Coupling Phenomena in Semiconductor Lasers and Applications to Self-Mix Interferometry

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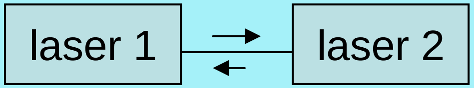
Summary

- Introduction
- Coupling regimes
- Weak coupling and Self-Mixing
- Developing Interferometers
- Experiments
- Conclusions

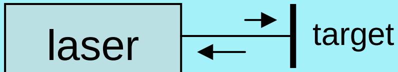
Introduction

◇ Coupling phenomena can take place:

- between two laser sources (and we call them *mutual-coupling* or *injection*)



- in a single source, as self-coupling of field to a remote target (and we call it *self-mixing*)



◇ The level of coupling may be *weak* (fraction of power interacting: down to 10^{-8}) or *strong* (fraction of power up to a few 10^{-2})

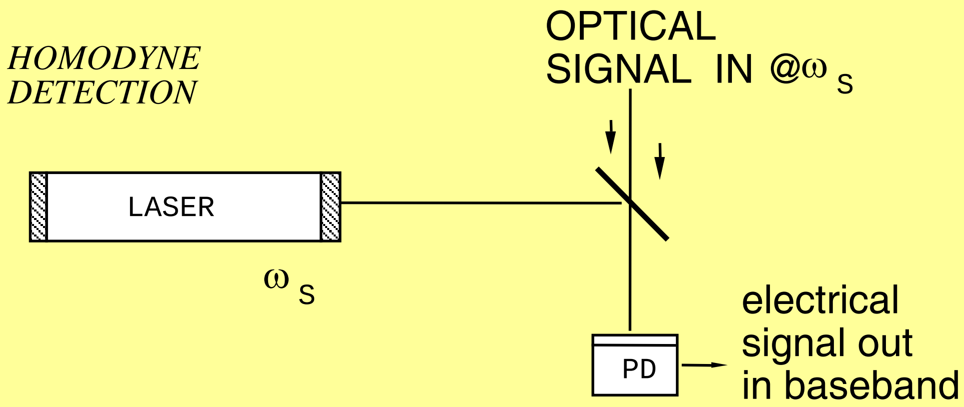
- At *weak level* we observe AM and FM *modulations* of the cavity field, carrying information on the external perturbation (coupled signal in mutual coupling) or amplitude/phase of returning field (in self-mixing)

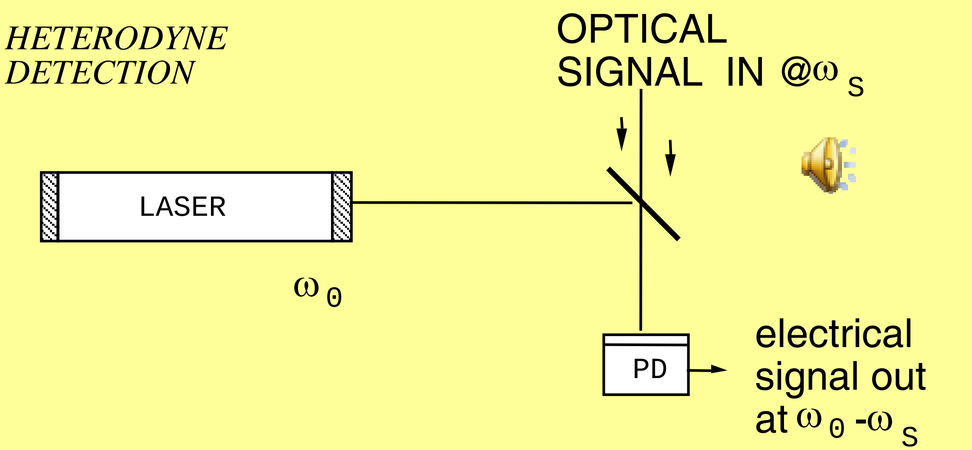
→ *interferometer* → *coherent (injection) detection*

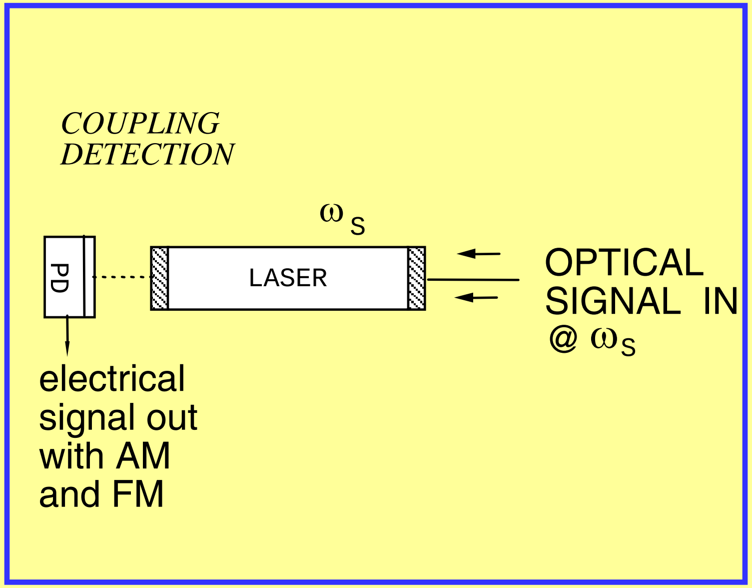
- At *strong* levels we get chaos, both in mutual coupling and self- mixing schemes)

→ *cryptography*

Mutual coupling as a new configuration of coherent detection

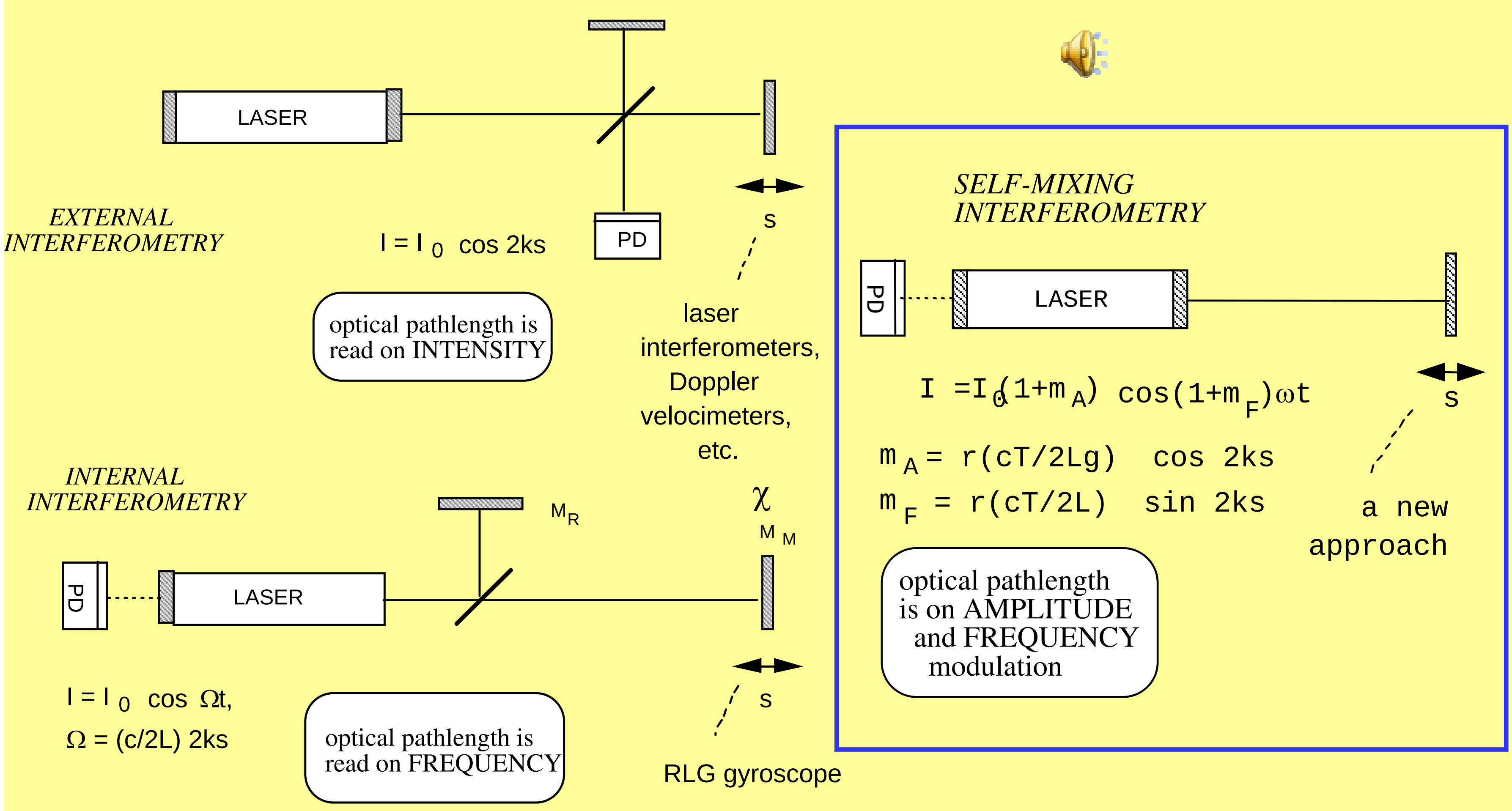






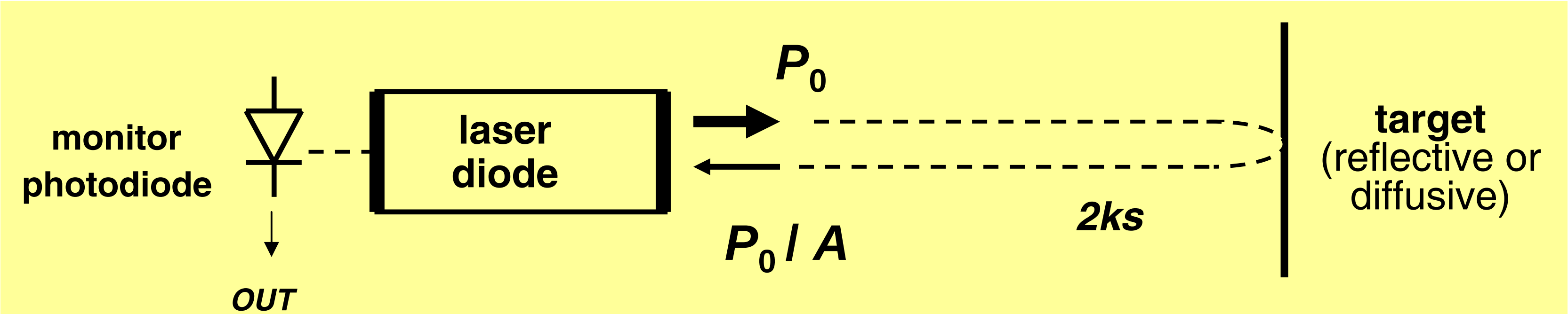
Despite the output signal is different, coupling detection belongs to schemes of coherent detection because dependence is on *field* and it always works in quantum-limited regime

Self-mixing as a new configuration of interferometer



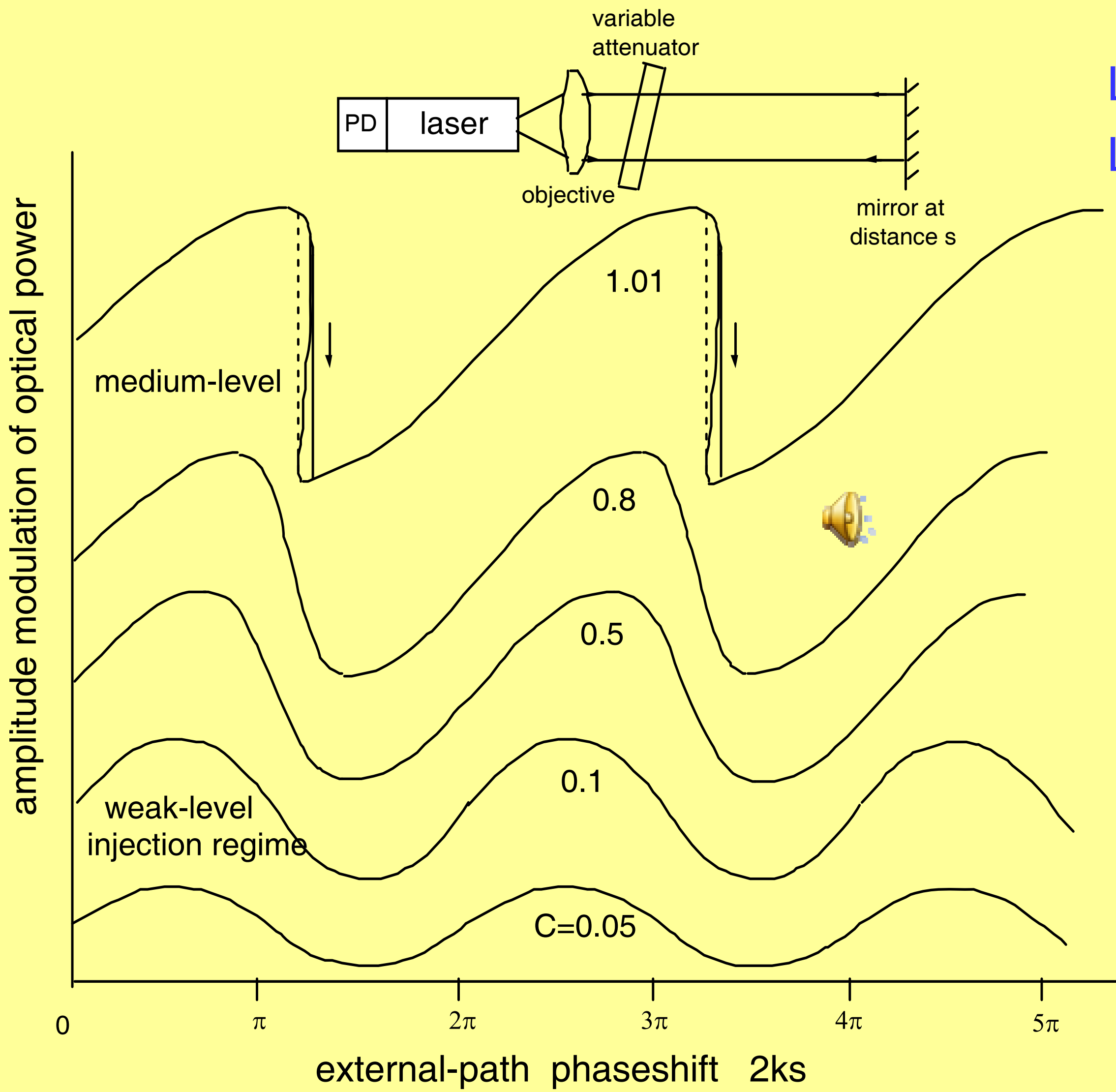
Compared to other schemes of interferometry, self-mixing yields a different output signal yet information contained in it is the same, a sine/cosine function of optical phase length 2ks

basic self-mix properties



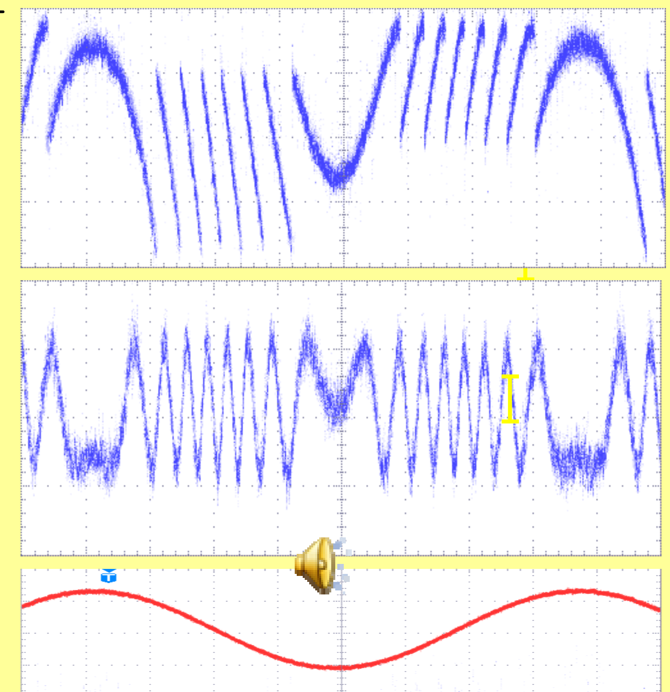
- light propagated to the target and back modulates in amplitude the cavity field and hence the emitted power
- output power from the laser is $P = P_0\,[1+m\cdot F(2ks)]$
- modulation index $m = A^{-1/2}\,[c/2s(\gamma-1/\tau)]$ depends on the *field* attenuation $A^{-1/2}$ (so, self-mix is a *coherent* process)
- waveform $F(2ks)$ is a periodic function of external phase $\phi = 2ks$, and for weak injection is a cosine function. F makes a full cycle every $\Delta s = \phi/2k = 2\pi/2k = \lambda/2$ (as in a plain interferometer)
- In general, the shape of F(…) depends on the injection parameter $C = (1+\alpha^2)^{1/2} A^{-1/2}\,[\varepsilon(1-R_2)/\sqrt{R_2}]\; s/n_{las}L_{las}$

injection level: weak and moderate



LD 1-channel interferometer

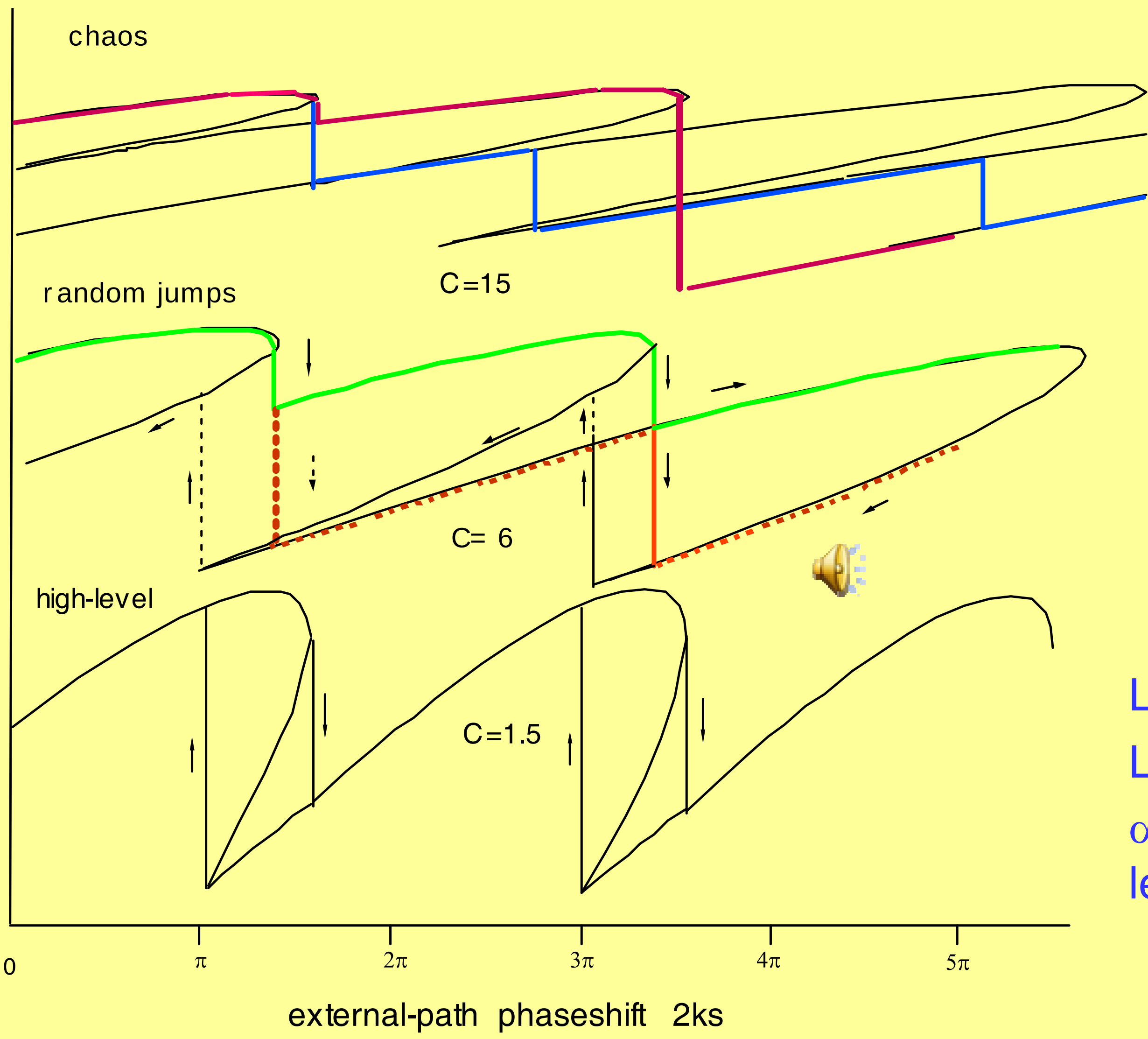
Laser Diode Vibrometer



He-Ne 2-channel interferometer, LDVs

Echo coherent-detectors

injection level: moderate and strong



Chaotic Generators

Angle Sensors

LD 1-channel interferometer

Laser Diode Vibrometer

α-factor and coherence length measurement

theories for self-mixing

◊ **rotating-vector addition**

qualitative and easy, but few results deduced

◊ **3-mirror model**

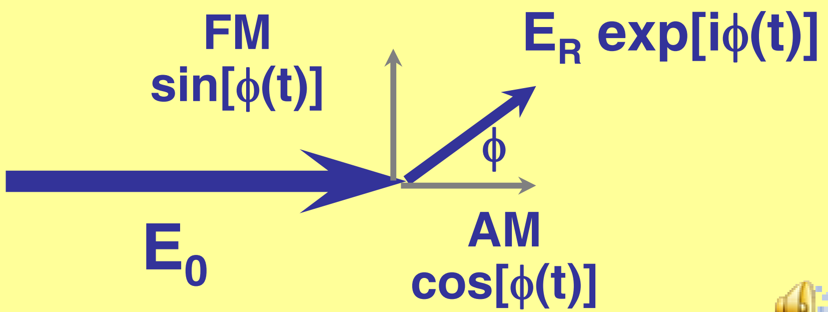
basic results deduced with a simple analysis

◊ **Lang-Kobayashi (laser diode) equations**

a complete description, yields a powerful treatment

rotating-vector addition

- In the laser cavity, frequency and amplitude modulation of the lasing field occur



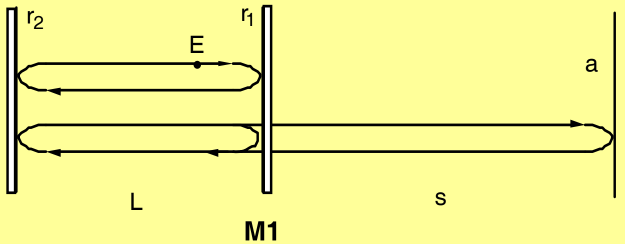
ϕ = 2ks

k = $2\pi/\lambda$

s(t) = target distance

- **AM is easily detected in a DL as a modulation superposed on the average power emitted by the source**
- **FM requires a frequency down-conversion, and we can only get it in a dual-mode, frequency-stabilized He-Ne laser**

3-mirror model



The II Barkhausen condition is applied to balance at M1: $E\, r_1\, r_2 \exp 2\alpha^* L \exp i2kL = E\, a \exp i2ks$

perturbed loop gain then follows as:

$G_{loop} = r_1\, r_2 \exp 2\alpha^* L \exp i2kL + a \exp i2ks$

and the zero-phase condition is

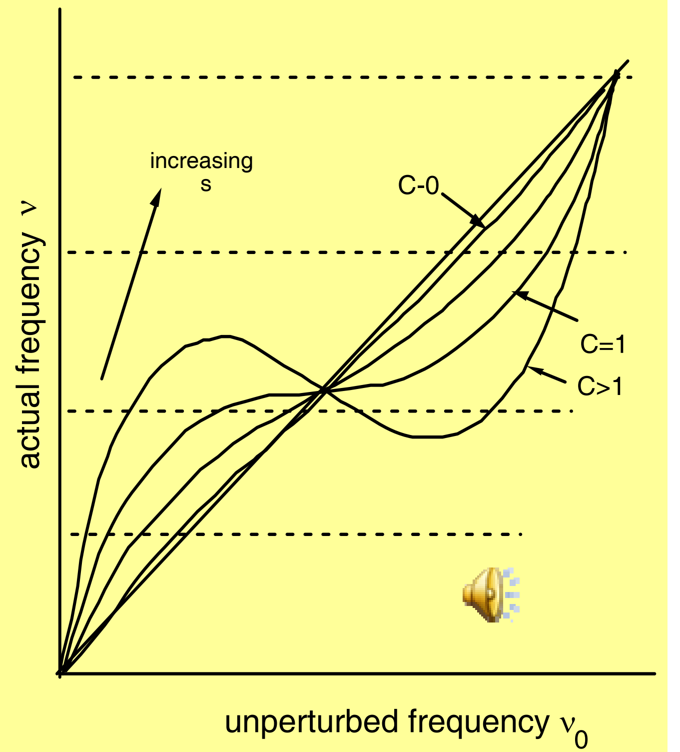
$r_1\, r_2 \exp 2\alpha^* L \sin 4\pi L n_l(\nu-\nu_0)/c + a \sin 2ks = 0$

The diagram at right

$$\boxed{\nu = \nu_0 + (c/4\pi L n_l)\, a \sin 4\pi s/\lambda}$$

is obtained for injection-perturbed frequency ν vs unperturbed frequency ν_0

Diagram shows that for C<1 there is one solution for ν, whereas for1<C<4.6 there are 3 solutions and **ECM** (ext cavity modes) start to be excited



Lang-Kobayashi equations

These Equations are the well-known Lamb's equation for an adiabatic active medium, adapted to a semiconductor medium where density of carriers is coupled to photon density (or field amplitude), see R. Lang, K. Kobayashi, *IEEE J. Quantum Electron.*, 1988

$$\frac{dE_0(t)}{dt} = \frac{1}{2}\left[G_N(N(t) - N_0) - \frac{1}{\tau_p}\right]E_0(t) \boxed{+ \frac{\chi}{\tau_L}E_0(t-\tau)\cos[\omega_0\tau + \phi(t) - \phi(t-\tau)]}$$

$$\frac{d\phi(t)}{dt} = \frac{1}{2}\alpha G_N(N(t) - N_T) \boxed{- \frac{\chi}{\tau_L}\frac{E_0(t-\tau)}{E_0(t)}\mathrm{sen}[\omega_0\tau + \phi(t) - \phi(t-\tau)]}$$

$$\frac{dN(t)}{dt} = R_P - \frac{N(t)}{\tau_S} - G_N[N(t) - N_0]E_0^2(t)$$

Solutions reveal: F(ϕ) waveforms, AM/FM modulation, C factor, bi- and multi-stability, line broadening, route to chaos, etc. Of course, equations are easily re-written for mutual coupling of E_1 and E_2.

features of self-mixing interferometer

Injection (of Self-mixing) interferometer vs conventional types

advantages:

- optical part-count is minimal
- self-aligned setup (measures where spot hits)
- no spatial, λ or stray-light filters required
- operates on a normal diffusing target surface
- signal is everywhere on the beam, also at the target side
- resolution is λ/2 with fringe counting and sub-λ with analog processing
- bandwidth up to hundreds kHz or MHz

disadvantages:

- reference is missing (in the basic setup)
- wavelength accuracy and long-term stability is poor (with LD)
- little flexibility of reconfiguration

Dolly on self-mixing applications

Metrology

- Displacement
- Vibration
- Velocity
- Distance
- Angle

Physical Quantities

- Coherence Length
- α - linewidth enhancement factor
- Remote echoes
- Return loss and Isolation factor

Sensing

- CD readout
- Scroll sensor

but...

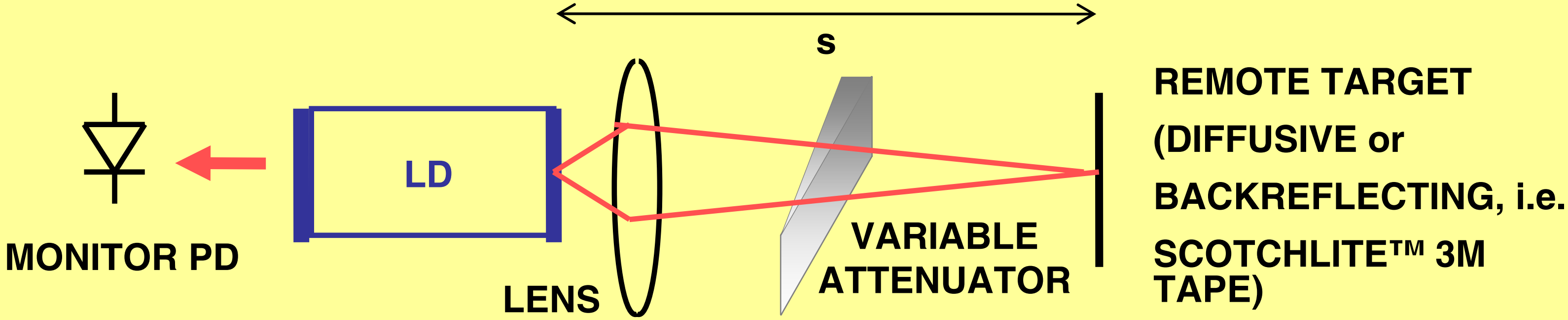
there are problems to be solved on the way of selfmix technology ..!

a) The first is:

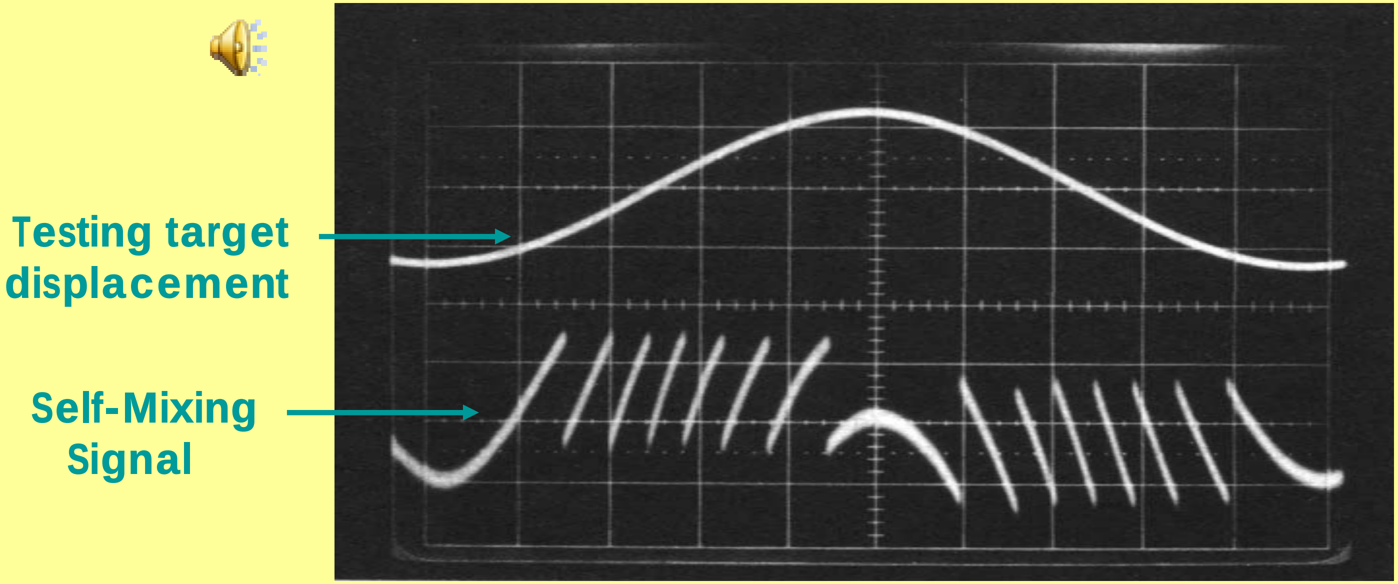
we need a second signal, *sin 2ks* or something equivalent to that, for a *digital processing,* because the plain *cos 2ks* signal is not enough to measure $\lambda/2$ displacements without sign ambiguity

- luckily enough, it happened that ....

Measuring displacements



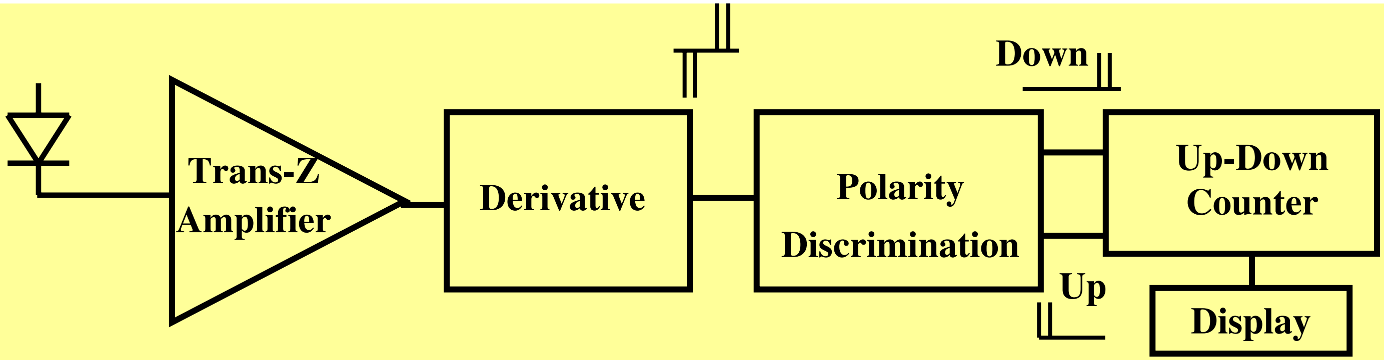
- best regime: moderate feedback C > 1, but also C< 4.6
- principle: counting of fast signal transitions with polarity

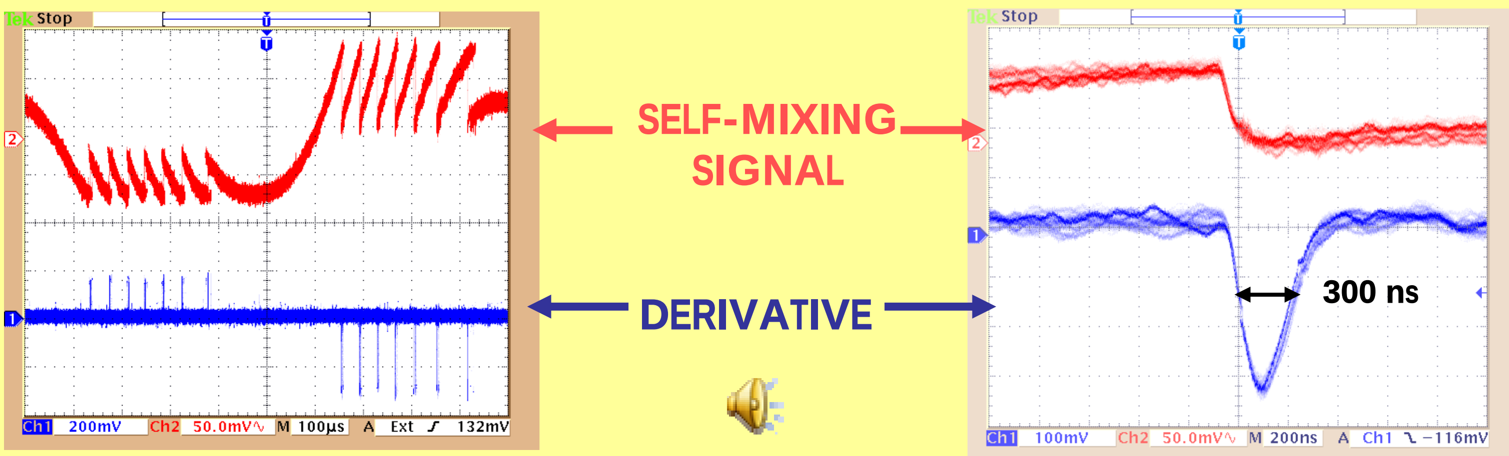


S.Donati, G.Giuliani, S.Merlo, J.Quant.El. <u>31</u> (1995) pp.113-19

cited by 142 (Google Scholar)

Displacement: circuit functions





100 µs/div

0.2 µs/div

- Resolution: 420 nm
- Max. Target speed: 0.4 m/s
- Distance range 0.4 ÷ 1.6 m

S.Donati, G.Giuliani, S.Merlo, J.Quant.El. 31 (1995) pp.113-19 cited by 142

Displacement: pushing the performance limit

On a corner-cube, the self-mix measures displacement up to ≥2m, in λ/2=0.42 μm steps, with a few ppm accuracy (see figure, from Donati et al., Trans. IM-45, 1996, pp.942-947).

Using a DFB laser, λ-drifts of ≤ 10^{-7} per year should be achieved.

Instead, on a diffuser target, signal is lost because of the speckle pattern **fading**

S.Donati, L.Falzoni, S.Merlo, Trans.Instr.Meas. 45 (1996) pp.942-47 cited by 25

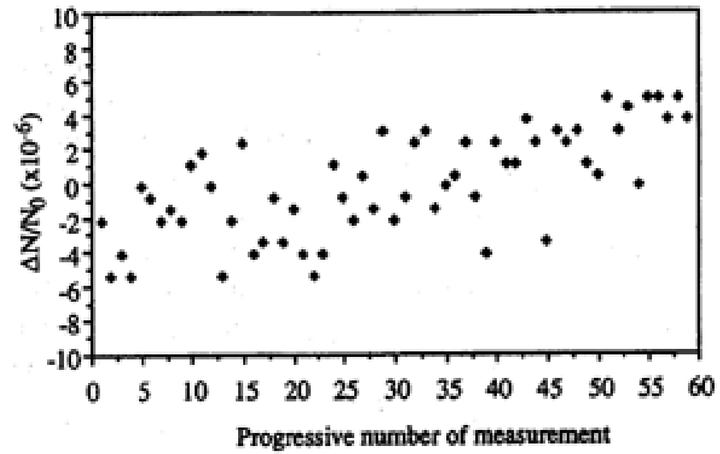


Fig. 5. Experimental residual error obtained with standing target after compensation of laser temperature variations. Every data point corresponds to a 2.28 °C temperature sweep of the laser.

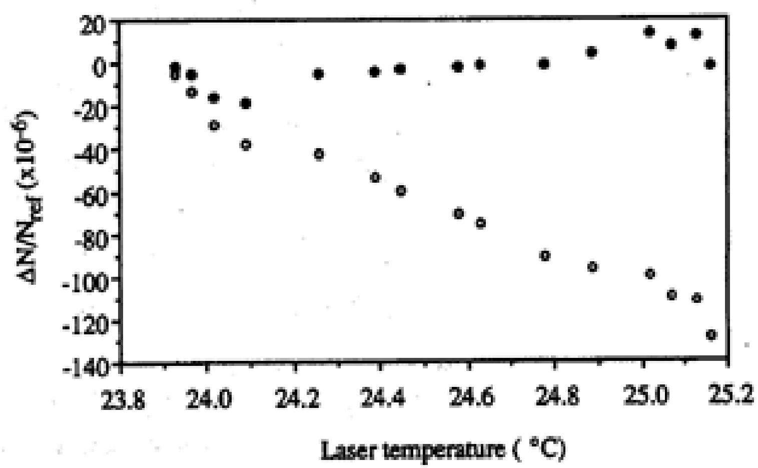
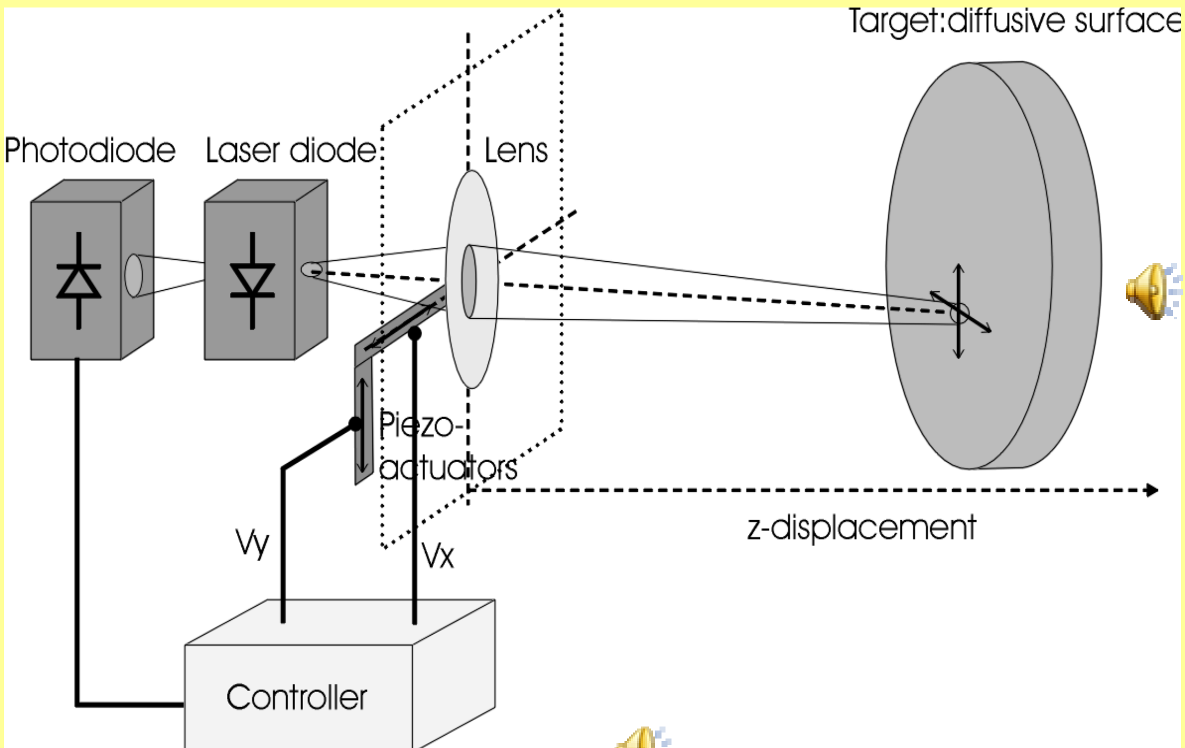


Fig. 6. $\Delta N/N_{ref}$ versus laser temperature, obtained for 22-cm target displacements: ○ experimental data before compensation, ● compensated results.

b) second problem: we need eliminate the speckle pattern statistics that gives *fading* of the selfmix signal because we want to be able to operate on diffuser (not a *specular*) target surface

- We may try tracking the bright speckle ...

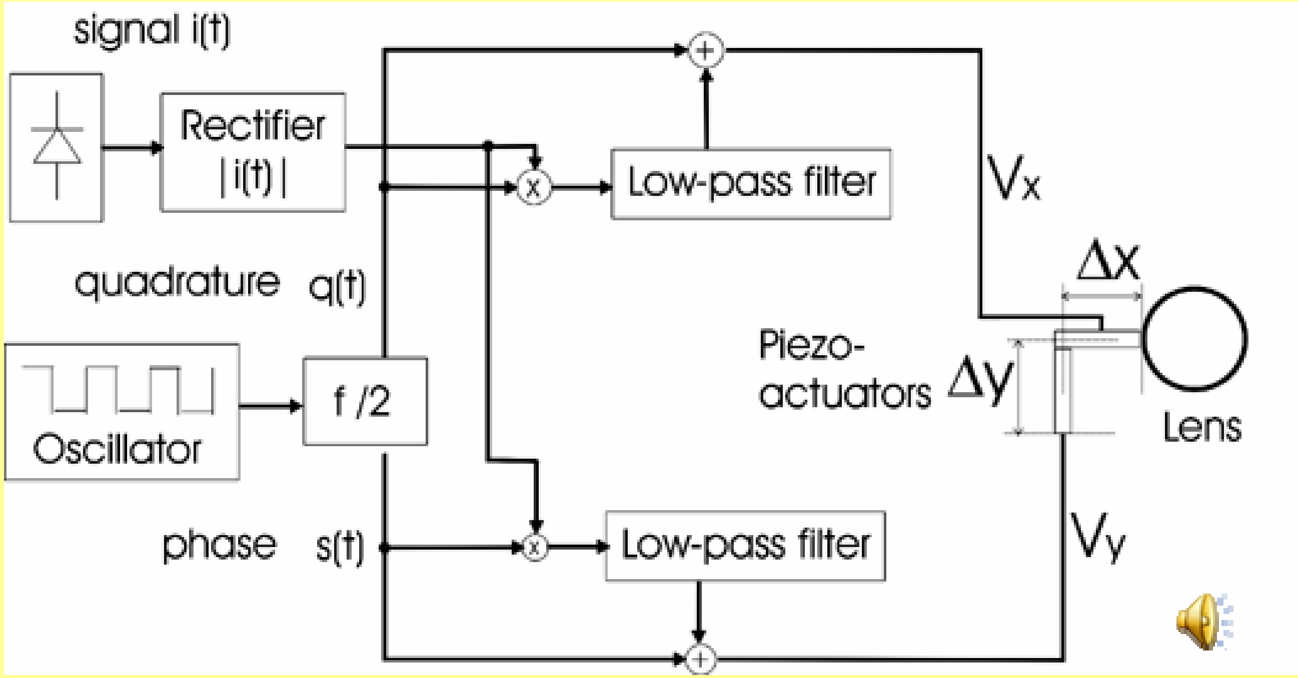
Displacement: the bright-speckle tracking (BST)



Tracking a bright-speckle permits to stay on a maximum of intensity and avoid fading. Operation on a diffuser target is then allowed, with little added error

S.Donati, M.Norgia, J.Quant.El. 37 (2001), pp.800-06 cited by 24

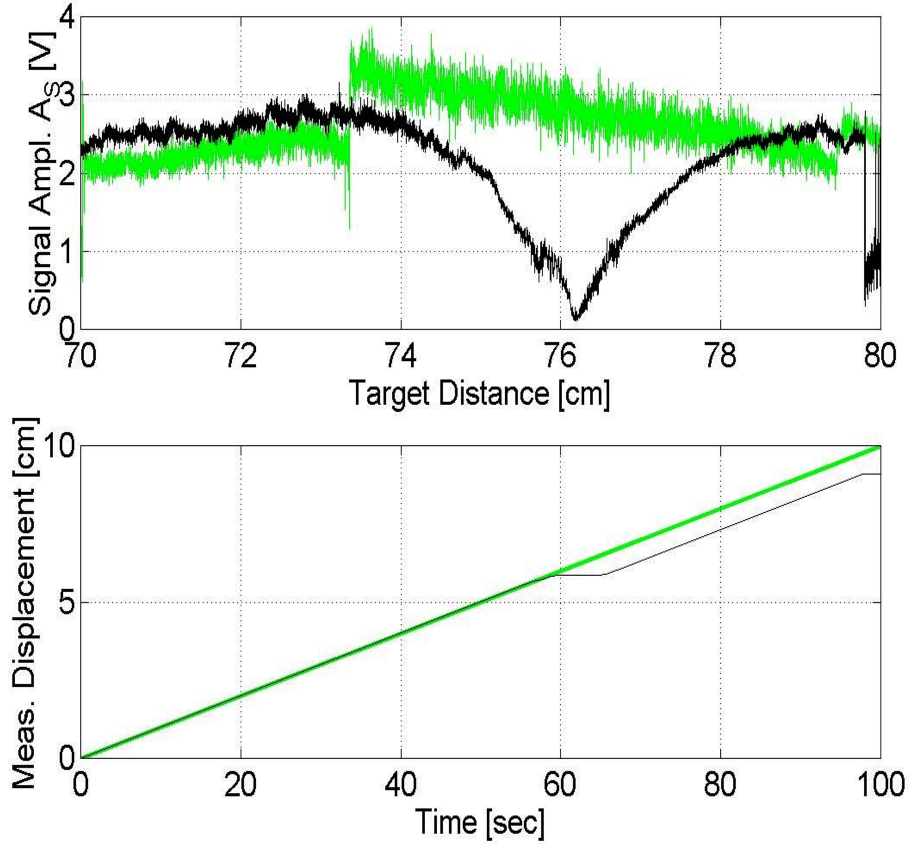
Speckle tracking technique



Block scheme of the speckle-tracking circuit. Signal from the photo-diode is rectified peak-to-peak and demodulated respect to the dither frequency, in phase and quadrature. Results are the X and Y error signals that, after low-pass filter, are sent to the piezo-actuators X and Y to track the maximum amplitude or stay locked on the bright speckle

BST improvement

Top: signal amplitude with (green line) and without (black line) speckle-tracking system, reveals that a fading (at 76 cm) has been removed
Bottom: corresponding displacement as measured by the SMI



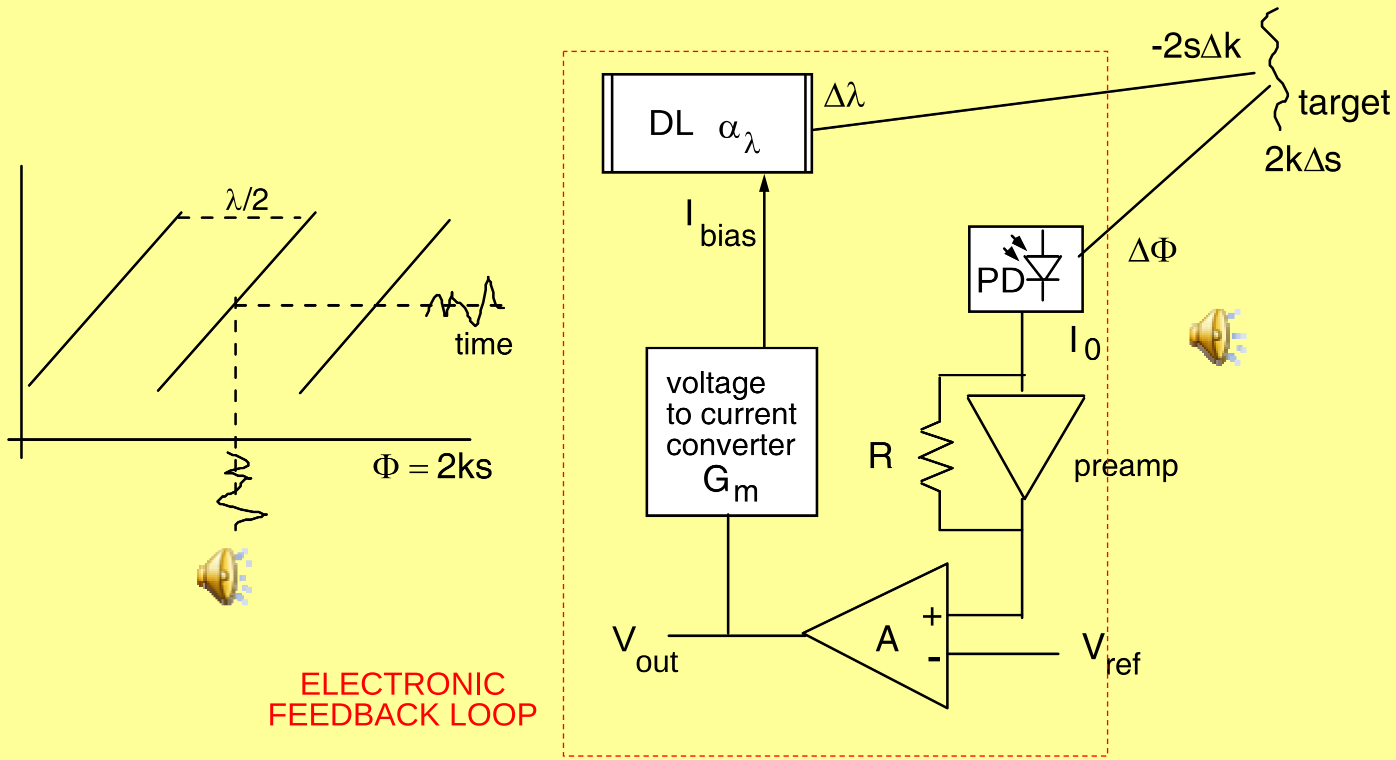
S.Donati, M.Norgia, Trans. Instr. Measur. IM-52 (2003), pp.1765-70

… and now that the digital measurement is OK

c) we want to make an *analogue processing* to measure nanometer (or <<λ) vibration amplitudes

we may do so if we are able to lock at half fringe

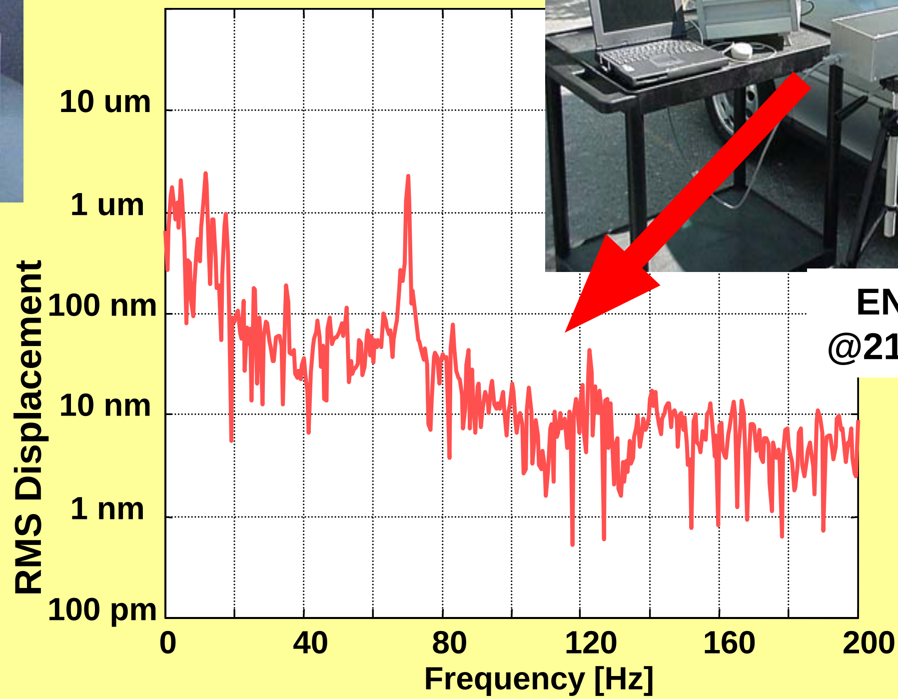
Vibration, mechanical

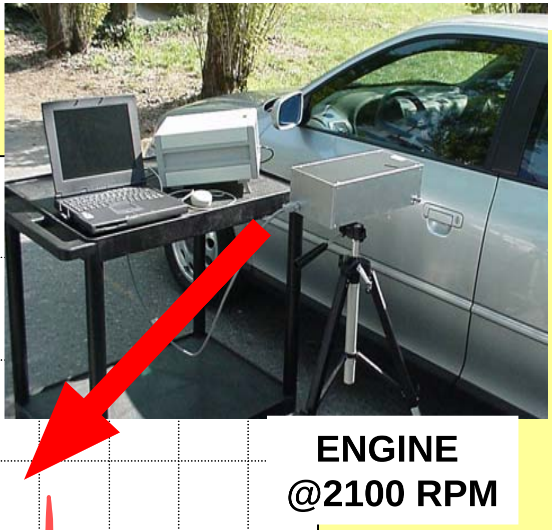


at C>1, fringe response is linear. With this circuit, we can lock the working point to half-fringe, through an active phase nulling. Output signal is the error signal **$\Delta V= [\alpha G_m]^{-1}\, \Delta s\ (\lambda/s)$**, independent from signal amplitude and speckle (if loop gain $G_{loop}=RG_m\alpha(s/\lambda)\sigma P_0$ is large)

S.Donati, G.Giuliani: Meas. Science Techn.,14, 2003, pp.24-32

Vibration: application to the automotive

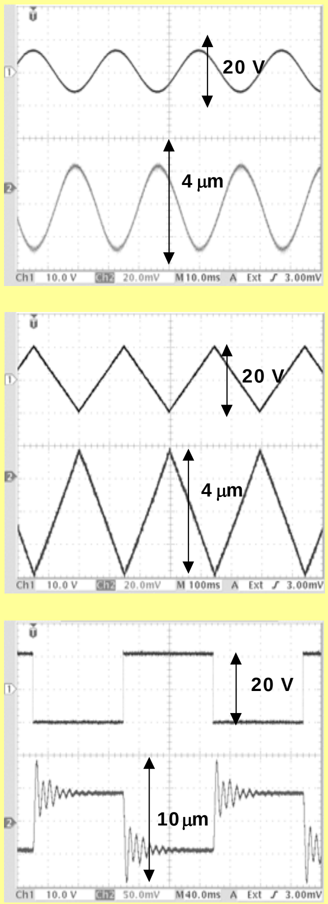




A developmental unit to test automotive vibrations has the following performances: detectable amplitude $\approx$ 100 pm/√Hz; max. amplitude: 600 μmp-p; bandwidth:70 kHz; dyn. Range is > 100 dB

performance of self-mix vibration pick-up

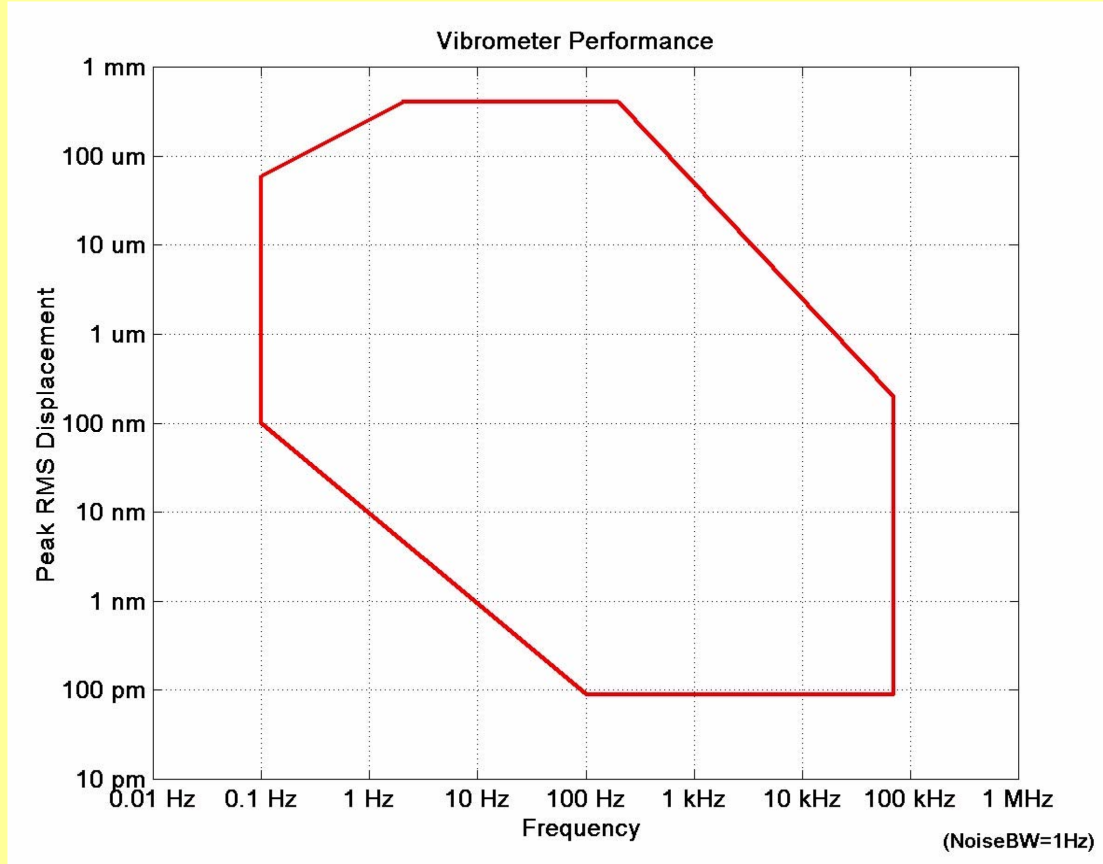
measuring PZT response



a)

b)

c)



Because of the servoing arrangement, the vibration signal finds a dynamic range much larger than λ/2 (in practice, up to ≈200 μm) (Donati et al., J.Optics A, vol.4 (2002), pp.S283-94).

end of part I
please go to part II

Coupling Phenomena in Semiconductor Lasers and Applications to Self-Mix Interferometry, part II