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Application of the optical fiber to generation and measurement of low-phase-noise microwaves

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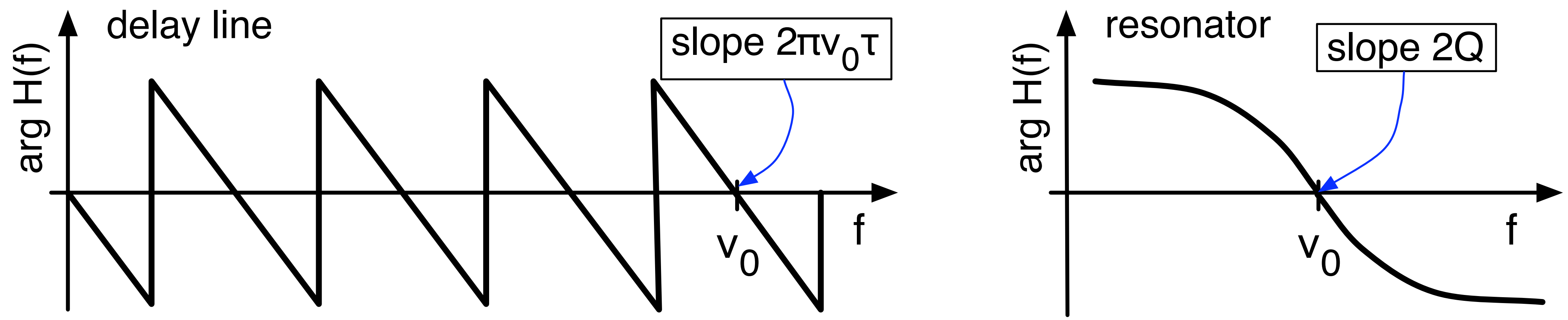
Outline

- Basics
- Single-channel phase noise measurements
- Cross-spectrum phase noise measurements
- Opto-electronic oscillator

home page http://rubiola.org

The delay-line as a discriminator

The delay line turns a frequency into a phase



comparing the slope: $Q_{\text{eq}} = \pi\nu_0\tau$

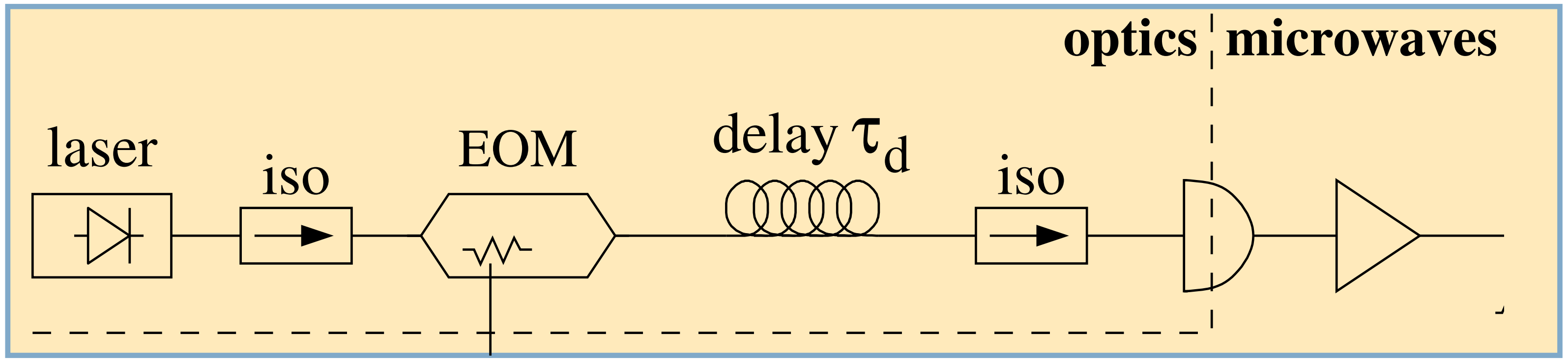
Virtues

- **Works at any frequency ν = n/τ, integer τ (the resonator does not)**
- ✔ Sφ measurement of an oscillator
- ✔ Dual-channel Sφ measurement of an oscillator
- Stabilization of an oscillator
- ✔ Opto-electronic oscillator

Problems & solution

- Coax cable: 50 dB attenuation limits to
  - 950 ns @ 1 GHz (Q=3000) - RG213
  - 300 ns @ 10 GHz (Q=11500) - RG402
- Optical fiber:
  - max delay is not limited by the attenuation
  - 1-100 μs delay is possible ($Q=10^5$–10^7 @ 31 GHz)

Opto-electronic delay line



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

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

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

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

thermal noise $N_t = FkT_0$

total white noise

shot, thermal

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

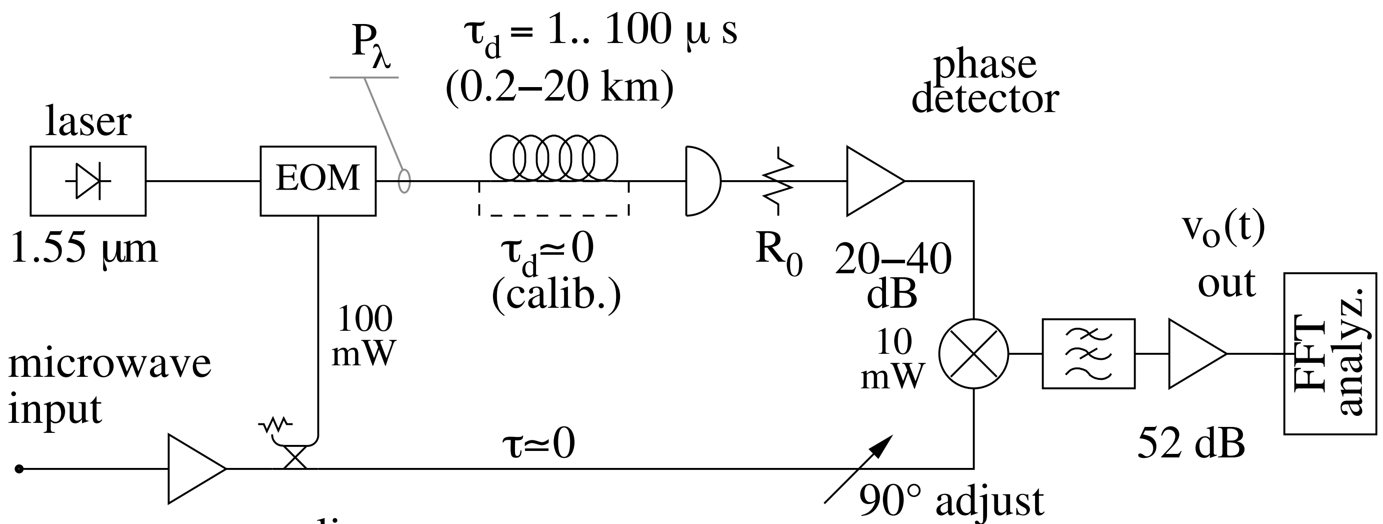
flicker phase noise

- amplifier GaAs: $b_{-1} \approx -100$ to -110 dBrad²/Hz, SiGe: $b_{-1} \approx -120$ dBrad²/Hz
- photodetector $b_{-1} \approx -120$ dBrad²/Hz [Rubiola & al. MTT/JLT 54(2), feb. 2006
- (mixer $b_{-1} \approx -120$ dBrad²/Hz)
- the phase flicker coefficient b_{-1} is about independent of power
- in a cascade, $(b_{-1})_{tot}$ adds up, regardless of the device order

optical-fiber phase noise? still an experimental parameter

Opto-electronic frequency discriminator

Rubiola-Salik-Huang-Yu-Maleki, JOSA-B 22(5) p.987–997 (2005)



Note that here one arm is a microwave cable

Laplace transforms

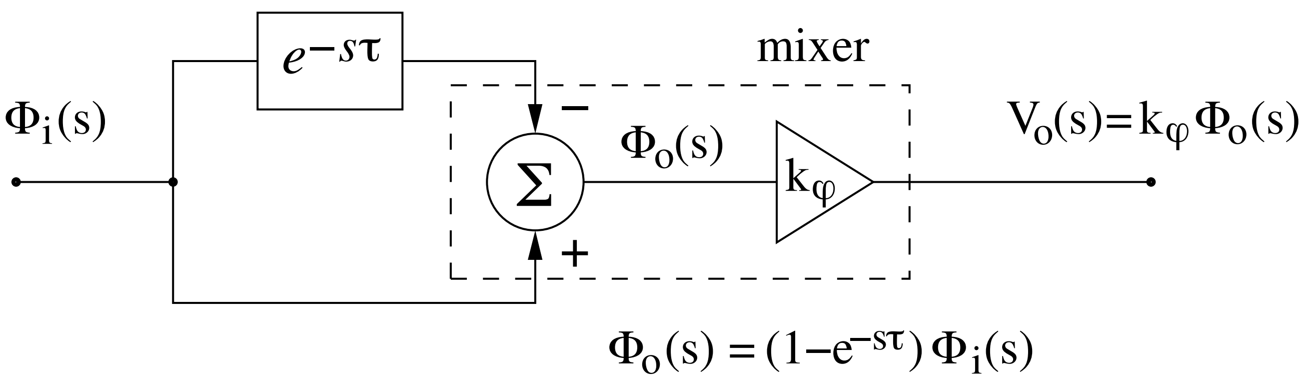
$$\Phi(s) = H_\varphi(s)\Phi_i(s)$$

$$|H_\varphi(f)|^2 = 4\sin^2(\pi f \tau)$$

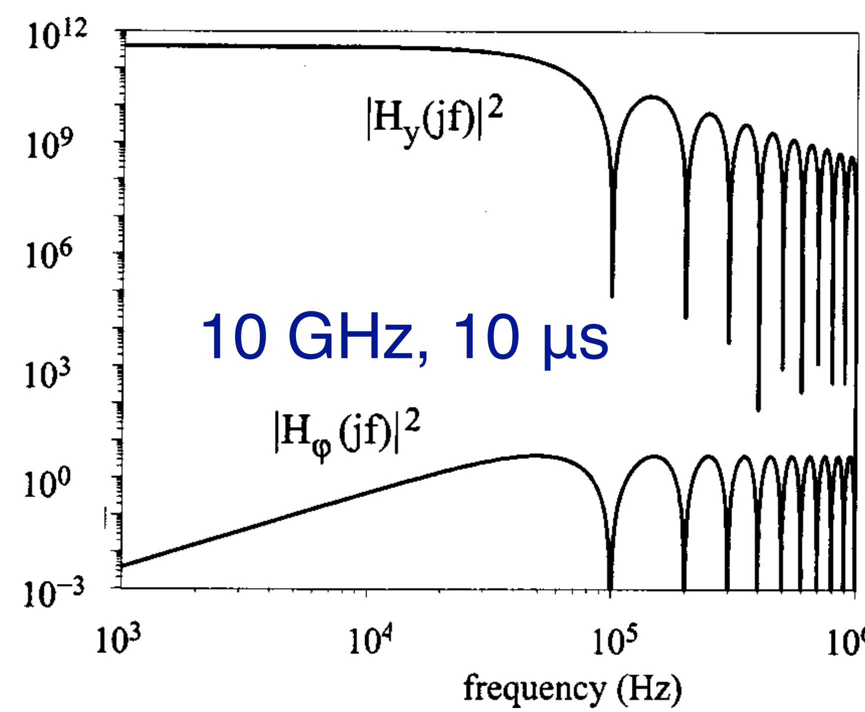
$$S_y(f) = |H_y(f)|^2\, S_{\varphi\, i}(s)$$

$$|H_y(f)|^2 = \frac{4\nu_0^2}{f^2}\, \sin^2(\pi f \tau)$$

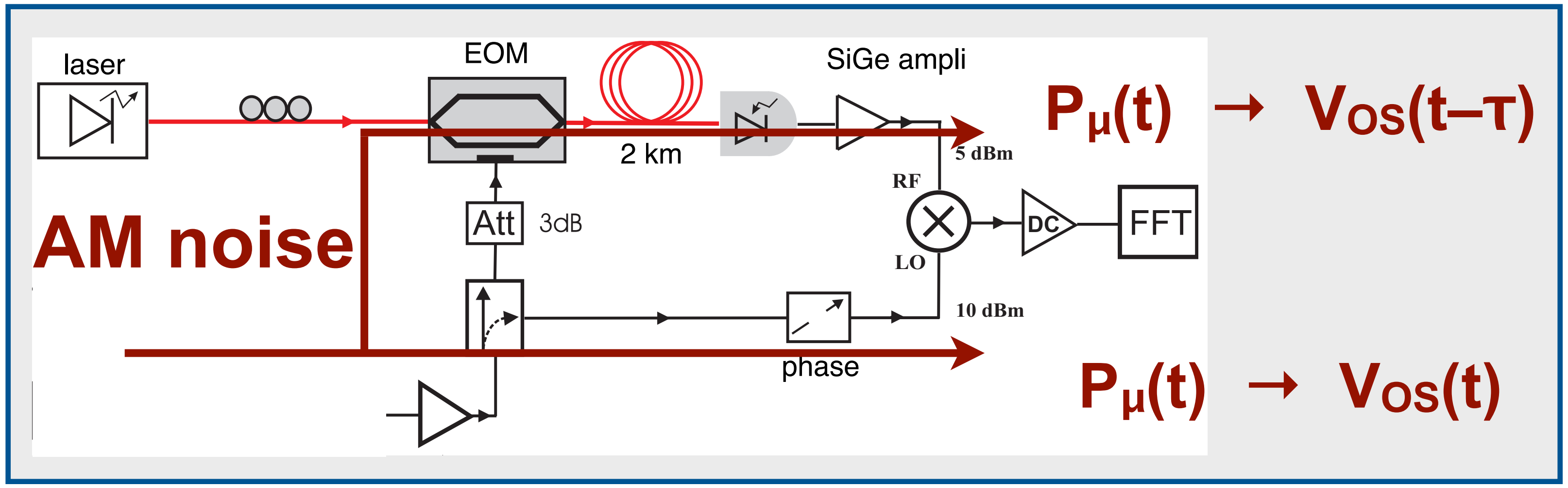
Laplace transforms



- **delay –> frequency-to-phase conversion**
- **works at any frequency**
- **long delay (microseconds) is necessary for high sensitivity**
- **the delay line must be an optical fiber**
  fiber: attenuation 0.2 dB/km, thermal coeff. 6.8 10^{-6}/K
  cable: attenuation 0.8 dB/m, thermal coeff. ~ 10^{-3}/K

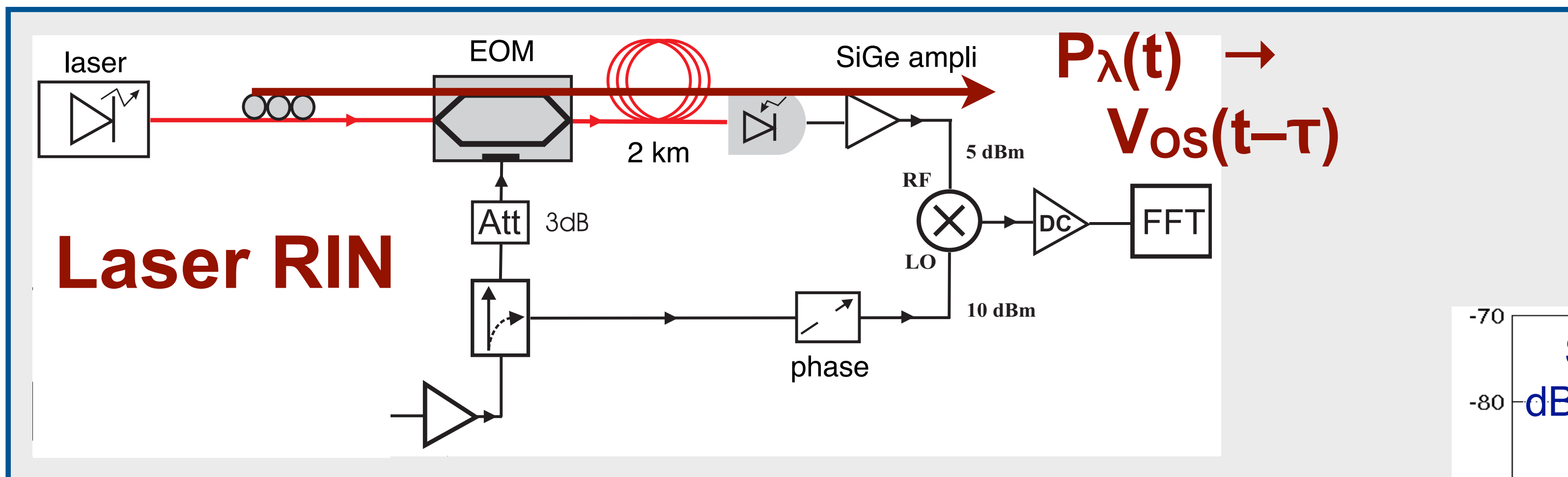


The effect of AM noise and RIN

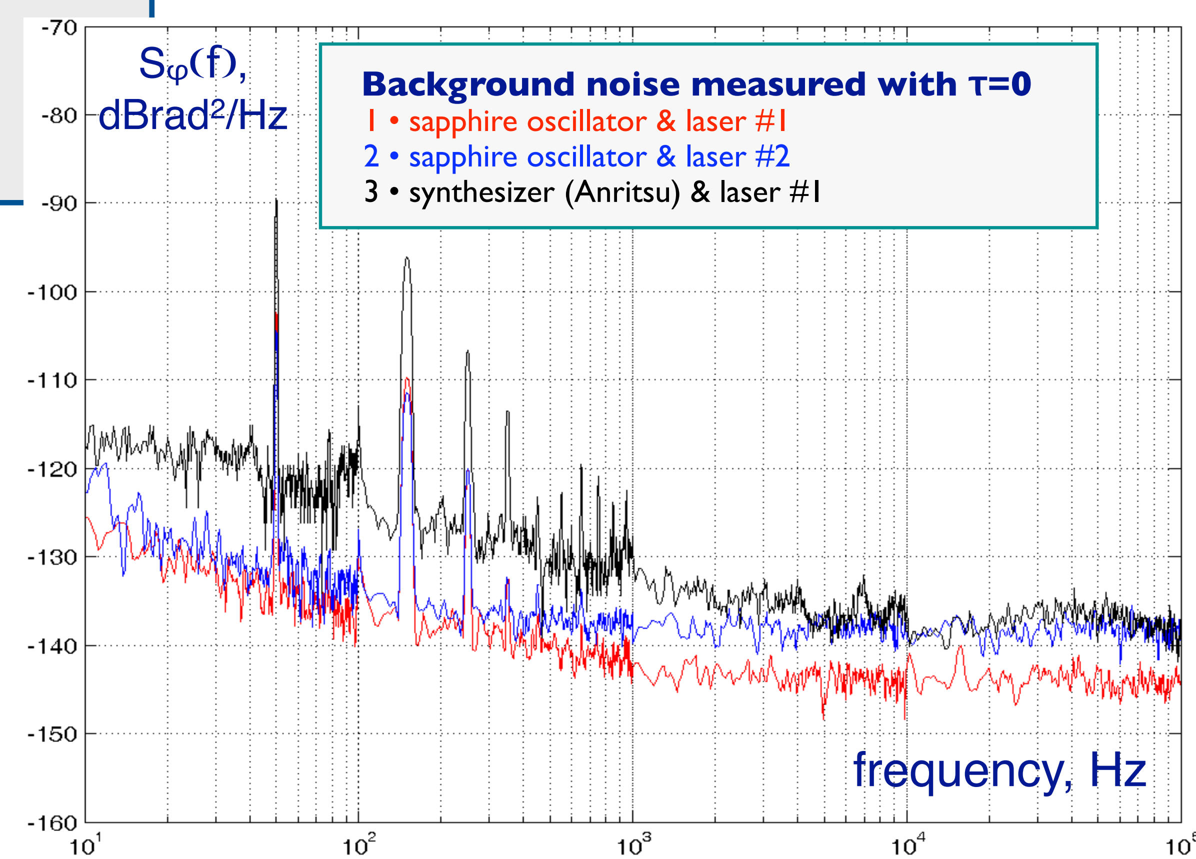


The AM noise turns into Vos fluctuation, which may limit the sensitivity

The delay de-correlates the AM noise. Thus there is no null of sensitivity



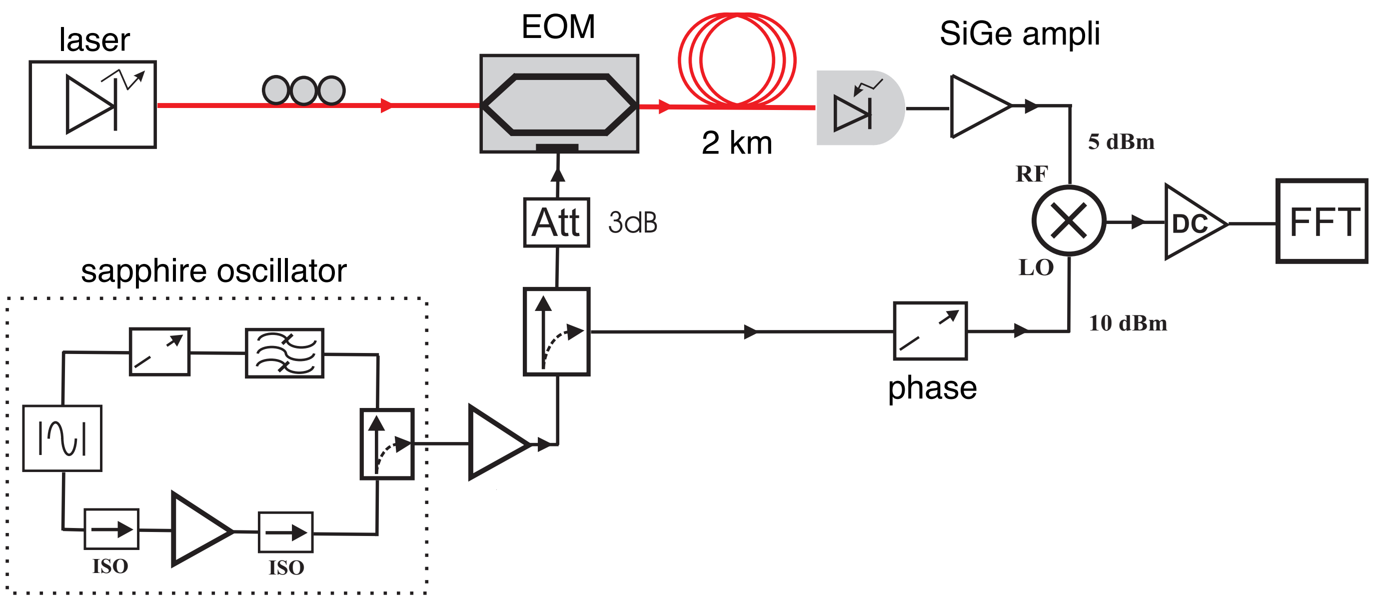
The laser RIN turns into Vos fluctuation, which may limit the sensitivity

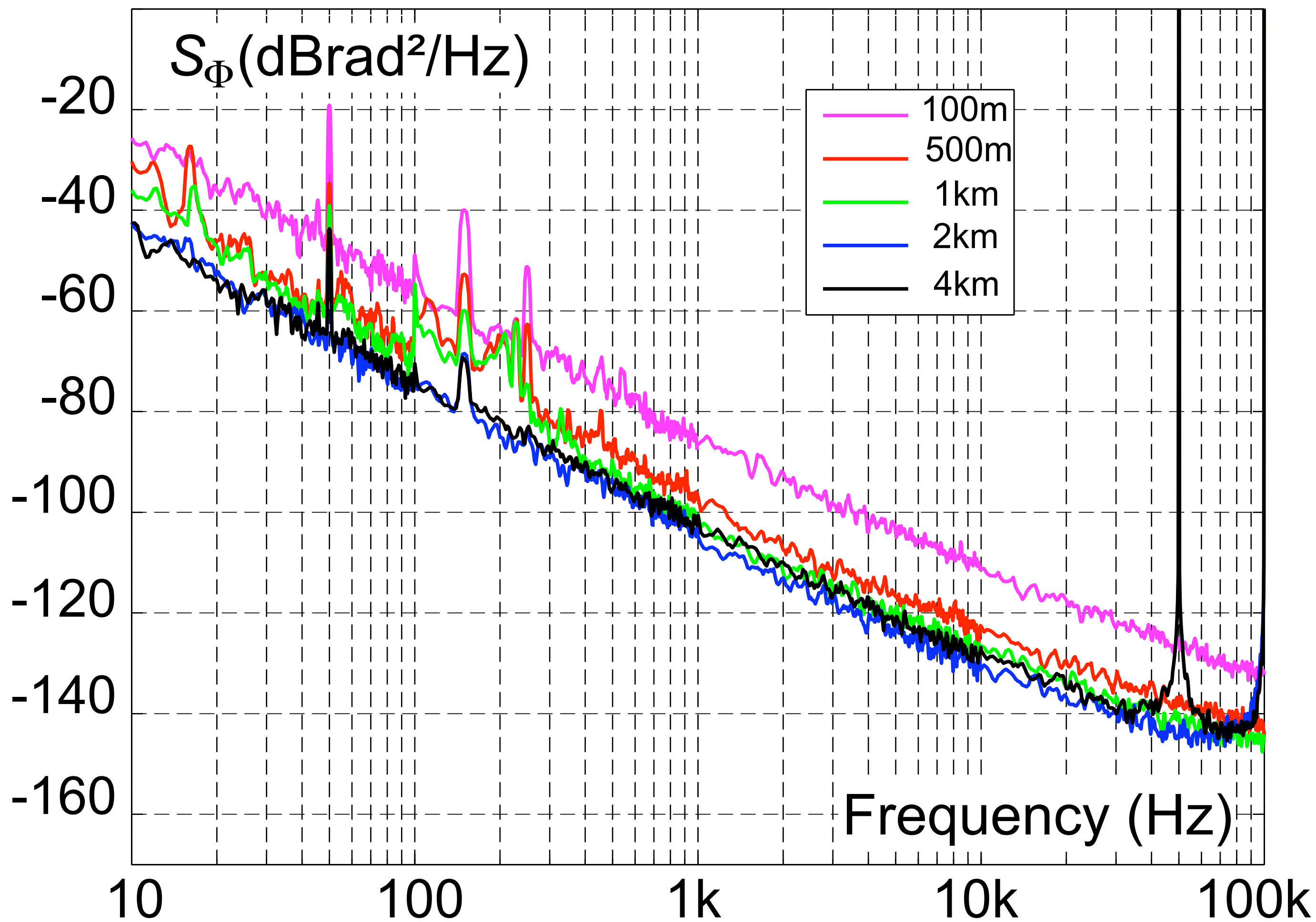


Instrument background measured at zero-length fiber

Lowest AM noise and Lowest RIN give the lowest background noise

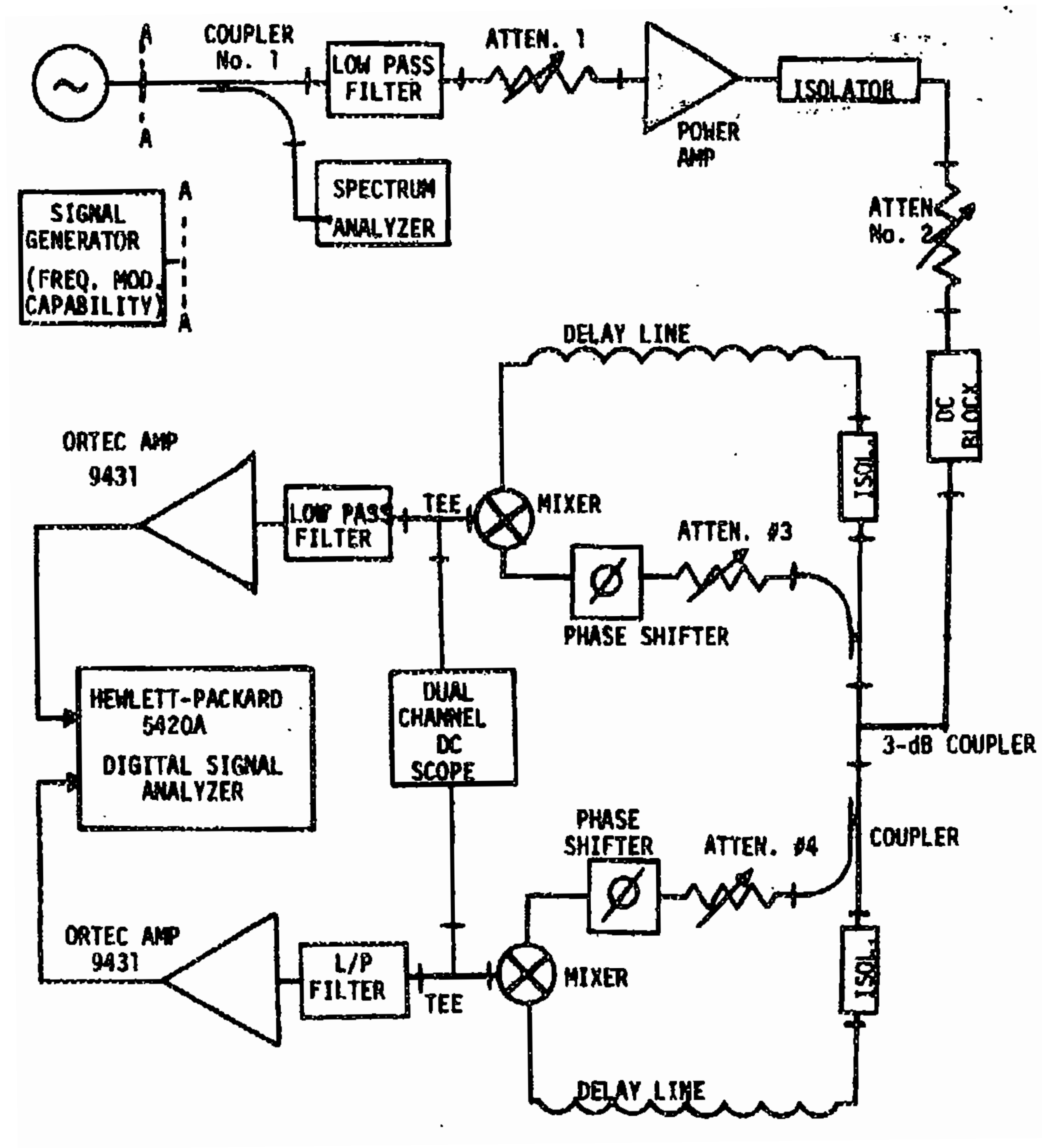
Measurement of a sapphire oscillator





- The instrument noise scales as 1/τ, yet the blue and black plots overlap
  magenta, red, green => instrument noise
  blue, black => noise of the sapphire oscillator under test
- We can measure the $1/f^3$ phase noise (frequency flicker) of a 10 GHz sapphire oscillator (the lowest-noise microwave oscillator)
- Low AM noise of the oscillator under test is necessary

Phase noise measurement



Original idea:
D. Halford's NBS notebook
F10 p.19-38, apr 1975

First published: A. L. Lance & al, CPEM Digest, 1978

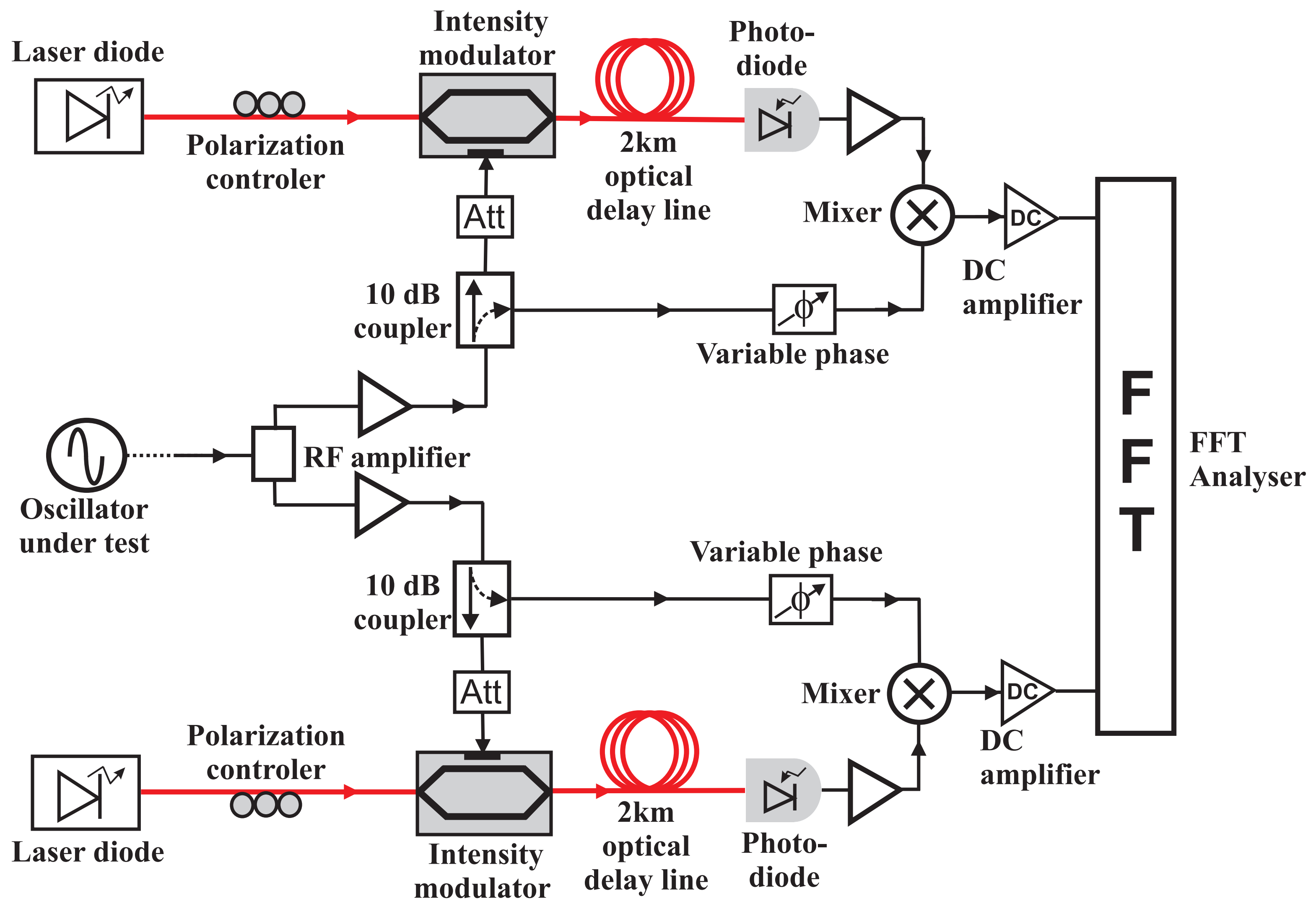
The delay line converts the frequency noise into phase noise

The high loss of the coaxial cable limits the maximum delay

Updated version:
The optical fiber provides long delay with low attenuation (0.2 dB/km or 0.04 dB/µs)

A.L. Lance, W.D. Seal, F. Labaar ISA Transact.21 (4) p.37-84, Apr 1982

Dual-channel (correlation) measurement

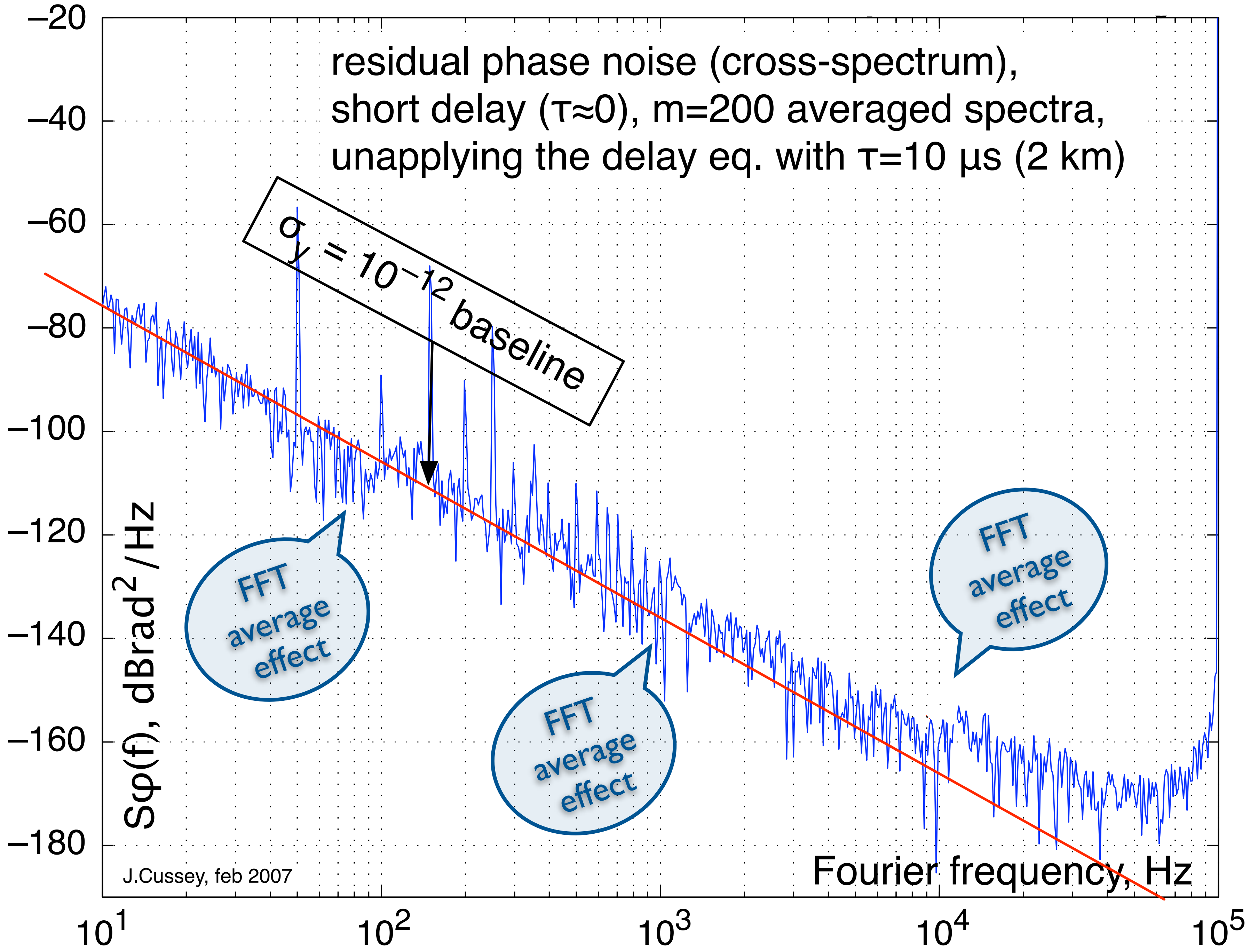


Improvements

- Understanding flicker (photodetectors and amplifiers)
- SiGe technology provides lower 1/f phase noise
- CATV laser diodes exhibit lower AM/FM noise
- Low Vπ EOMs show higher stability because of the lower RF power
- Optical fiber sub-mK temperature controlled

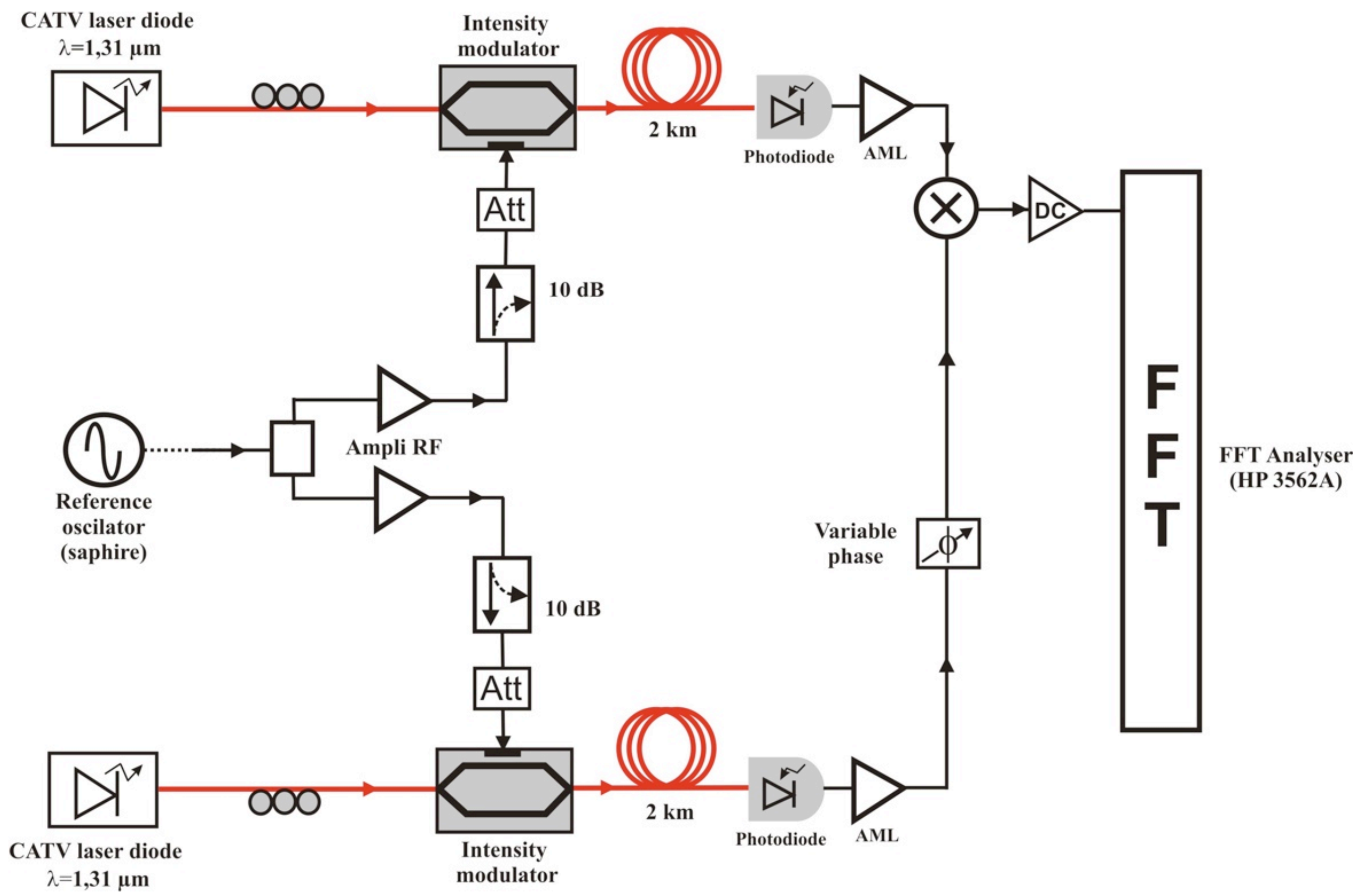
derives from: E. Salik, N. Yu, L. Maleki, E. Rubiola, Proc. Ultrasonics-FCS Joint Conf., Montreal, Aug 2004 p.303-306

Dual-channel (correlation) measurement



the residual noise is clearly limited by the number of averaged spectra, m=200

Measurement of the delay-line noise (1)

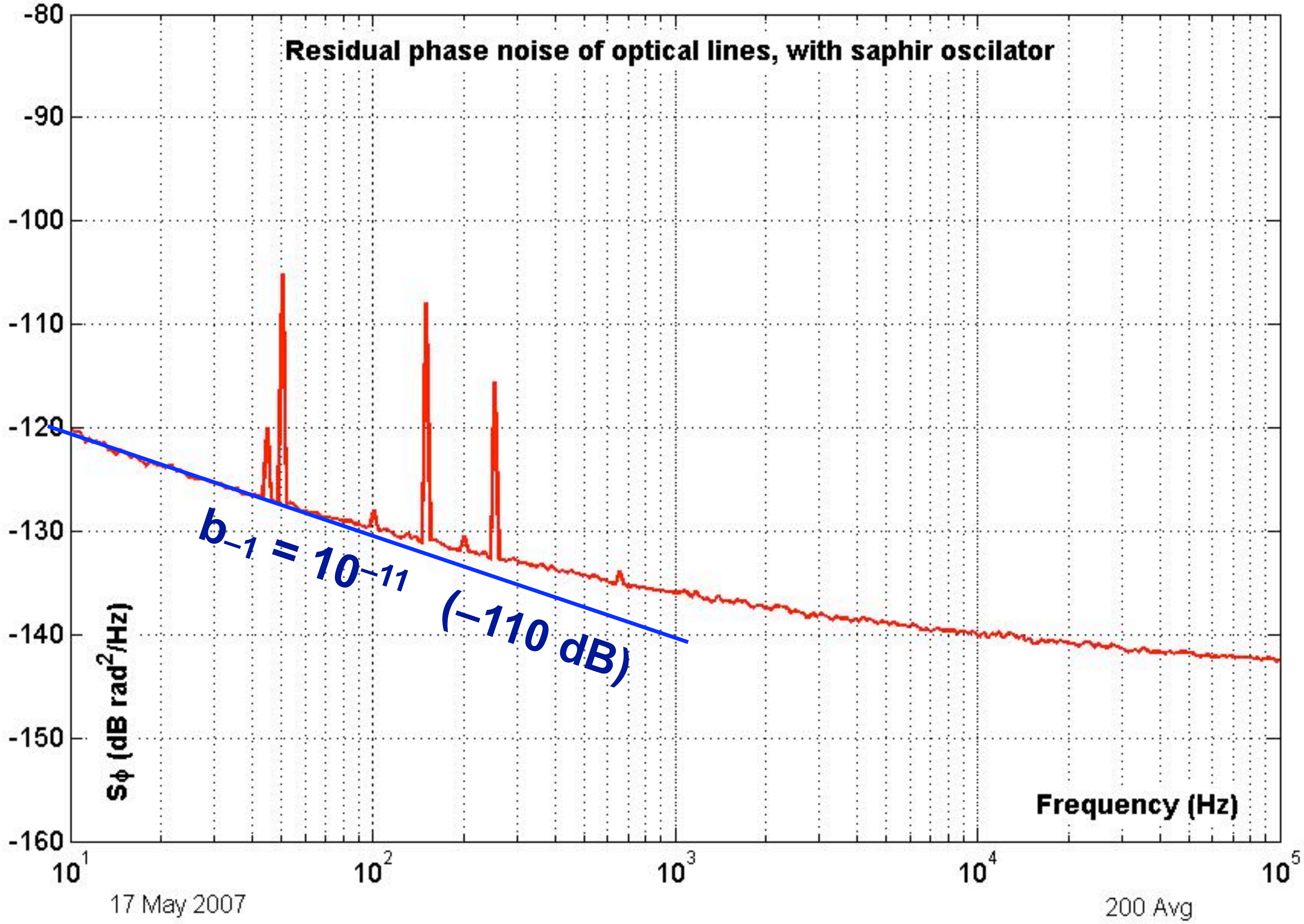


- matching the delays, the oscillator phase noise cancels
- this scheme gives the **total** noise

  2 × (ampli + fiber + photodiode + ampli) + mixer

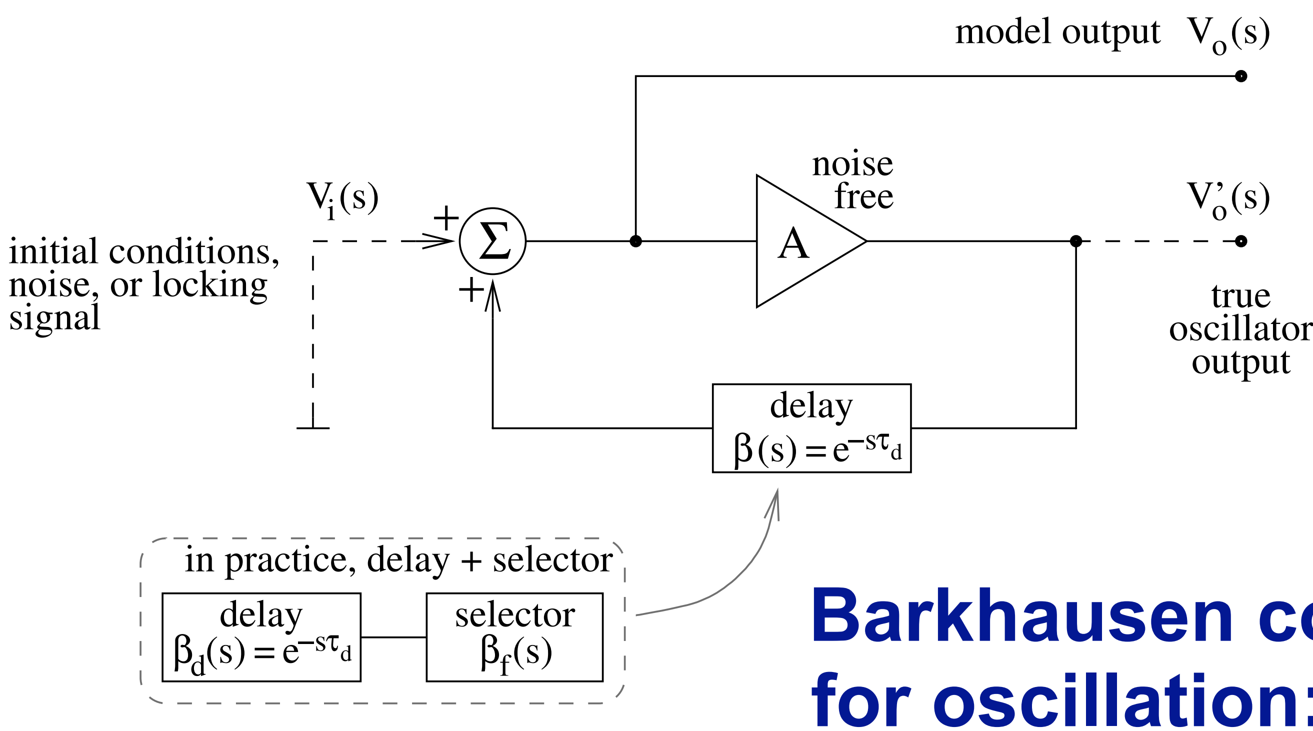
  thus it enables only to assess an upper bound of the delay-line noise

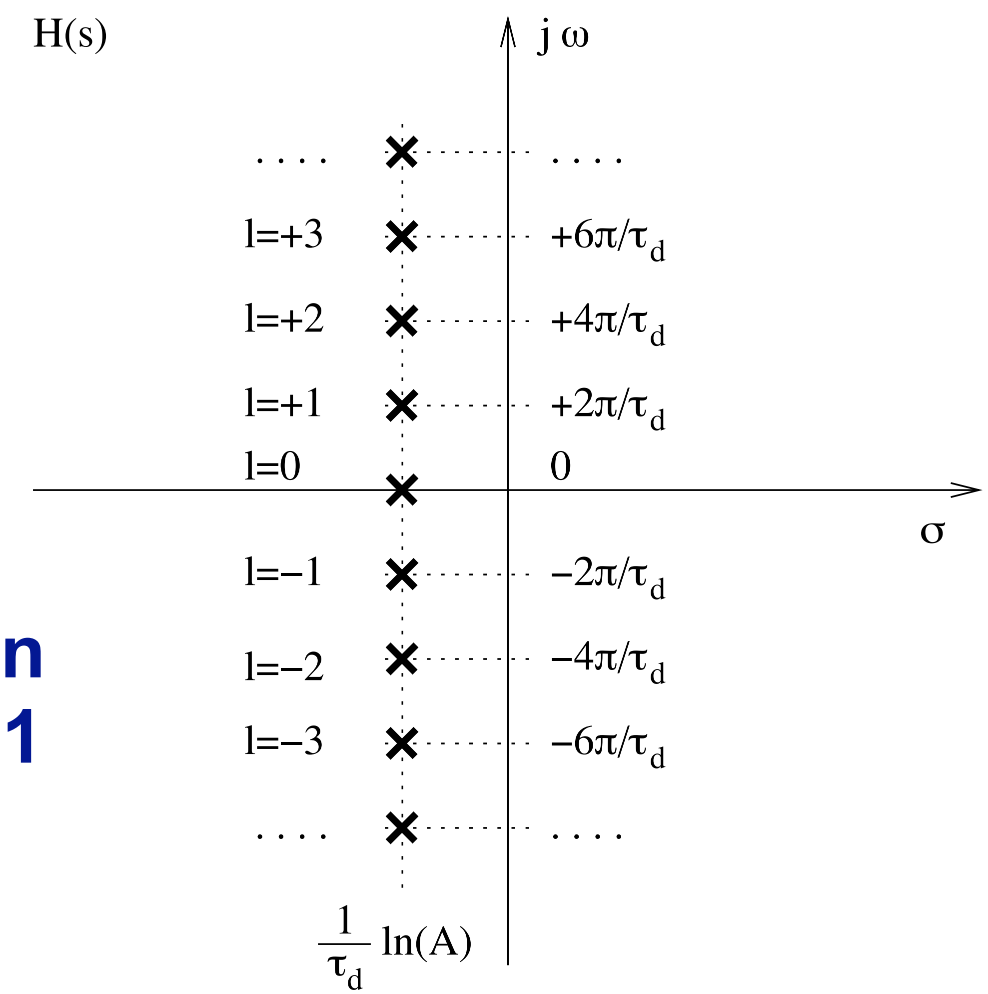
Measurement of the delay-line noise (2)



- The method enables only to assess an **upper bound of the delay-line noise** $b_{-1} \leq 5\times10^{-12}$ rad^2/Hz for L = 2 km (–113 dBrad^2/Hz)
- We believe that this residual noise is the signature of the two GaAs power amplifier that drives the MZ modulator

Delay-line oscillator – operation





Barkhausen condition for oscillation: Aß = 1

General feedback theory

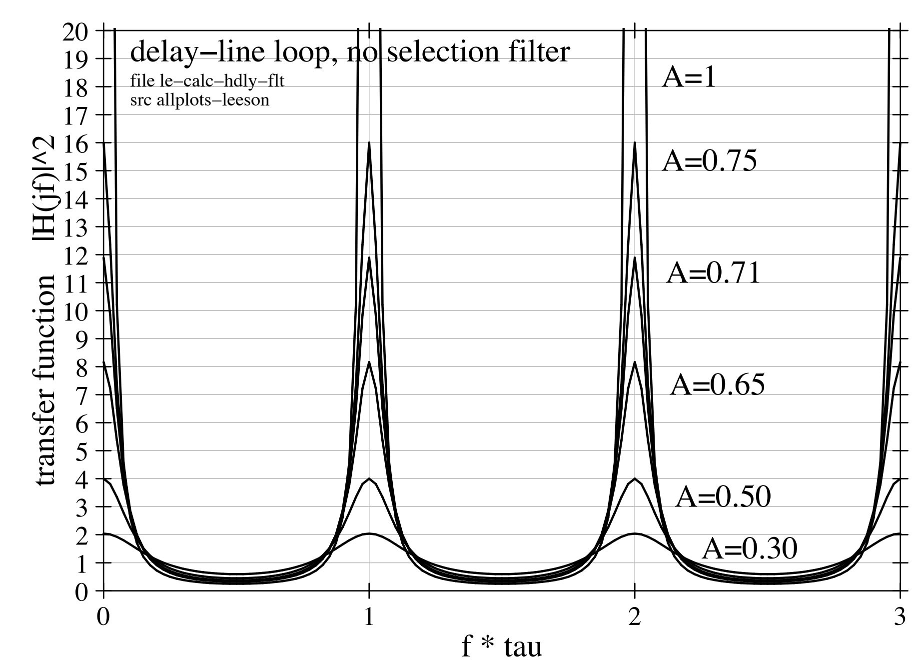
$$H(s) = \frac{V_o(s)}{V_i(s)} = \frac{1}{1 - A\beta(s)}$$

Delay-line oscillator

$$H(s) = \frac{1}{1 - Ae^{-s\tau_d}}$$

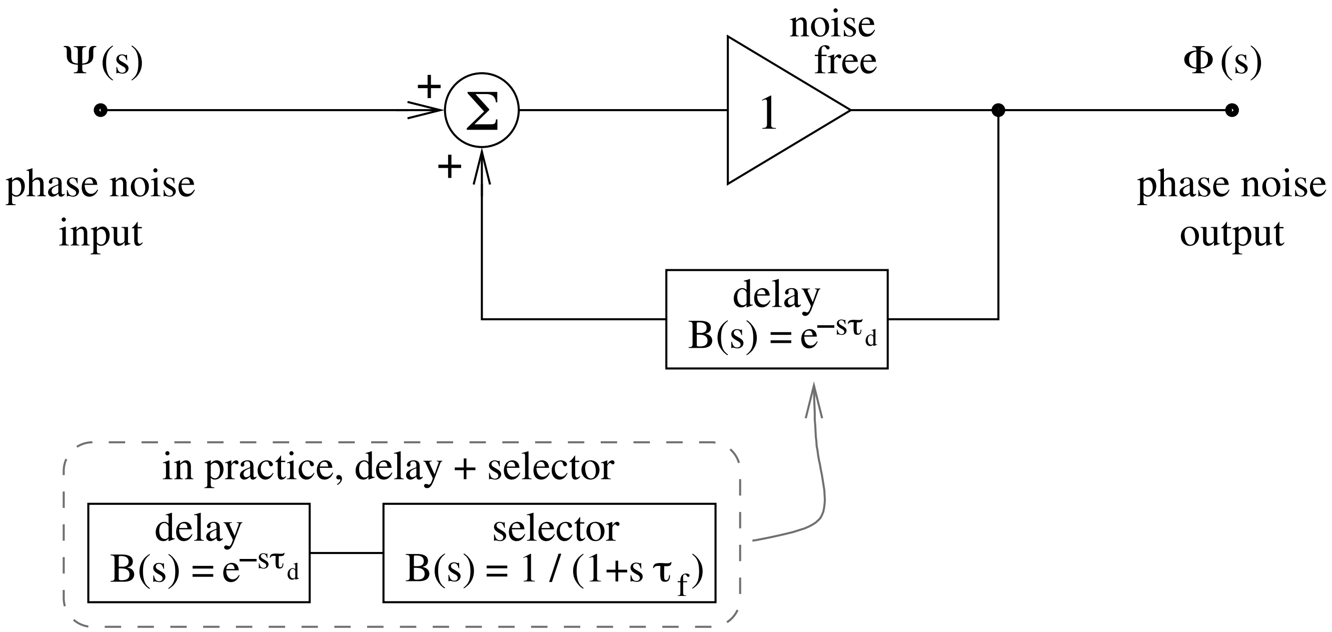
Location of the roots

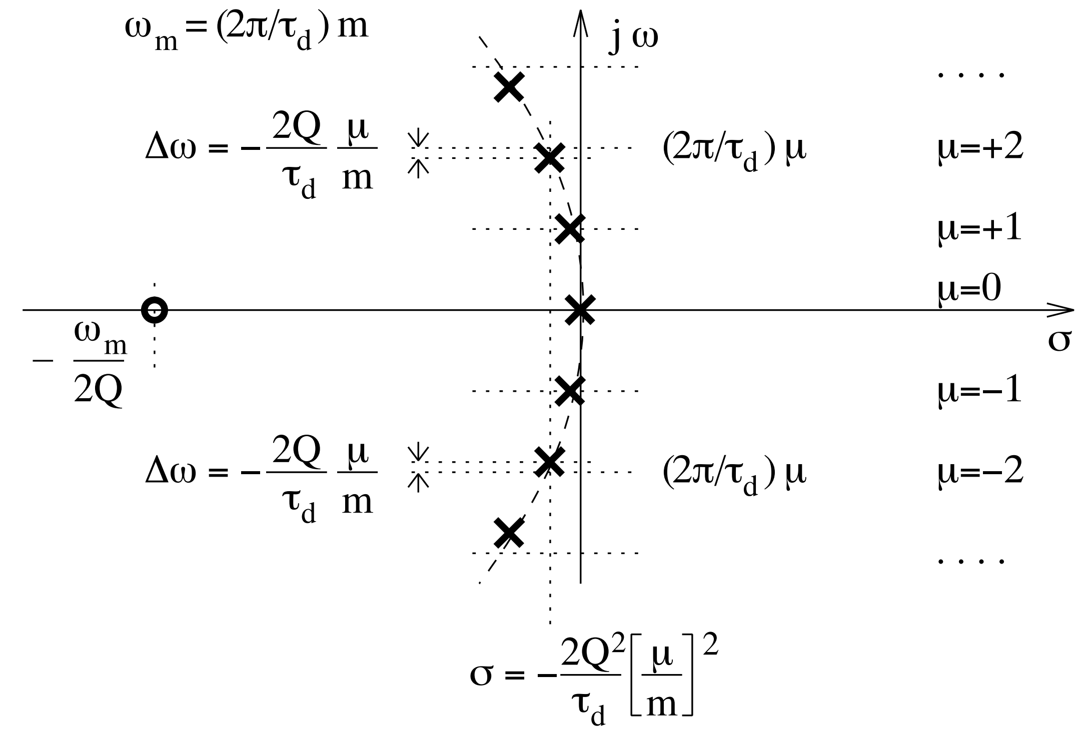
$$s_l = \frac{1}{\tau_d}\ln(A) + j\frac{2\pi}{\tau_d}l \qquad \text{integer } l \in (-\infty, \infty)$$



E. Rubiola, *Phase Noise and Frequency Stability in Oscillators*, Cambridge 2008, ISBN13 9780521886772

Delay-line oscillator – phase noise





General feedback theory

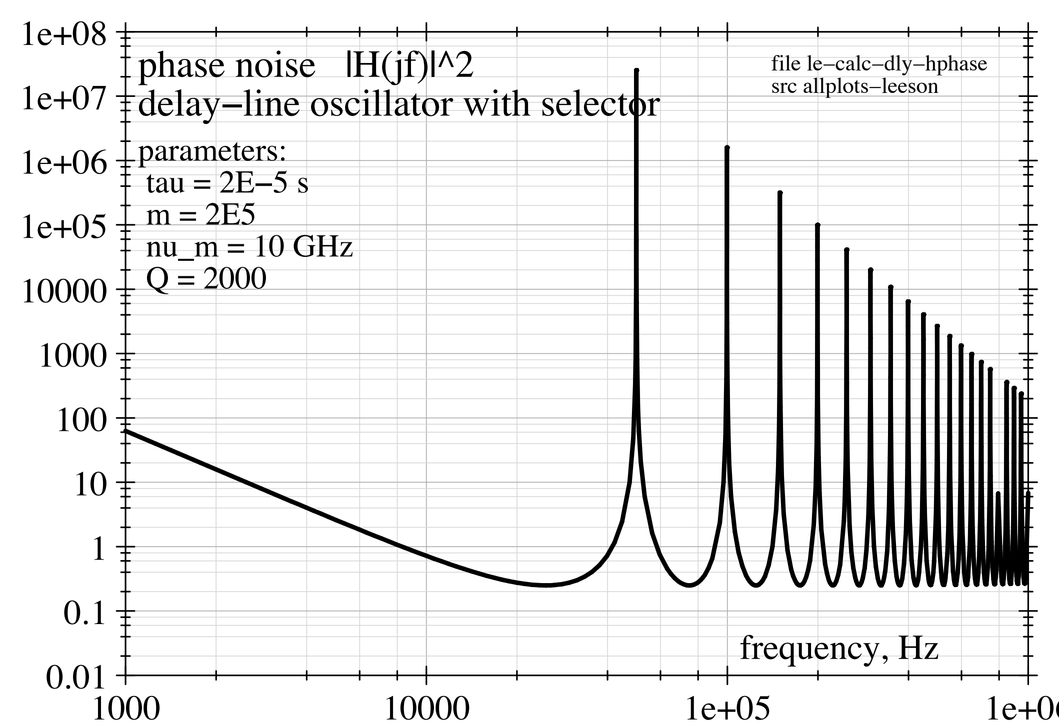
$$H(s) = \frac{\Phi(s)}{\Psi(s)} = \frac{1}{1 - B(s)}$$

Delay-line oscillator

$$H(s) = \frac{1 + s\tau_f}{1 + s\tau_f - e^{-s\tau_d}}$$

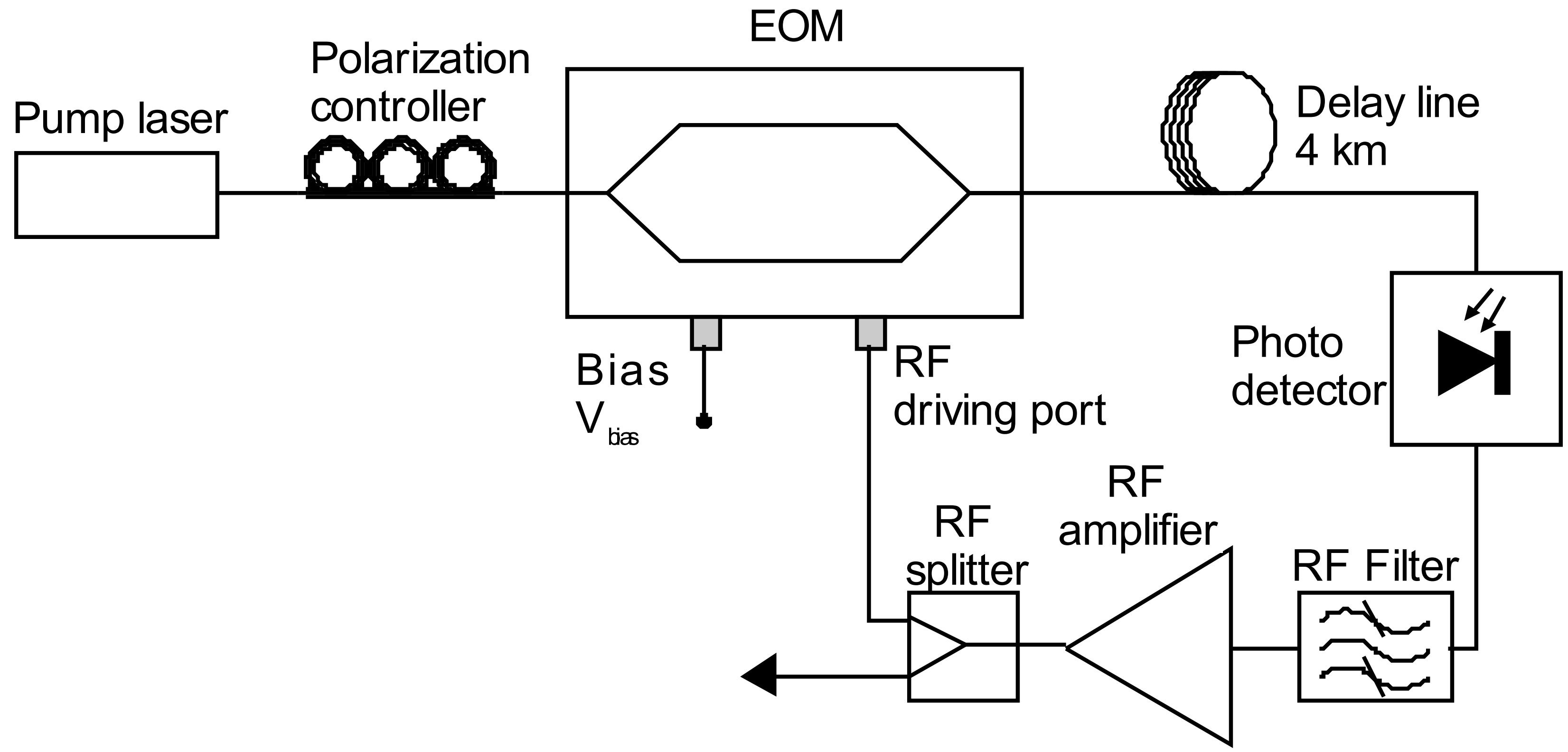
Location of the roots

$$s_\mu = -\frac{2Q^2}{\tau_d}\left(\frac{\mu}{m}\right)^2 + j\frac{2\pi}{\tau_d}\mu - \frac{2Q}{\tau_d}\,\frac{\mu}{m}$$



E. Rubiola, *Phase Noise and Frequency Stability in Oscillators*, Cambridge 2008, ISBN13 9780521886772

Delay-line oscillator – expected flicker



$Q_{eq} = \pi \nu_0 \tau$

$f_L = \frac{\nu_0}{2Q}$

$Q_{eq} = 3\times10^5 \leftarrow L = 4\text{km}$

$f_L = \frac{1}{4\pi^2\tau^2}$

f_L=8kHz

Leeson formula

$S_\varphi(f) \simeq \frac{f_L^2}{f^2} S_\psi(f) \quad \text{for } f \ll f_L$

10^{-11}

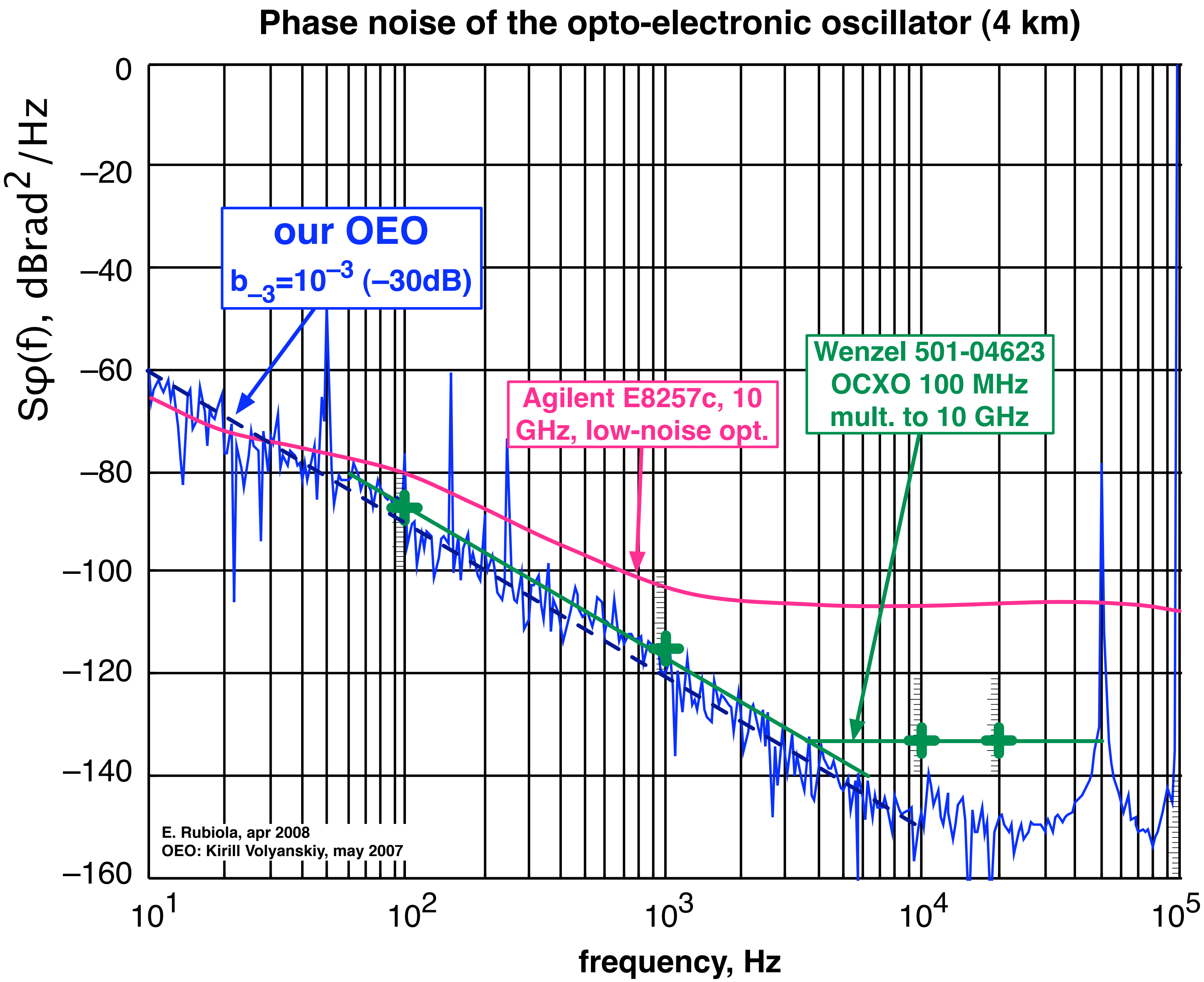
$b_{-3} = 6.3\times10^{-4}$ (–32 dB)

$h_{-1} = b_{-3}/\nu_0^2$ 6.3×10^{-24}

$\sigma_y^2 = 2\ln(2)\, h_{-1}$ 8.8×10^{-24}

$\sigma_y \simeq 2.9\times10^{-12}$ **Allan deviation**

Delay-line oscillator – measured noise



- 1.310 nm DFB CATV laser
- Photodetector DSC 402 (R = 371 V/W)
- RF filter ν_0 = 10 GHz, Q = 125
- RF amplifier AML812PNB1901 (gain +22dB)

expected phase noise
$b_{-3} \approx 6.3\times10^{-4}$ (–32 dB)

Conclusions

- **The optical fiber is suitable to a wide range of microwave frequency with fine pitch**
- **At room temperature, short-term stability is similar/ better to a sapphire oscillator**
- **Single- and dual-channel phase noise measurements**
- **Opto-electronic oscillator, theory and experiments**

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