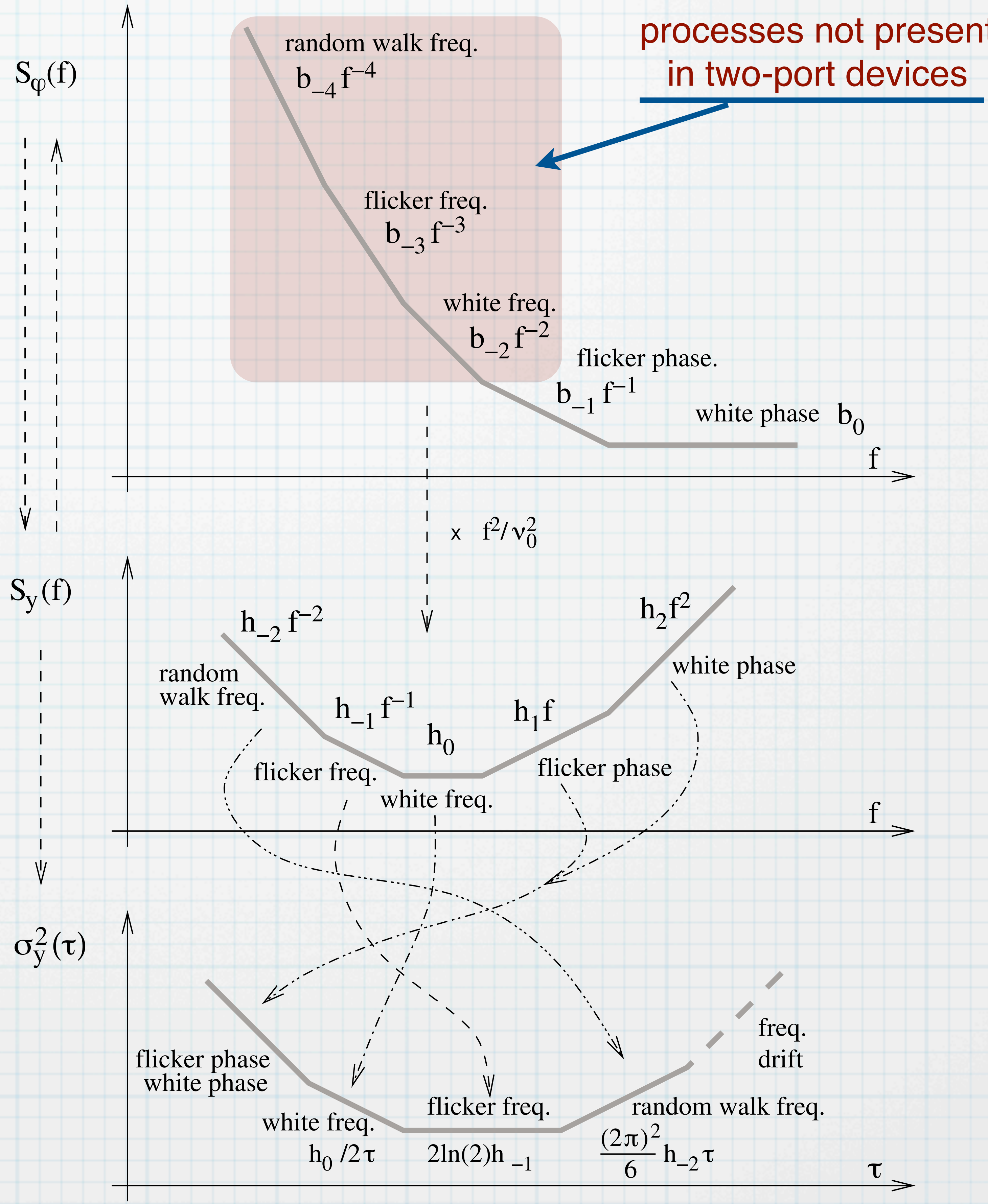
random fractional-frequency fluctuation

$$y(t) = \frac{\dot\varphi(t)}{2\pi\nu_0} \quad \Rightarrow \quad S_y = \frac{f^2}{\nu_0^2} S_\varphi(f)$$

Allan variance
(two-sample wavelet-like variance)

$$\sigma_y^2(\tau) = \mathbb{E}\left\{\frac{1}{2}\left[\overline{y}_{k+1} - \overline{y}_k\right]^2\right\} .$$

approaches a half-octave bandpass filter (for white),
hence it converges for processes steeper than 1/f



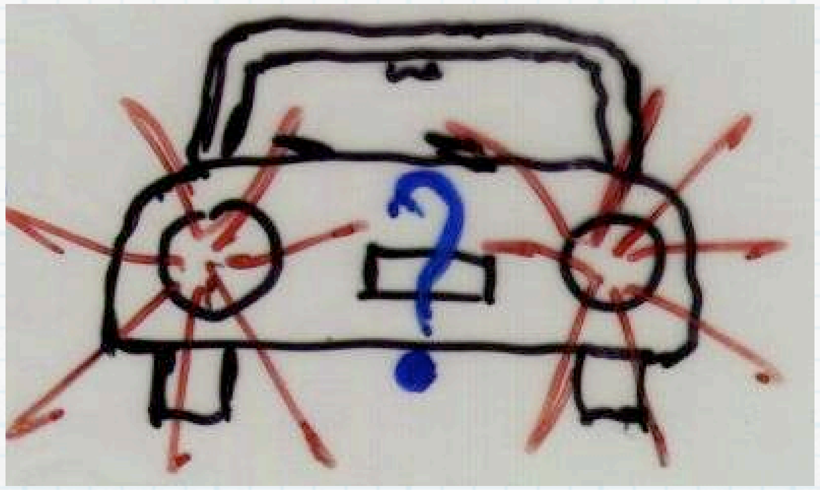
E. Rubiola, *The Leeson Effect* Chap.1, arXiv:physics/0502143

Relationships between spectra and variances

noise type	$S_\varphi(f)$	$S_y(f)$	$S_\varphi \leftrightarrow S_y$	$\sigma_y^2(\tau)$	mod $\sigma_y^2(\tau)$
white PM	b_0	$h_2 f^2$	$h_2 = \dfrac{b_0}{\nu_0^2}$	$\dfrac{3 f_H h_2}{(2\pi)^2}\tau^{-2}$ $2\pi\tau f_H \gg 1$	$\dfrac{3 f_H \tau_0 h_2}{(2\pi)^2}\,\tau^{-3}$
flicker PM	$b_{-1} f^{-1}$	$h_1 f$	$h_1 = \dfrac{b_{-1}}{\nu_0^2}$	$[1.038 + 3\ln(2\pi f_H \tau)]\,\dfrac{h_1}{(2\pi)^2}\,\tau^{-2}$	$0.084\, h_1 \tau^{-2}$ $n \gg 1$
white FM	$b_{-2} f^{-2}$	h_0	$h_0 = \dfrac{b_{-2}}{\nu_0^2}$	$\dfrac{1}{2} h_0\, \tau^{-1}$	$\dfrac{1}{4} h_0\, \tau^{-1}$
flicker FM	$b_{-3} f^{-3}$	$h_{-1} f^{-1}$	$h_{-1} = \dfrac{b_{-3}}{\nu_0^2}$	$2\ln(2)\; h_{-1}$	$\dfrac{27}{20}\ln(2)\; h_{-1}$
random walk FM	$b_{-4} f^{-4}$	$h_{-2} f^{-2}$	$h_{-2} = \dfrac{b_{-4}}{\nu_0^2}$	$\dfrac{(2\pi)^2}{6} h_{-2}\tau$	$0.824\,\dfrac{(2\pi)^2}{6} h_{-2}\,\tau$
linear frequency drift $\dot{y}$				$\dfrac{1}{2}\,(\dot{y})^2\,\tau^2$	$\dfrac{1}{2}\,(\dot{y})^2\,\tau^2$

f_H is the high cutoff frequency, needed for the noise power to be finite.

Basic problem: how can we measure a low random signal (noise sidebands) close to a strong dazzling carrier?



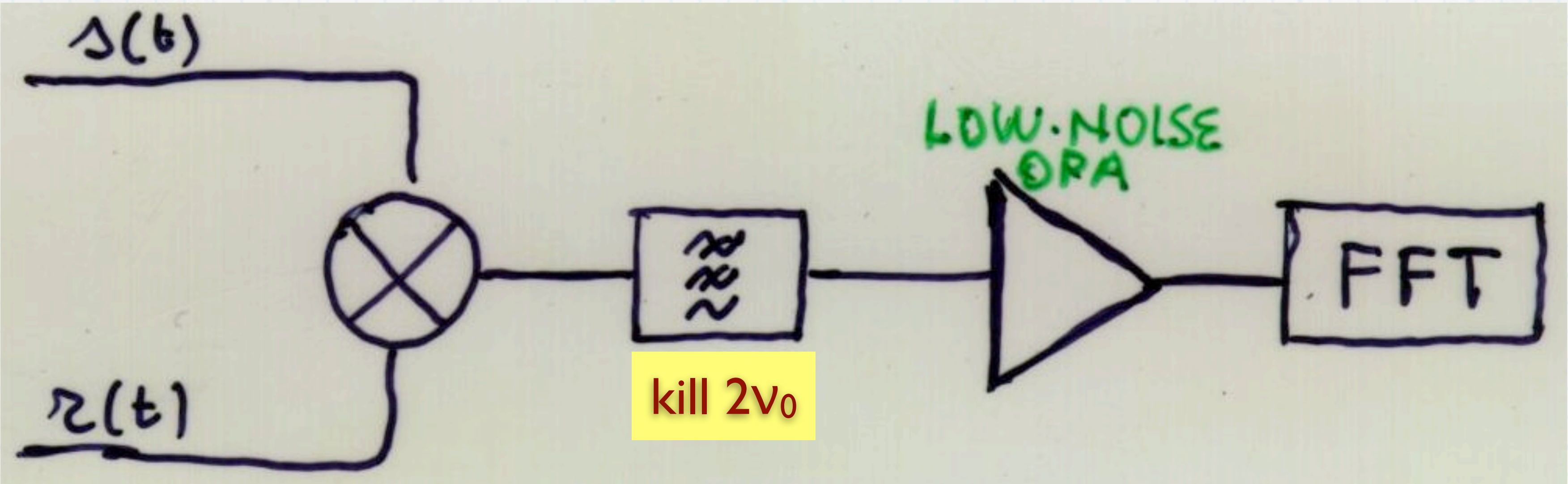
solution(s): suppress the carrier and measure the noise

convolution (low-pass)	$s(t) * h_{lp}(t)$	distorsiometer, audio-frequency instruments
time-domain product	$s(t) \times r(t - T/4)$	traditional instruments for phase-noise measurement (saturated mixer)
vector difference	$s(t) - r(t)$	bridge (interferometric) instruments

Double-balanced mixer

Saturated double-balanced mixer

phase-to-voltage detector $v_o(t) = k_\phi\, \phi(t)$



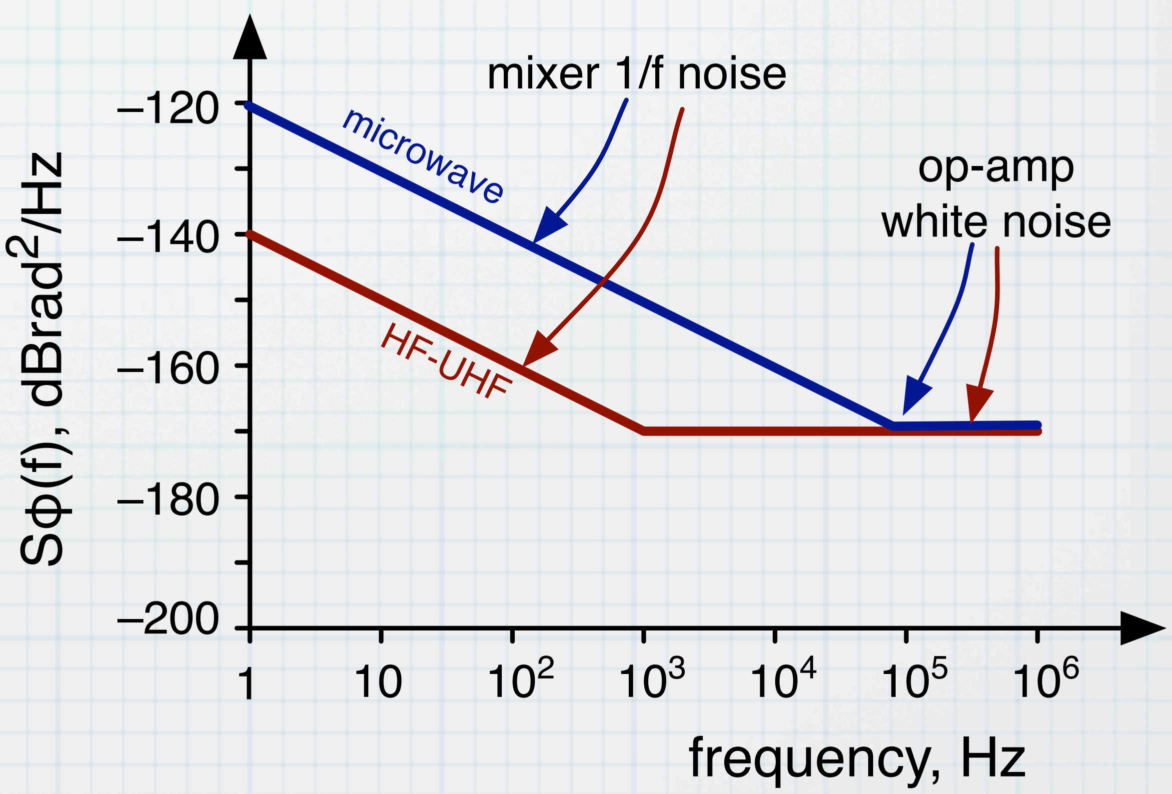
1 – Power
- narrow power range:
- ±5 dB around P_{nom} = 8–12 dBm
- r(t) and s(t) should have ~ same P

2 – Flicker noise
- due to the mixer internal diodes
- typical S_φ = –140 dBrad²/Hz at 1 Hz
- in average-good conditions

3 – Low gain
- k_φ ~ –10 to –14 dBV/rad typ. (0.2-0.3 V/rad)

4 – White noise
- due to the operational amplifier

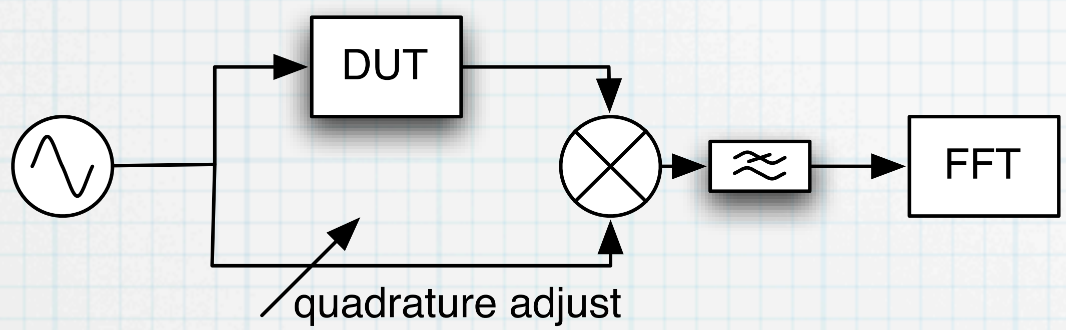
mixer background noise



E. Rubiola, *Tutorial on the double-balanced mixer*, arXiv/physics/0608211,

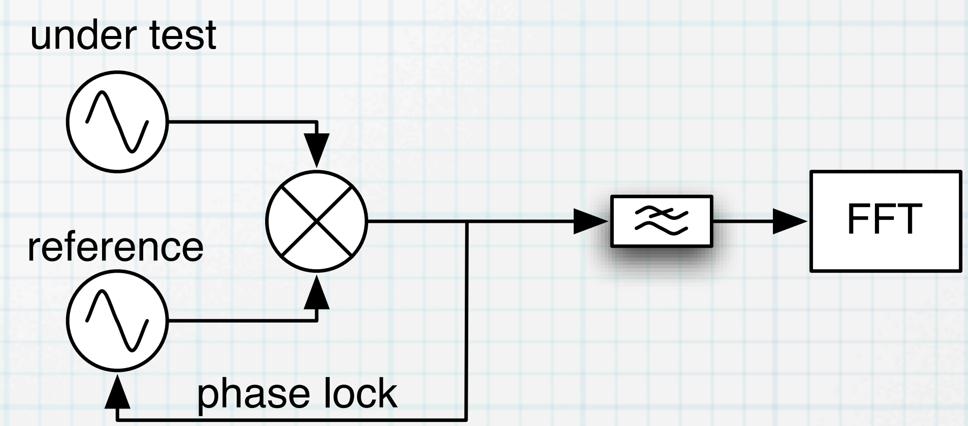
Mixer-based schemes

two-port device under test



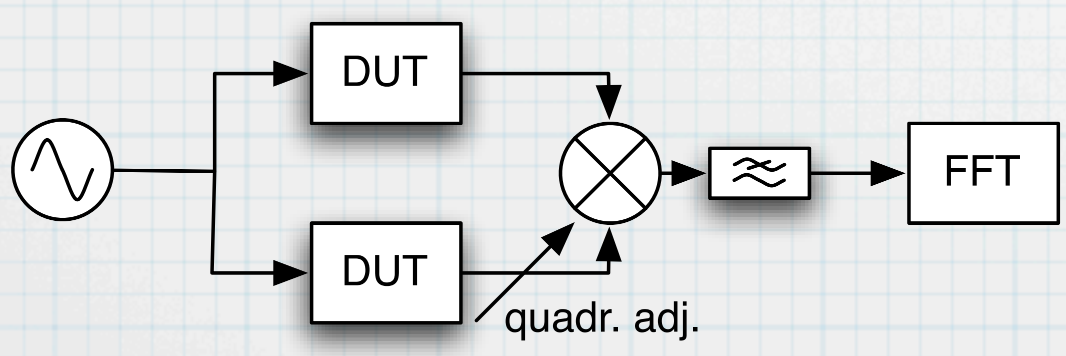
measure two oscillators

best use a tight loop

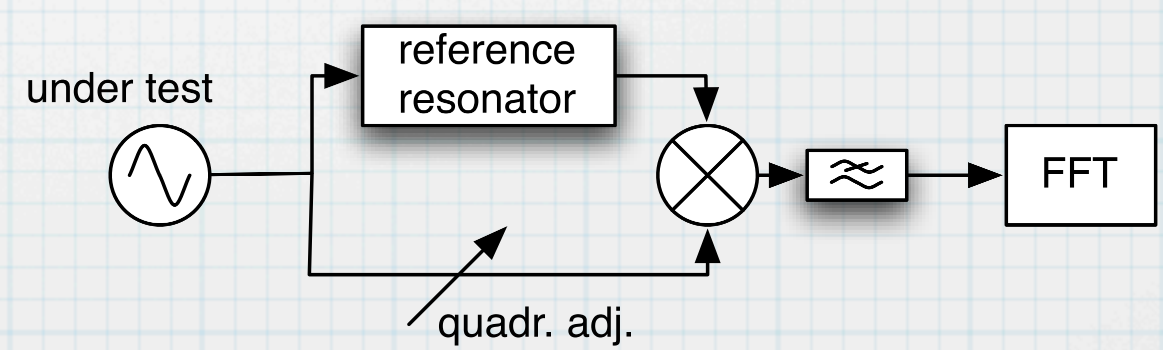


two two-port devices under test

3 dB improved sensitivity

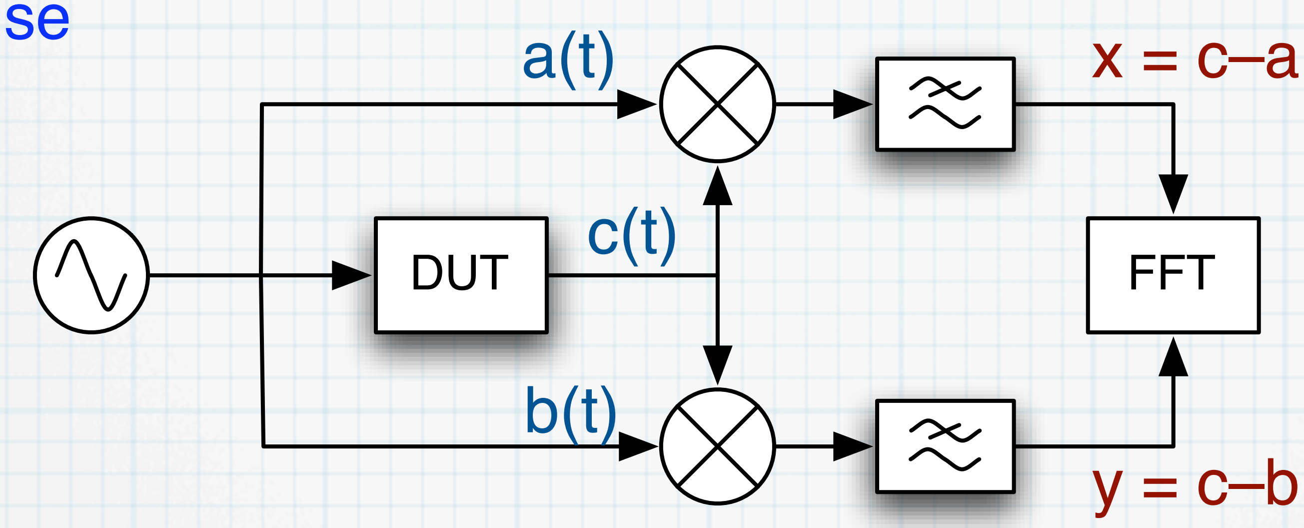


measure an oscillator vs. a resonator



Correlation measurements

a(t), b(t) –> mixer noise
c(t) –> DUT noise



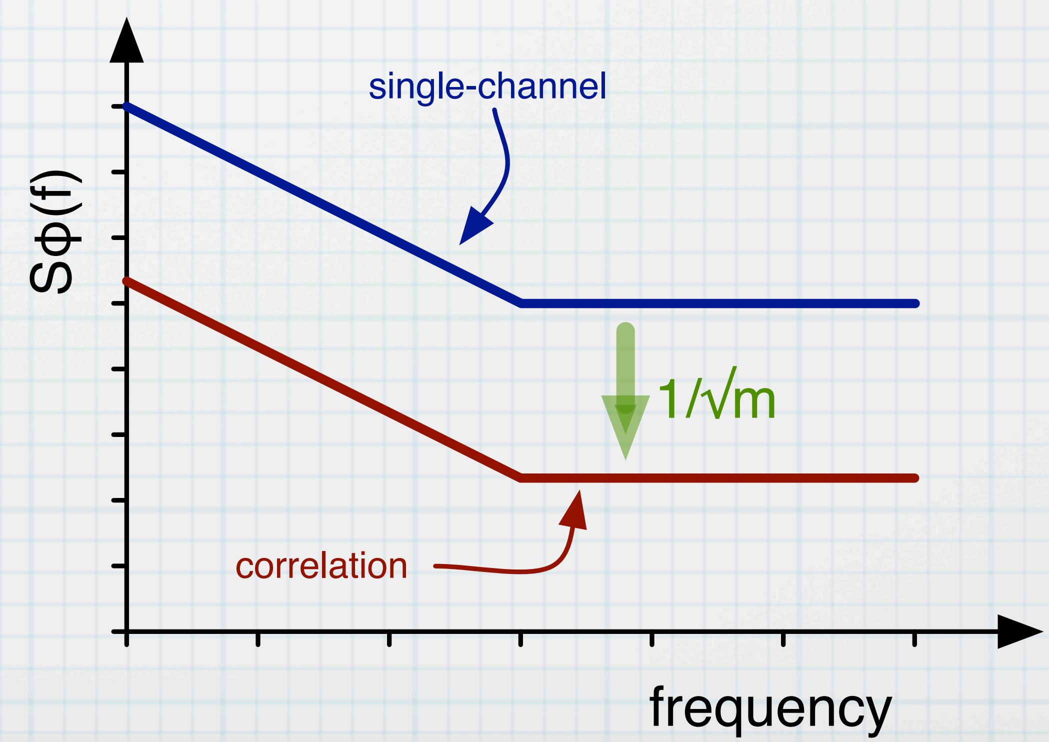
basics of correlation

$$
\begin{aligned}
S_{yx}(f) &= \mathbb{E}\left\{Y(f)X^*(f)\right\} \\
&= \mathbb{E}\left\{(C-A)(C-B)^*\right\} \\
&= \mathbb{E}\left\{CC^* - \underbrace{AC^*}_{0} - \underbrace{CB^*}_{0} + \underbrace{AB^*}_{0}\right\} \\
&= \mathbb{E}\left\{CC^*\right\}
\end{aligned}
$$

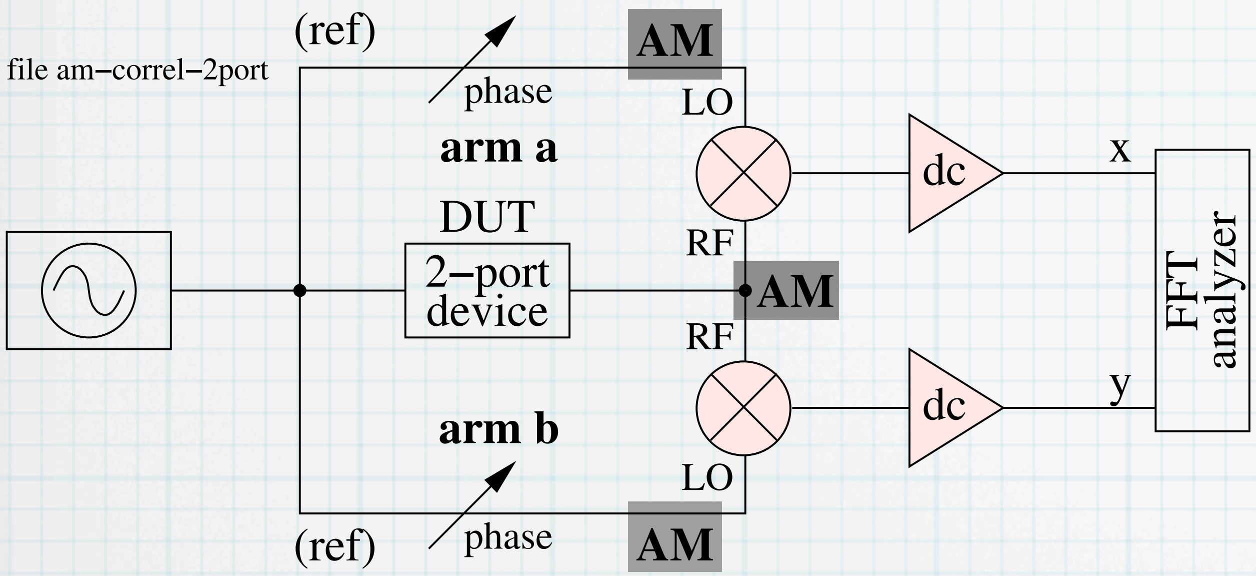
$$S_{yx}(f) = S_{cc}(f)$$

in practice, average on m realizations

$$
\begin{aligned}
S_{yx}(f) &= \left\langle Y(f)X^*(f)\right\rangle_m \\
&= \left\langle CC^* \underbrace{- AC^* - CB^* + AB^*}_{\to\, 0 \text{ as } 1/\sqrt{m}}\right\rangle_m \\
&= \left\langle CC^*\right\rangle_m + O(1/m)
\end{aligned}
$$



Pollution from AM noise

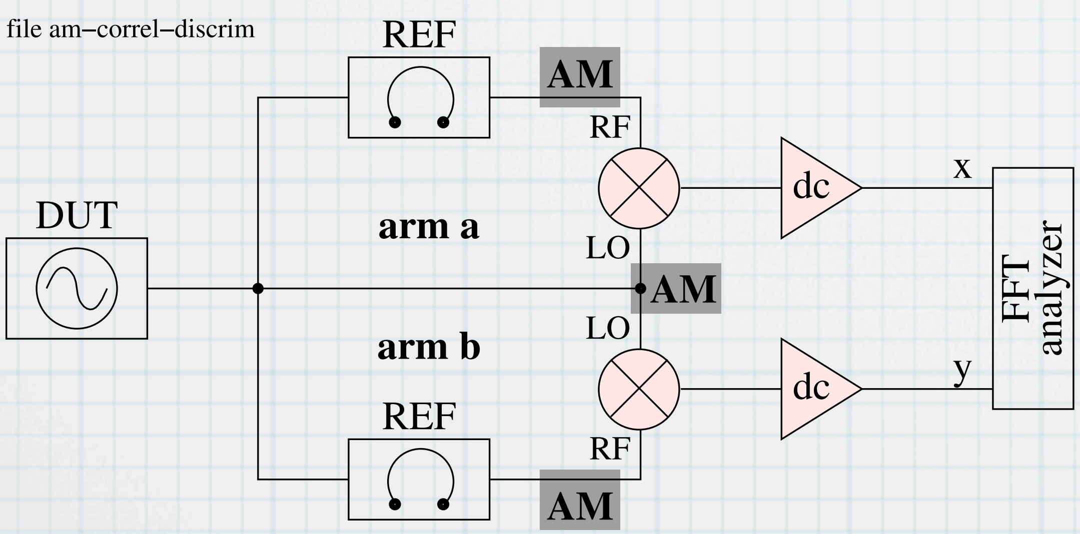


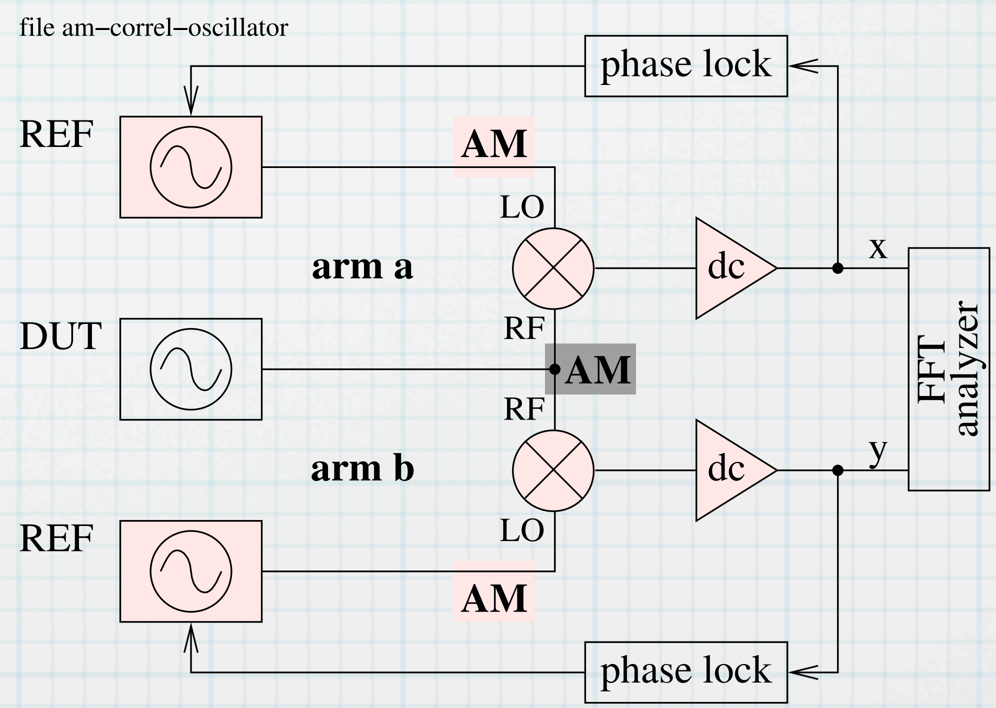
The mixer converts power into dc-offset, thus AM noise into dc-noise, which is mistaken for PM noise

$$v(t) = k_\phi \, \phi(t) + k_{LO} \, \alpha_{LO} + k_{RF} \, \alpha_{RF}$$

rejected by correlation and avg

not rejected by correlation and avg

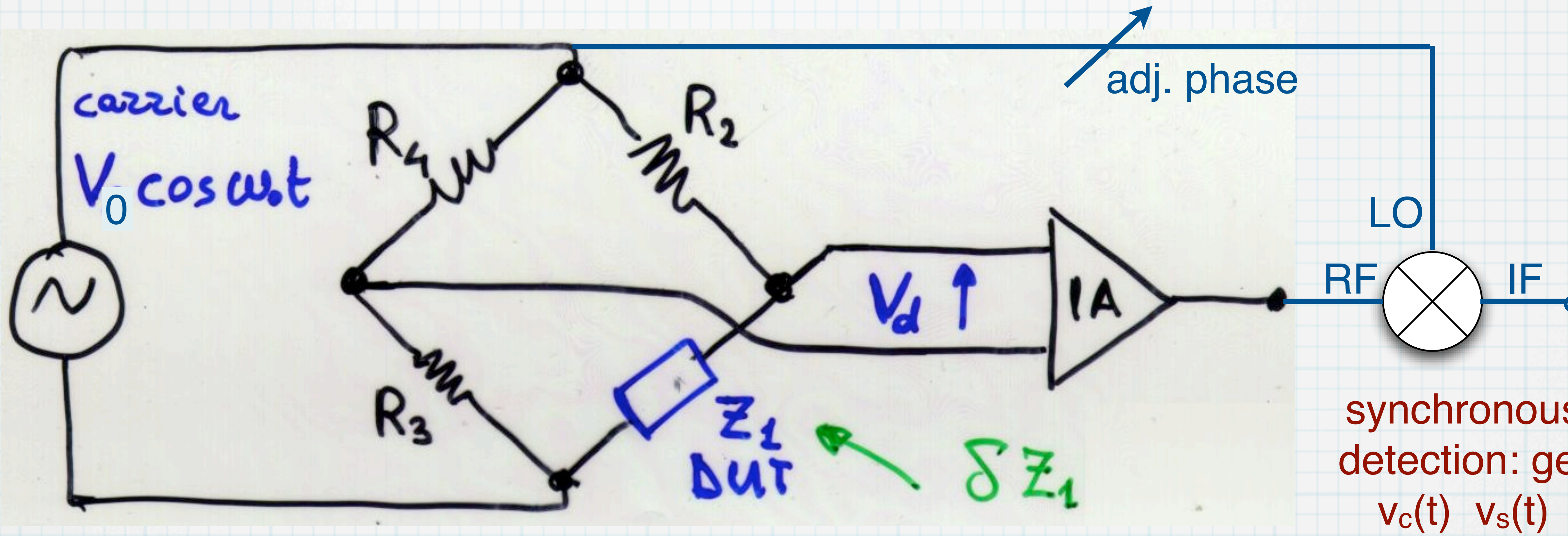




E. Rubiola, R. Boudot, *The effect of AM noise on correlation phase noise measurements*, arXiv/physics/0609147

Bridge techniques

Wheatstone bridge



synchronous detection: get $v_c(t)$ $v_s(t)$ (AM or PM noise)

equilibrium: $V_d = 0$ –> carrier suppression

static error δZ_1 –> some residual carrier

real δZ_1 => in-phase residual carrier $V_{re} \cos(\omega_0 t)$

imaginary δZ_1 => quadrature residual carrier $V_{im} \sin(\omega_0 t)$

fluctuating error δZ_1 => noise sidebands

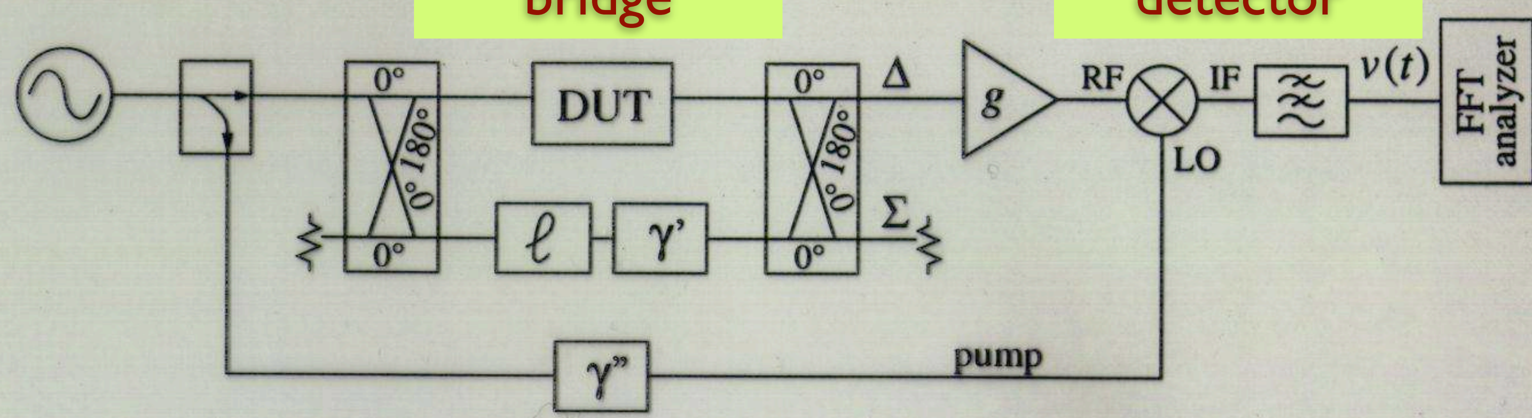
real δZ_1 => AM noise $v_c(t) \cos(\omega_0 t)$

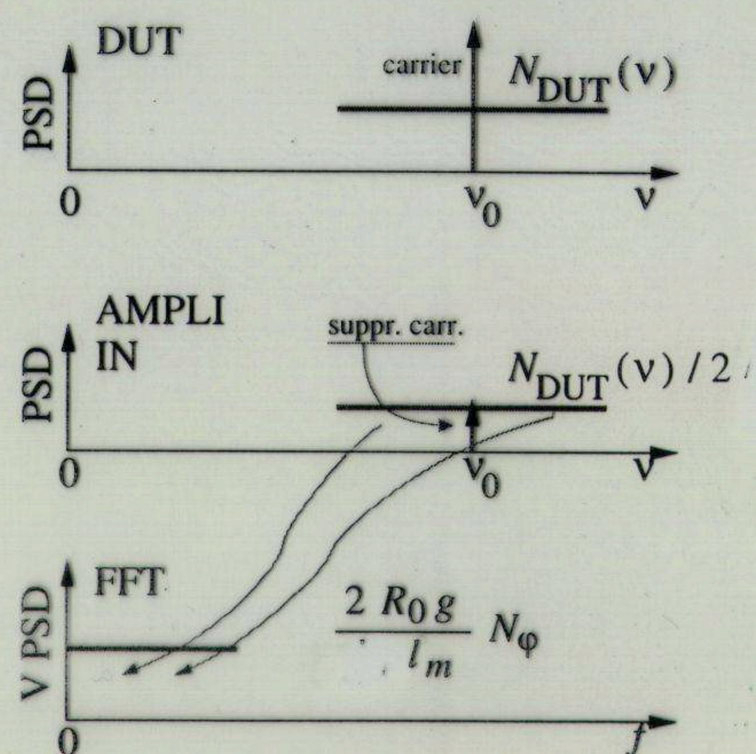
imaginary δZ_1 => PM noise $-v_s(t) \sin(\omega_0 t)$

Bridge (interferometric) PM and AM noise measurement

bridge

detector





High carrier suppression:

no carrier ⇒ the amplifier can't flicker

High gain:

$$k_\varphi = \frac{v(t)}{\varphi(t)} = \sqrt{\frac{R_0 g P_0}{l_m}} - \textit{dissip. losses}$$

Low Noise Floor:

$$S_{\varphi 0} = \frac{2Fk_B T_0}{P_0} + \textit{dissip. losses}$$

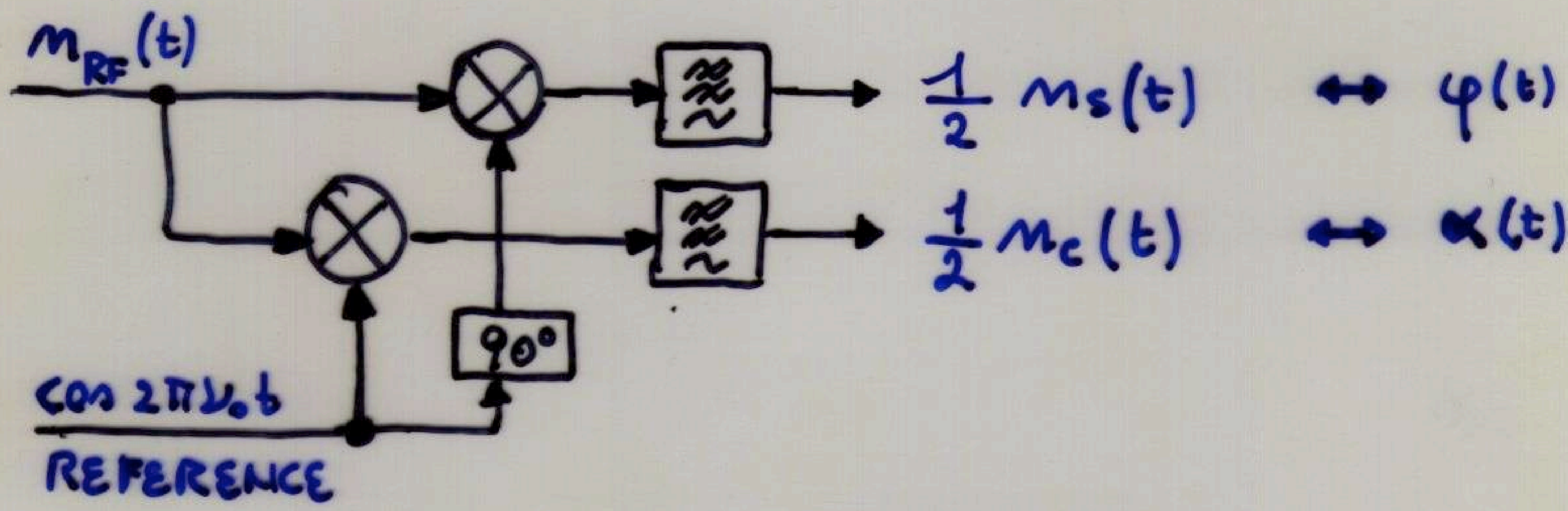
High immunity to 50 Hz B fields

Improved, from RSI **70** 1 pp. 220-225, Jan 1999

and rejection of the master-oscillator noise

yet, difficult for the measurement of oscillators

Synchronous detection



REMEMBER:

$$\cos^2 \omega t = \frac{1}{2}(1+\cos 2\omega t)$$

$$\sin^2 \omega t = \frac{1}{2}(1-\cos 2\omega t)$$

$$\sin \omega t \cos \omega t = \frac{1}{2} \sin 2\omega t$$

Advanced bridge techniques

Mechanical stability

any flicker spectrum $S(f) = h_{-1}/f$ can be transformed

into the Allan variance $\sigma^2 = 2\ln(2)\, h_{-1}$

(roughly speaking, the integral over one octave)

a phase fluctuation is equivalent to a length fluctuation

$$L = \frac{\varphi}{2\pi}\lambda = \frac{\varphi}{2\pi}\,\frac{c}{\nu_0} \qquad S_L(f) = \frac{1}{4\pi^2}\,\frac{c^2}{\nu_0^2}\,S_\varphi(f)$$

-180 dBrad^2/Hz at $f = 1$ Hz and $\nu_0 = 9.2$ GHz ($c = 0.8\,c_0$) is equivalent to

$S_L = 1.73{\times}10^{-23}$ m^2/Hz $\qquad$ ($\sqrt{S_L} = 4.16{\times}10^{-12}$ m/$\sqrt{\mathrm{H}z}$)

a residual flicker of -180 dBrad^2/Hz at $f = 1$ Hz off the $\nu_0 = 9.2$ GHz carrier

($h_{-1} = 1.73{\times}10^{-23}$) is equivalent to a mechanical stability

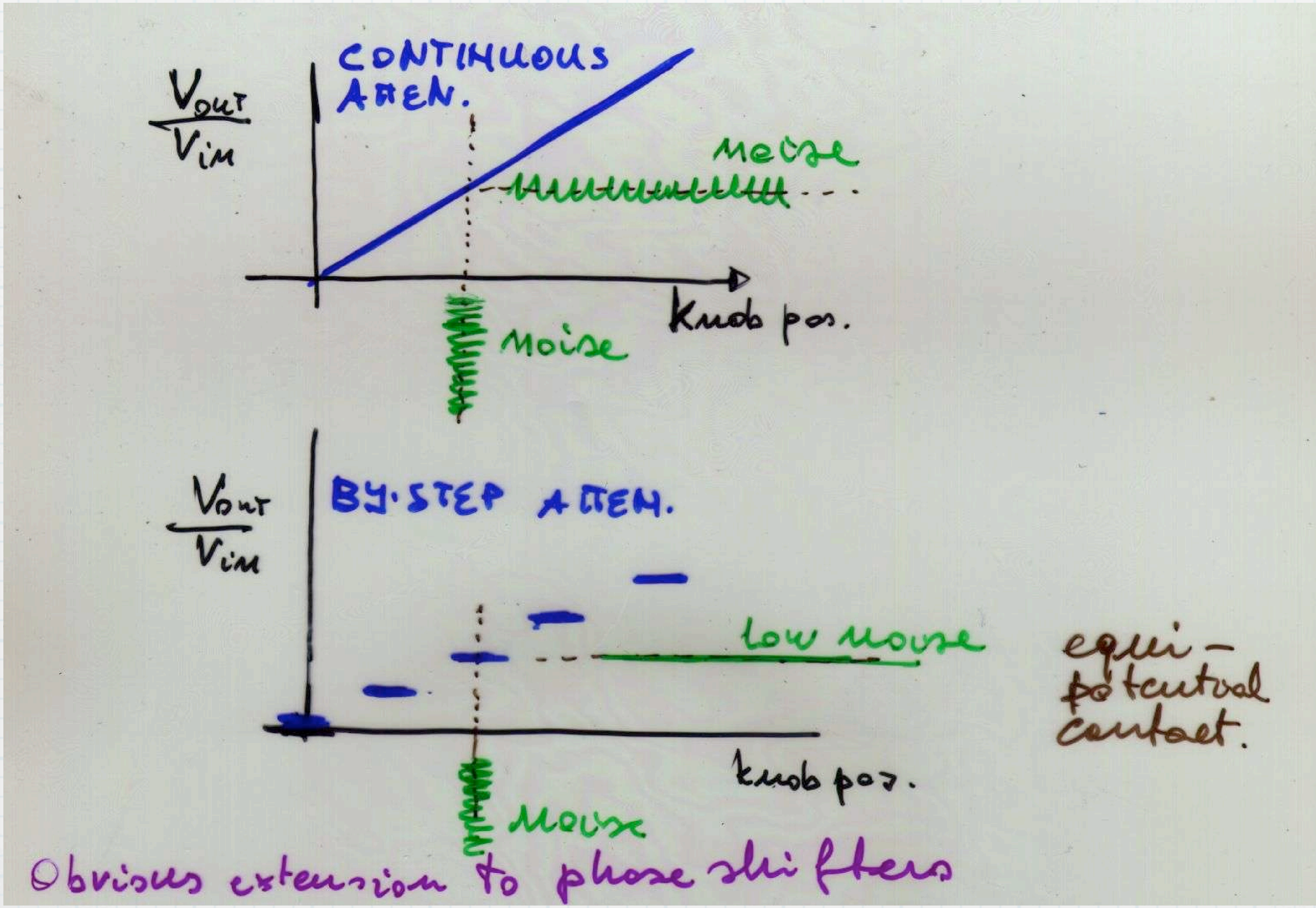
$$\sigma_L = \sqrt{1.38 \times 1.73{\times}10^{-23}} = 4.9{\times}10^{-12} \quad \mathrm{m}$$

 # don't think "that's only engineering" !!!

I learned a lot from non-optical microscopy

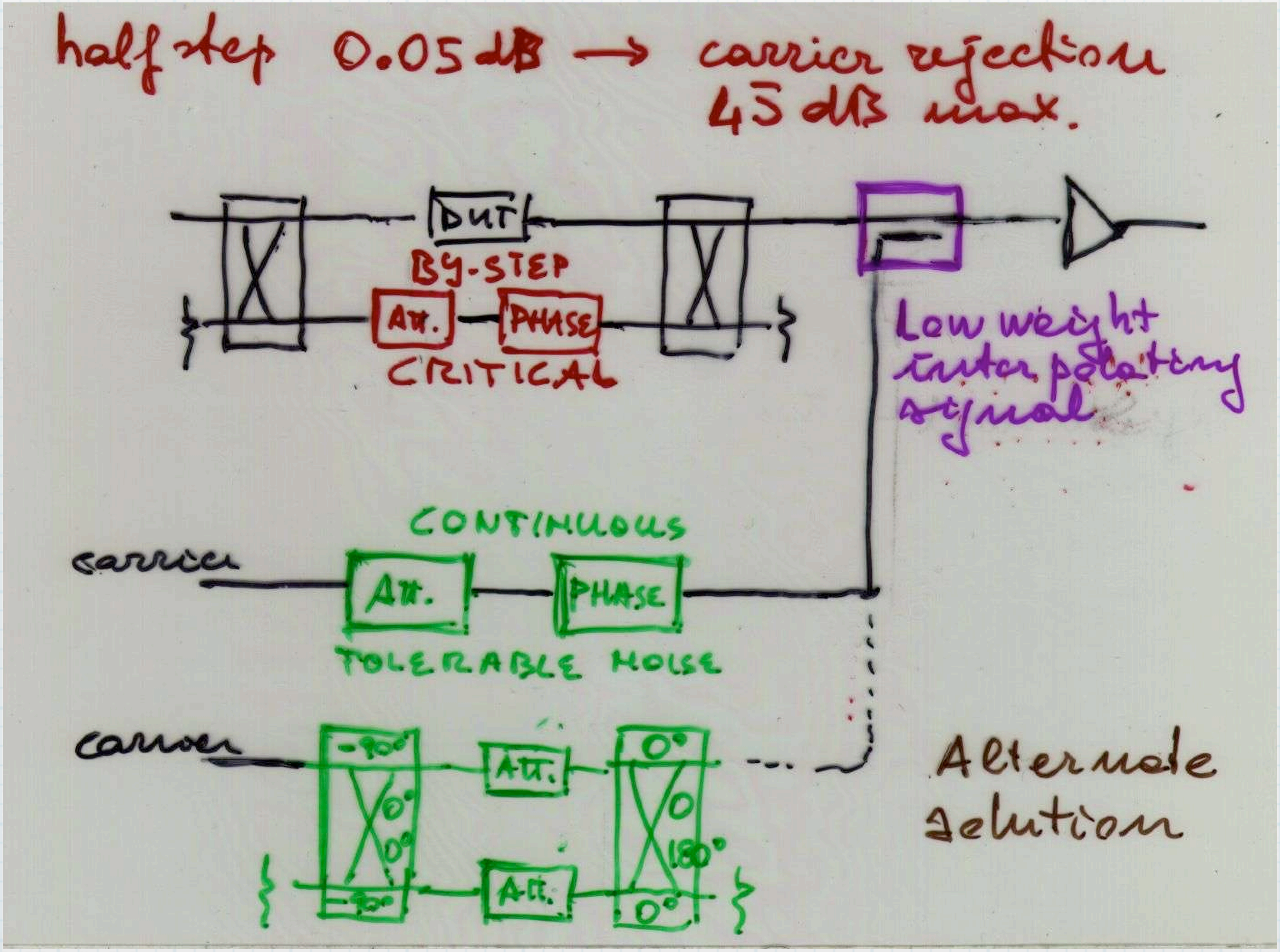
bulk solid matter is that stable

Origin of flicker in the bridge

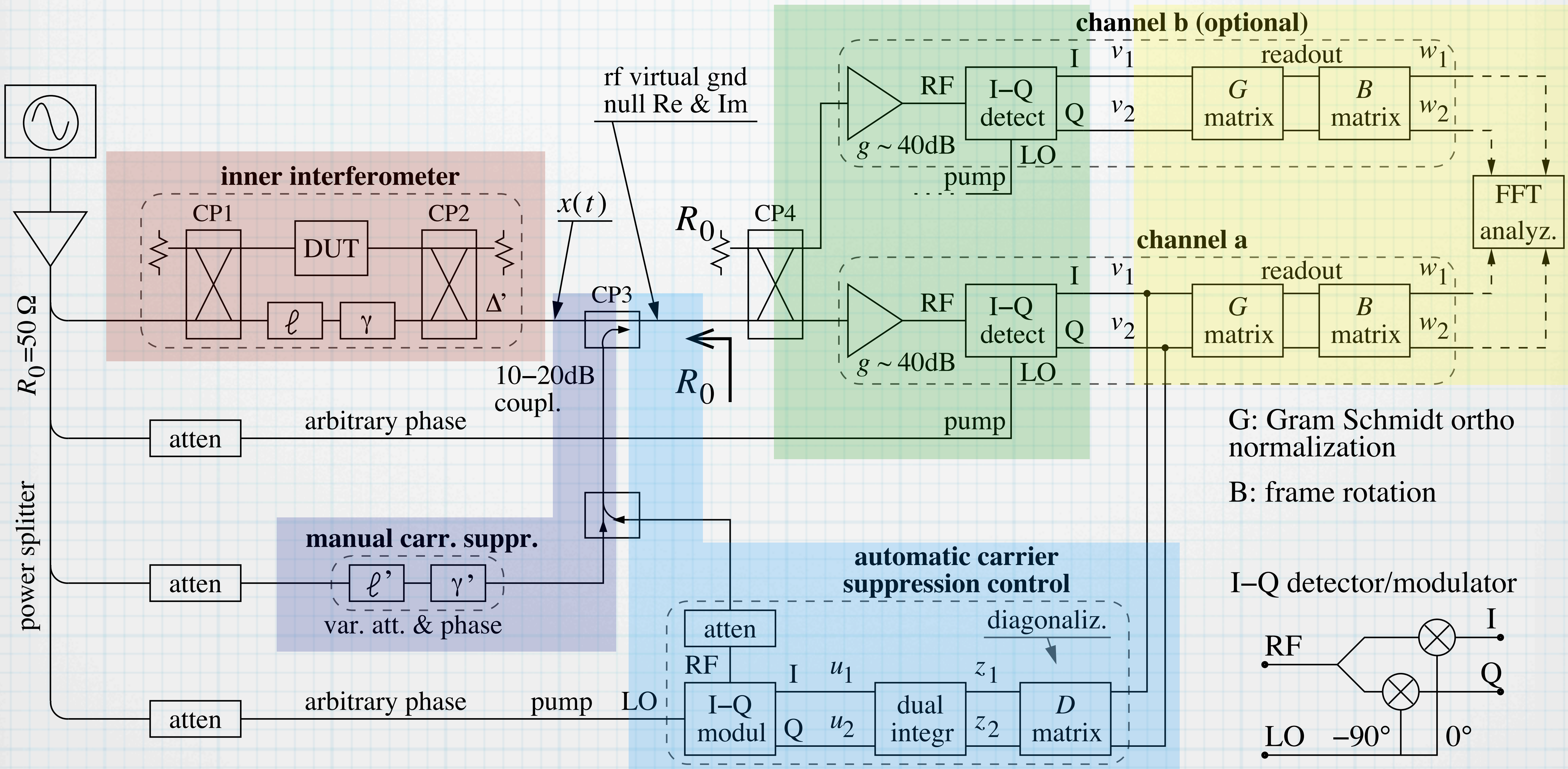


In the early time of electronics, flicker was called “contact noise”

Coarse and fine adjustment of the bridge null are necessary

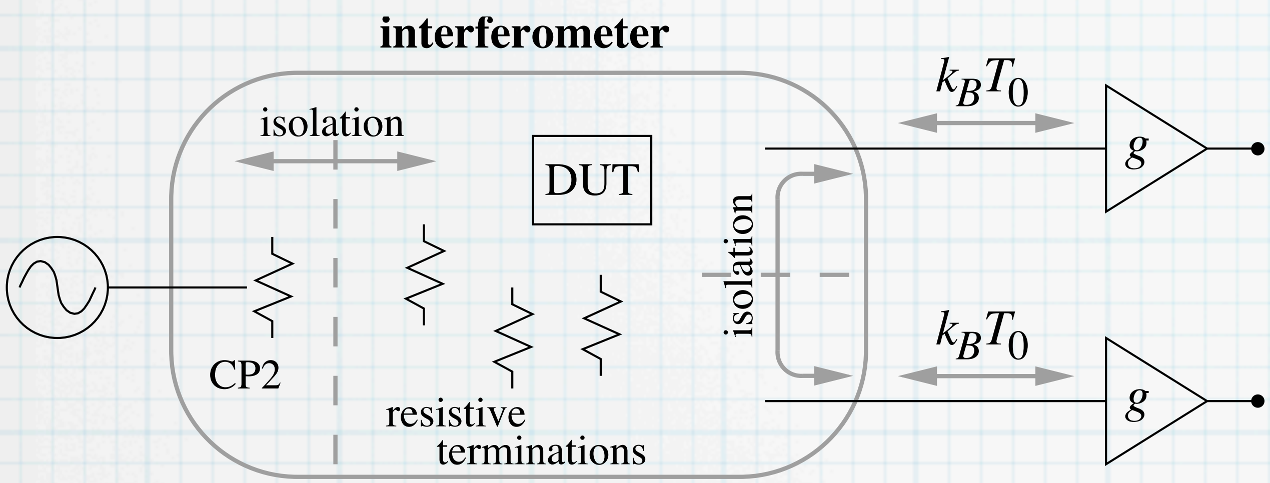


Flicker reduction, correlation, and closed-loop carrier suppression can be combined

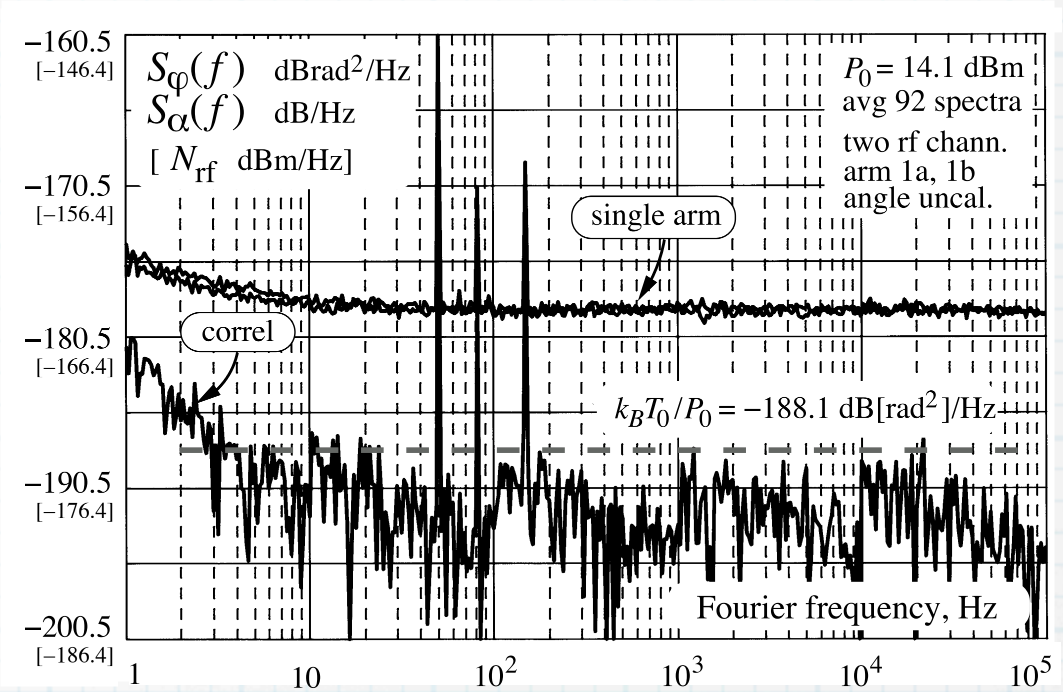


E. Rubiola, V. Giordano, Rev. Scientific Instruments 73(6) pp.2445-2457, June 2002

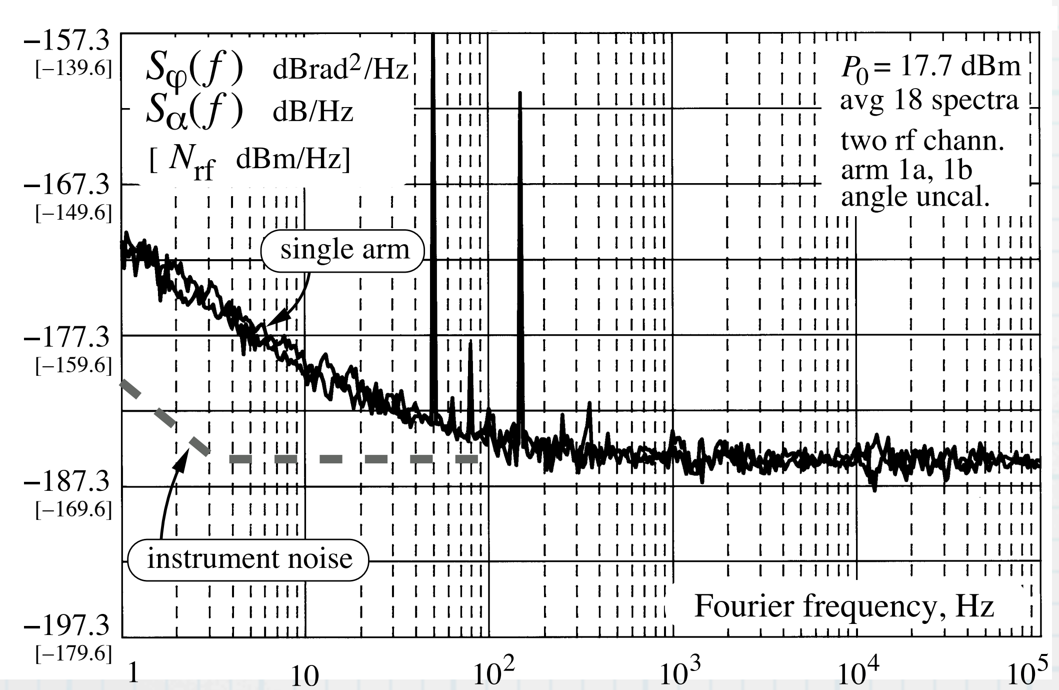
Example of results



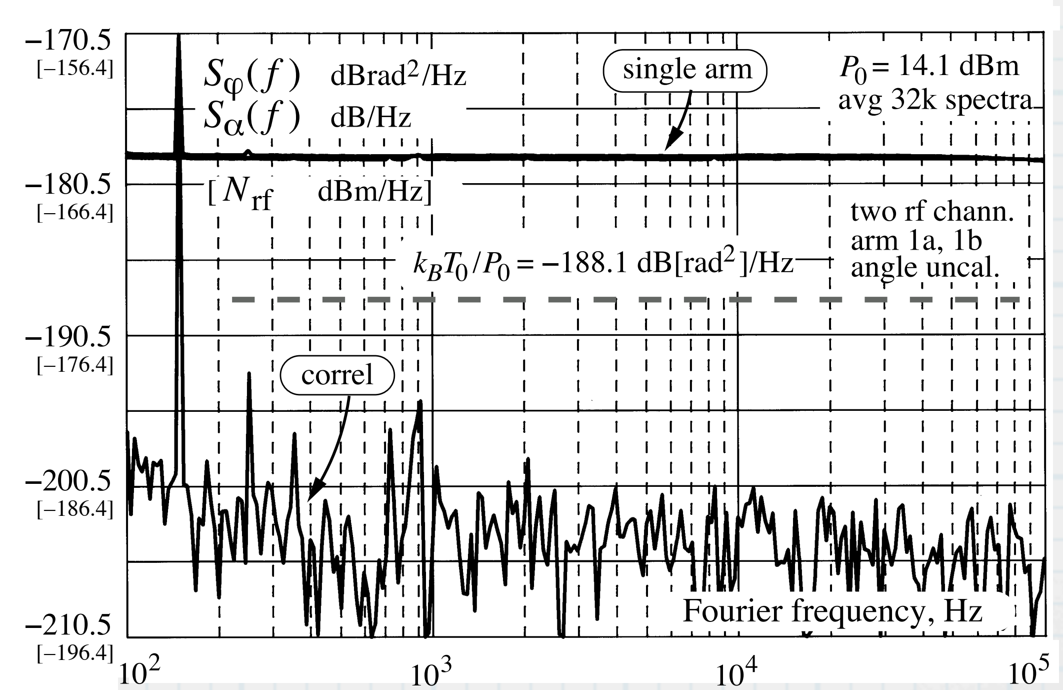
Correlation-and-averaging rejects the thermal noise



Residual noise of the fixed-value bridge, in the absence of the DUT



Noise of a pair of HH-109 hybrid couplers measured at 100 MHz



Residual noise of the fixed-value bridge. Same as above, but larger m

±45° detection

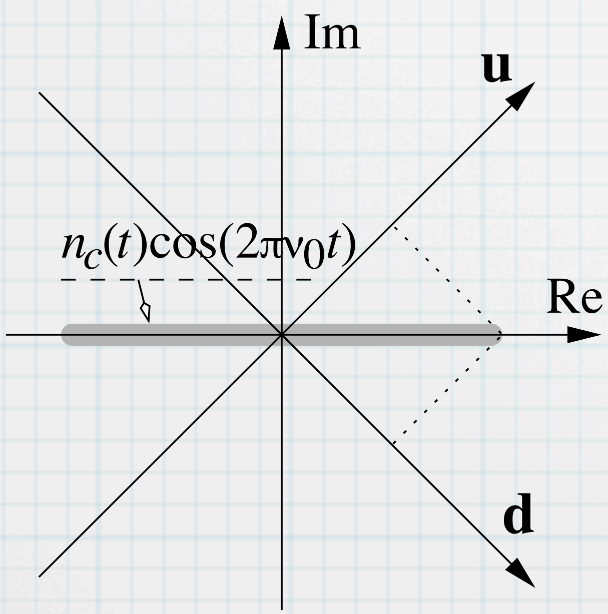
DUT noise without carrier $n_c(t)\cos\omega_0 t - n_s(t)\sin\omega_0 t$

UP reference $u(t) = V_P \cos(\omega_0 t - \pi/4)$

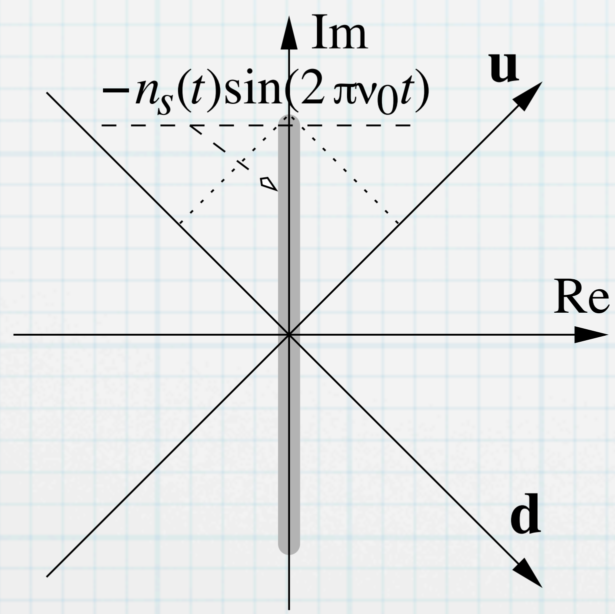
DOWN reference $d(t) = V_P \cos(\omega_0 t + \pi/4)$

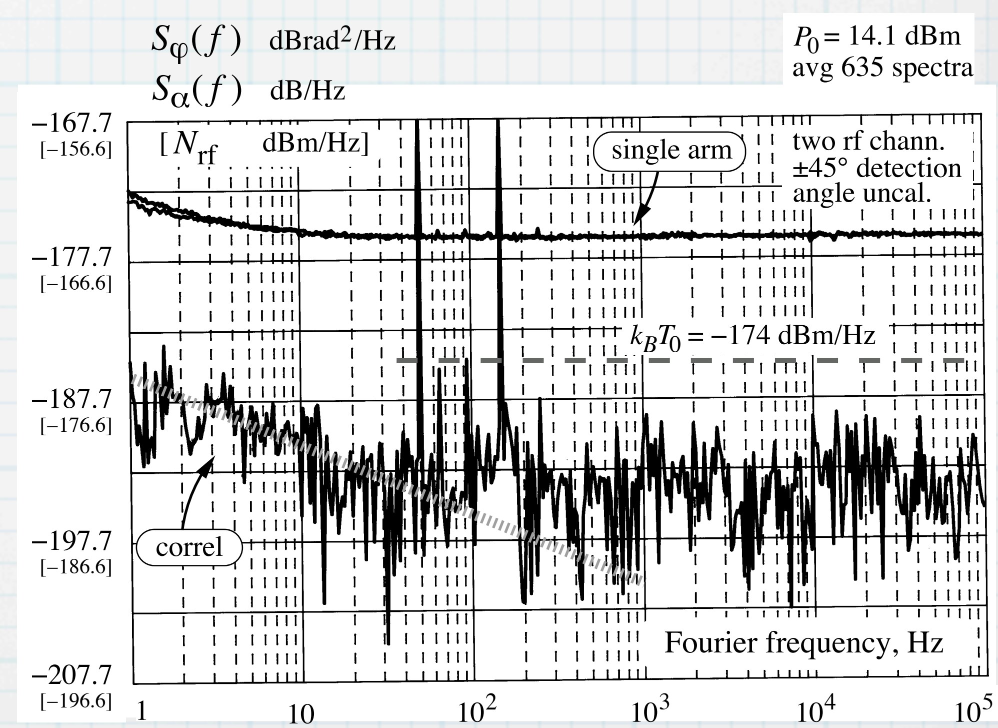
cross spectral density $S_{ud}(f) = \dfrac{1}{2}\left[S_\alpha(f) - S_\varphi(f)\right]$

in–phase noise detection



quadrature noise detection

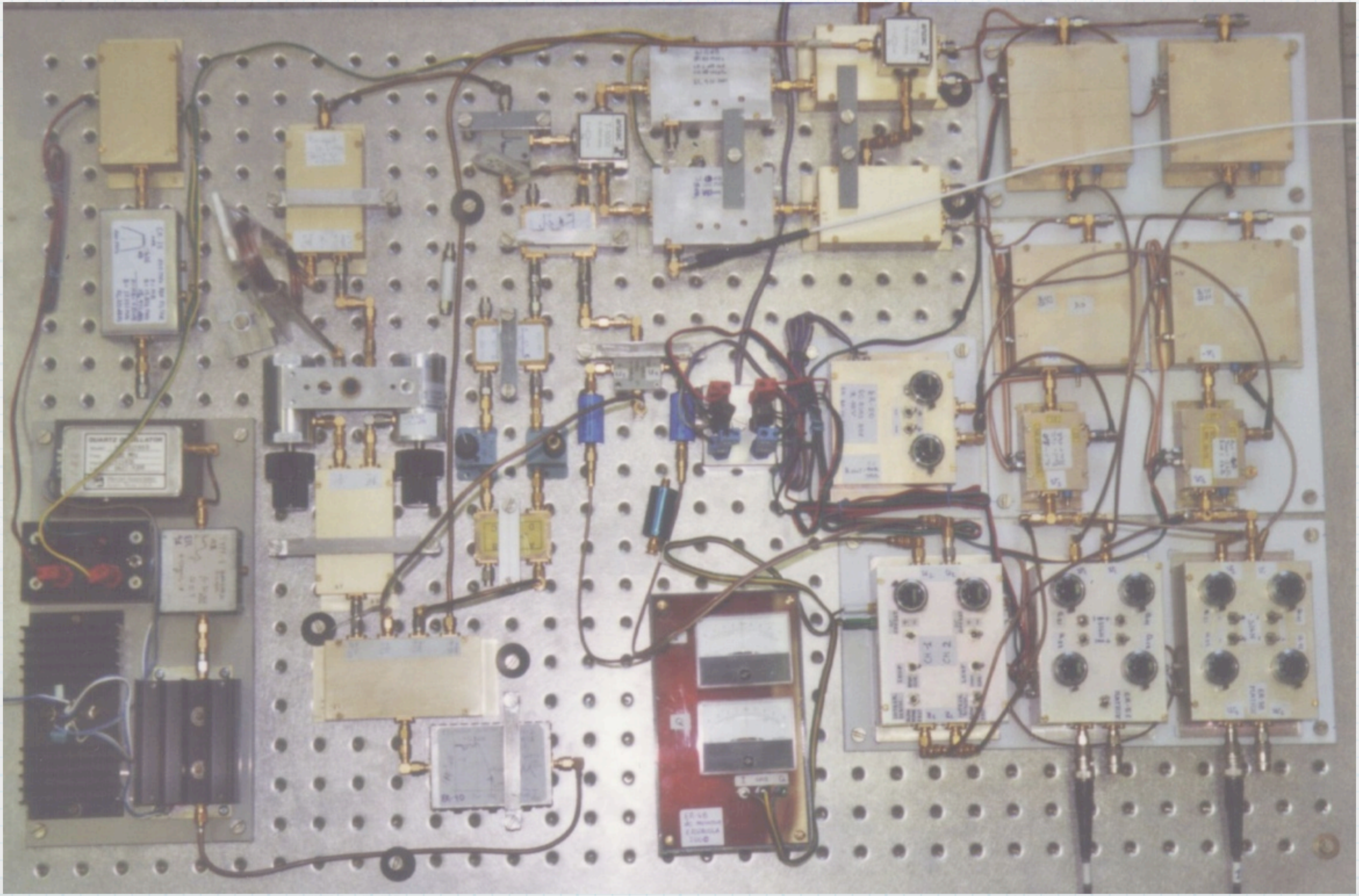




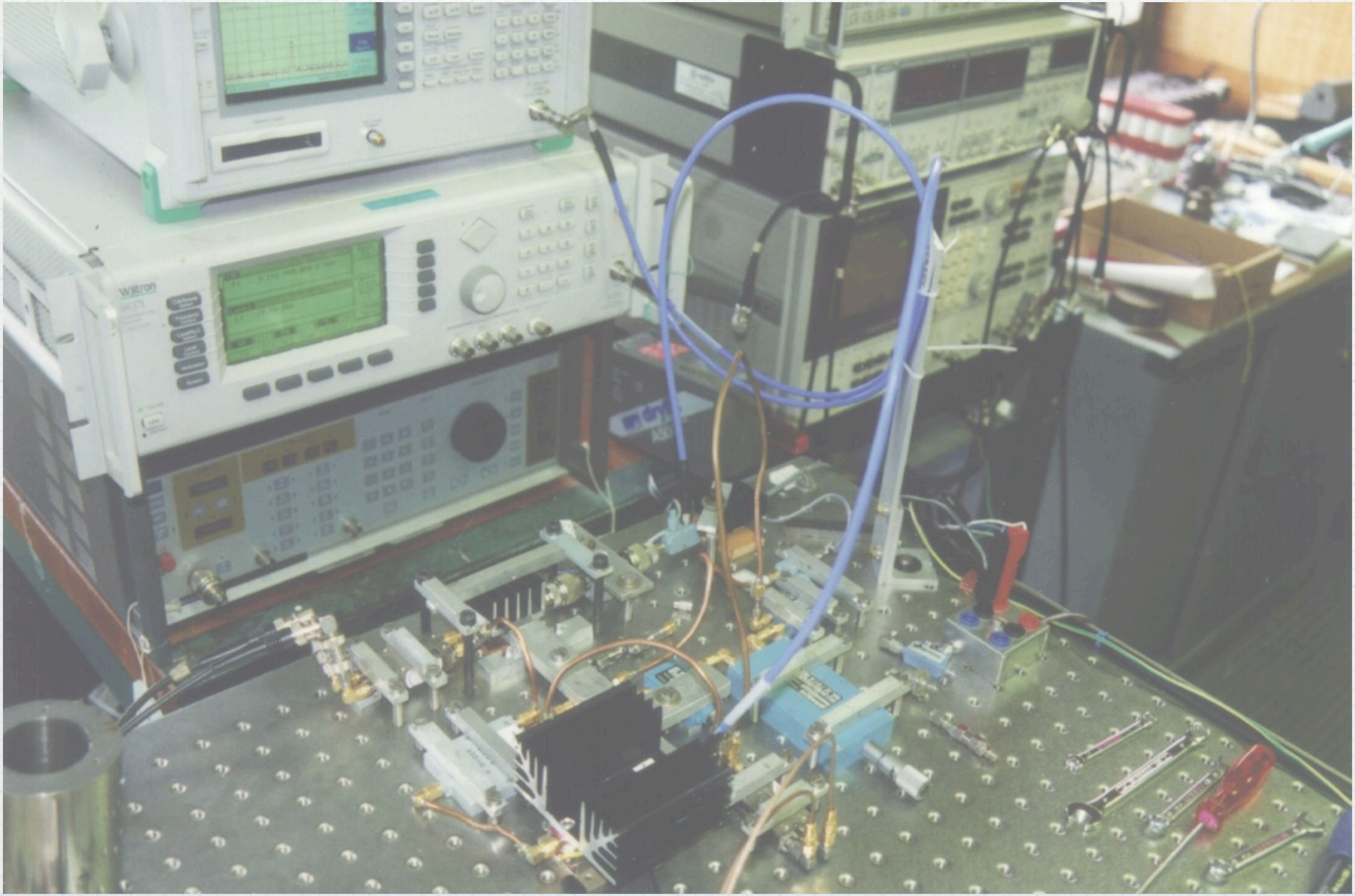
Residual noise, in the absence of the DUT

Smart and nerdy, yet of scarce practical usefulness
First used at 2 kHz to measure electromigration on metals (H. Stoll, MPI)

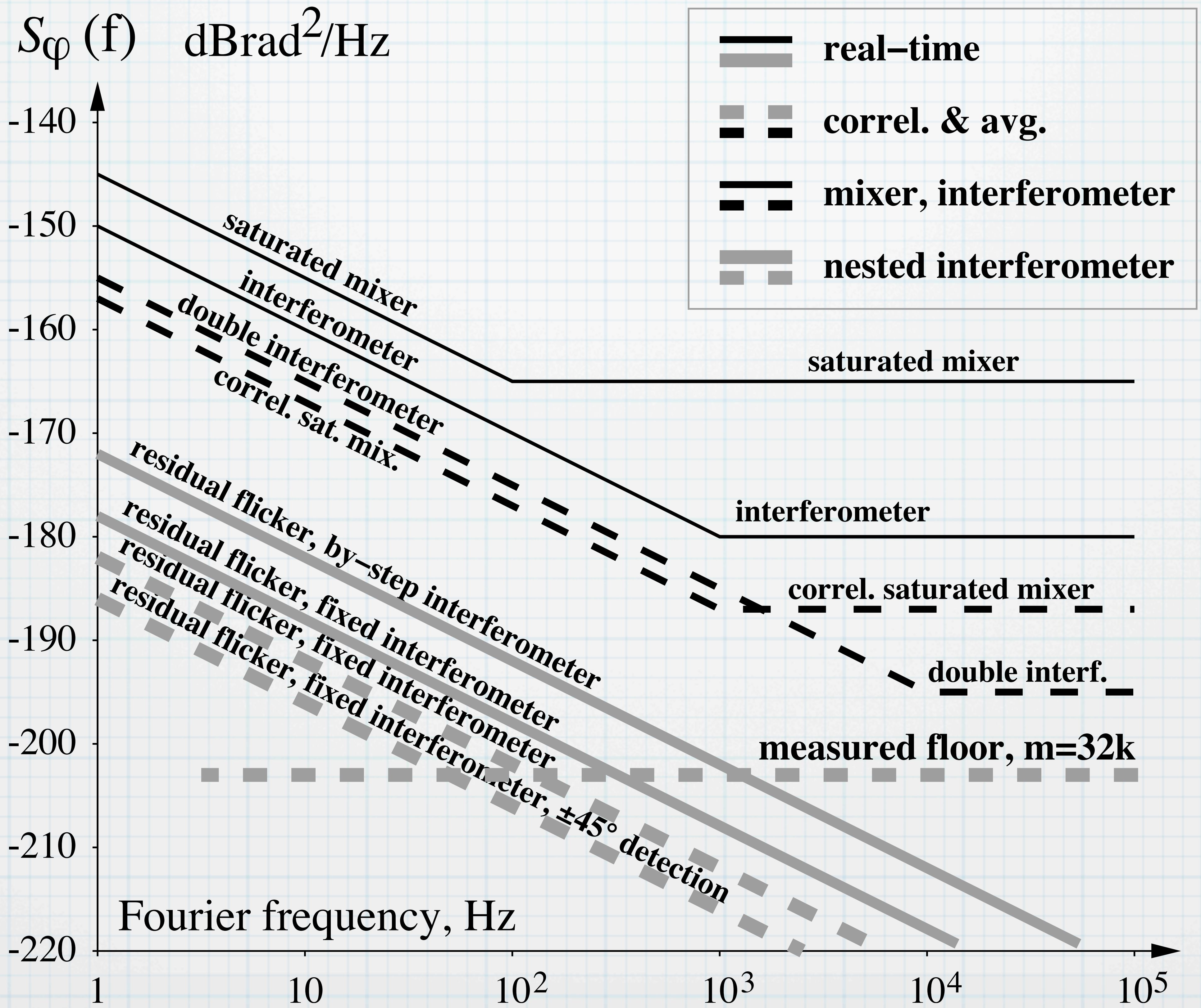
The complete machine (100 MHz)



A 9 GHz experiment (dc circuits not shown)



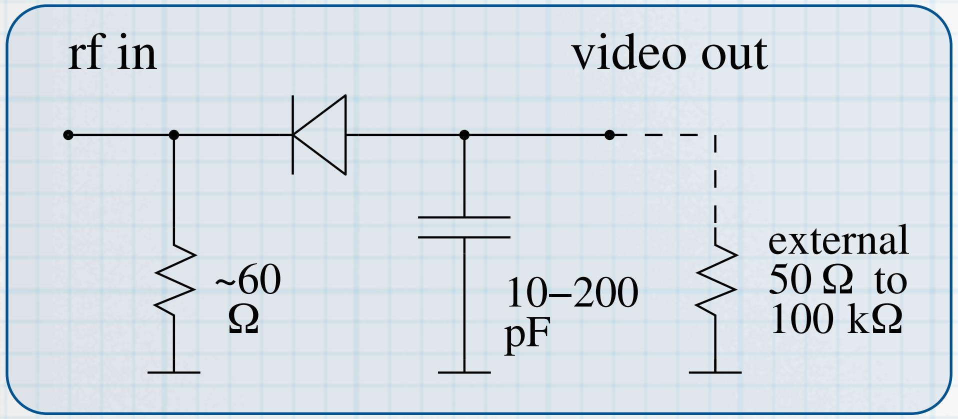
Comparison of the background noise



AM noise

Tunnel and Schottky power detectors

law: $v = k_d P$

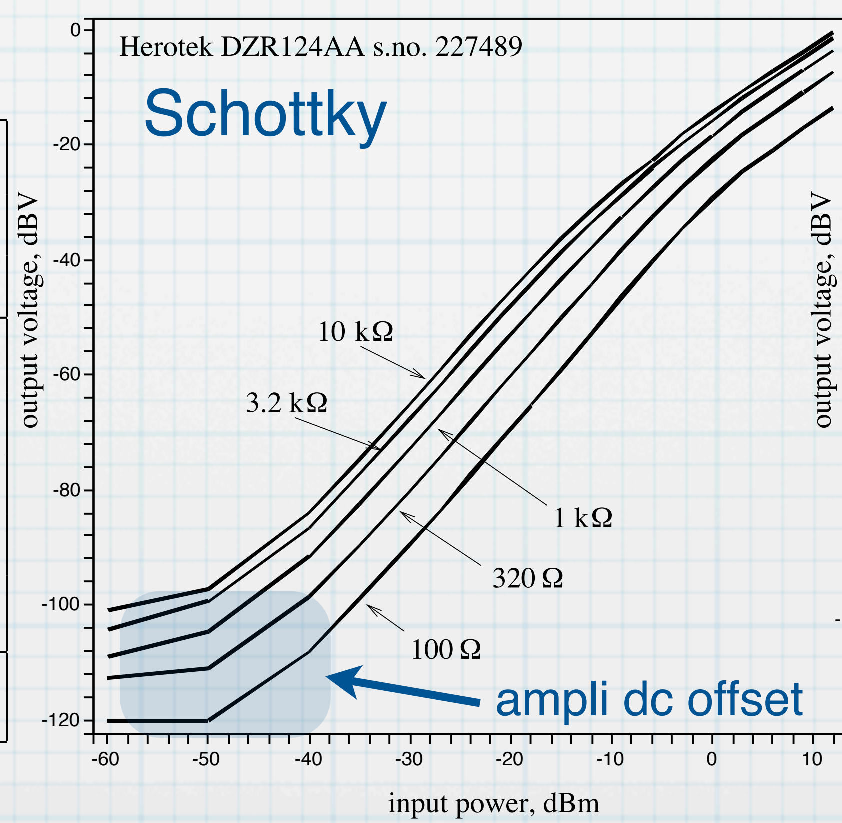


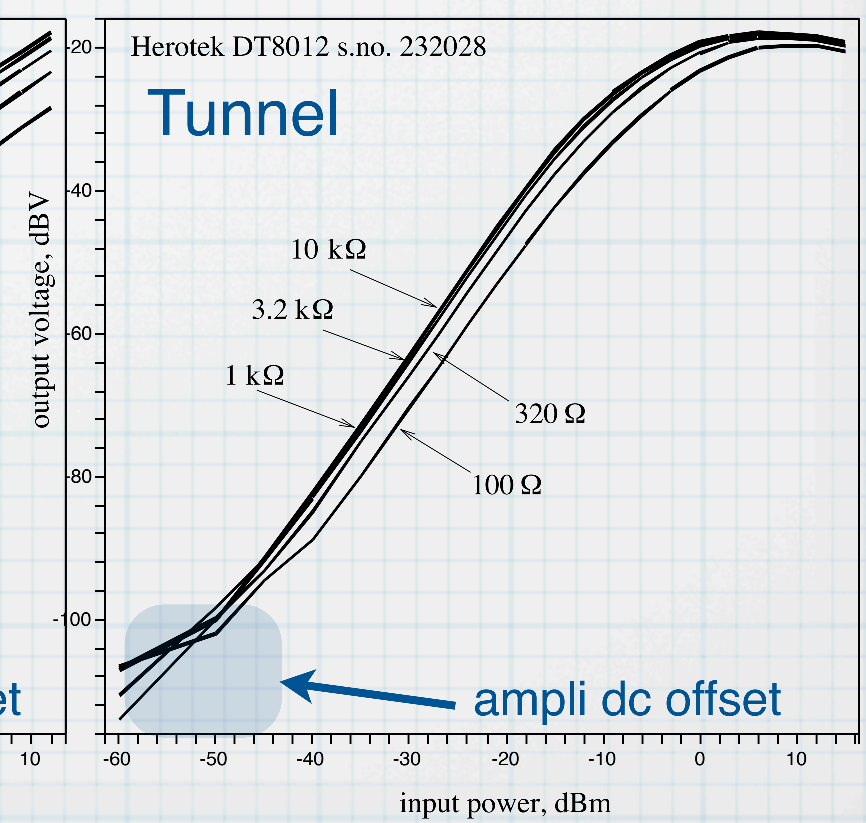
The "tunnel" diode is actually a backward diode. The negative resistance region is absent.

parameter	Schottky	tunnel
input bandwidth	up to 4 decades 10 MHz to 20 GHz	1–3 octaves up to 40 GHz
VSVR max.	1.5:1	3.5:1
max. input power (spec.)	−15 dBm	−15 dBm
absolute max. input power	20 dBm or more	20 dBm
output resistance	1–10 kΩ	50–200 Ω
output capacitance	20–200 pF	10–50 pF
gain	300 V/W	1000 V/W
cryogenic temperature	no	yes
electrically fragile	no	yes

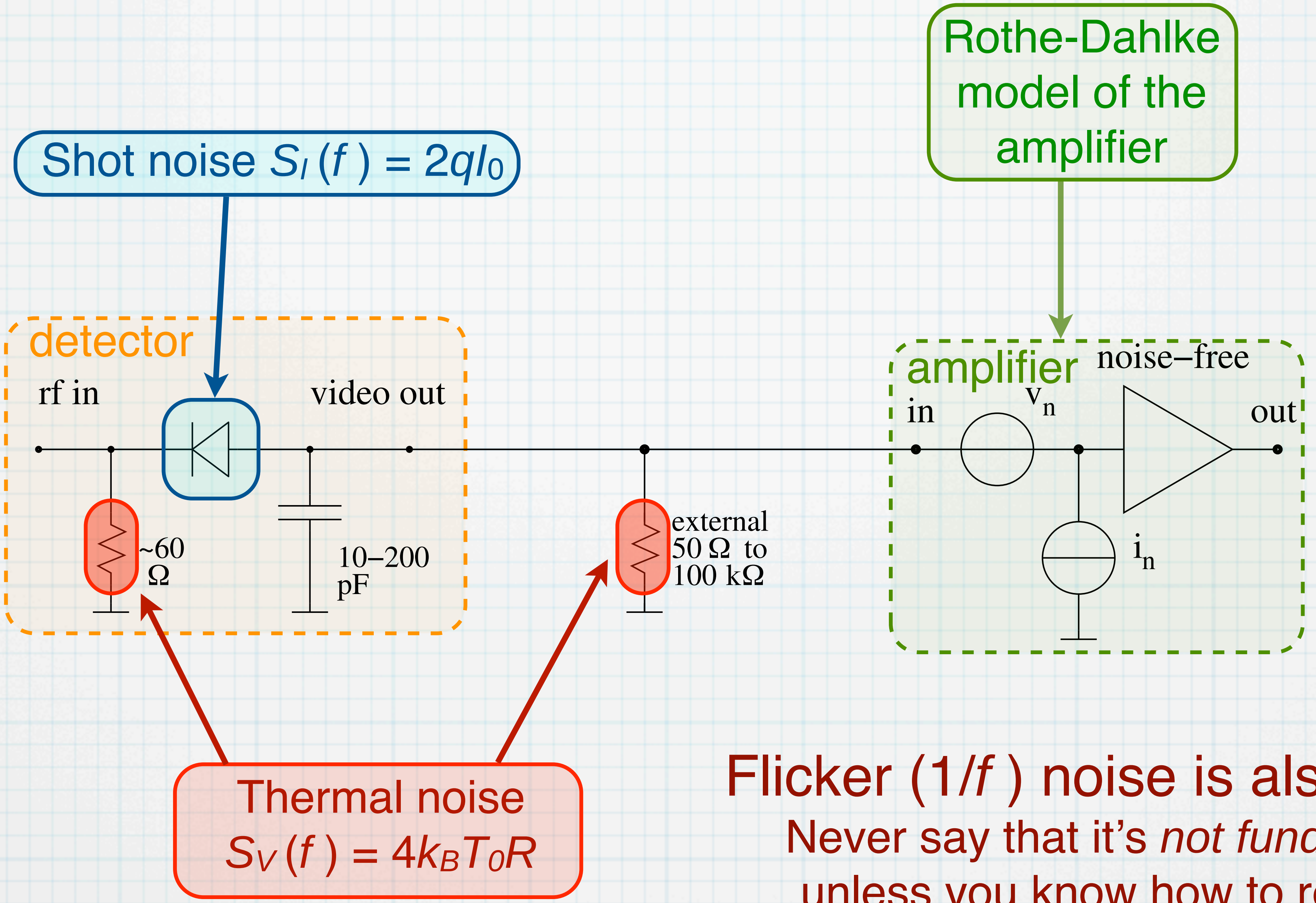
Measured

load resistance, Ω	detector gain, A^{-1} DZR124AA (Schottky)	DT8012 (tunnel)
1×10^2	35	292
3.2×10^2	98	505
1×10^3	217	652
3.2×10^3	374	724
1×10^4	494	750
conditions: power −50 to −20 dBm		





Noise mechanisms



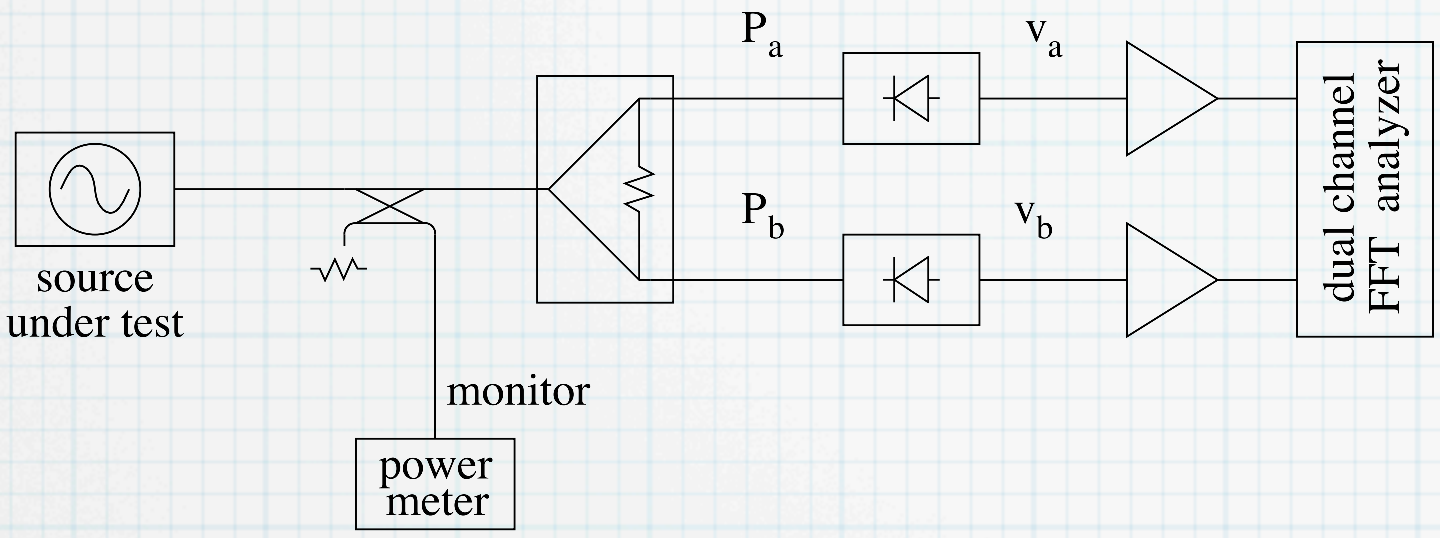
Flicker (1/*f*) noise is also present

Never say that it's *not fundamental*, unless you know how to remove it

In practice

the amplifier white noise turns out to be higher than the detector noise and the amplifier flicker noise is even higher

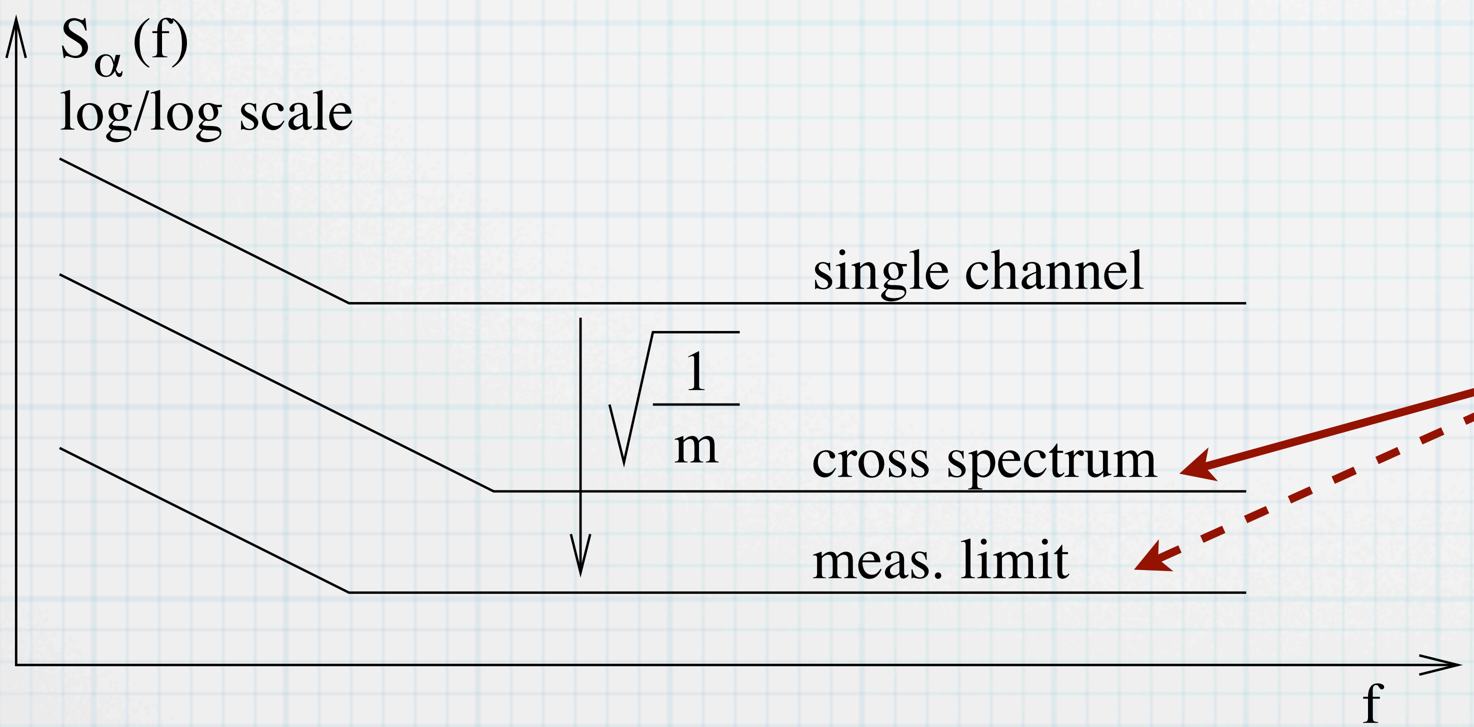
Cross-spectrum method



$$v_a(t) = 2k_a P_a \alpha(t) + \text{noise}$$
$$v_b(t) = 2k_a P_b \alpha(t) + \text{noise}$$

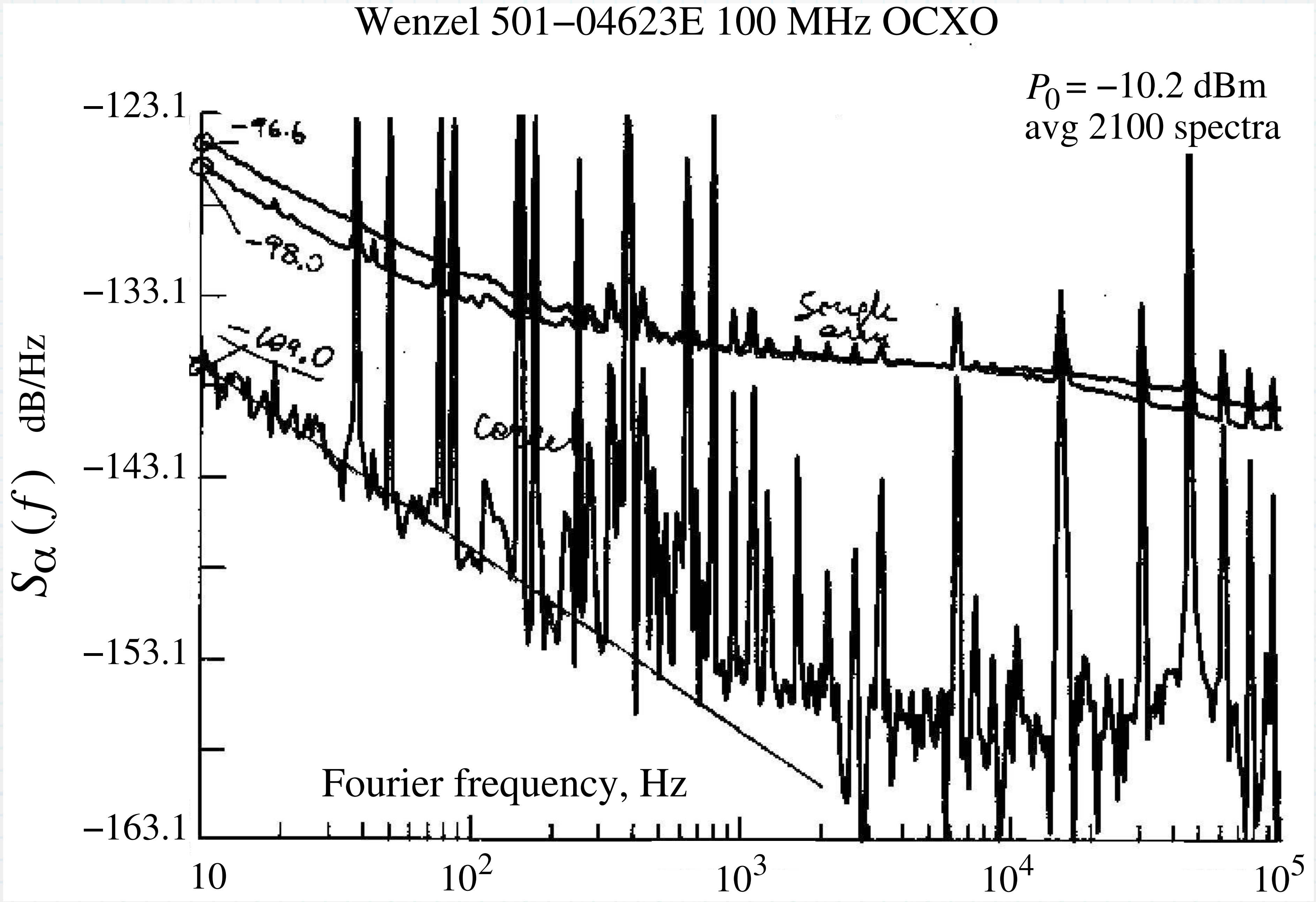
The cross spectrum $S_{ba}(f)$ rejects the single-channel noise because the two channels are independent.

$$S_{ba}(f) = \frac{1}{4k_a k_b P_a P_b} S_\alpha(f)$$



- Averaging on m spectra, the single-channel noise is rejected by √1/2m
- A cross-spectrum higher than the averaging limit validates the measure
- The knowledge of the single-channel noise is not necessary

Example of AM noise spectrum



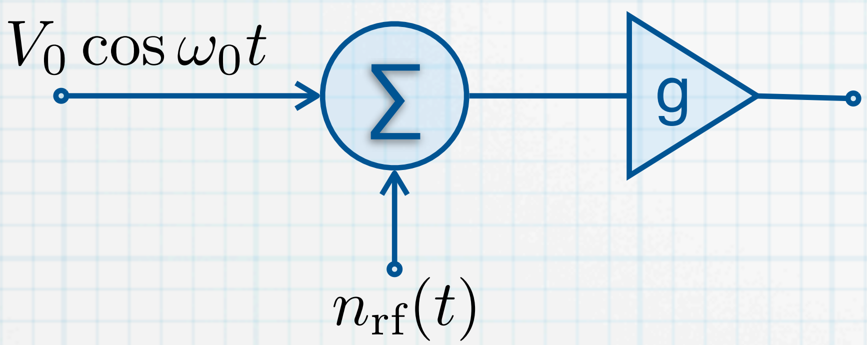
flicker: $h_{-1} = 1.5\times10^{-13}\ \mathrm{Hz}^{-1}\ (-128.2\ \mathrm{dB}) \quad\Rightarrow\quad \sigma_\alpha = 4.6\times10^{-7}$

Single-arm 1/f noise is that of the dc amplifier
(the amplifier is still not optimized)

Systems

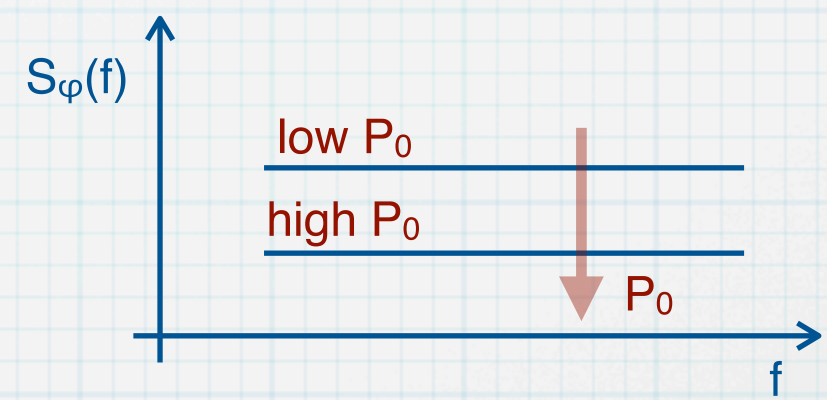
Additive (white) noise in amplifiers etc.

Noise figure F
Input power P_0



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

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



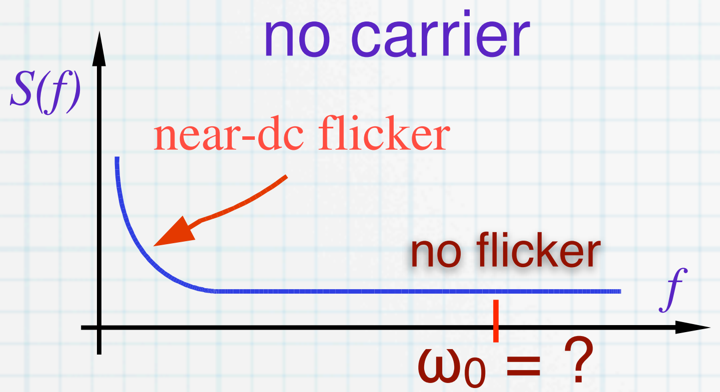
Cascaded amplifiers (Friis formula)

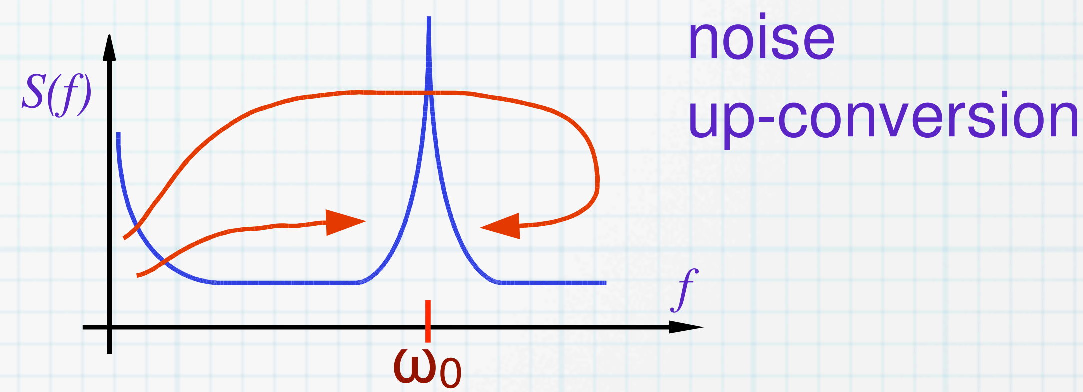
$$N = F_1 k T_0 + \frac{(F_2 - 1) k T_0}{g_1^2} + \ldots$$

As a consequence, (phase) noise is chiefly that of the 1st stage

Parametric (flicker) noise in amplifiers etc.

parametric up-conversion of the near-dc 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 amplifier

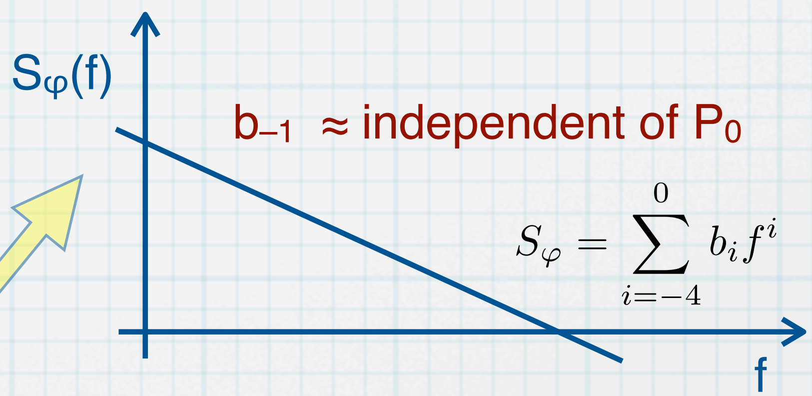
expand and select the ω_0 terms

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

get AM and PM noise

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

independent of V_i (!)



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

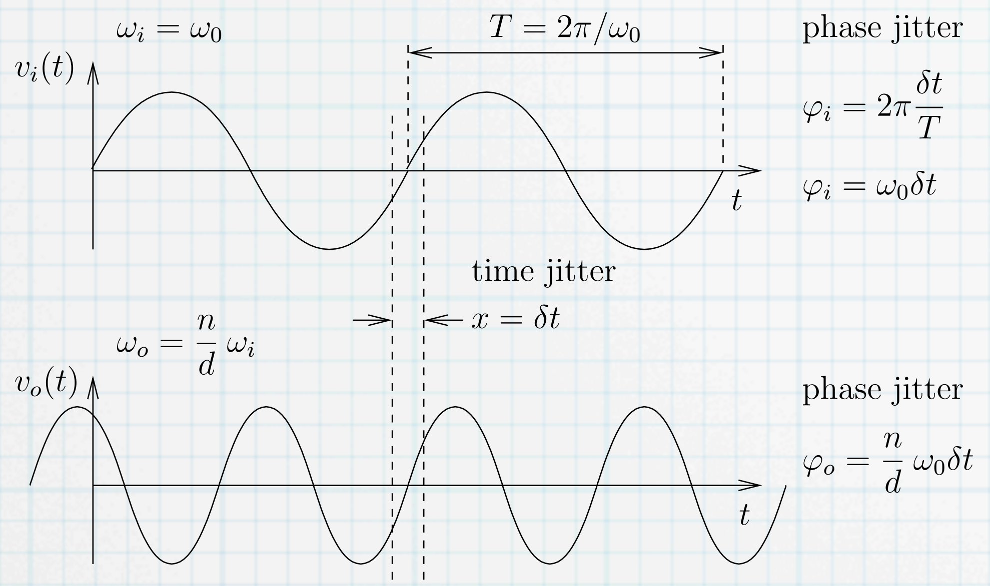
m cascaded amplifiers

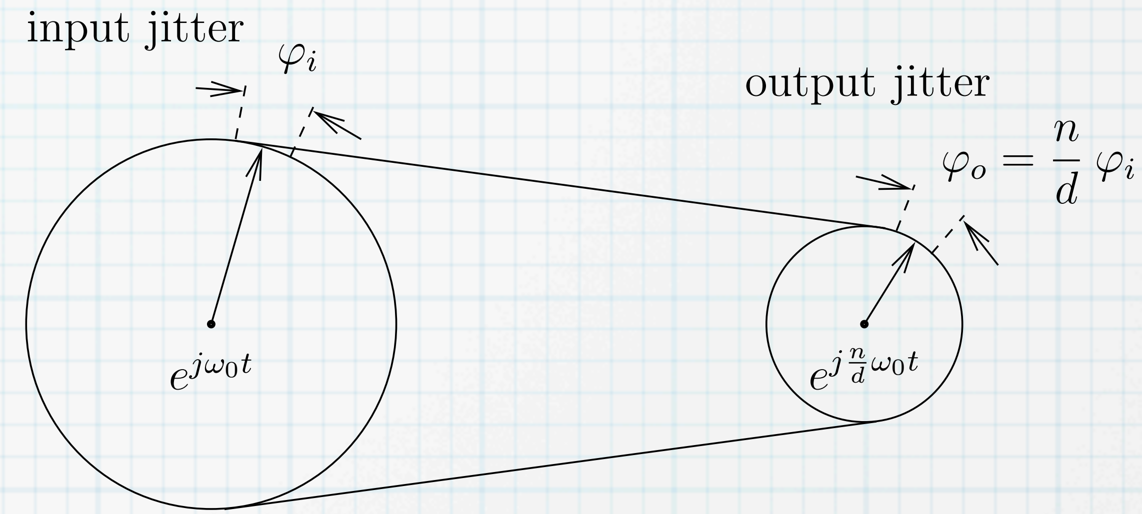
$$(b_{-1})_{\text{cascade}} = \sum_{i=1}^{m} (b_{-1})_i$$

In practice, each stage contributes ≈ equally

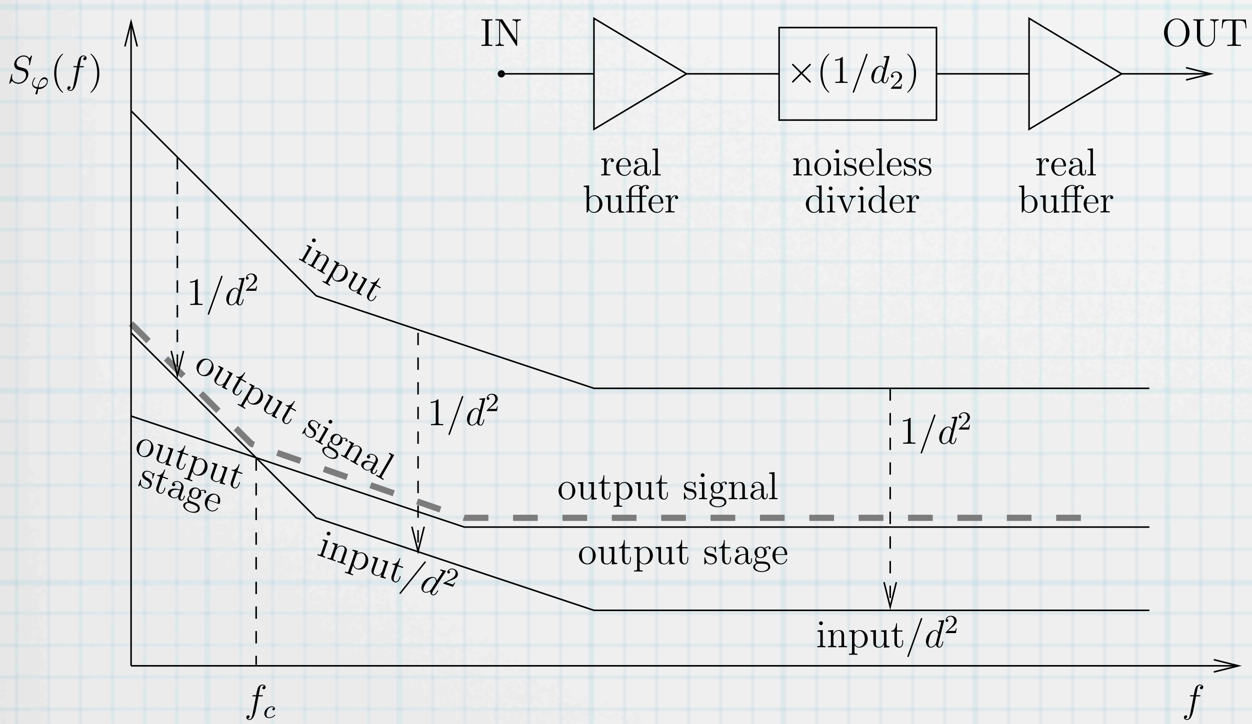
Frequency synthesis

The ideal noise-free frequency synthesizer repeats the input time jitter

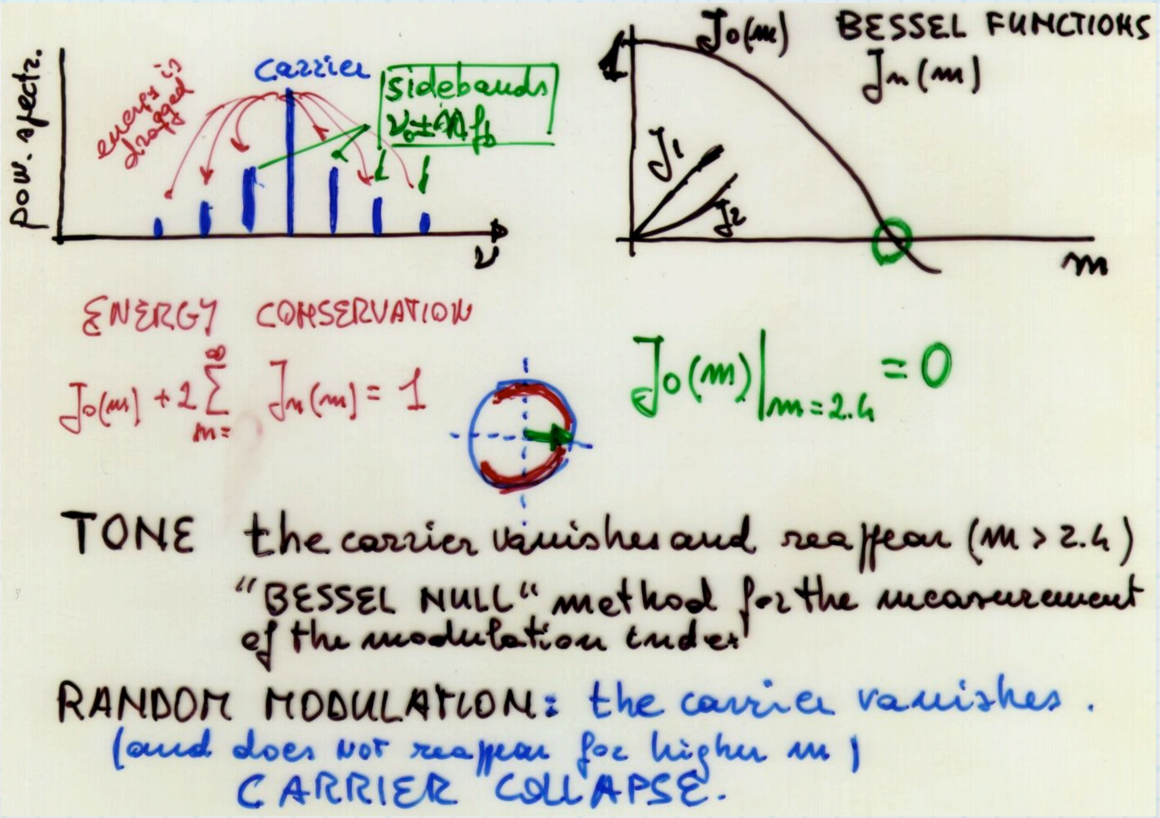




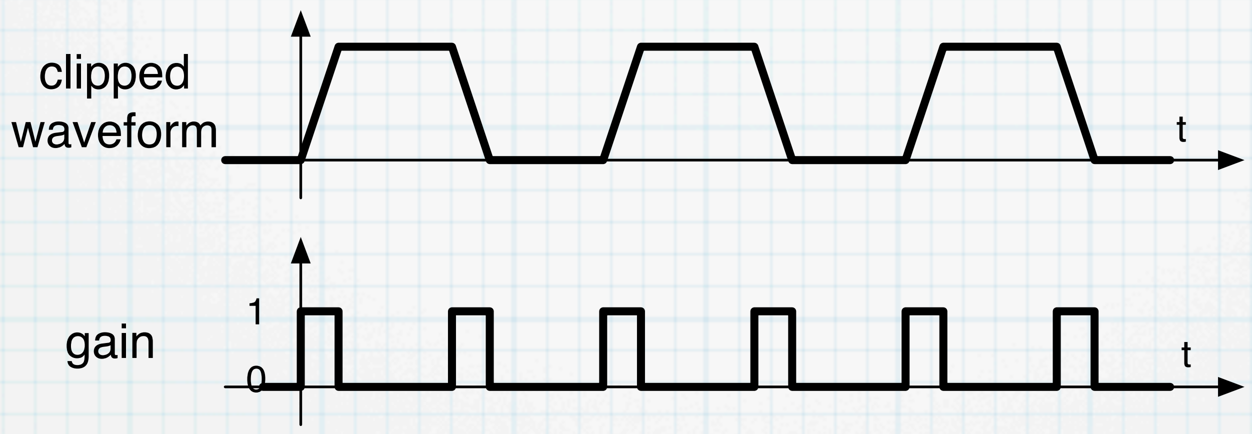
After division, the noise of the output buffer may be larger than the input-noise scaled down



After multiplication, the scaled-up phase noise sinks energy from the carrier. At m ≈ 2.4, the carrier vanishes



Saturation and sampling



Saturation is equivalent to reducing the gain

Digital circuits, for example, amplify (linearly) only during the transitions

Photodiode white noise

intensity modulation
$$P(t) = \overline{P}(1 + m\cos\omega_\mu t)$$

photocurrent
$$i(t) = \frac{q\eta}{h\nu}\,\overline{P}(1 + m\cos\omega_\mu t)$$

microwave power
$$\overline{P}_\mu = \frac{1}{2}\,m^2 R_0 \left(\frac{q\eta}{h\nu}\right)^2 P^2$$

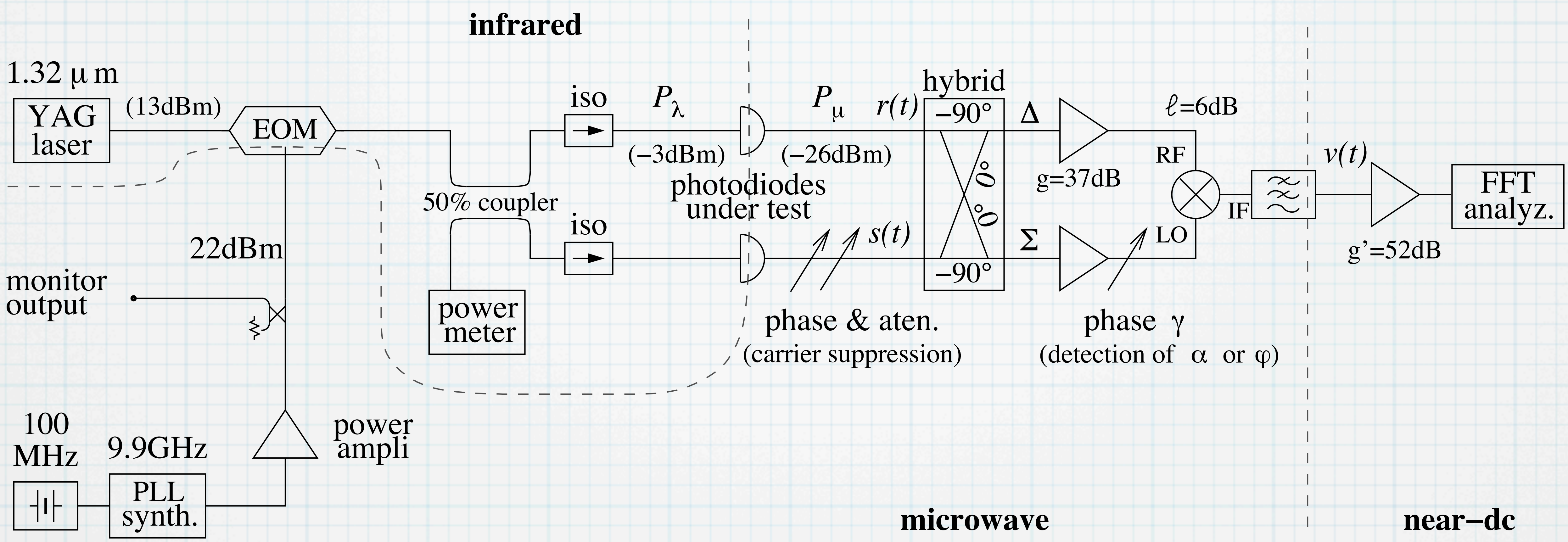
shot noise
$$N_s = 2\,\frac{q^2\eta}{h\nu}\,\overline{P}R_0$$

thermal noise
$$N_t = FkT_0$$

total white noise (one detector)
$$S_{\varphi 0} = \frac{2}{m^2}\left[2\frac{h\nu_\lambda}{\eta}\,\frac{1}{\overline{P}} + \frac{FkT_0}{R_0}\left(\frac{h\nu_\lambda}{q\eta}\right)^2\left(\frac{1}{\overline{P}}\right)^2\right]$$

Threshold power ≈ 0.5–1 mW

Photodetector noise

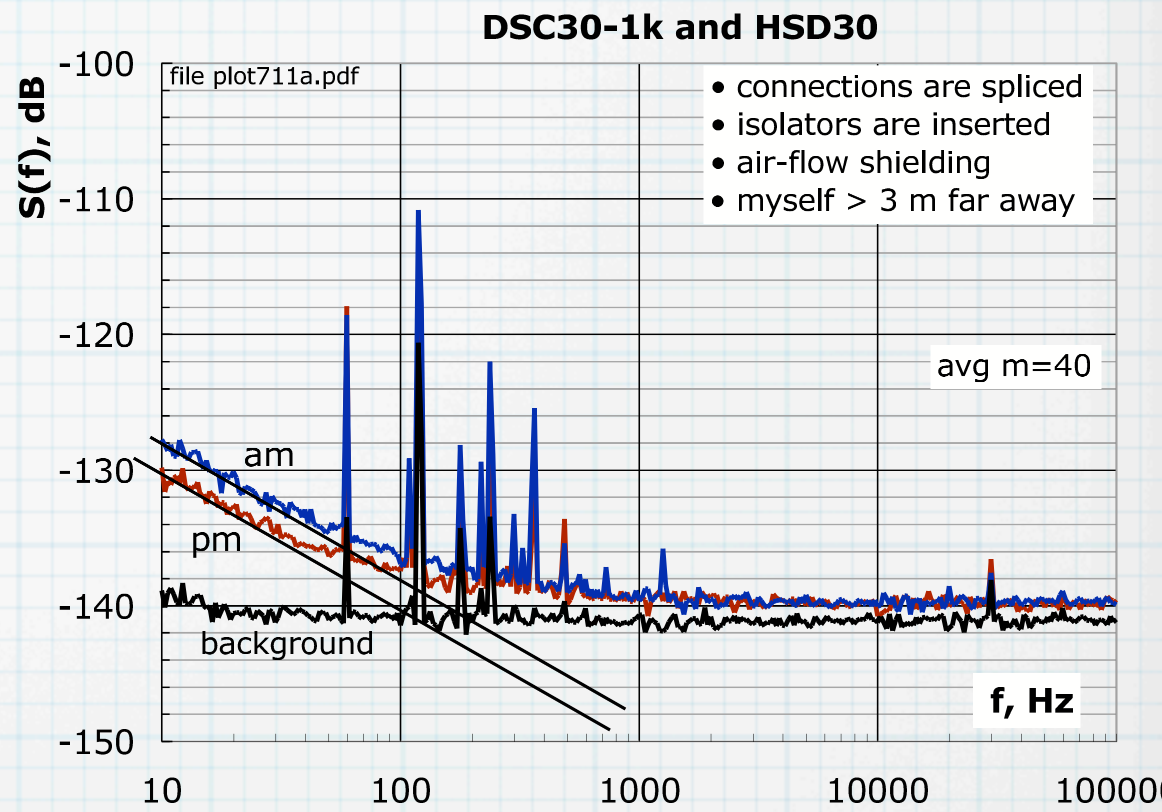


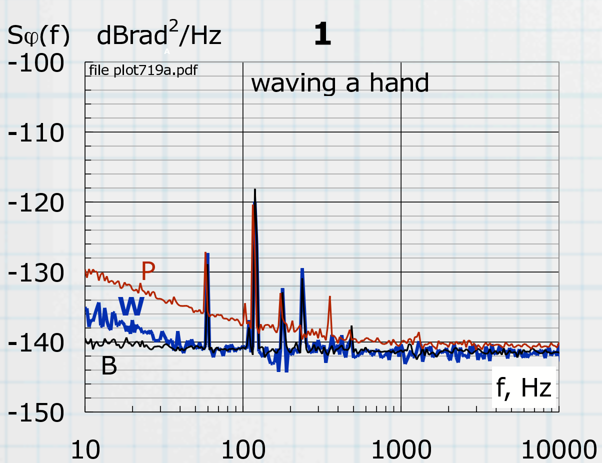
photodiode	$S_\alpha(1\,\text{Hz})$ estimate	$S_\alpha(1\,\text{Hz})$ uncertainty	$S_\varphi(1\,\text{Hz})$ estimate	$S_\varphi(1\,\text{Hz})$ uncertainty
HSD30	−122.7	−7.1 / +3.4	−127.6	−8.6 / +3.6
DSC30-1K	−119.8	−3.1 / +2.4	−120.8	−1.8 / +1.7
QDMH3	−114.3	−1.5 / +1.4	−120.2	−1.7 / +1.6
unit	dB/Hz	dB	dBrad^2/Hz	dB

The noise of the Σ amplifier is not detected Electron. Lett. **39** 19 p. 1389 (2003)

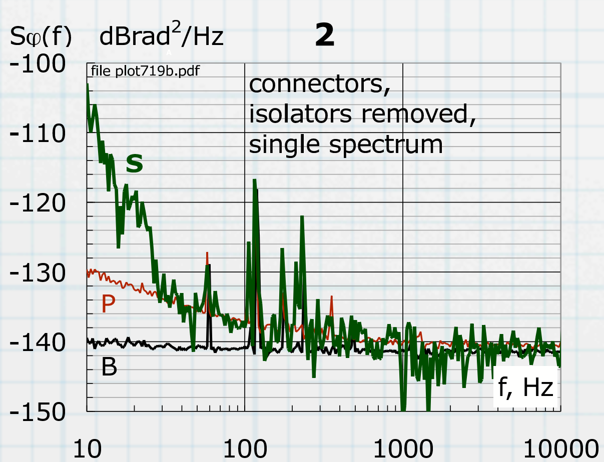
Photodetector noise

- the photodetectors we measured are similar in AM and PM 1/f noise
- the 1/f noise is about -120 dB[rad²]/Hz
- other effects are easily mistaken for the photodetector 1/f noise
- environment and packaging deserve attention in order to take the full benefit from the low noise of the junction

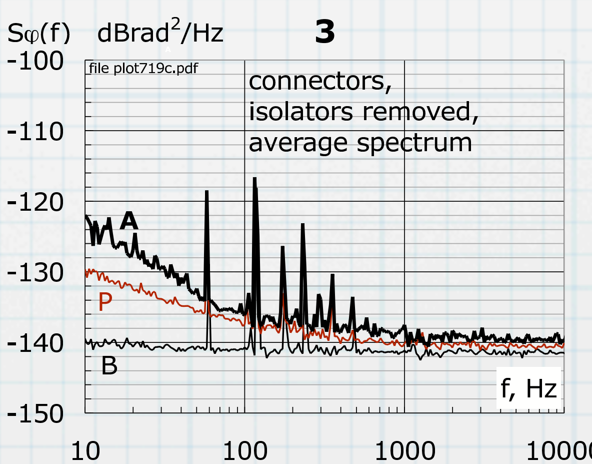




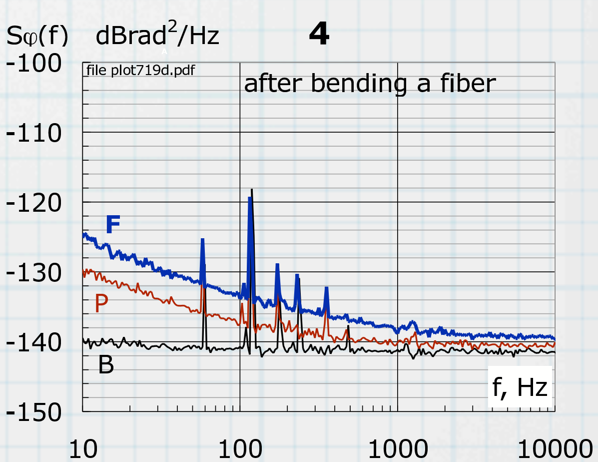
W: waving a hand 0.2 m/s, 3 m far from the system
B: background noise
P: photodiode noise



S: single spectrum, with optical connectors and no isolators
B: background noise
P: photodiode noise



A: average spectrum, with optical connectors and no isolators
B: background noise
P: photodiode noise



F: after bending a fiber, 1/f noise can increase unpredictably
B: background noise
P: photodiode noise

Physical phenomena in optical fibers

Birefringence. Common optical fibers are made of amorphous Ge-doped silica, for an ideal fiber is not expected to be birefringent. Nonetheless, actual fibers show birefringent behavior due to a variety of reasons, namely: core ellipticity, internal defects and forces, external forces (bending, twisting, tension, kinks), external electric and magnetic fields. The overall effect is that light propagates through the fiber core in a non-degenerate, orthogonal pair of axes at different speed. Polarization effects are strongly reduced in polarization maintaining (PM) fibers. In this case, the cladding structure stresses the core in order to increase the difference in refraction index between the two modes.

Rayleigh scattering. This is random scattering due to molecules in a disordered medium, by which light looses direction and polarization. A small fraction of the light intensity is thereby back-scattered one or more times, for it reaches the fiber end after a stochastic to-and-fro path, which originates phase noise. In the early fibers it contributed 0.1 dB/km to the optical loss.

Bragg scattering. In the presence of monocromatic light (usually X-rays), the periodic structure of a crystal turns the randomness of scattering into an interference pattern. This is a weak phenomenon at micron wavelengths because the inter-atom distance is of the order of 0.3--0.5 nm. Bragg scattering is not present in amorphous materials.

Brillouin scattering. In solids, the photon-atom collision involves the emission or the absorption of an acoustic phonon, hence the scattered photons have a wavelength slightly different from incoming photons. An exotic form of Brillouin scattering has been reported in optical fibers, due to a transverse mechanical resonance in the cladding, which stresses the core and originates a noise bump on the region of 200--400 MHz.

Raman scattering. This phenomenon is somewhat similar to Rayleigh scattering, but the emission or the absorption of an optical phonon.

Kerr effect. This effect states that an electric field changes the refraction index. So, the electric field of light modulate the refraction index, which originates the 2nd-order nonlinearity.

Discontinuities. Discontinuities cause the wave to be reflected and/or to change polarization. As the pulse can be split into a pulse train depending on wavelength, this effect can turn into noise.

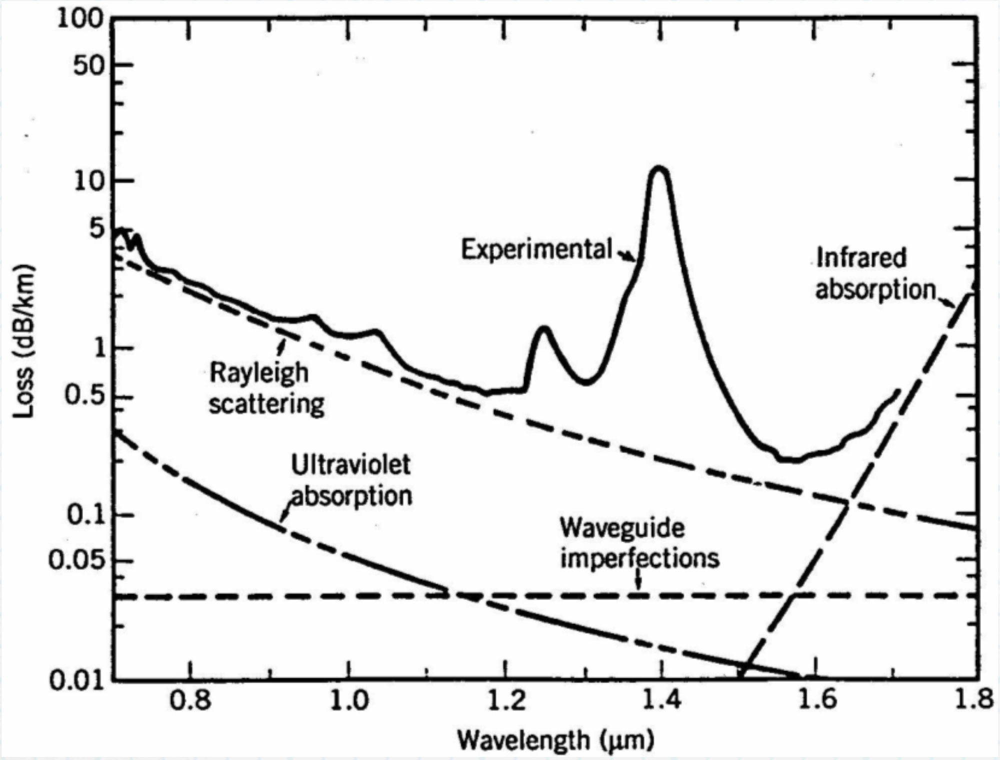
Group delay dispersion (GVD). There exist dispersion-shifted fibers, that have a minimum GVD at 1550 nm. GVD compensators are also available.

Polarization mode dispersion (PMD). This effect rises from the random birefringence of the optical fiber. The optical pulse can choose many different paths, for it broadens into a bell-like shape bounded by the propagation times determined by the highest and the lowest refraction index. Polarization vanishes exponentially along the light path. It is to be understood that PMD results from the vector sum over multiple forward paths, for it yields a well-shaped dispersion pattern.

PMD-Kerr compensation. In principle, it is possible that PMD and Kerr effect null one another. This requires to launch the appropriate power into each polarization mode, for two power controllers are needed. Of course, this is incompatible with PM fibers.

Which is the most important effect? In the community of optical communications, PMD is considered the most significant effect. Yet, this is related to the fact that excessive PMD increases the error rate and destroys the eye pattern of a channel. In the case of the photonic oscillator, the signal is a pure sinusoid, with no symbol randomness. My feeling is that Rayleigh scattering is the most relevant stochastic phenomenon.

Rayleigh scattering



Rayleigh scattering contributes some 0.1 dB/km to the loss

G. Agrawal, *Fiber-optic communications systems*, Wiley 1997

Stochastic scattering