Coupling Phenomena in Semiconductor Laser and Application to Interferometry and Cryptography

Silvano Donati
Department of Electronics, University of Pavia, Pavia, Italy
e-mail: silvano.donati@unipv.it
web: http://www.unipv.it/donati

Summary

Part I

- Coupling regimes in laser diodes
- Low-level coupling and Self-Mixing Interferometry

Part II

- Generation and Synchronization of Optical Chaos
- Application to Chaos Cryptography mainly Chaotic Coding and Masking

conclusions

Part I
Coupling Phenomena and Application to Self-Mixing

Participants:

Group of Electro-Optics, University of Pavia

Silvano Donati

Sabina Merlo - Guido Giuliani

Michele Norgia

European Contract: Selmix (Brite EEC)

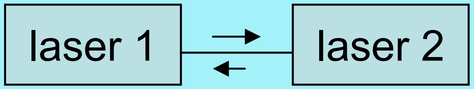
other units:

University of Nantes – SEEM – Fogale (F)

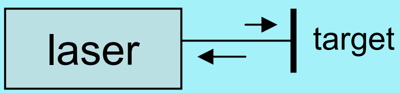
Jenoptik (D) – Quanta System (I)

Part I - introduction

- Coupling phenomena can take place:
  - between two laser sources (and then are called *mutual-coupling* or *injection*)



  - in a single source, by self-coupling of field to a remote target (and this is called *self-mixing*)



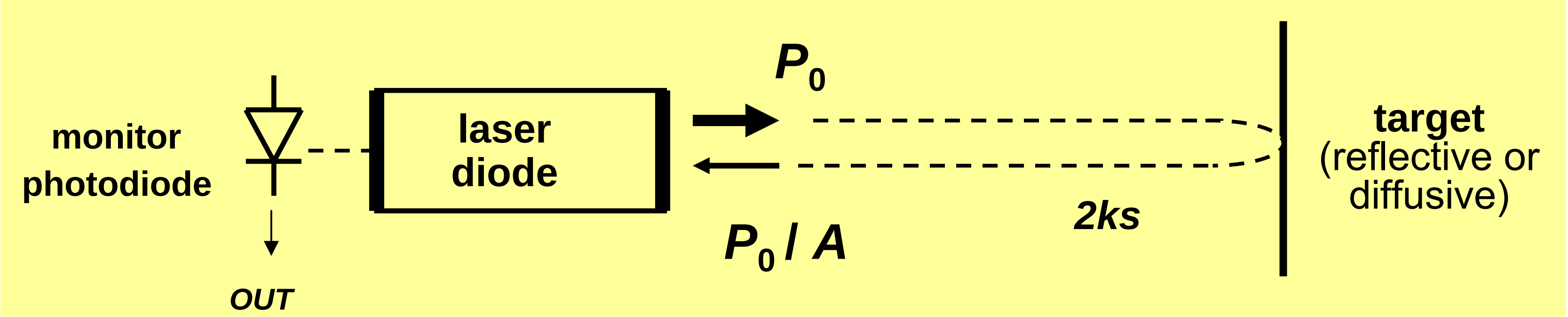
- The level of coupling may be *weak* (fraction of power interacting: down to 10^{-8}) or *strong* (fraction of power up to a few 10^{-2})

◊ At *weak* levels we observe *modulation* of the cavity field, carrying information on the external perturbation (coupled signal in mutual coupling) or amplitude/phase of returning field (in self-mixing)

◊ At *strong* levels we get *chaos*, useful for cryptography (both in mutual coupling and self-mixing schemes)

Now, let us start analyzing the weak level case: self-mixing, a new configuration of *interferometer*

self-mix signal properties



- self-mix power output is $P = P_0\,[1 + m\cdot F(2ks)]$

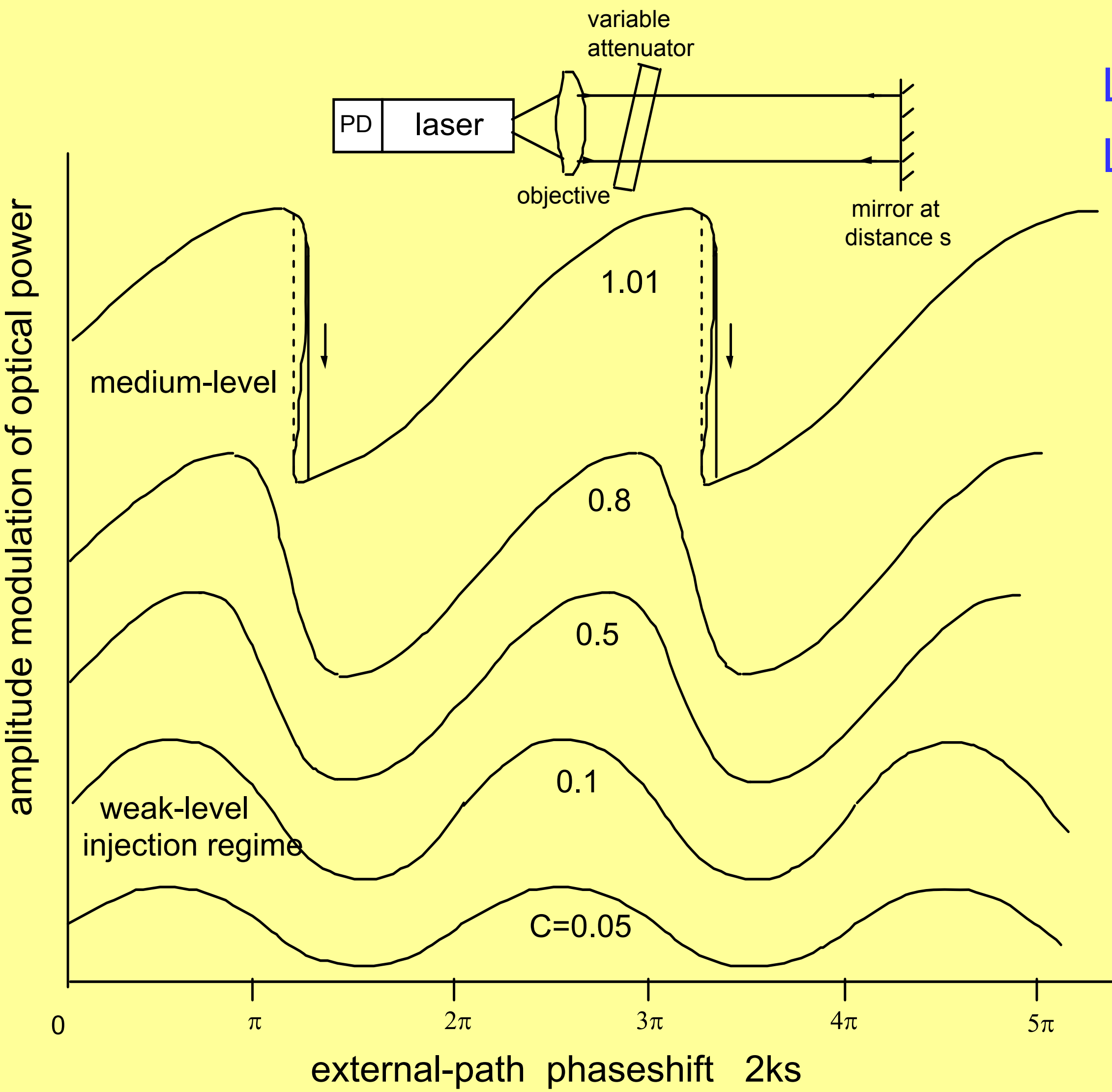
  where $m = A^{-1/2}\,[c/2s/(\gamma-1/\tau)]$

is the modulation index (it depends on $A^{-1/2}$, the *field* attenuation)

- F(2ks) is a periodic function of external phase $\phi = 2ks$, typ. a sine/cosine function as in a normal interferometers (weak injection) so F makes a full cycle every $\Delta s = \phi/2k = 2\pi/2k = \lambda/2$
- In general, waveform F(…) depends on $C = \kappa s(1+\alpha^2)^{1/2}/n_{las}L_{las}$, the injection parameter, where

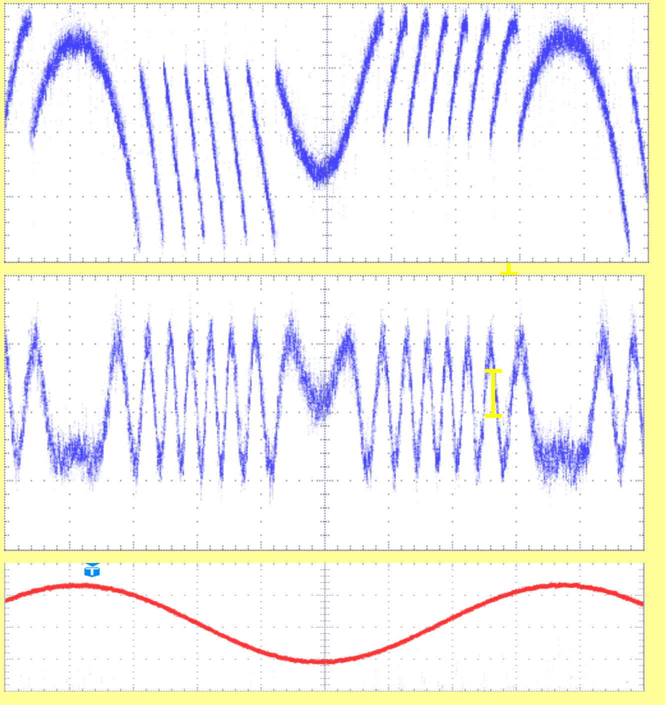
  $\kappa = A^{-1/2}\,[\varepsilon(1-R_2)/\sqrt{R_2}\,]$ accounts for attenuation

injection level: weak and moderate



LD 1-channel interferometer

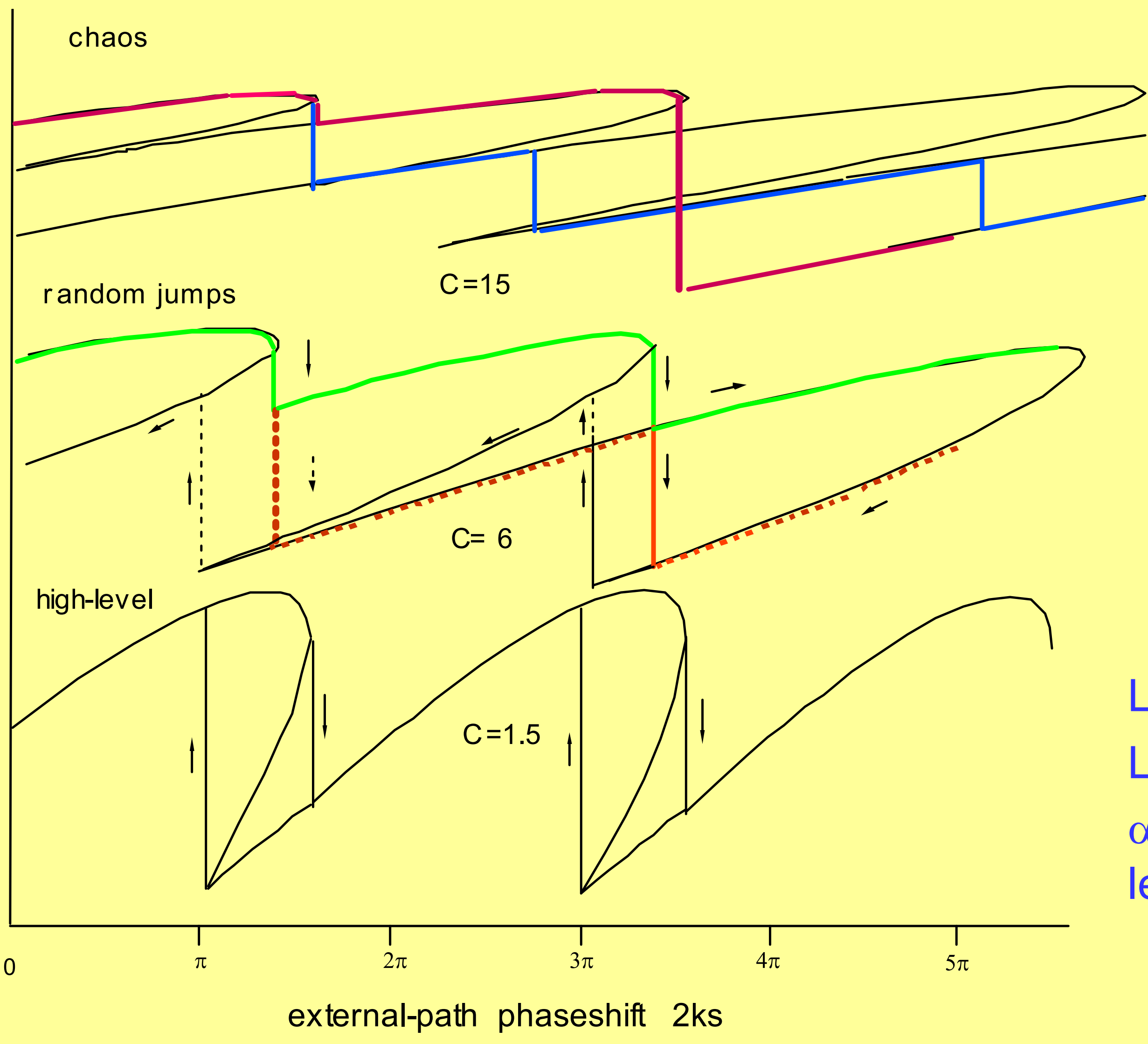
Laser Diode Vibrometer



He-Ne 2-channel interferometer, LDVs

Echo coherent-detectors

injection level: moderate and strong



Chaotic Generators

Angle Sensors

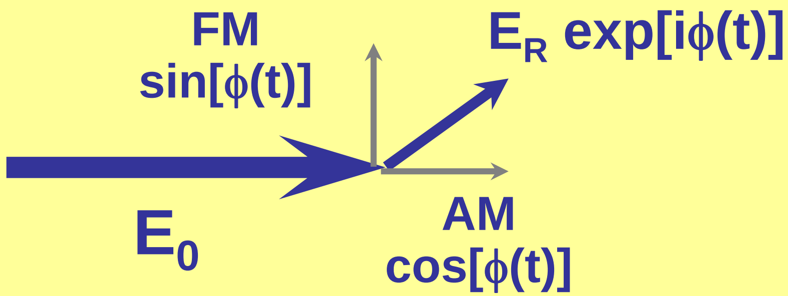
LD 1-channel interferometer

Laser Diode Vibrometer

α-factor and coherence length measurement

theories for self-mixing

◊ rotating-vector addition (a simple explanation, C<<1)



$\phi = 2ks$

$k = 2\pi/\lambda$

$s(t) =$ target distance

◊ 3-mirror model

basic results deduced with a simple analysis, including the mode-hopping regime

◊ Lang-Kobayashi (laser diode) equations

a complete description, yields a powerful treatment covering low (selmix) and high injection (chaos) levels

Agreement of theoretical prediction and experimental evidence is good at all the levels of self (and mutual) injection

L-K equations to analyze coupling and self-coupling

$$(d/dt)E_i(t) = {}^1/_2 \{g_N(N_i-N_0)(1-\Gamma\, E_i^2)-1/\tau_p\}\, E_i(t) + $$
$$+ (K_{ij}/\tau_{in})E_j(t-\tau_{ext}) \cos [2ks_{ext}+\phi(t)- \phi(t-\tau_{ext})]$$

$$d\phi_i /dt = {}^1/_2\, \alpha_{en}\, \{g_N(N_i-N_{tr})(1-\Gamma E_{i0}^2)-1/\tau_p\} + $$
$$+ (K_{ij}/\tau_{in})\, E_j(t-\tau_{ext})/E_i(t) \sin [2ks_{ext}+\phi(t)- \phi(t-\tau_{ext})]$$

$$(d/dt)N_i = J_i\eta/ed - N_i/\tau_r - g_N(N_i-N_{i0})\, (1-\Gamma E_i^2)\, E_i^2(t)+\sigma\, H_{ij}\, E_j^2(t)$$

here, $k=2\pi/\lambda$ and τ_{ext} is the round trip time to the external retro-reflector at distance s_{ext}, so that $s_{ext}=2c\tau$, and $2ks_{ext}=\omega_0\tau_{ext}$, K_{ij}=strength of coherent feedback, H_{ij}=strength of incoherent feedback, i,j=1,2 for the two modes, i=j=1 for self-coupling.

L-K equations can be written for two coupled lasers or for a single laser subjected to feedback (or self-coupling) either coherent or incoherent. Despite small differences, the dynamic behaviour is much the same in all cases.

features of self-mixing interferometer

Self-mixing interferometer vs conventional types

advantages:

- optical part-count is minimal
- self-aligned setup
- 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
- λ/2-resolution with fringe counting and sub-λ with analog processing bandwidth up to hundreds kHz or MHz (after some thought)

disadvantages:

- reference is missing (...in the basic setup)
- wavelength accuracy and long-term stability is poor (with F-P 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…

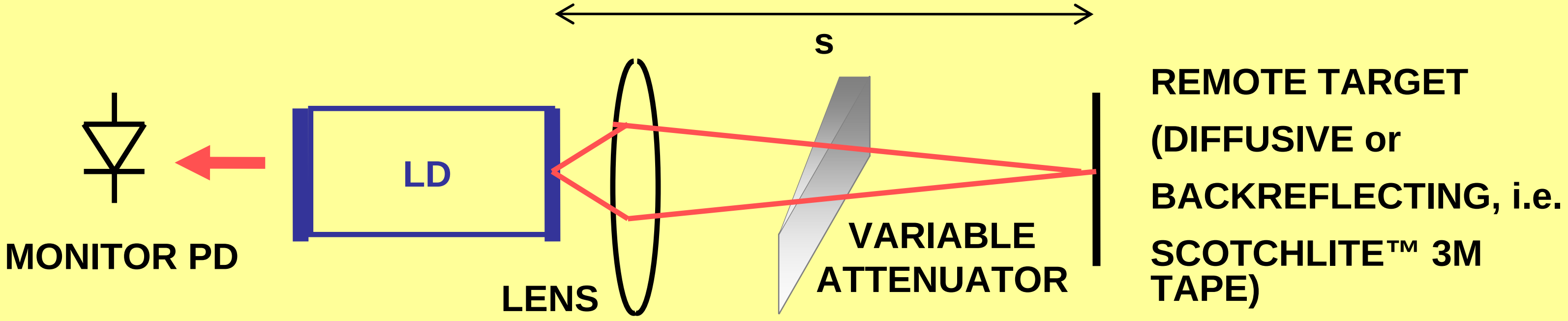
there are problems to be solved on the way of selfmix technology ..!

a) The first is:

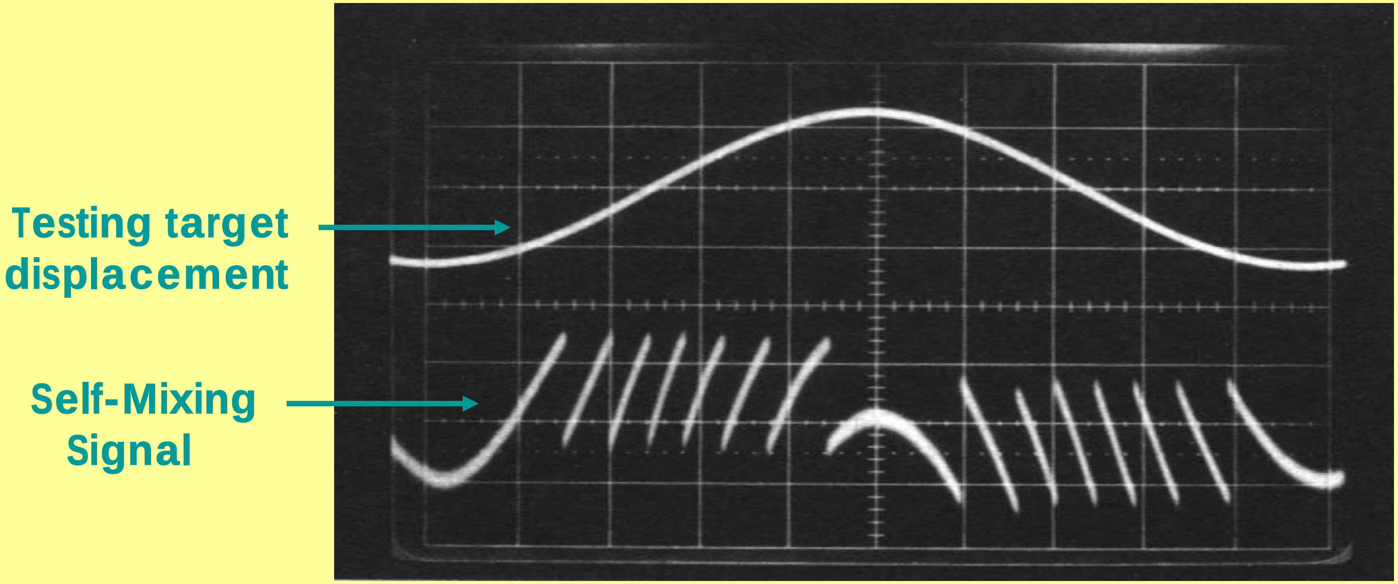
we need a second signal, *sin 2ks* or something equivalent to that, for a *digital processing,* because the plain *cos 2ks* signal is not enough to measure $\lambda/2$ displacements without sign ambiguity

- luckily enough, it happened that ....

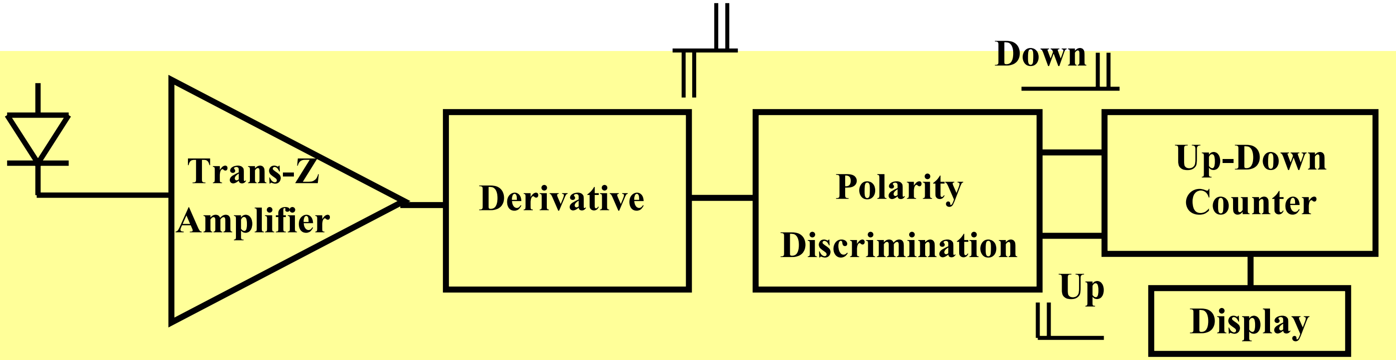
Measuring displacements

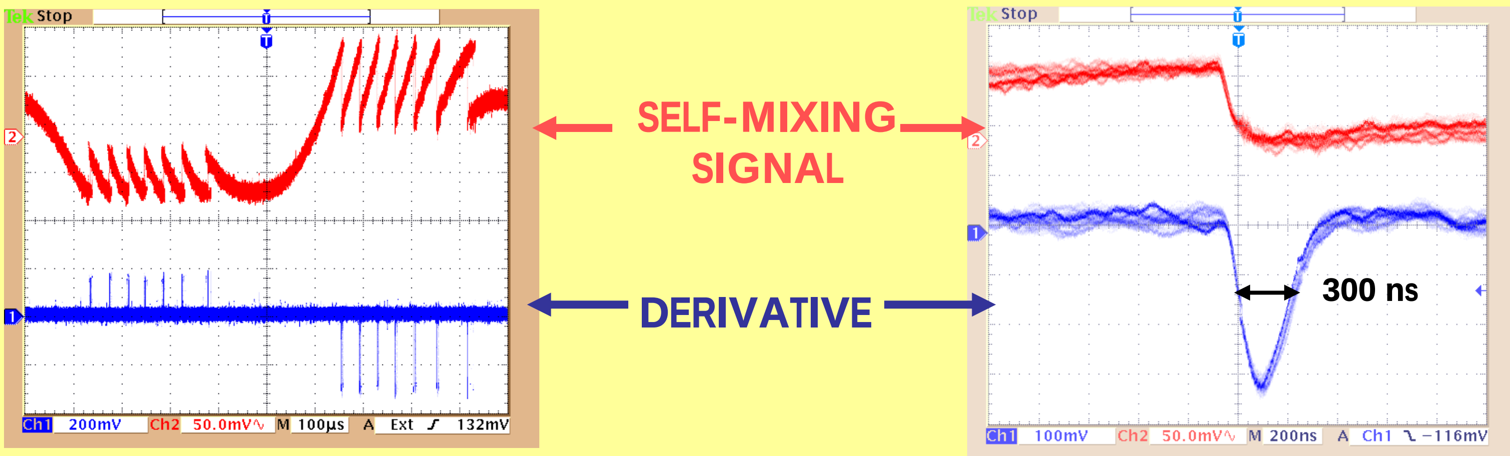


- best regime: moderate feedback C > 1, but also C< 4.6
- principle: counting of fast signal transitions with polarity



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 102 (Google Scholar)

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

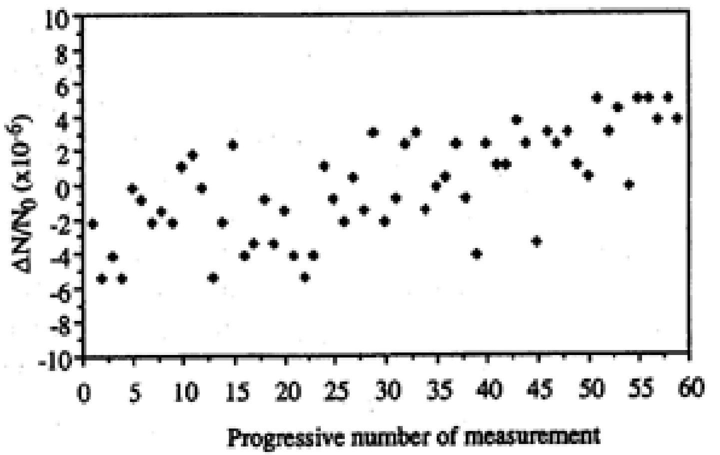


Fig. 5. Experimental residual error obtained with standing target after compensation of laser temperature variations. Every data point corresponds to a 2.28 °C temperature sweep of the laser.

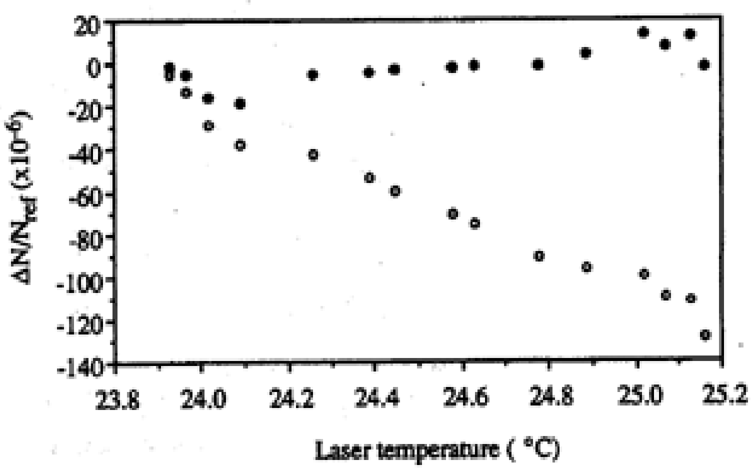
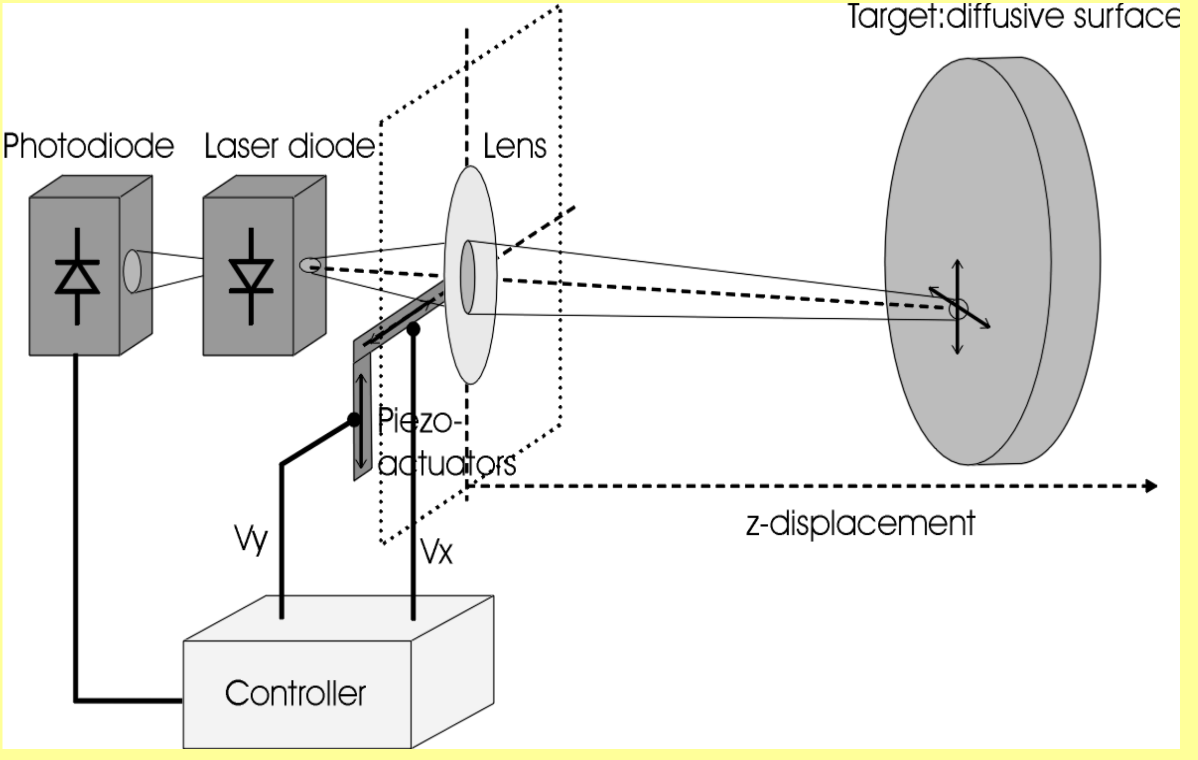


Fig. 6. $\Delta N/N_{ref}$ versus laser temperature, obtained for 22-cm target displacements: ○ experimental data before compensation, ● compensated results.

b) the second: 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 on a diffuse target: the bright-speckle tracking

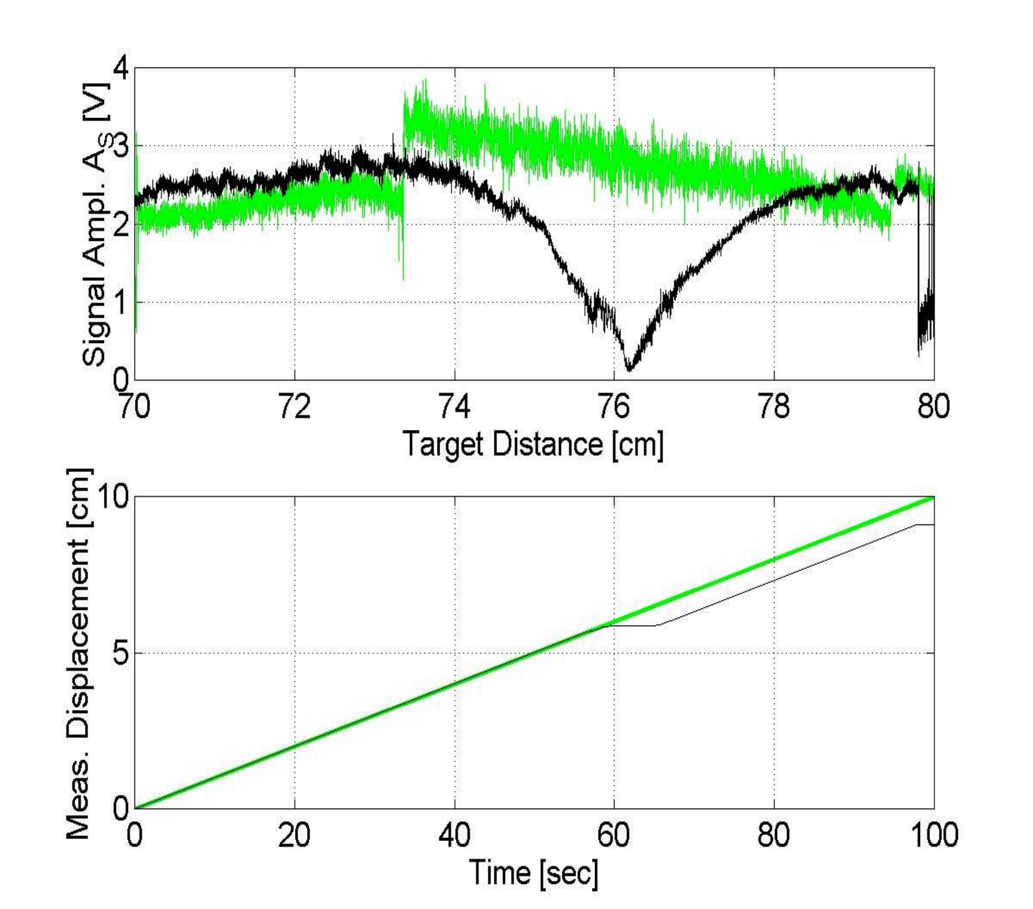


Tracking a bright-speckle (BST) permits to stay on a maximum of intensity and avoid fading. Operation on a diffuser target is then allowed, with little added error (typ. few μm on a 1-m stroke)

S.Donati, M.Norgia, J.Quant.El. 37, 2001, pp.800-8006 cited by 21

improvement with BST

Top: self-mix signal amplitude without speckle tracking shows a fading at 76 cm with (black line). With speckle-tracking (green line) fading is removed. Minor jump-ups are when system finds an adjacent bright speckle. Bottom: corresponding displacement has the counting error removed



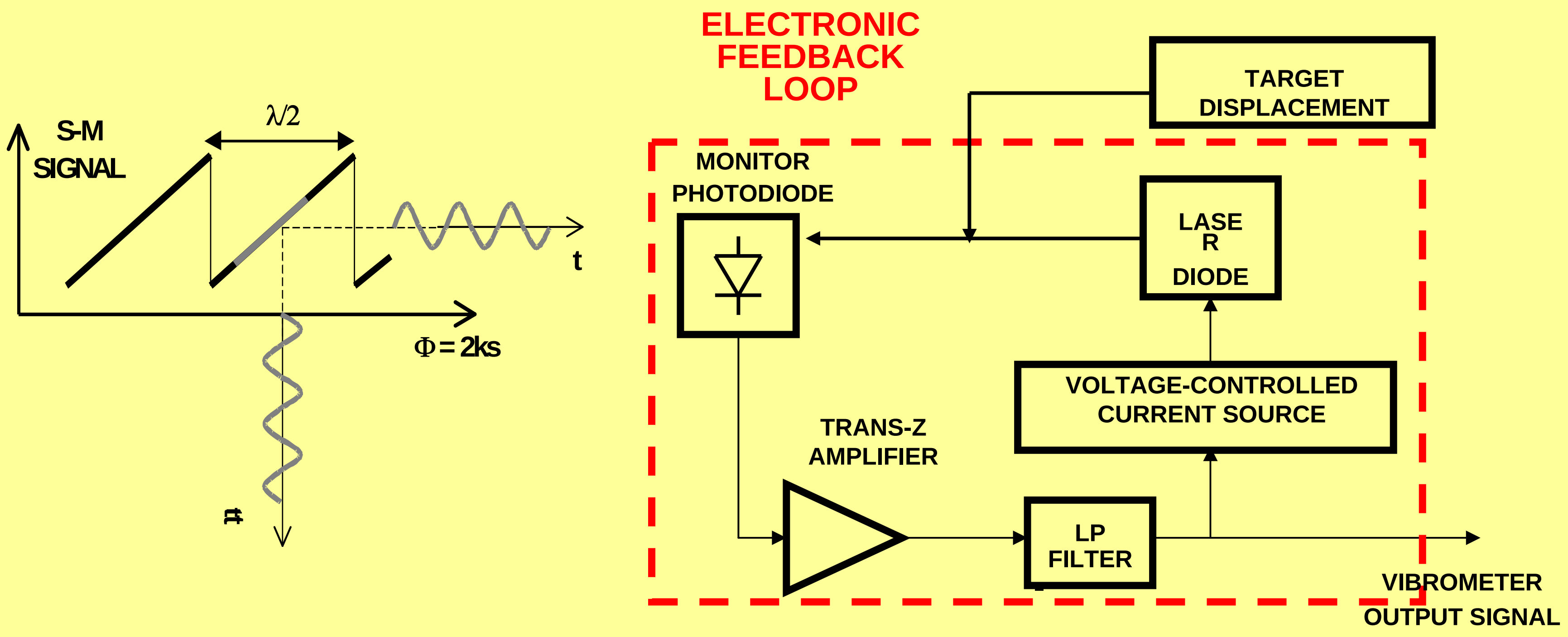
S.Donati, M.Norgia, Trans. Instr. Measur. IM-52 (2003), pp.1765-70

… 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

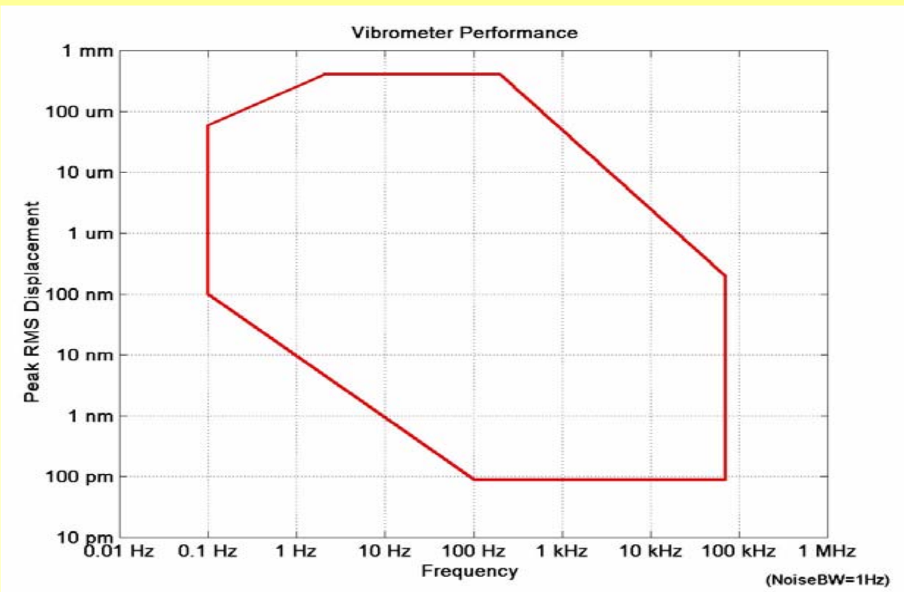
Vibration, mechanical

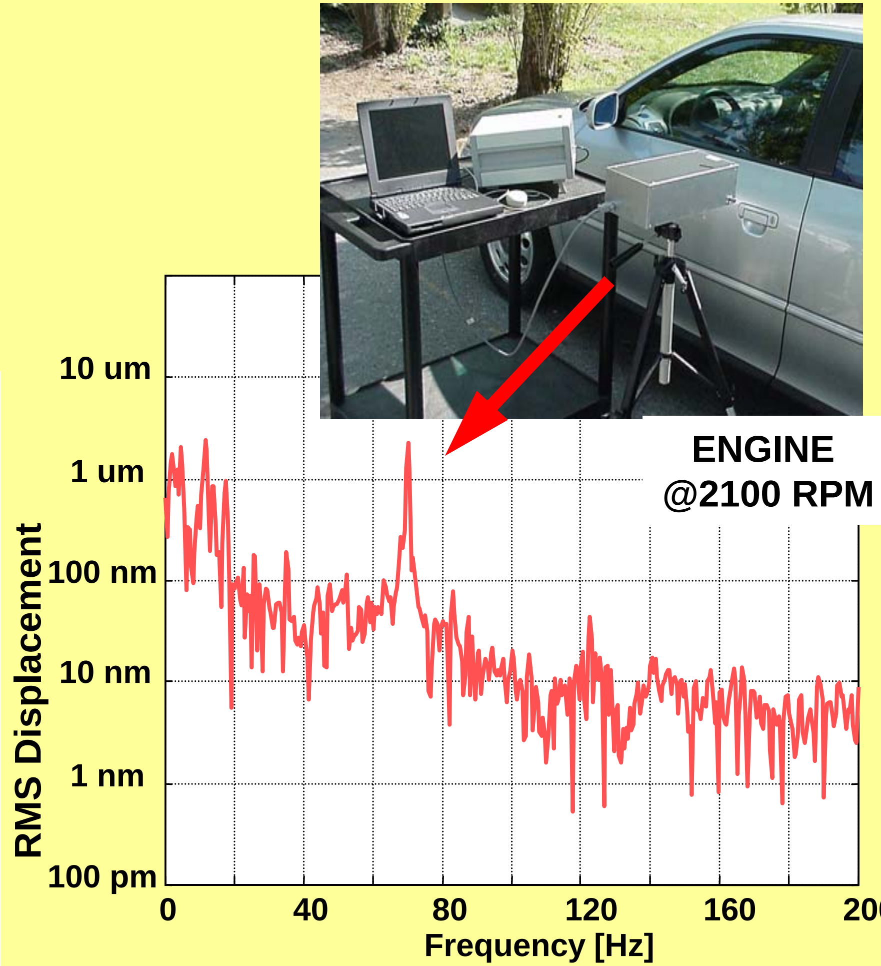


Working with a diode laser at C>1, a region of ample linearity is found along the fringe. With the circuit shown here, we can lock the working point to half fringe, through an active phase nulling

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

Vibration: application to the automotive



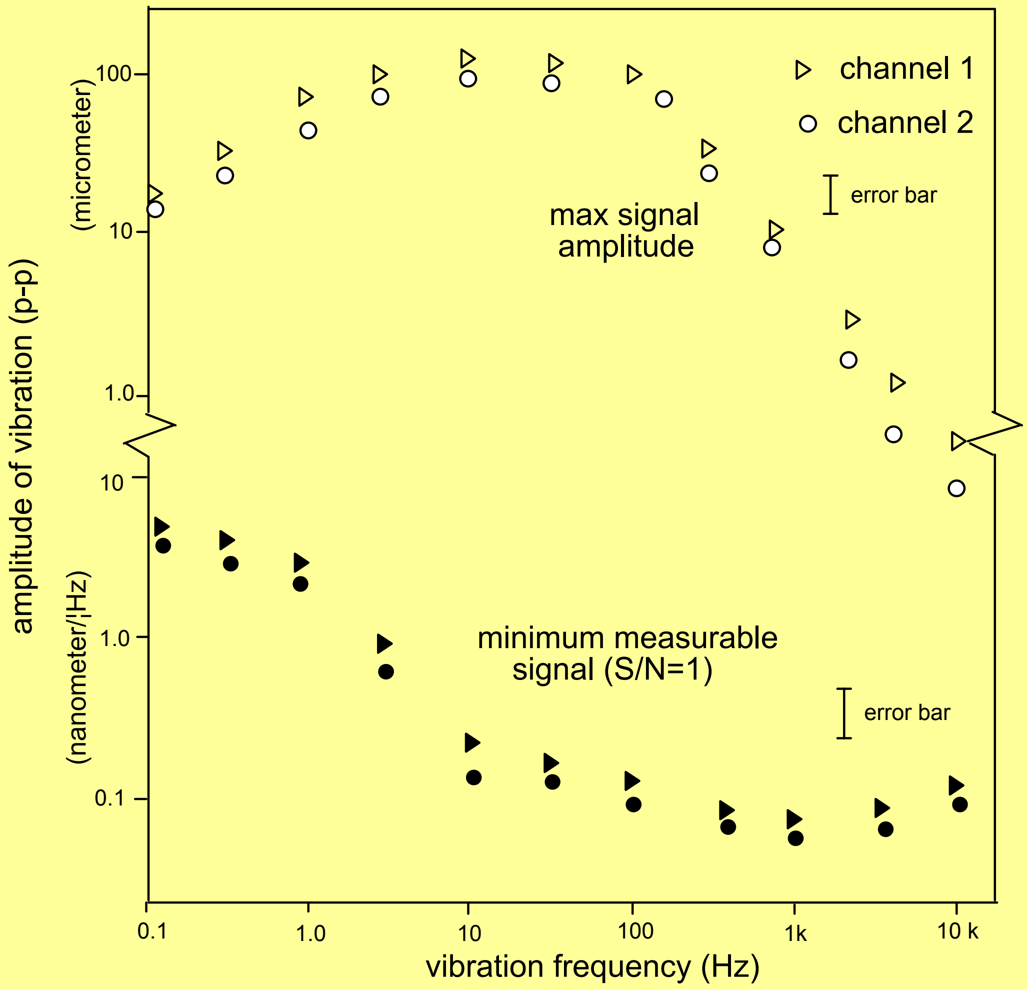


A developmental unit to test automotive vibrations has the following performances: detectable amplitude ≈100 pm/√Hz; max. amplitude: 600 μmp-p ; bandwidth:70 kHz; dyn. Range is > 100 dB

d) last, we want to procure a *reference* to our measurement, so be able to measure nanometer (or <<λ) amplitudes of vibrations superposed to large (micrometer, or even hundreds of micrometer) common-mode signals

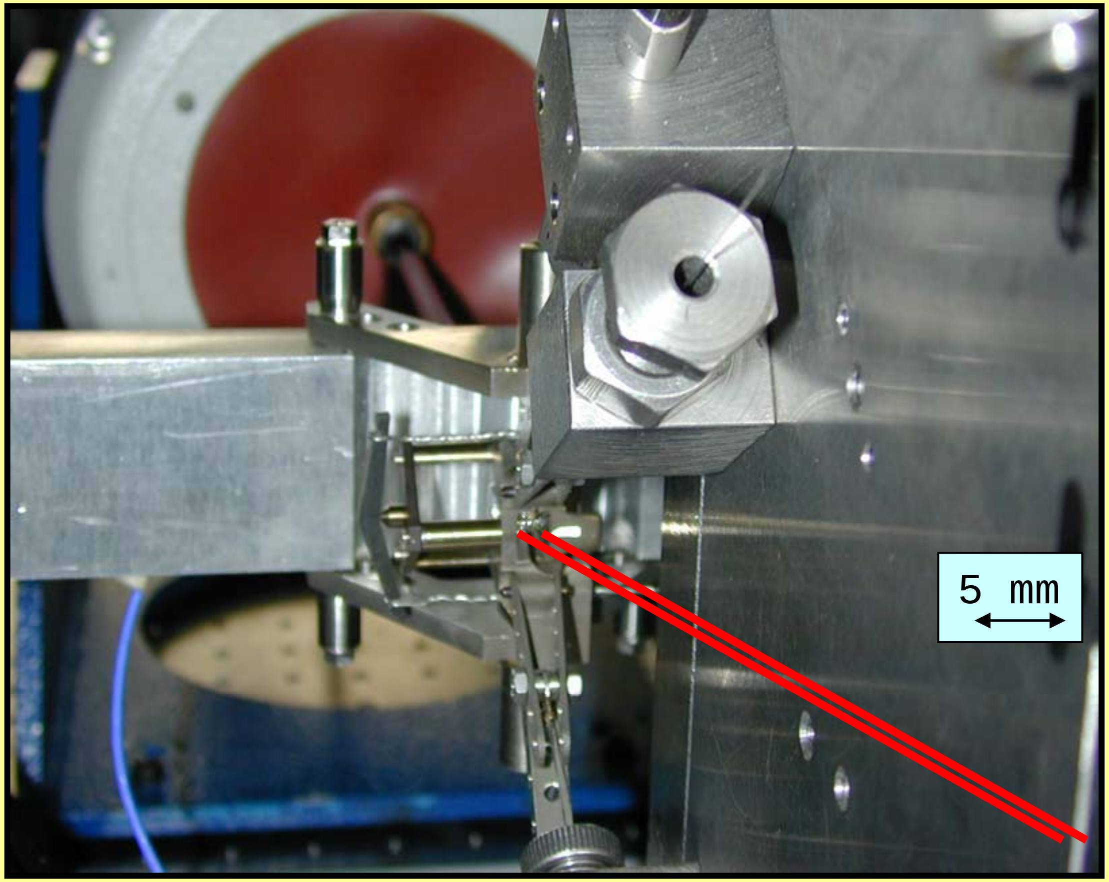
Reference channel is finally added to self-mix

Using a large feedback-loop gain,
$G_{loop}=RG_m\alpha(s/\lambda)\sigma P_0 >>1$ (≈200 in our case)
output is the amplified error ΔV, equal to $[\alpha G_m]^{-1}\,\Delta s\,(\lambda/s)$, independent from amplitude P of received signal
- speckle amplitude-fading is compensated out, it only affects the loop-gain available for the servo action
-Thus, we can use <u>two channels</u> and make a reliable subtraction of the common mode displacement/vibration

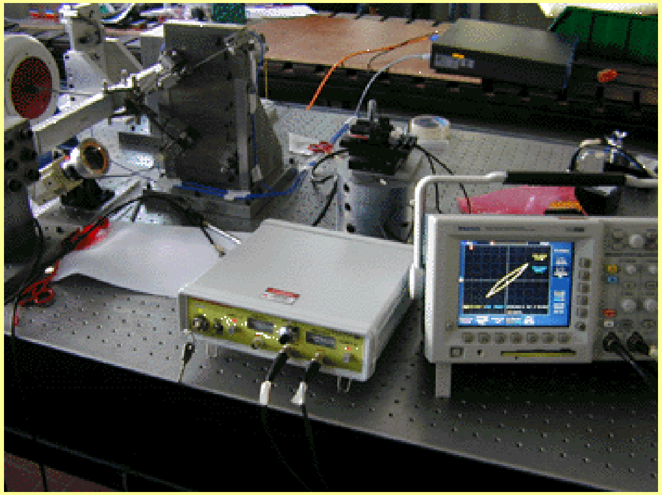


S.Donati, M.Norgia, G.Giuliani: Applied Optics 45 (2006), pp.7264-68

Differential vibrometer: application to fatigue study



Laser head

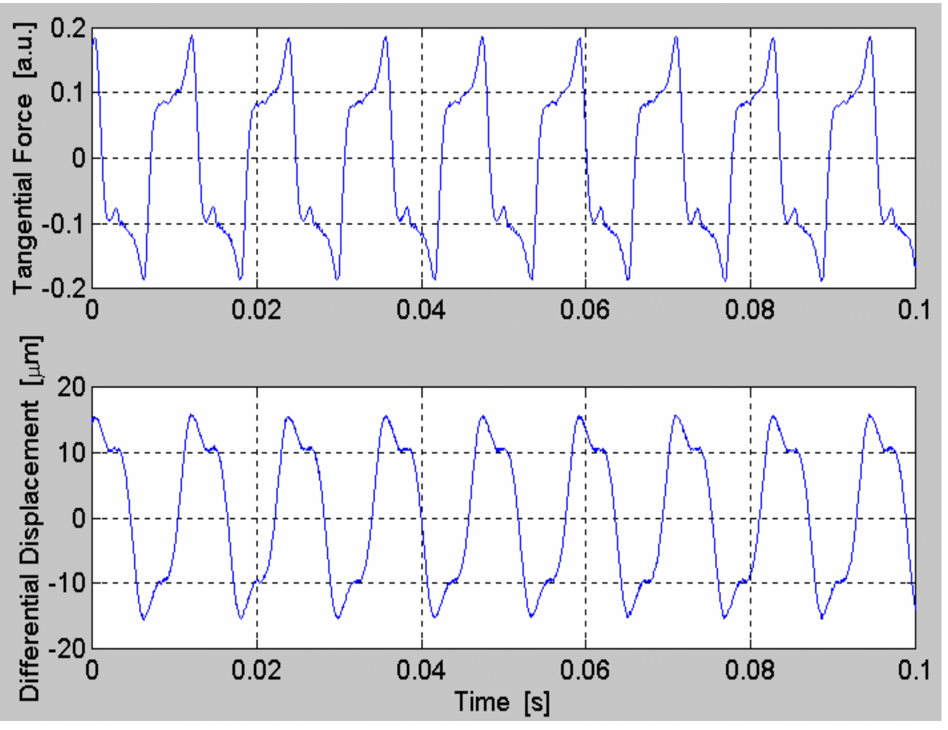


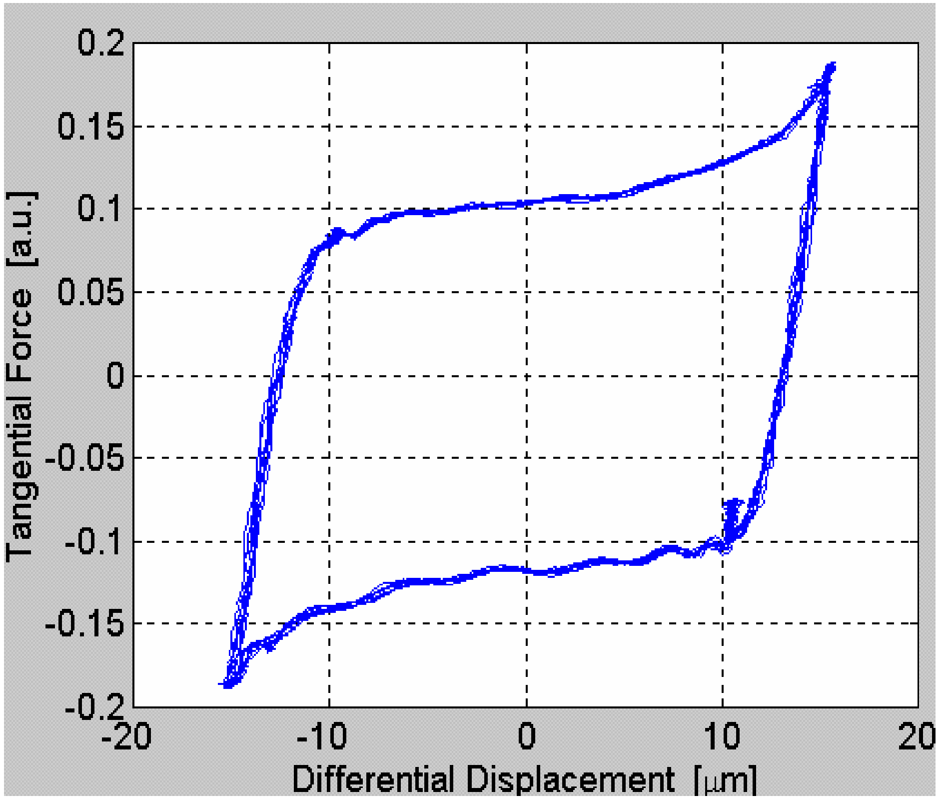
instrumentation

because of the servo loop, the vibrometer can work in differential mode despite the speckle statistics

Differential Vibrometer: measuring the F-D diagram

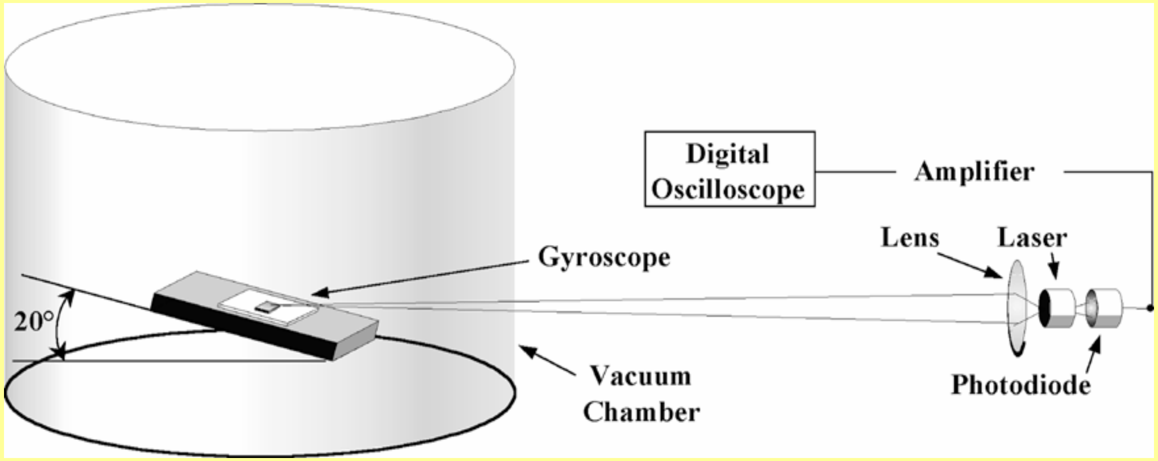
Force-Displacement measurement in dynamical regime

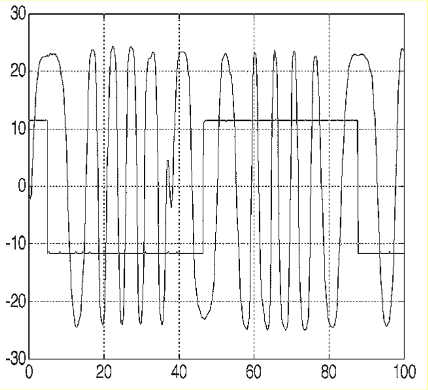




S.Donati, M.Norgia, G.Giuliani: Applied Optics 45 (2006), pp.7264-68

Vibration, MEMS

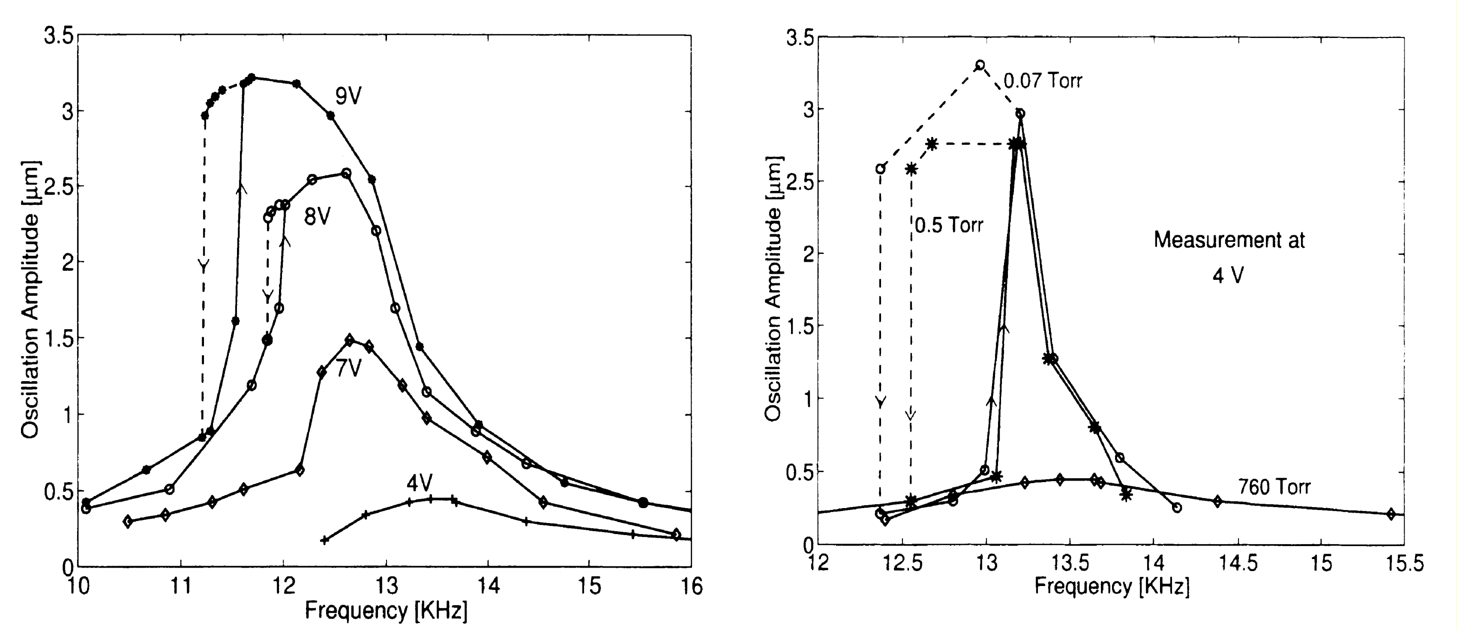




The self-mixing vibrometer has been used to measure the mechanical properties of Si-machined MEMS. Light from the laser is focused on the vibrating mass of the MEMS chip through the plain glass wall of the vacuum chamber. Light on still parts or outside target doesn't disturb operation. The out-of-plane vibration of the MEMS mass is viewed at an angle ($\Phi \approx 20°$), and the appropriate cos Φ correction on s(t) is applied to the fringe signal (left) giving the displacement waveform.

(V.Annovazzi, S.Donati, S.Merlo: Trans. Mechatr. 1, 2001, pp.1-6).

Testing MEMS response



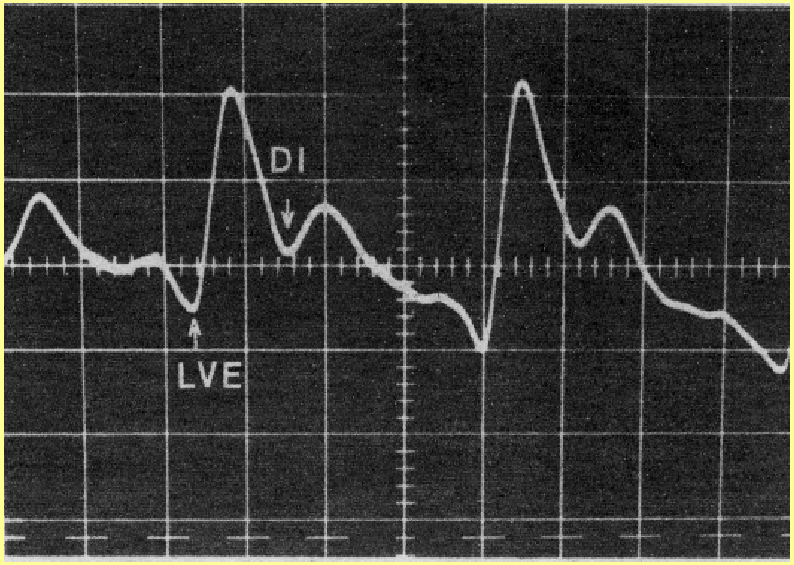
MEMS frequency response measured by the SMI vibrometer. Left: drive voltage is increased up to incipient hysteresis at 8-9 V, indicating the risk of creep in the structure. Right: at increasing ambient pressure, the Q-factor is damped because of air friction.

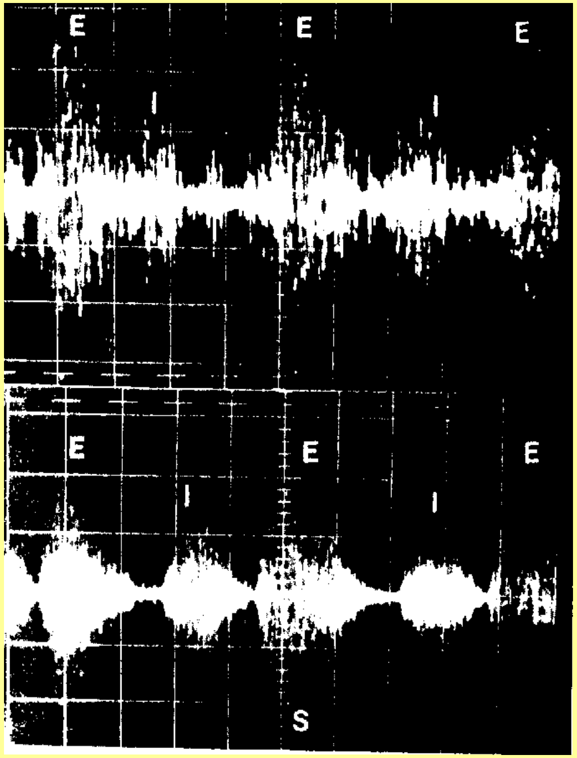
(S.Donati et al.: Proc. LEOS Workshop on MEMS, 2000, pp.89-90).

Principle has also been used for micromiror MEMS arrays

(V.Annovazzi, M.Benedetti, S.Merlo: J.Select.Topics Quant.Electr.10, 204,pp.536-44)

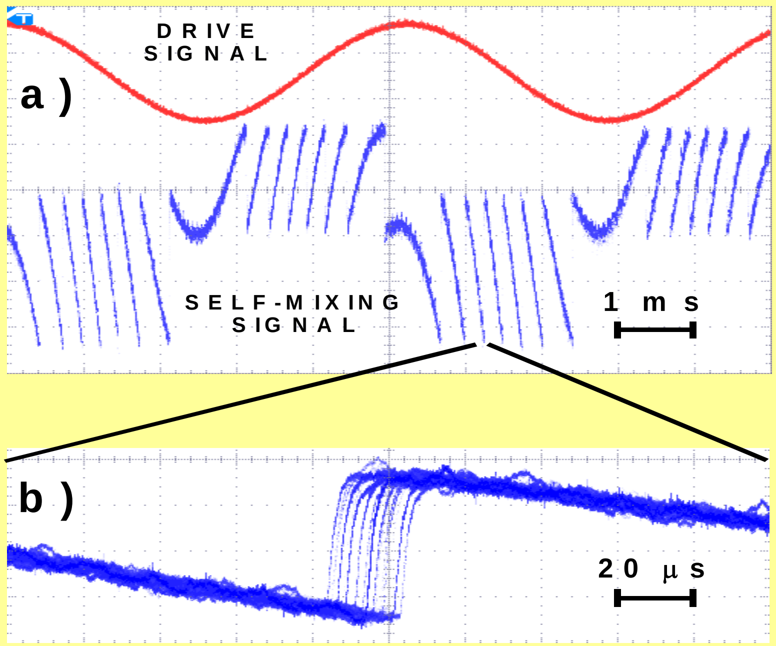
Application to bio signals pick-up

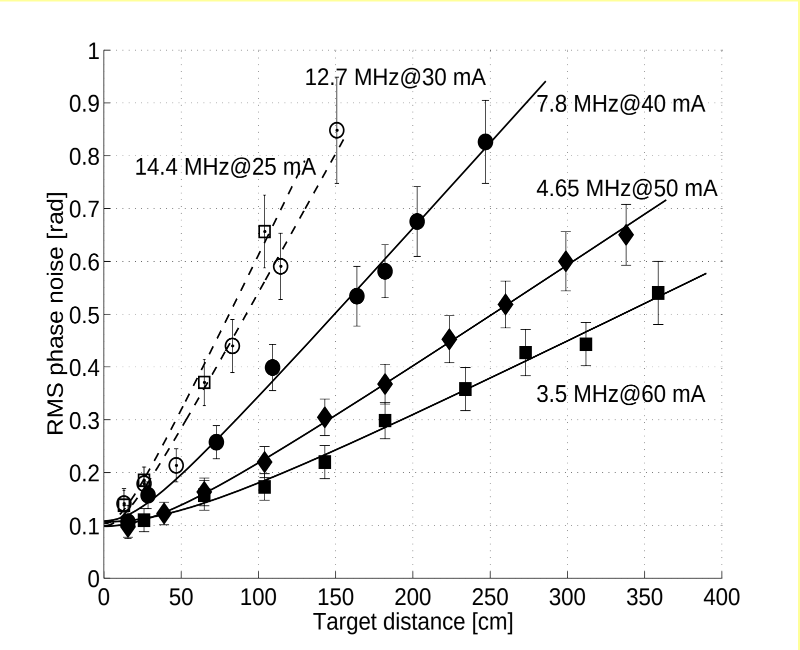




Two samples of biomedical signals measured by a He-Ne SMI
left: pulsation of blood on a finger tip (0.5 μm/div, 0.3 s/div), right: respiratory sounds detected on the back compared to acoustical.
S.Donati, V.Speziali, Laser+ElektroOptik.12,1980, pp.34-5.

Measuring coherence length





phase variance for a target displacement ΔL at L_0 is:

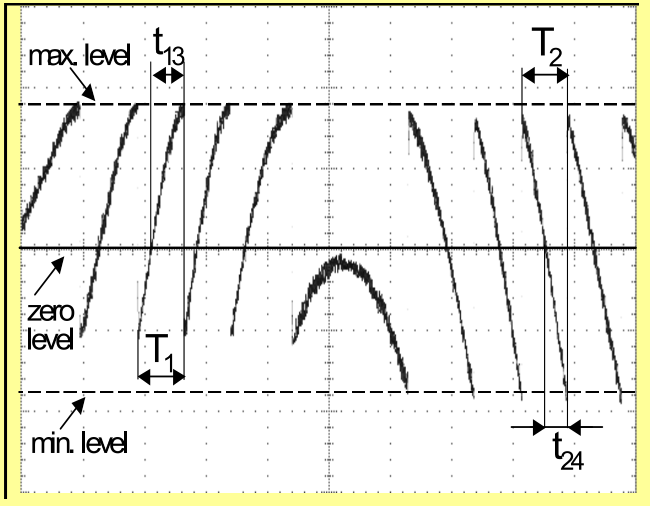
$\langle \Delta\phi^2 \rangle = 2k\,[\nu_0{}^2 \langle \Delta L^2 \rangle + L_0{}^2 \langle \Delta\nu^2 \rangle]$

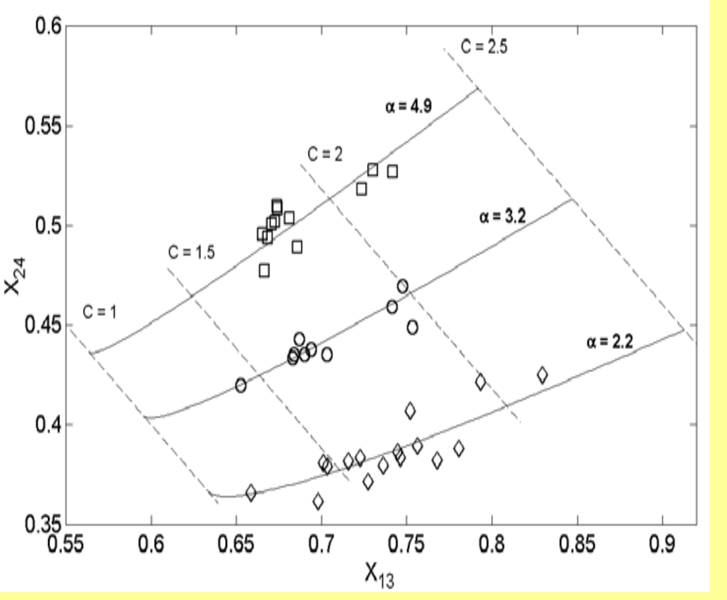
applying a sawtooth drive to L_0, we can measure the phase jitter $\langle \Delta\phi^2 \rangle$ and fit it to a line $L_0{}^2 \langle \Delta\nu^2 \rangle$ + const.

The method requires much less lab space that one based on arm mismatch (or delayed heterodyne) on the coherence length

(G.Giuliani, M.Norgia: Phot.Techn.Lett,. vol.PTL-12 2000, pp.1028-30)

Measuring α -the linewidth enhancement factor (by self-mixing - of course !!)





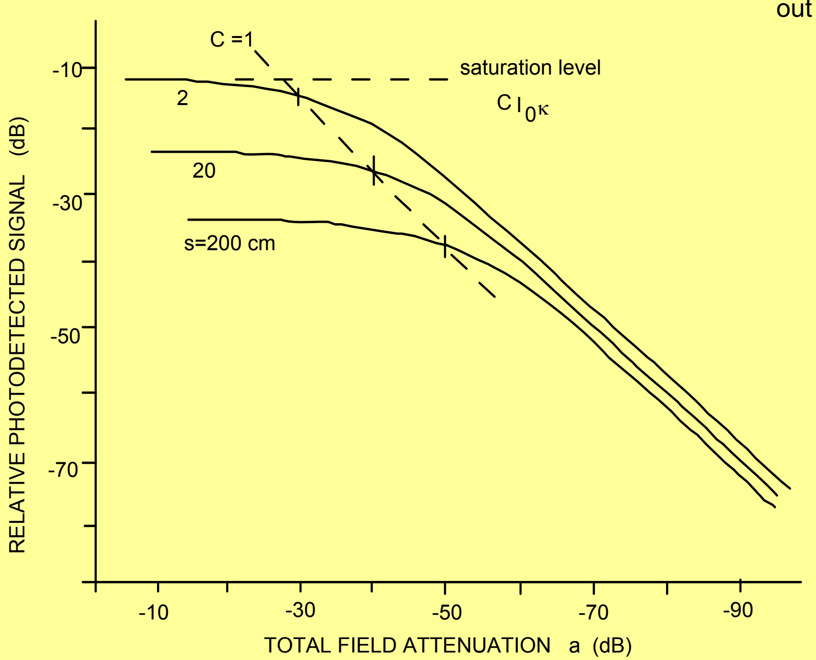
Waveform F(ϕ) depends on the alfa factor, as

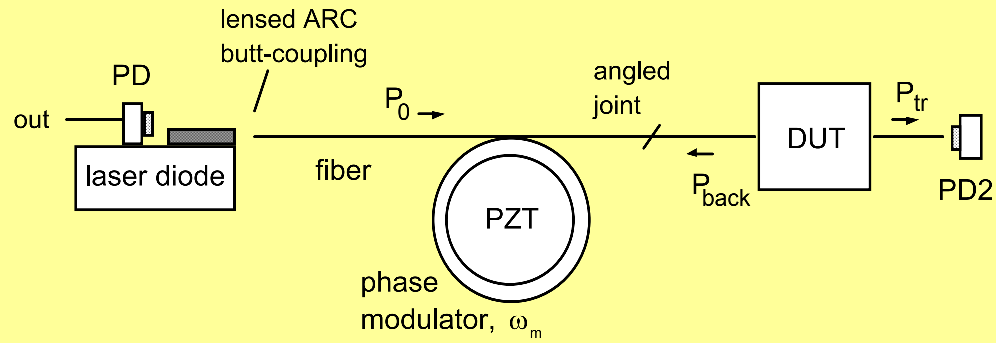
$$\phi_{13} = \sqrt{C^2 - 1} + \frac{C}{\sqrt{1+\alpha^2}} + \arccos\left(-\frac{1}{C}\right) - \arctan(\alpha) + \frac{\pi}{2}$$

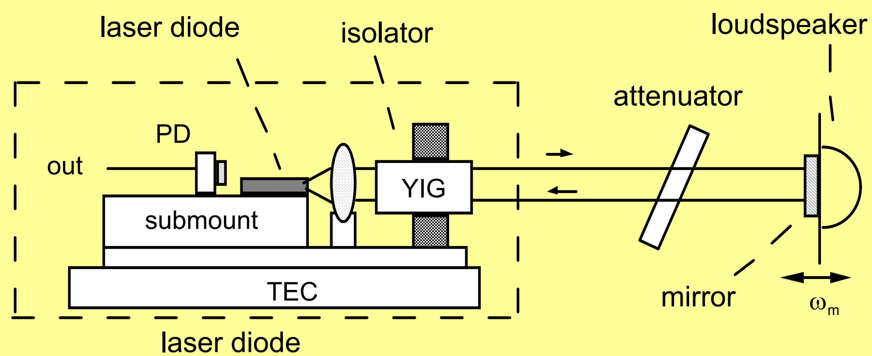
we first draw a nomogram of $\phi=\phi(\alpha, C)$, then measure waveform details and plot the resulting $\phi=2ks$ to extract parameters related to α. The method also provides the C - factor of injection

Y.Yu, G.Giuliani, S.Donati: Phot.Techn.Lett., 16, 2004, pp.990-93 cited by 24

Measuring return loss and isolation loss



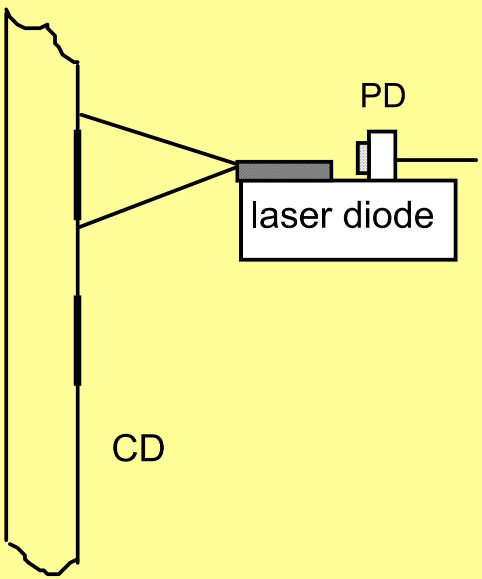


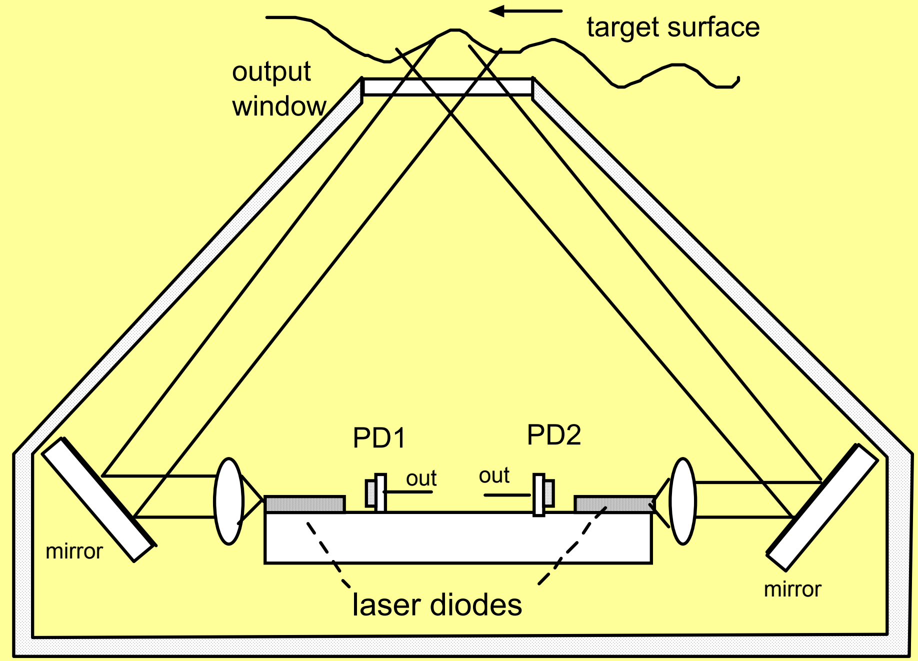


To measure the return loss or the isolation loss, we add modulation of a path length at ω_0 through an in-line PZT Φ-modulator or a remote loudspeaker.The SMI signal output is then on a carrier ω_0 and its amplitude provides the RL or the IL.

(S.Donati, M.Sorel: Proc.OFC'97, paper WJ8; Phot Techn Lett.28,1996, pp.43-49)

Consumer applications: CD readout and Scroll sensor





Unwritten portions of the CD surface reflect light and give a large signal, whereas pits diffuse light and give a small return. Signal is detected by the rear PD photodiode.
Ukita,Uenishi,Katagiri:Appl.Opt. 33,1994 pp.5557-63

Two laser beams shine the target at ±45°. Signals 2k×s returned to each laser are opposite in sign, and after subtraction of PD currents, speed and the direction of external target are obtained.
Hewett: Meas.Sci. Technol., 13,2002, pp.2001-06; also: Philips US Patent

Part II - Chaos and Cryptography in Coupled Lasers

Summary

theory and simulations

Chaos generators

Chaos Synchronization

Chaotic Coding and Masking

experimental

DOC generators evaluation

Masking, amplitude & phase, CSK

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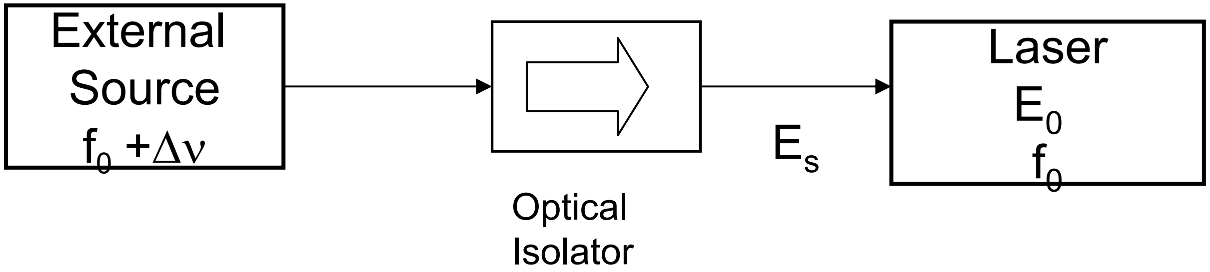
- *the EEC Program 'OCCULT'*

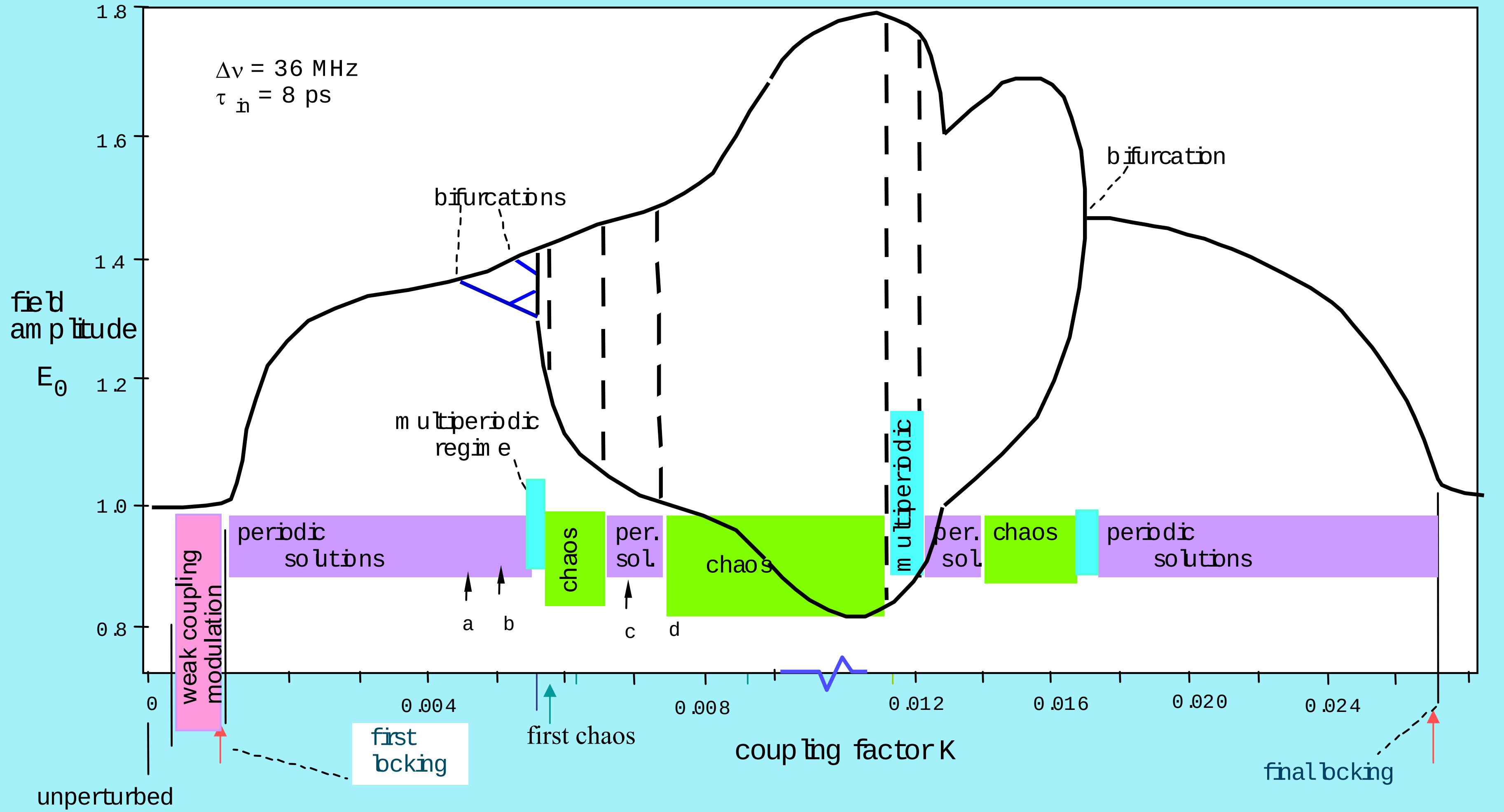
Injected Oscillator as a Reference Model



- We started with *injection between oscillators* as a model to complex system generating high-level dynamics and chaos
- Using the L-K equations, we are able to explain all details found at increasing $K = E_s/E_0$, a rich dynamics including:
  - *weak* (injection) *modulation*
  - *multi-periodicity*
  - *chaos* ♦ *intermittency*
  - *final locking*

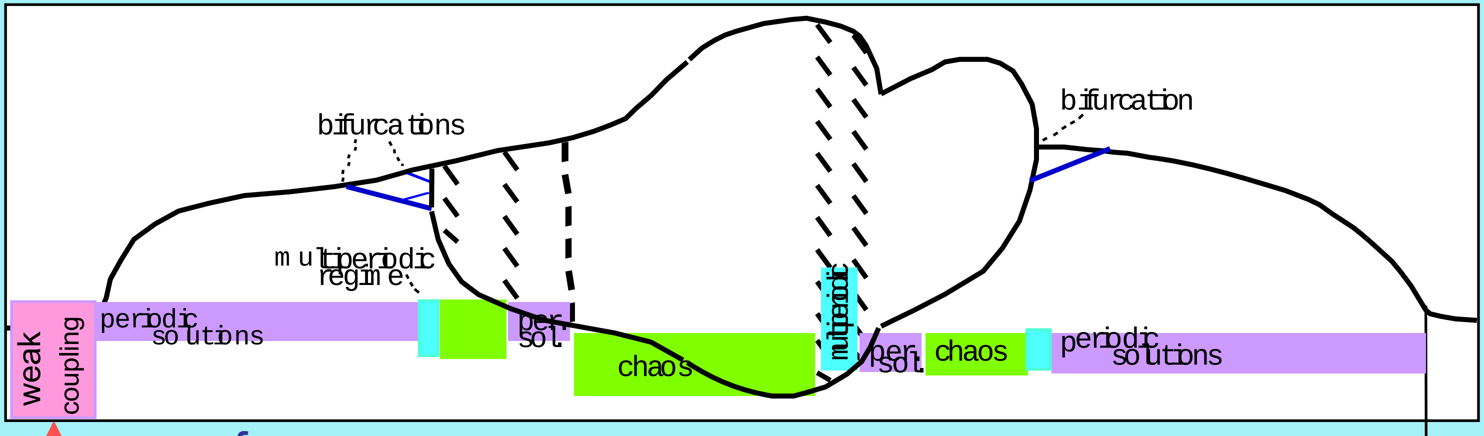
Annovazzi, Donati, Manna J.Quant.Electr.30, 1994, pp.1537-41 [36d] cited by 41

Solutions of L-K equations display the dynamic route to chaos



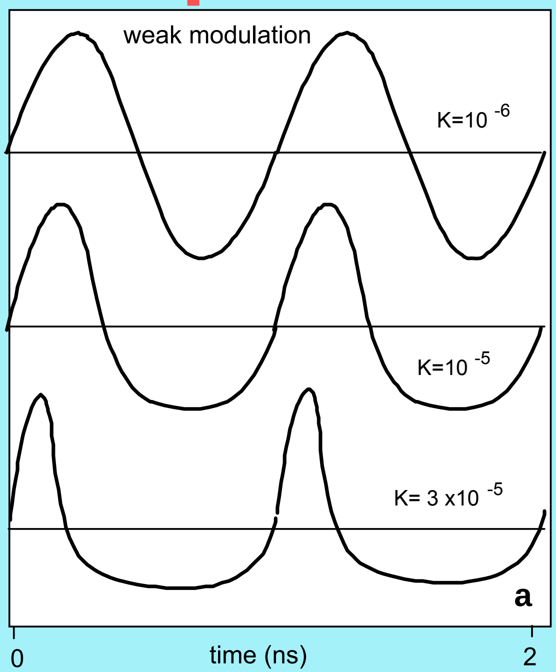
At increasing level $K=E_s/E_0$ of injection, a first locking is found, then system goes into period doublings and then bifurcations. Finally, it breaks into chaos (K≈ 0.006). At even larger K, the regime is multi-periodic alternate to chaos, up to K≈0.01, and only at K=0.027 the final locking is reached. More in detail…

1: weak coupling (injection modulation) regime

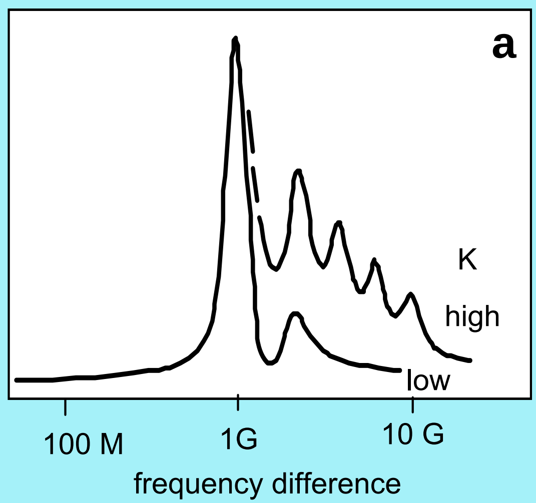


a

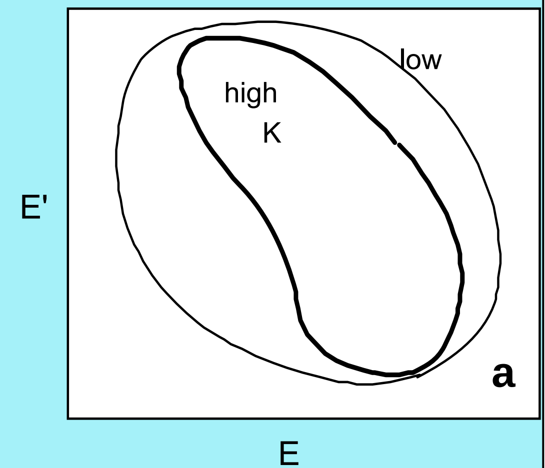
waveform of beating



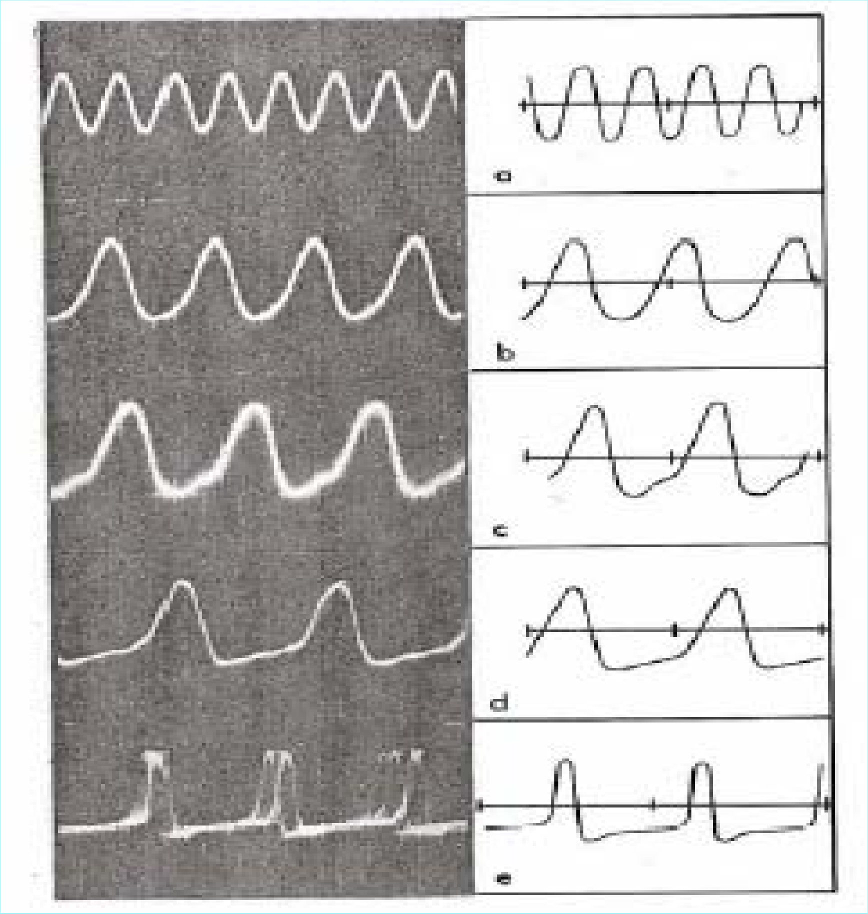
electrical spectrum



state diagram



1: weak coupling (injection modulation) experiment

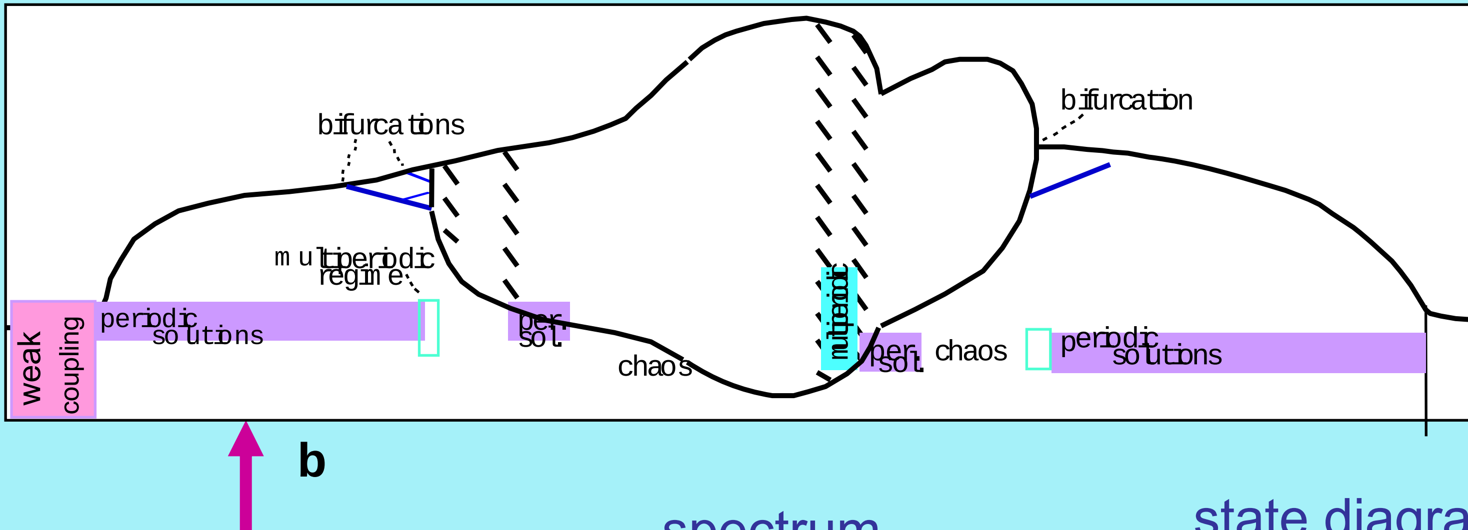


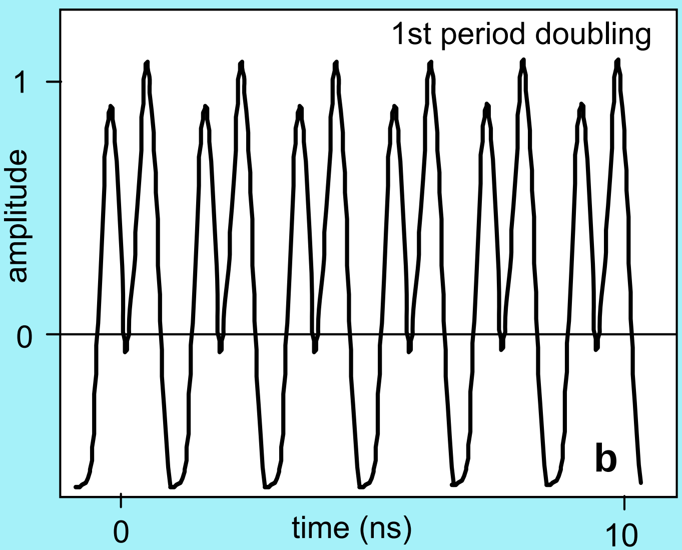
experimental IM waveforms in a dual-mode He-Ne laser and corresponding theoretical from Lamb's eq.for K=0.3, 0.7, 0.85, 0.90 and 0.97

Experiments on injection modulation (IM) nicely confirm theory
A first locking is found at K=0.001, as predicted by Adler equation, then in between there are multi-periodicity and chaos regimes and final locking is found at a much higher K (=0.027)

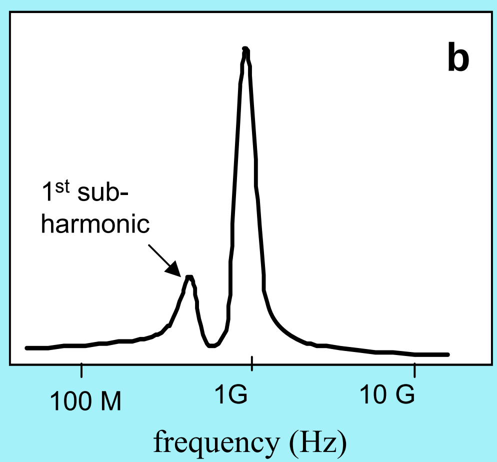
Annovazzi, Donati: J.Quant.Electr.16,1980, pp.859-64

2: periodic solutions

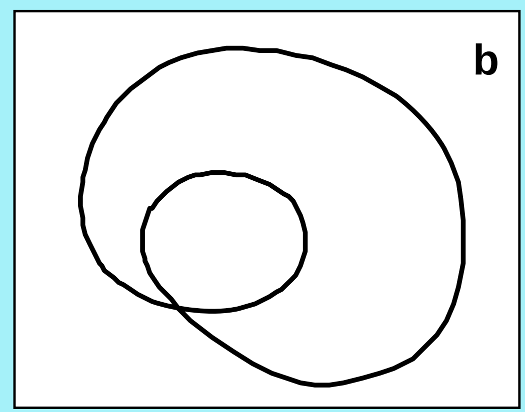




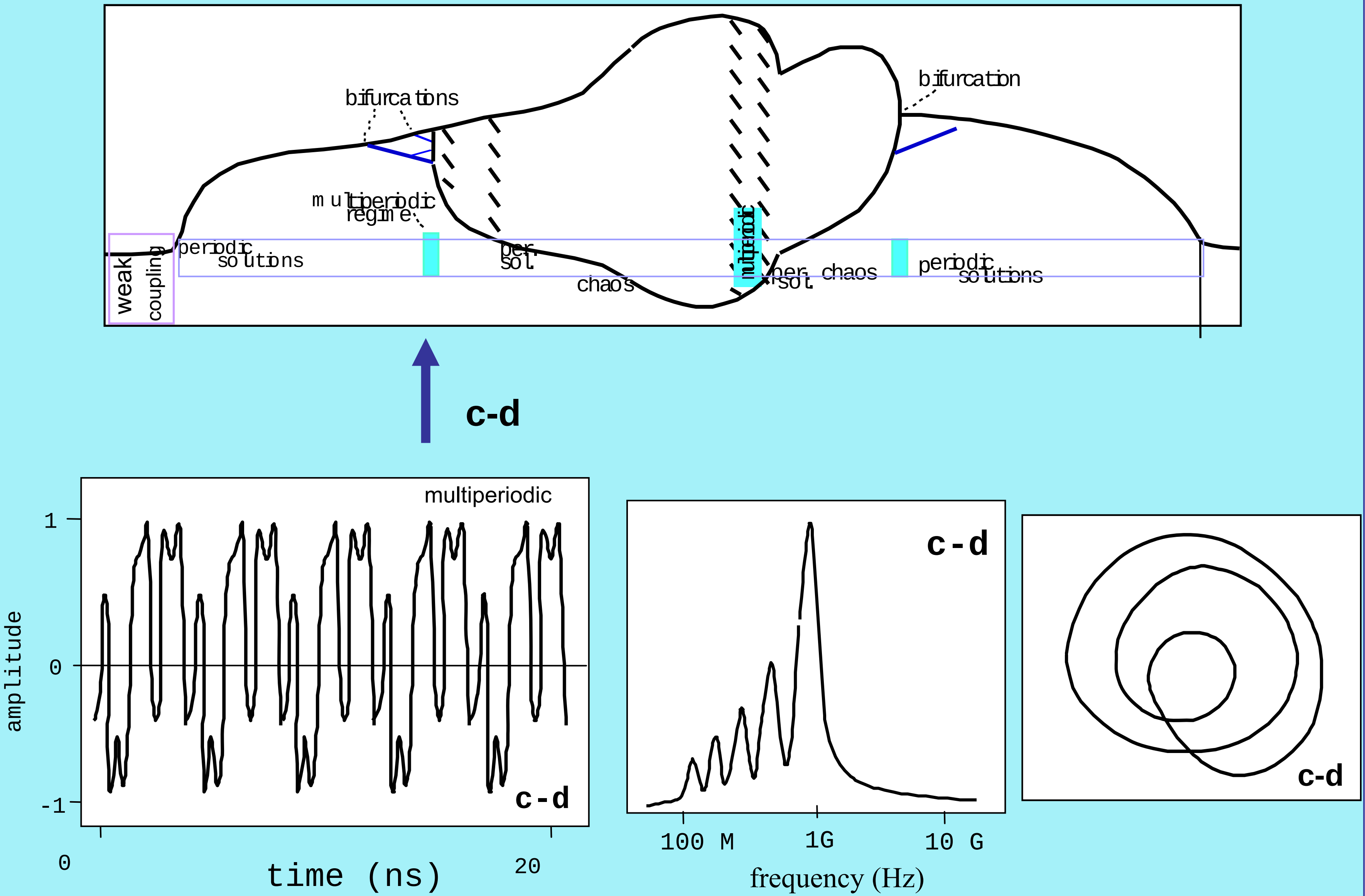
spectrum



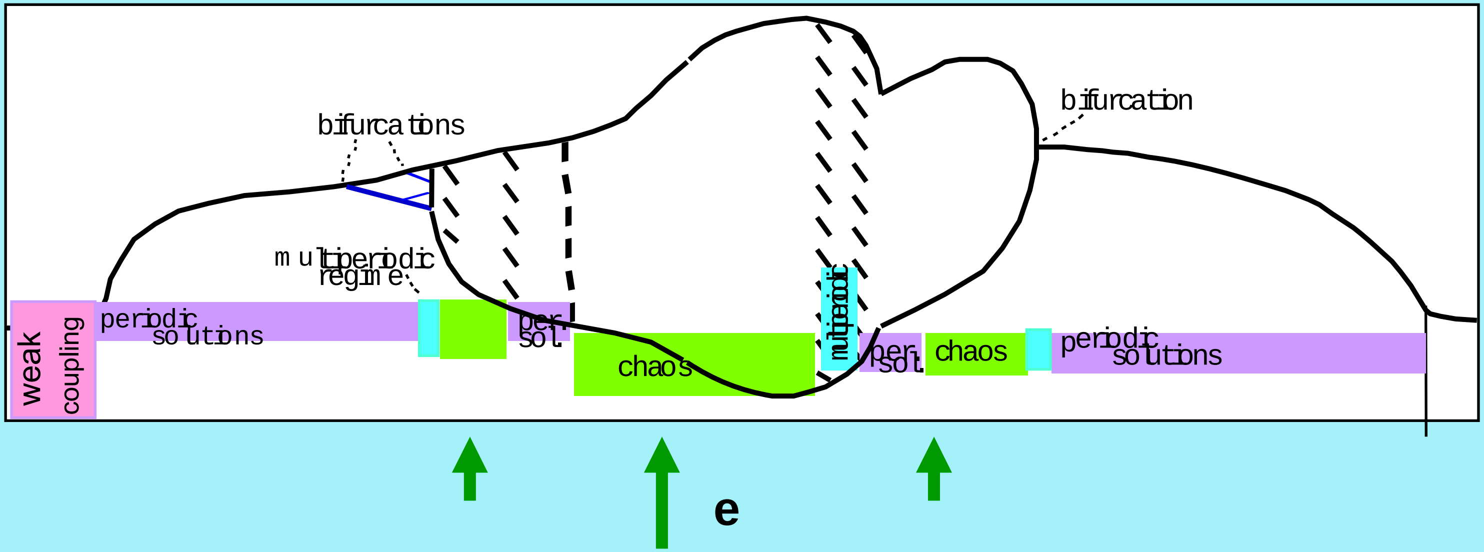
state diagram



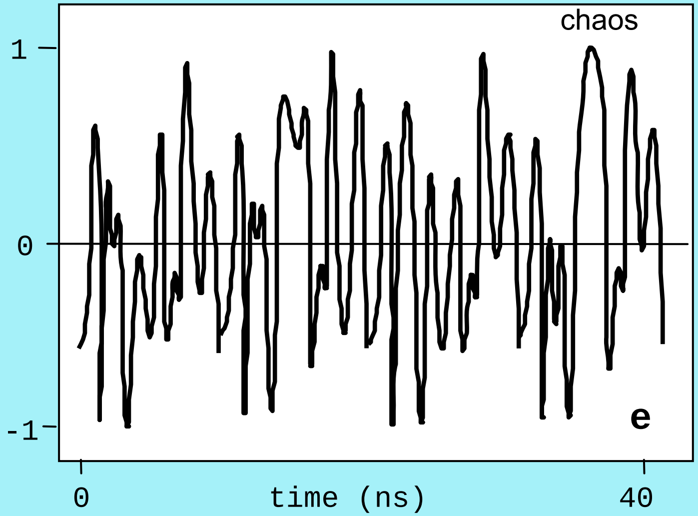
3: multiperiodic regime, w/ bifurcations



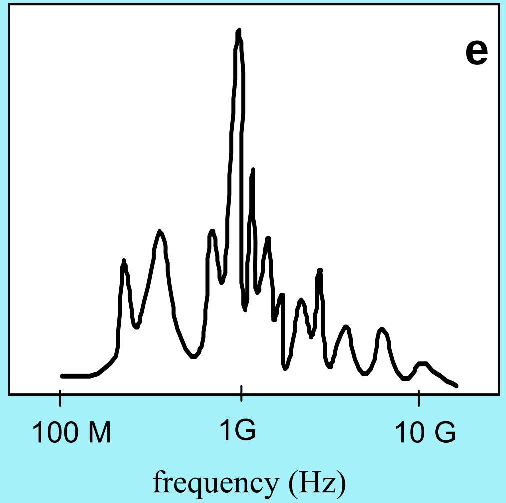
4: chaos



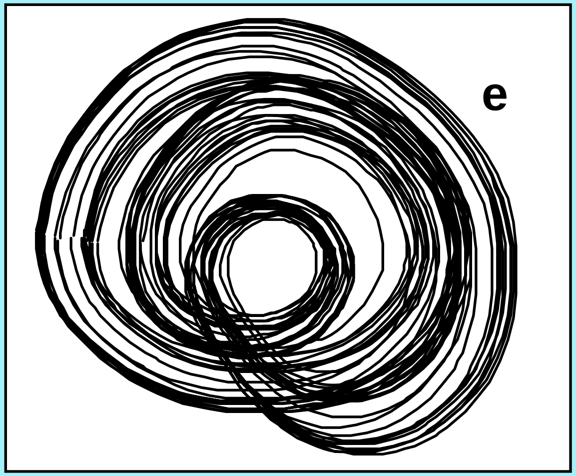
bifurcations
bifurcation
multiperiodic regime
weak coupling
periodic solutions
per. sol.
chaos
multiperiodic
per. sol.
chaos
periodic solutions
e



chaos
1
0
-1
e
0
time (ns)
40



e
100 M
1G
10 G
frequency (Hz)



e

Understanding the new dynamical regimes

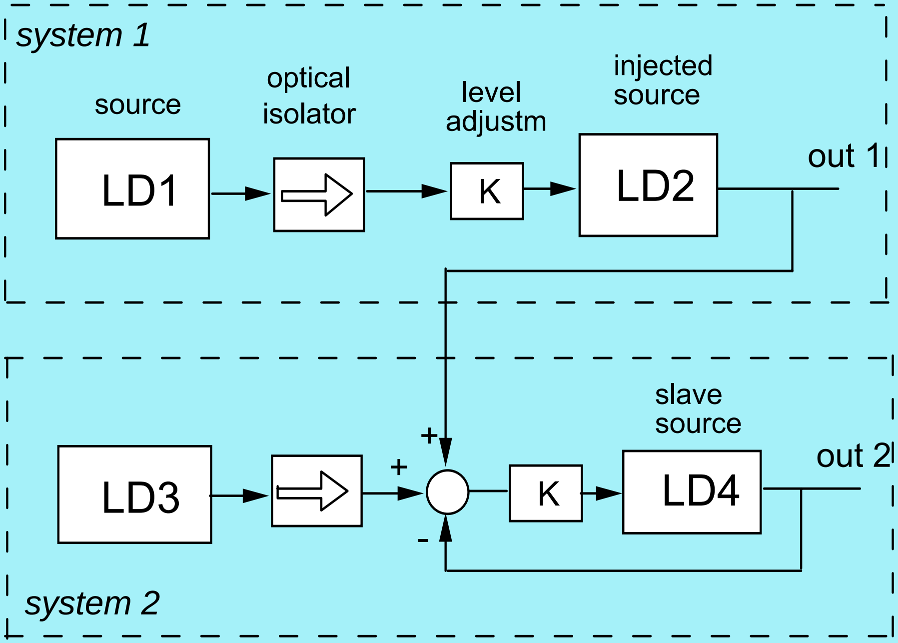
- The apparently subtle waveforms $E_0 \cos\Delta\omega$ of beating, found in the new dynamical regimes, namely: *weak modulation, periodic, multi-periodic and chaos* are kind of ***eigenfunctions*** of the complex system (the coupled laser system), like sinusoidal oscillations are the free response (eigenfunctions) of a linear system

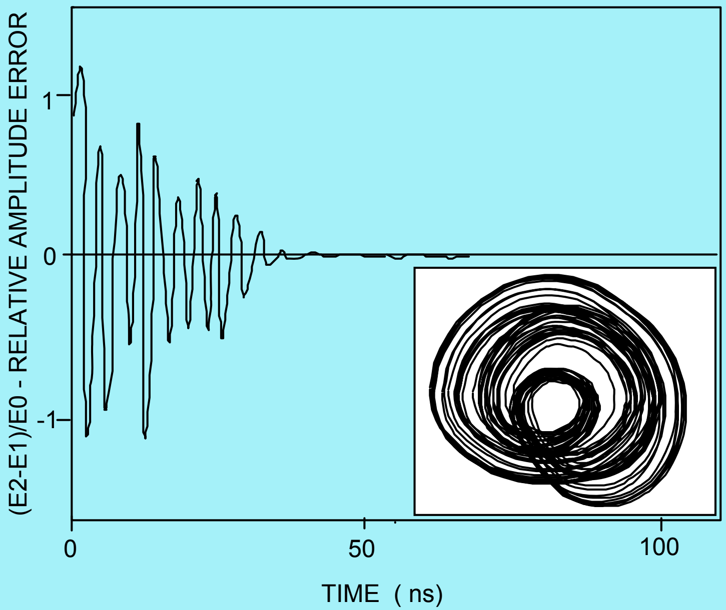
- a conjecture then follows: by injecting from the external the beating waveform into the system, this should react adjusting itself to follow the dynamical evolution represented by it – or: ***be synchronized***

- of course, we need the system be ***not too far*** from the state generating the injected waveform, like we need for frequency in oscillations

attempting synchronization

Two chaotic systems (each w/ two coupled LDs) are synchronized by using feedback of optical fields at the input node. Scheme shown below is robust against small mismatch of parameters and initial conditions

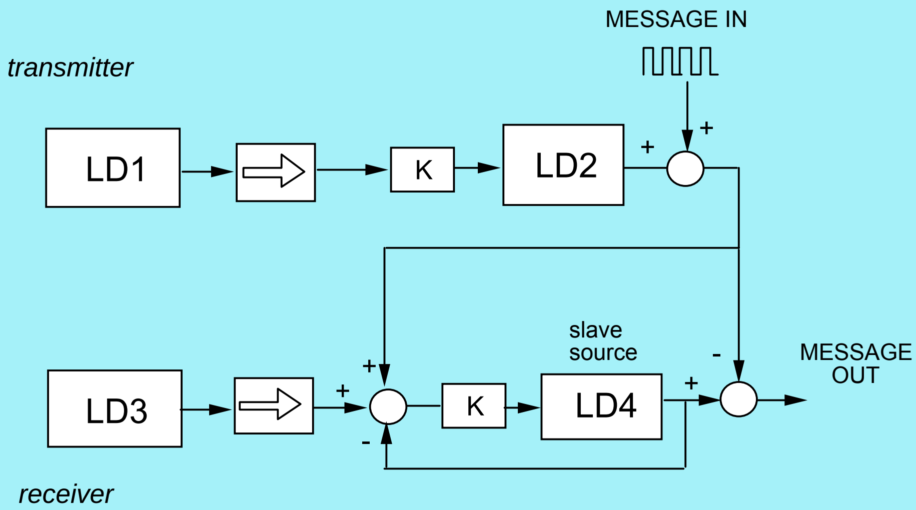


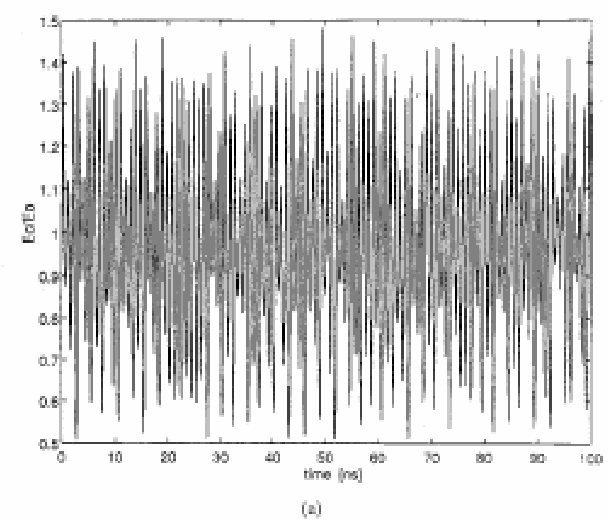


the master chaos generator flies freely, while the slave starts from an arbitrary quiescent point. By coupling, it readily gets tracked to master within <1% error

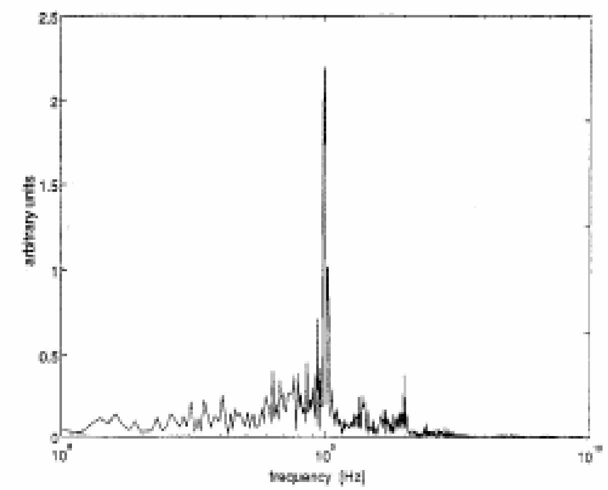
Annovazzi, Donati, Scire': J.Quant. Electr. 32, **1996** pp.953-59 [43d] cited by 72

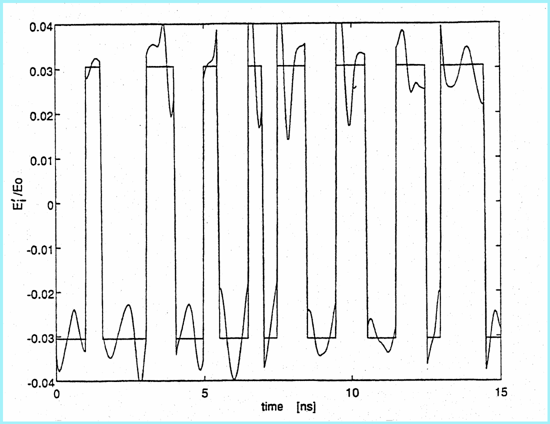
A simple coding scheme: Chaotic Masking





Transmitter adds chaos to signal, at optical field level; receiver is identical and synchronizes to the chaotic waveform, then subtract it to the received field unveiling the signal



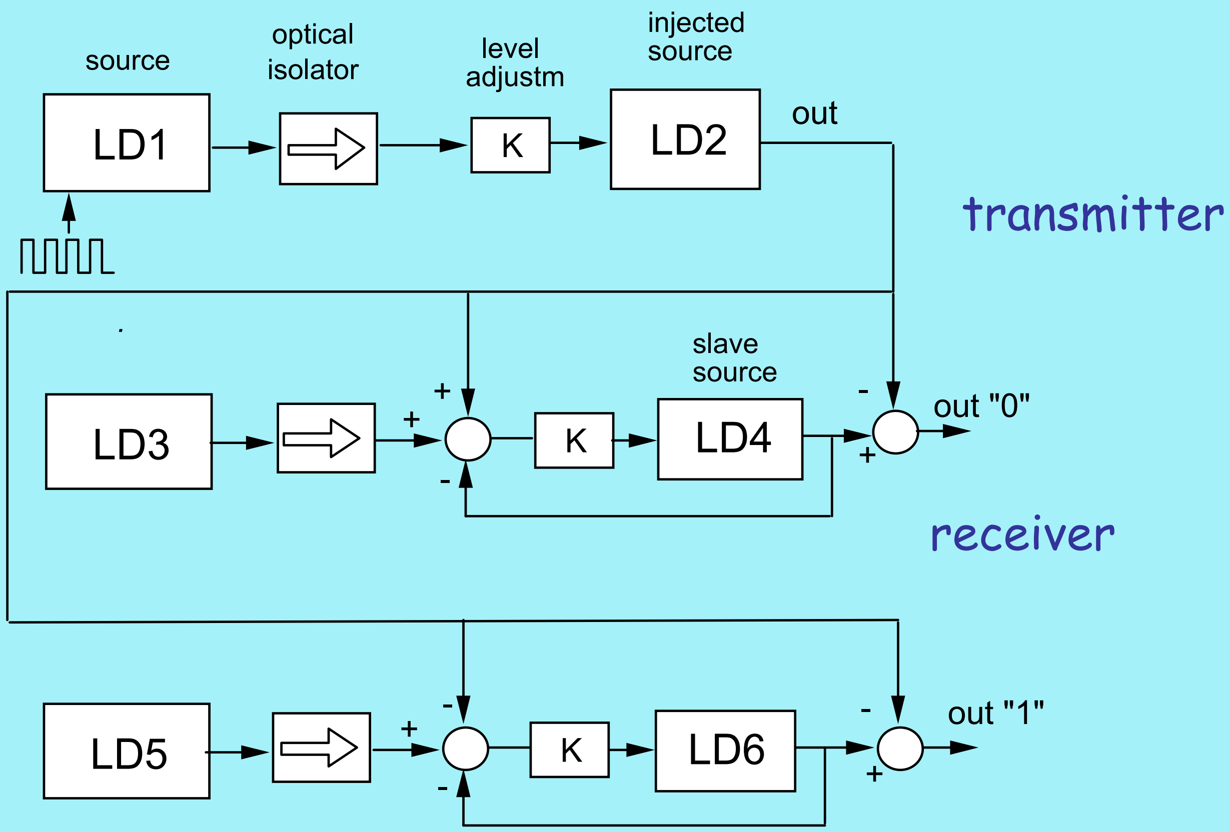


reconstructed waveform

time domain and frequency spectrum of CM signal

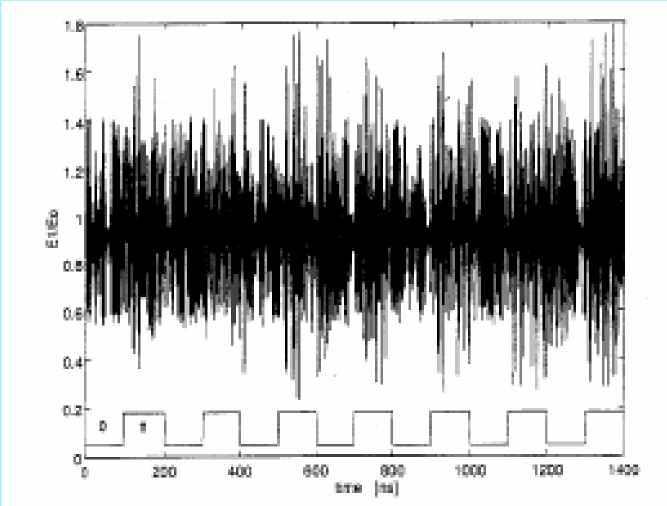
Chaos-Shift-Keying (CSK)

A more ingenious scheme of secure communication is the CSK (chaos-shift-keying): System 1 is switched between two closely spaced orbits, representing "0"and "1", by changing the pump J. Systems 2 and 3 replicate the pump J_1 and J_0 and will synchronize on the "0"and the "1", respectively.

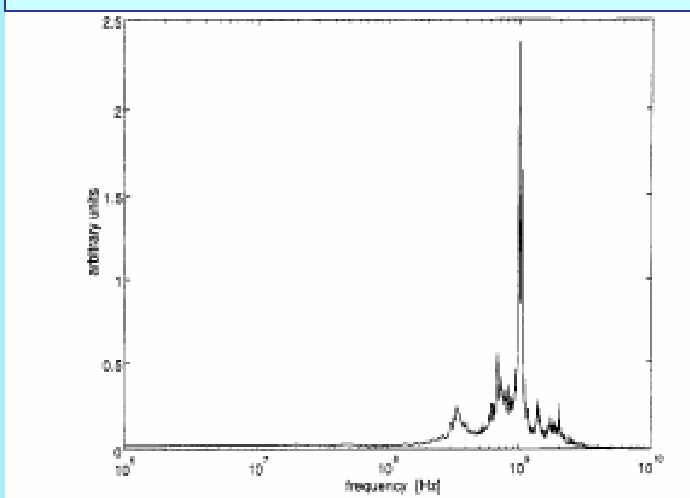


Annovazzi, Donati, Scire': J.Quant. Electr. 32, **1996** pp.953-59 [43d] cited by 72

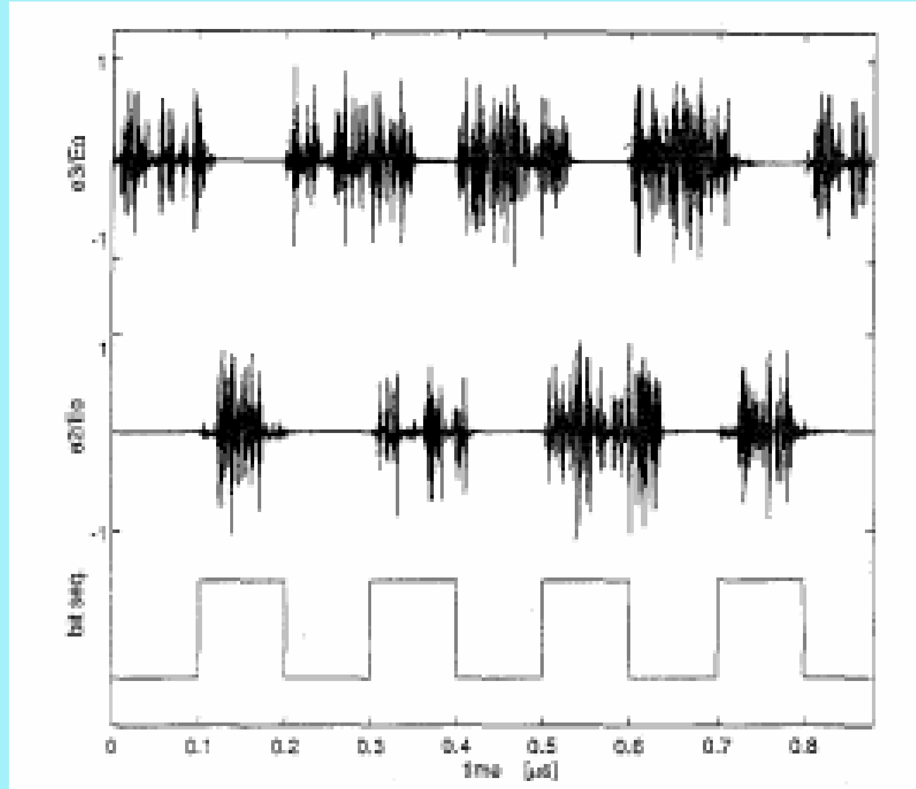
Signals in a CSK transmission: time-domain and spectrum



time domain of the CSK waveform and transmitted signal



frequency spectrum of CSK



Normalized signal error with the CSK system. A square wave message is send from system 1. Systems 2 and 3 reach the correct bit level after a short transient.

Looking for a minimum-part-count chaos generator

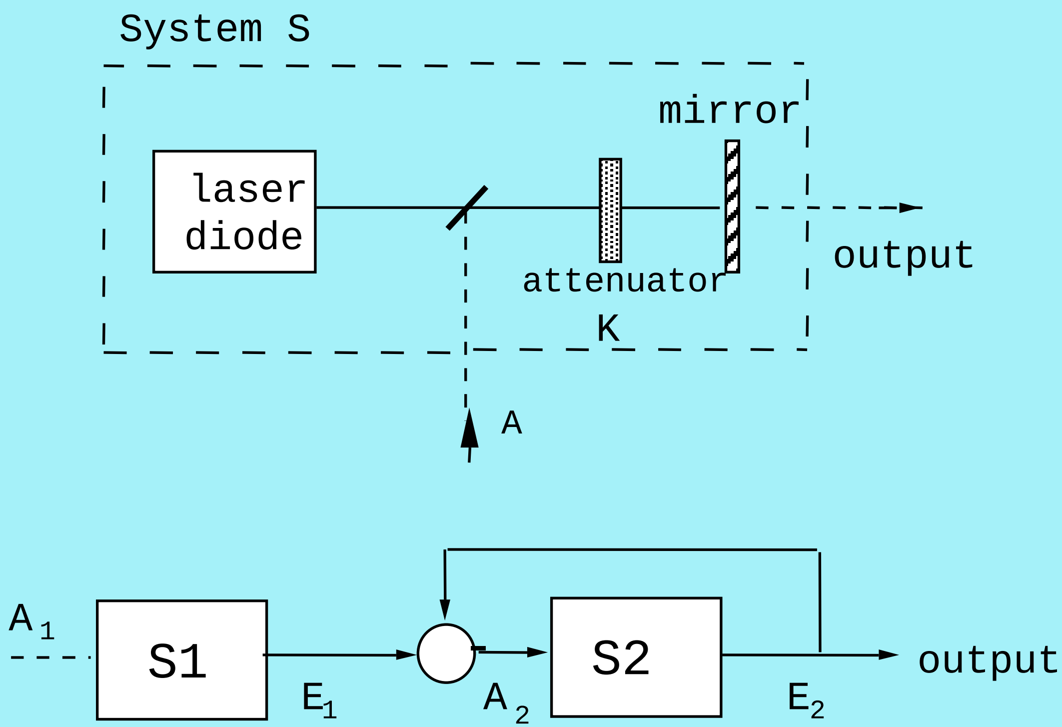
Now that the 2-laser injected system has been demonstrated, good for chaos generation and cryptography, a question is in order:

- how critical is the system structure and its working parameters (K, $\Delta\nu$) ?
- answer: it's *not critical*. if structure is changed (for example, with a symmetrical injection) phenomenology is the same, though values of regime boundaries and dynamical waveforms change

Then an engineering question:

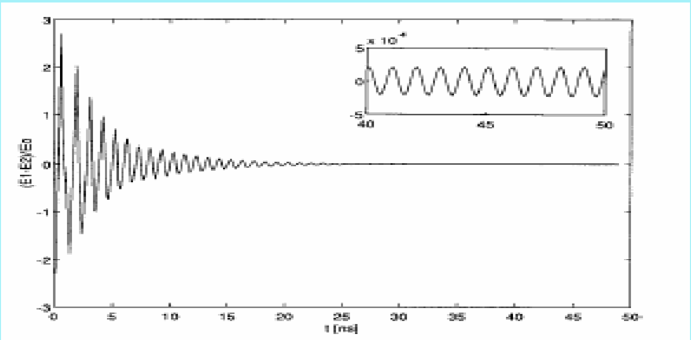
- can be the 2-laser injected system be simplified ?
- answer, yes, removing one laser and going to DOF

Delayed Optical Feedback chaos generator



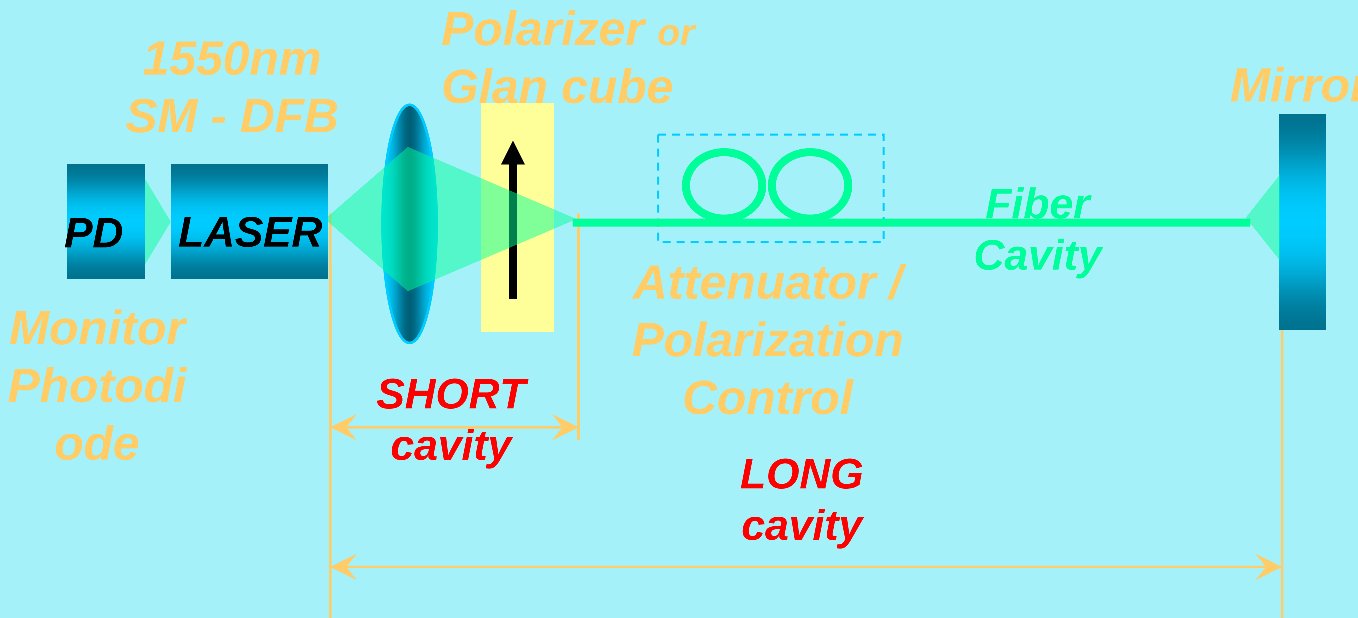
DOF or delayed optical feedback [once again, a self-mixing scheme !] is much simpler compared to the 2-laser injected scheme.
Analyzed with L-K equations, the DOF system is shown functionally equivalent to the 2-laser and is fast to synchronize.

system synchronizes quickly, yet a residual ripple (see inset) remains at the 0.05% level of error η



Annovazzi, Donati, Scire: J. Quant. Electr. 33, 1997 pp.1449-54 [49d] cited by 54

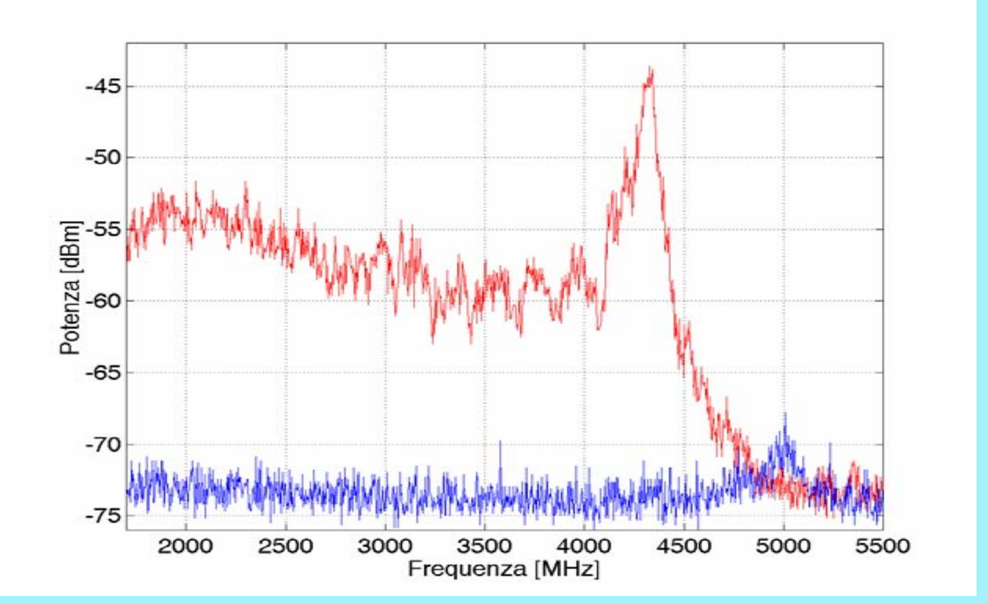
Setup for evaluation of the DOF chaos generator in the 3rd window

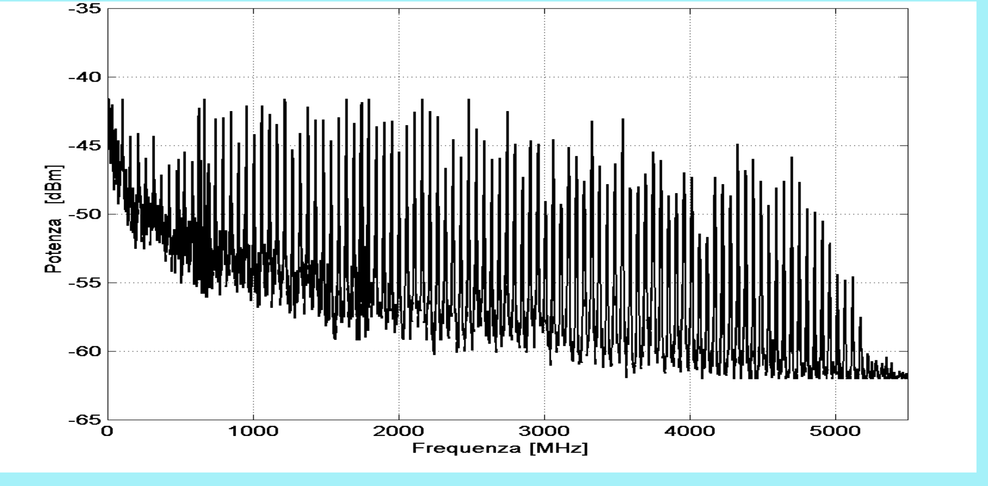


Experimentally, two possible ways of generating DOF chaos are found: with a *short cavity* (length <<c/ν_2 , where ν_2 = modulation frequency cutoff), and with a long cavity (length >>c/ν_2). Typical lengths are 1-2 cm and 0.5-1 m respectively, for ν_2=5 GHz. Feedback is co-/incoherent and affects the required matching of length (within a fraction of λ for coherent)

Annovazzi, Merlo, Norgia, Scire'- J. Quant. Electr. 38, 2002, pp.1171-78

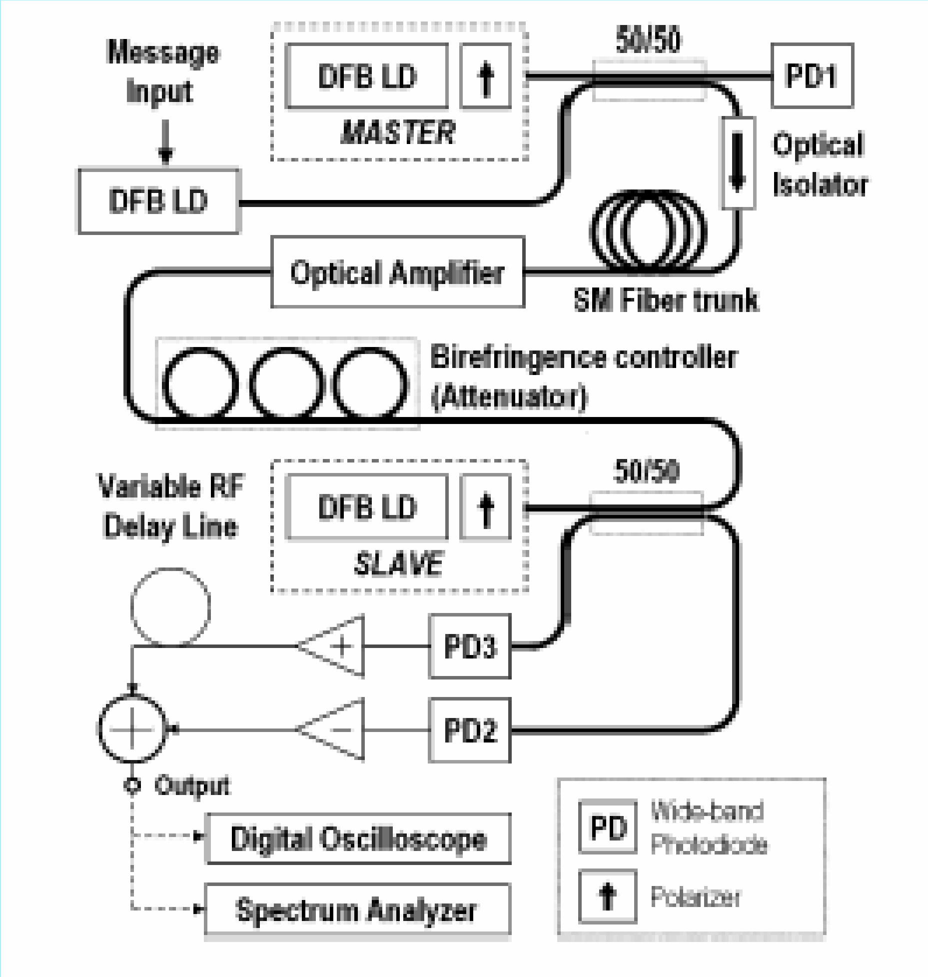
Spectrum of chaos for short and long cavities





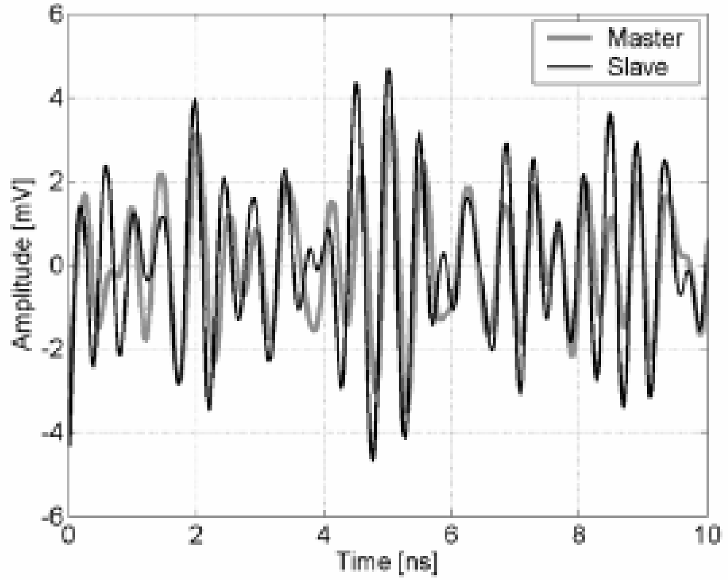
Short cavities (top) yield a nearly continuous electrical spectrum, which is sensitive to fraction-of-λ changes of the actual external cavity length

Long cavities (bottom) present a spectrum made of a series of spikes that increase in number and amplitude with increasing length and isn't sensitive to cavity length

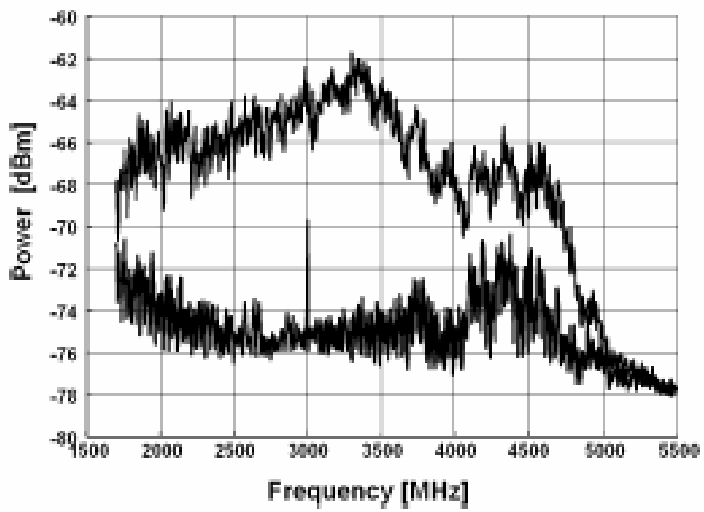


Experiment of an ACM (Additive Chaos Masking) scheme, performed with short-cavity DOF chaos generators using DFB lasers at 1550-nm. Master chaos synchronizes the slave and a balanced detector draws signal out. The setup entails propagation through a TLC fiber

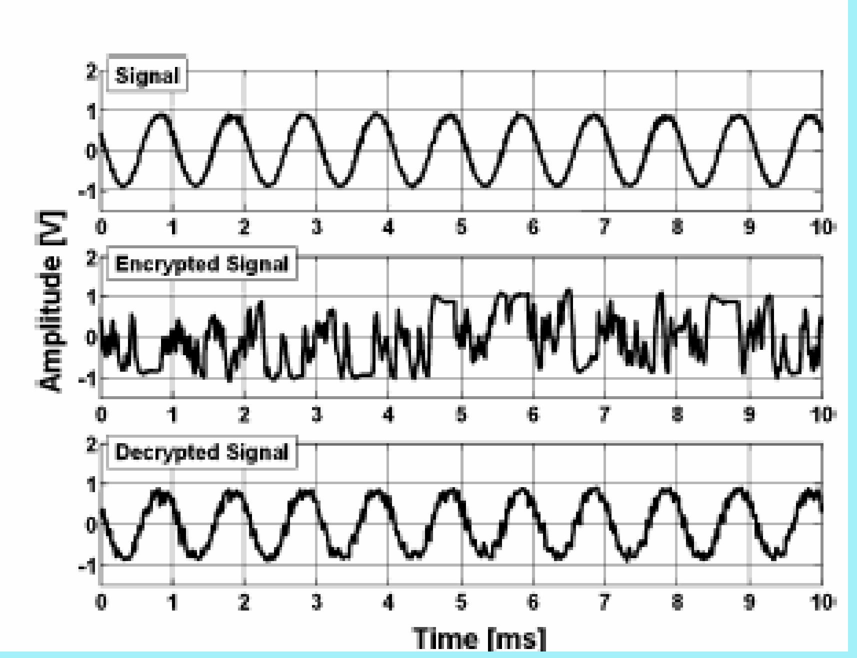
Annovazzi, et al.: Phot. Techn. Lett. 17, 2005, p.1995-98



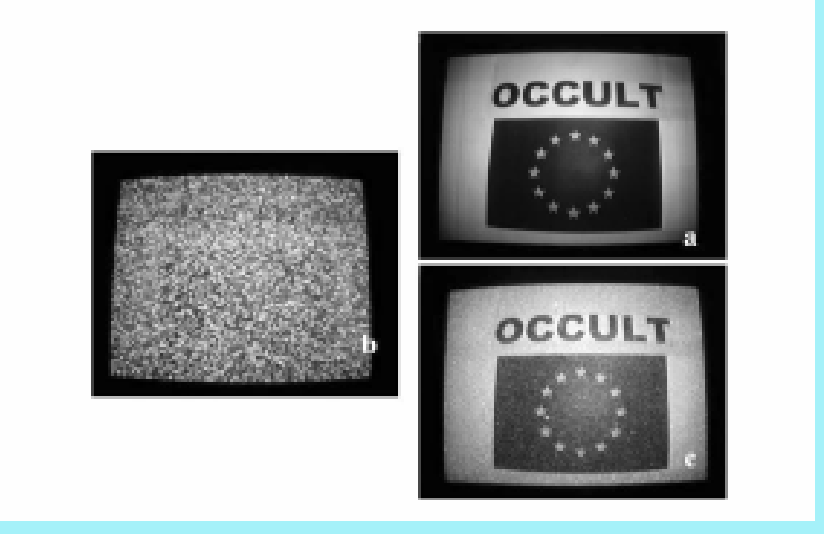
ig. 2. Time series of synchronized master and slave lasers.



Time-domain waveform of the chaotic amplitude (upper figure, for master and slave) and frequency-domain difference between master and slave, revealing the spike of extracted carrier at 3GHz (lower trace in bottom figure)

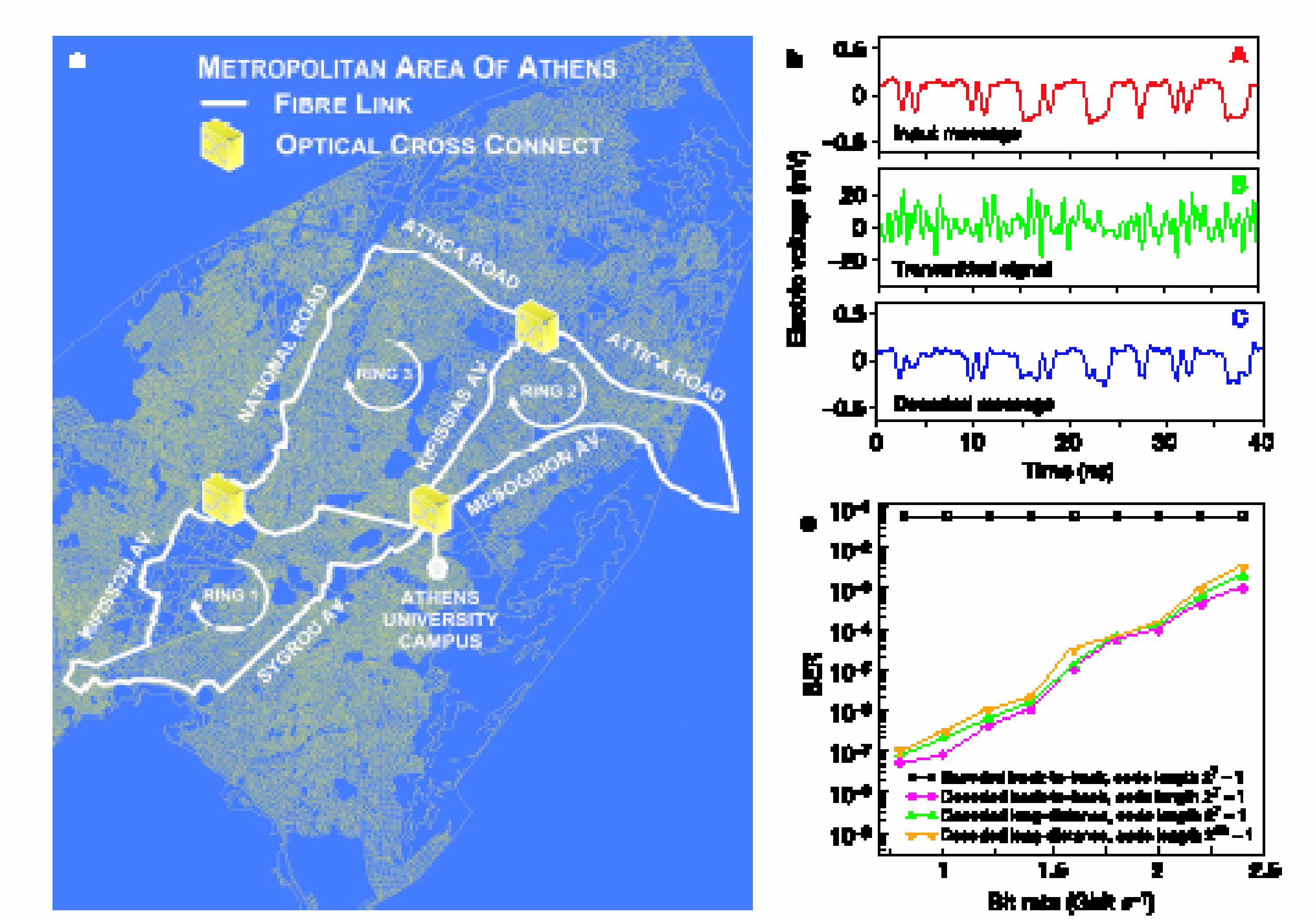


Transmission of a 1-kHz audio signal over the 2.4-GHz carrier with ACM:
a – no encryption,
b – encrypted, c- decrypted



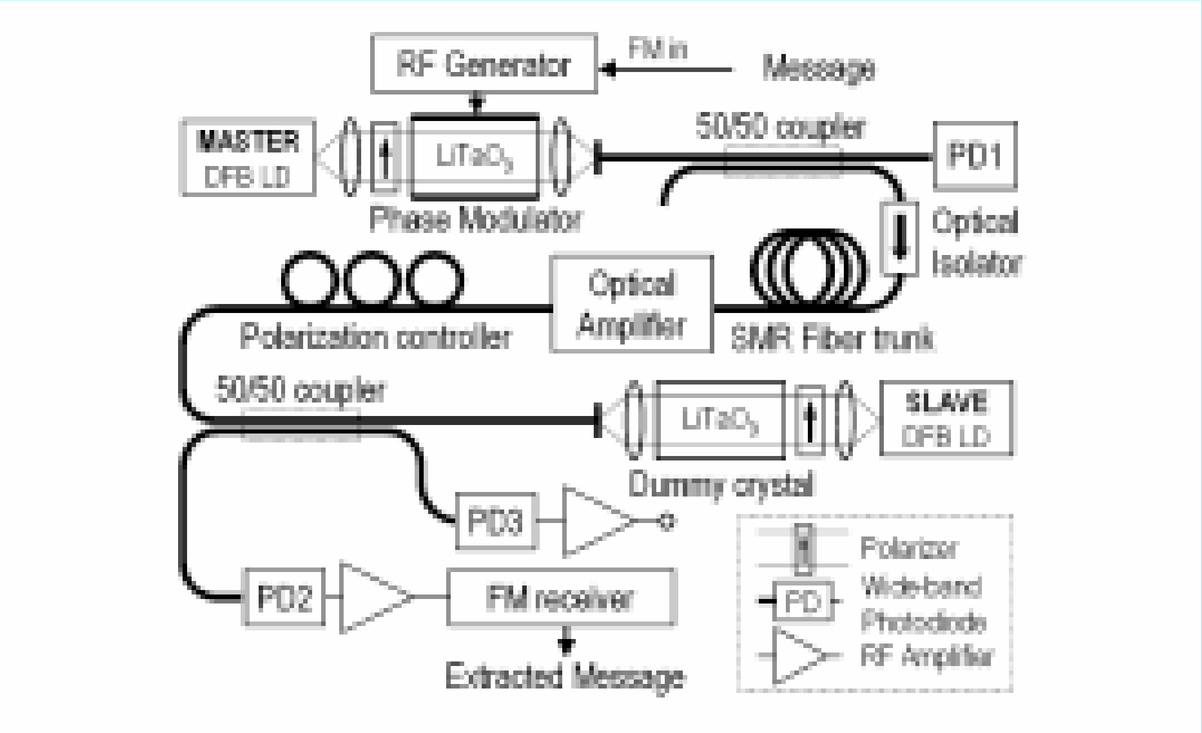
Transmission of a still video frame over the 2.4-GHz carrier with ACM:
a – no encryption, b – encrypted, c- decrypted

Layout of the transmission experiment
on a 120 km G-652 fiber trunk



Annovazzi, et al.: Nature Lett.,438, Nov.2005, p.7343-346

An improved scheme: P-CSK Phase Modulation Shift Keying



The most recent scheme (P-CSK) uses a phase modulator driven by signal in the master generator, so that length l of the short cavity and hence the chaos waveform are changed. Only when δl=0 is the slave synchronized . When δl≠0 a difference in master/slave chaos waveforms is found, a kind of amplitude demodulation. Subtraction of master and slave reveals the hidden message

Annovazzi, Benedetti, Merlo, et al.: Phot. Techn. Lett.19, 2007, p.76-78

how large is the dimensionality of the chaos-coded cryptography ?

(present view)

same-chip diode, short cavity, P-CSK

cavity length	adjusted @ ≈0.01 (λ)	100
laser drive current	adjusted @ ≈ 5% (30mA)	20
coupling factor	adjusted @ ≈10% (Krange)	10
frequency detuning (or chip temp)	≈5% (f-range)	20
Time delay synchronism	adjusted @ ≈10% (delay-range)	20
total		$8\ 10^6$

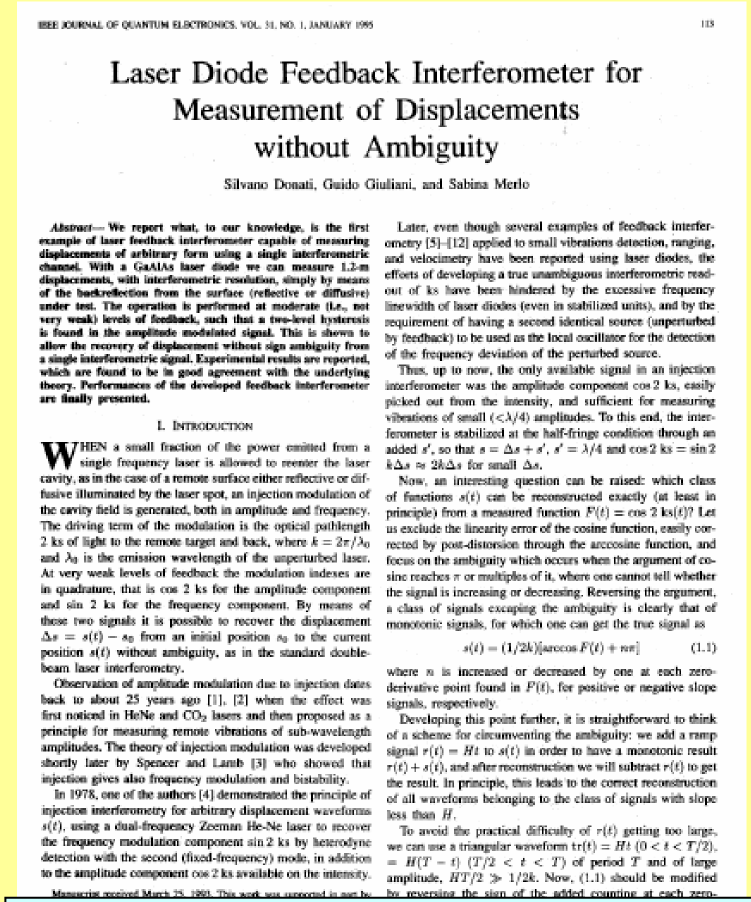
a comment on
chaos cryptography vs *quantum* cryptography

	chaos	quantum
dimensionality	~10^7	virtually ∞
one-photon at a time requirement	no	yes
close to 1 efficiency of detector req'nt	no	yes
bandwidth	GHz	kHz

in conclusion …

COUPLING PHENOMENA PROVIDE A RICH PHENOMENOLOGY, AND ARE USEFUL FOR NEW *INSTRUMENTAL* TECHNIQUES AS WELL AS SECURE SCHEMES OF *COMMUNICATION* BASED ON OPTICAL CHAOS

To probe further, part I



IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 31, NO. 1, JANUARY 1995 113

Laser Diode Feedback Interferometer for Measurement of Displacements without Ambiguity

Silvano Donati, Guido Giuliani, and Sabina Merlo

***Abstract*— We report what, to our knowledge, is the first example of laser feedback interferometer capable of measuring displacements of arbitrary form using a single interferometric channel. With a GaAlAs laser diode we can measure 1.2-m displacements, with interferometric resolution, simply by means of the backreflection from the surface (reflective or diffusive) under test. The operation is performed at moderate (i.e., not very weak) levels of feedback, such that a two-level hysteresis is found in the amplitude modulated signal. This is shown to allow the recovery of displacement without sign ambiguity from a single interferometric signal. Experimental results are reported, which are found to be in good agreement with the underlying theory. Performances of the developed feedback interferometer are finally presented.**

I. Introduction

When a small fraction of the power emitted from a single frequency laser is allowed to reenter the laser cavity, as in the case of a remote surface either reflective or diffusive illuminated by the laser spot, an injection modulation of the cavity field is generated, both in amplitude and frequency. The driving term of the modulation is the optical pathlength 2 ks of light to the remote target and back, where $k = 2\pi/\lambda_0$ and λ_0 is the emission wavelength of the unperturbed laser. At very weak levels of feedback the modulation indexes are in quadrature, that is cos 2 ks for the amplitude component and sin 2 ks for the frequency component. By means of these two signals it is possible to recover the displacement $\Delta s = s(t) - s_0$ from an initial position s_0 to the current position $s(t)$ without ambiguity, as in the standard double-beam laser interferometry.

Observation of amplitude modulation due to injection dates back to about 25 years ago [1], [2] when the effect was first noticed in HeNe and CO_2 lasers and then proposed as a principle for measuring remote vibrations of sub-wavelength amplitudes. The theory of injection modulation was developed shortly later by Spencer and Lamb [3] who showed that injection gives also frequency modulation and bistability.

In 1978, one of the authors [4] demonstrated the principle of injection interferometry for arbitrary displacement waveforms $s(t)$, using a dual-frequency Zeeman He-Ne laser to recover the frequency modulation component sin 2 ks by heterodyne detection with the second (fixed-frequency) mode, in addition to the amplitude component cos 2 ks available on the intensity.

Later, even though several examples of feedback interferometry [5]–[12] applied to small vibrations detection, ranging, and velocimetry have been reported using laser diodes, the efforts of developing a true unambiguous interferometric readout of ks have been hindered by the excessive frequency linewidth of laser diodes (even in stabilized units), and by the requirement of having a second identical source (unperturbed by feedback) to be used as the local oscillator for the detection of the frequency deviation of the perturbed source.

Thus, up to now, the only available signal in an injection interferometer was the amplitude component cos 2 ks, easily picked out from the intensity, and sufficient for measuring vibrations of small ($<\lambda/4$) amplitudes. To this end, the interferometer is stabilized at the half-fringe condition through an added s', so that $s = \Delta s + s'$, $s' = \lambda/4$ and cos 2 ks = sin 2 $k\Delta s \approx 2k\Delta s$ for small Δs.

Now, an interesting question can be raised: which class of functions $s(t)$ can be reconstructed exactly (at least in principle) from a measured function $F(t) = \cos 2\,ks(t)$? Let us exclude the linearity error of the cosine function, easily corrected by post-distorsion through the arccosine function, and focus on the ambiguity which occurs when the argument of cosine reaches π or multiples of it, where one cannot tell whether the signal is increasing or decreasing. Reversing the argument, a class of signals escaping the ambiguity is clearly that of monotonic signals, for which one can get the true signal as

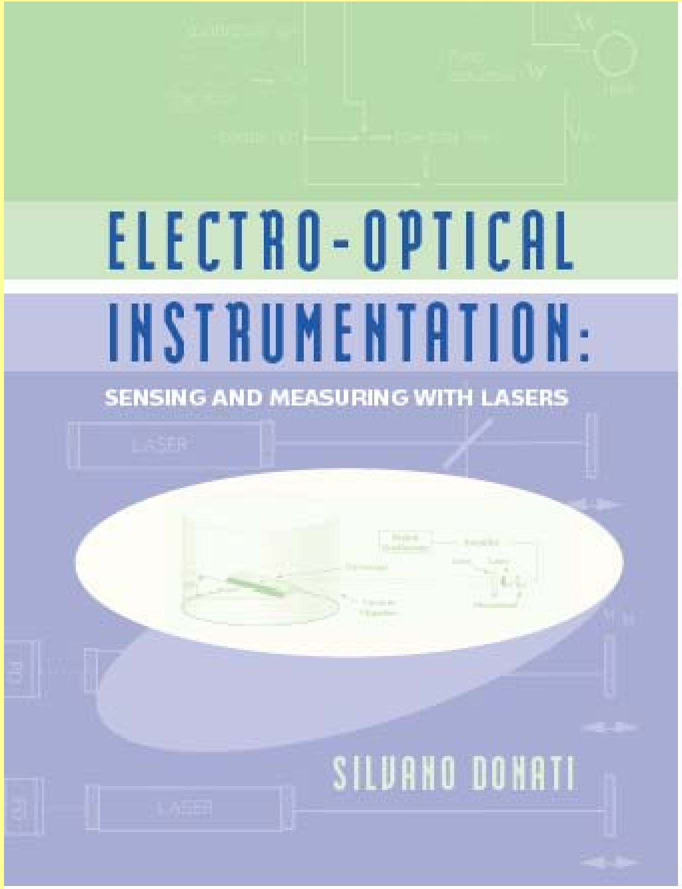
$$s(t) = (1/2k)[\arccos F(t) + n\pi] \qquad (1.1)$$

where n is increased or decreased by one at each zero-derivative point found in $F(t)$, for positive or negative slope signals, respectively.

Developing this point further, it is straightforward to think of a scheme for circumventing the ambiguity: we add a ramp signal $r(t) = Ht$ to $s(t)$ in order to have a monotonic result $r(t) + s(t)$, and after reconstruction we will subtract $r(t)$ to get the result. In principle, this leads to the correct reconstruction of all waveforms belonging to the class of signals with slope less than H.

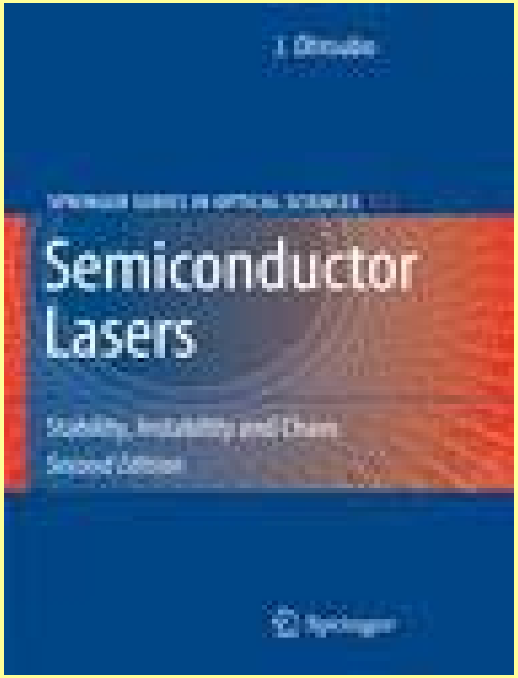
To avoid the practical difficulty of $r(t)$ getting too large, we can use a triangular waveform $tr(t) = Ht$ $(0 < t < T/2)$, $= H(T - t)$ $(T/2 < t < T)$ of period T and of large amplitude, $HT/2 \gg 1/2k$. Now, (1.1) should be modified

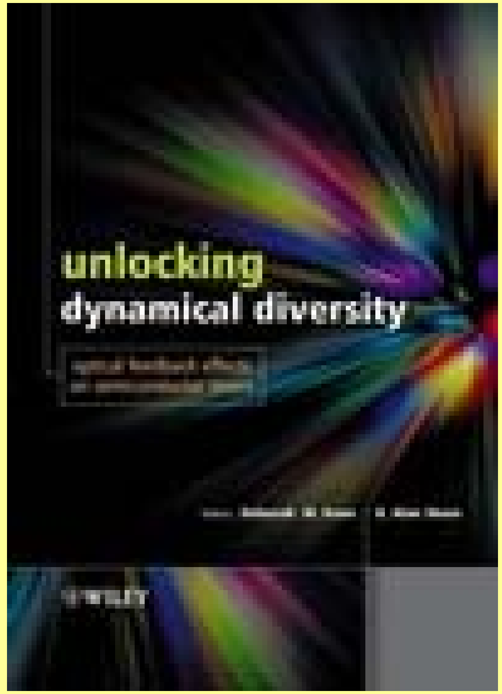
See my web and this [37d] in particular, my seminal work on self-mixing, appeared in IEEE-JQE (cited by 102)



A book on electrooptical methods for measurements, Prentice Hall 2004, treats self -mix interferometry in detail

To probe further, part II





J. Ohtsubo:"Semiconductor Lasers: Stability, Instability and Chaos". Springer Series Optical Sciences <u>111</u> Springer-Verlag, New York, 2006, ISBN 3-540-23675-9

D.M.Kane and K.A.Shore (Editors): "Unlocking Dynamical Diversity: Optical Feedback Effects on Semiconductor Lasers" J.Wiley, March 2005 ISBN: 978-0-470-85619-2

S.Donati, C. Mirasso (Editors): *Feature Issue* on Optical Chaos and Applications to Cryptography, IEEE J. Quant Electr., <u>38</u>, Sept 2002, pp.1137-1196