Optical feedback interferometry: basic concepts and metrological applications

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Introduction

Mirror
Grating
Phase conj. Refl.
Diffusive target
…

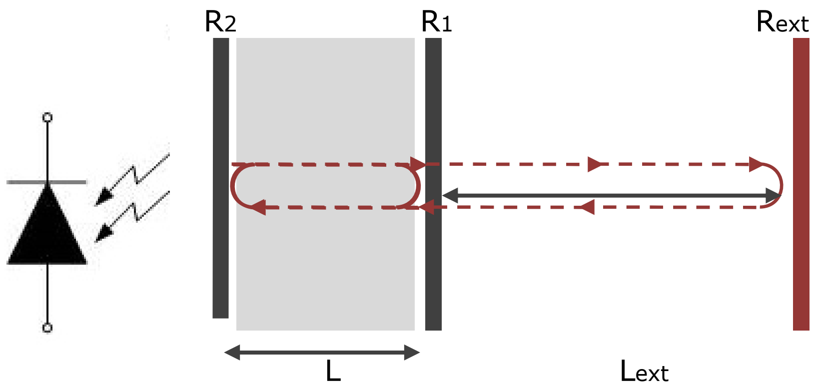
- Almost any laser can be made unstable in time by optical feedback *(feeding part of the output light back into the laser cavity)*
- Semiconductor lasers are very sensitive to back injection
  - 1st motivation: studying optical feedback from the ends of optical fibers into telecom s.c. lasers.
- PROBLEM:
  - Even small amount of optical feedback may dramatically increase the output noise
- OPENING:
  - convenient tool for probing basic physics of s.c. lasers
  - wheal t of applications
- *MAIN MESSAGE*:

  self-mixing makes a laser source capable of sensing its external environment

Outline

- optical feedback interferometry
  - self-mixing effect in semiconductor lasers
  - Lang-Kobayashi model
- applications in metrology
  - linear displacement (single channel)
  - translations and rotations (multiple channels): 6 DoF
  - absolute distance
  - displacement or rotation velocity
  - vibrations
  - longitudinal and volume deformations (strain fiber sensor)
- laser ablation sensor
  - *real-time* characterization of laser ablation process
  - study of the ablation dynamics in the thermal regime
  - simultaneous measurement of multiple target displacements
- self-mixing in quantum cascade lasers
  - ultra-stability of QCLs vs optical feedback
  - nonlinear mixing → towards subwavelength (nm) resolution
  - terahertz imaging

Optical Feedback (self-mixing) Interferometry



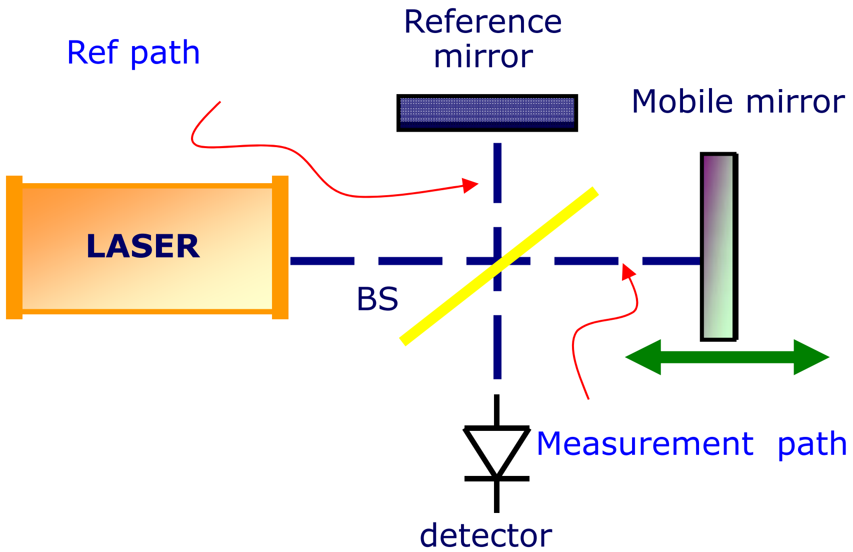
3 mirror Fabry-Perot cavity model

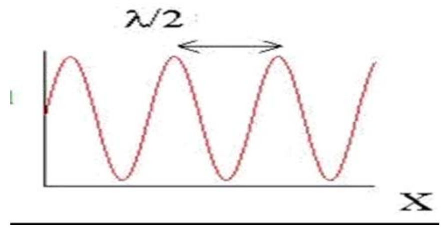
***Self-mixing* perturbes:**

- threshold current (I_{th})
- emitted power (P_{out})
- lasing spectrum (λ)
- bandwidth ($\Delta\lambda$)
- junction voltage (V)

- coherent superposition inside the laser cavity (L) of the cavity field with the radiation back-reflected, or even scattered, by an external target
- modulations of the laser power and frequency
- can be revealed anywhere along the light path, also at the target side
- feedback levels: fraction of power $10^{-8} \rightarrow 10^{-2}$
- moderate feedback → regular amplitude modulations induced by the relative phase
  - intrinsic asymmetry → retrieval of the phase-change sign by a single channel detection.
- high feedback → the laser may enter an instable or even chaotic regime

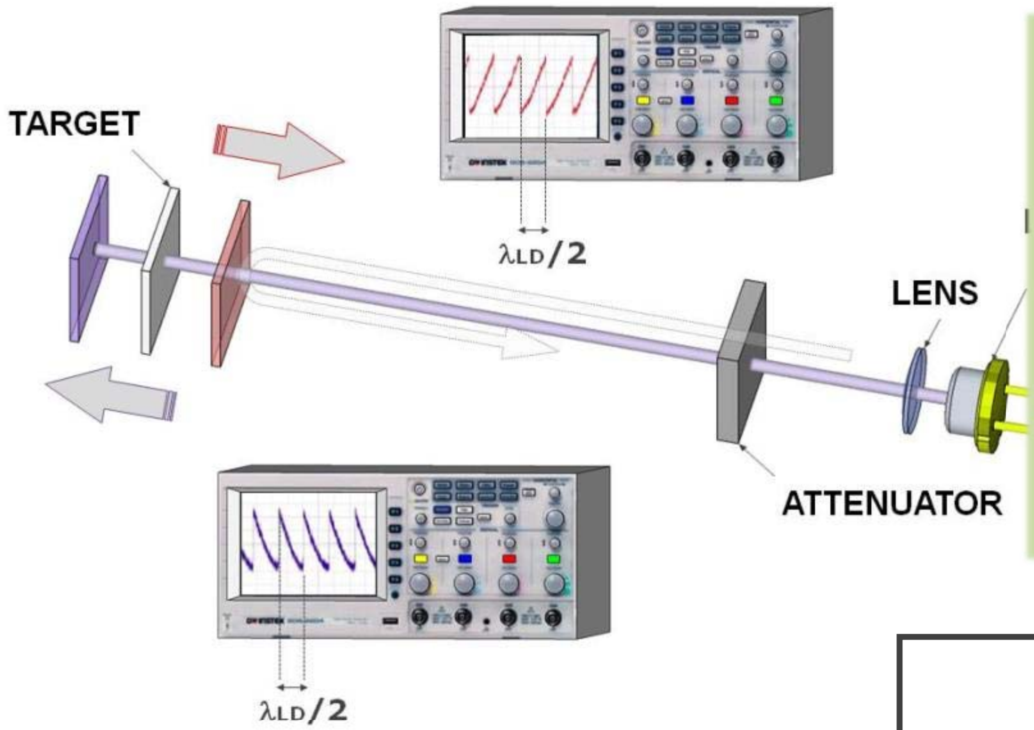
External laser interferometry





- Linear superposition
- Symmetric fringes, λ/2 period
- *Direction ambiguity*
- *Bulky, critical alignment unsuitable for field applications*

Optical Feedback Interferometry: moderate feedback regime

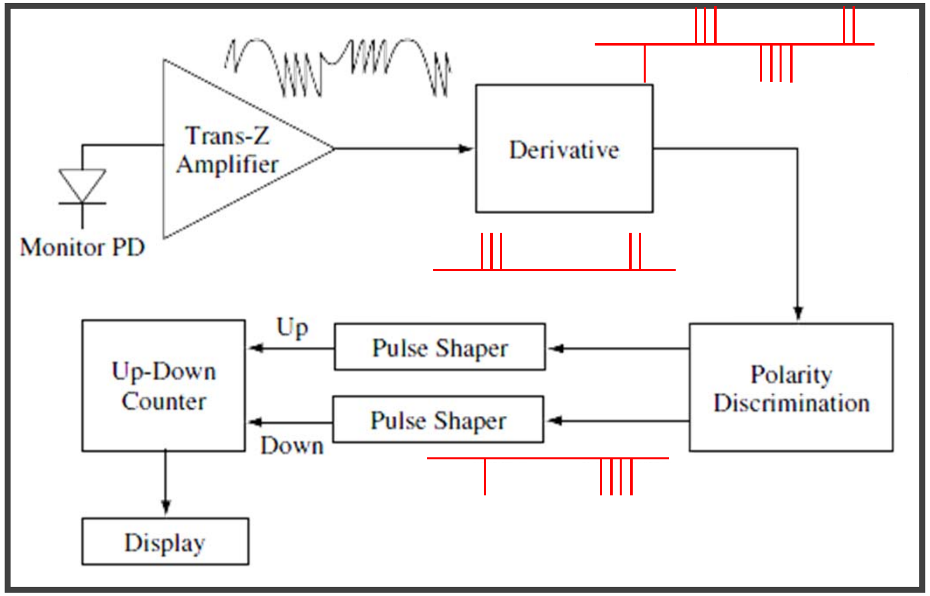


Features:

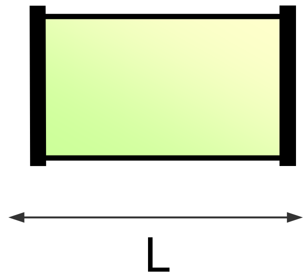
- internal detector
- internal reference arm
- internal beam-splitter
- coherent sensing
- Non-linear superposition
- asymmetric fringes
- The laser acts both as the source and the detector

Advantages:

- part-count minimal, self-aligned
- works on diffusive target surfaces
- resolution:
  - -$\lambda/2$ (fringe counting)
  - -sub-λ (analog processing)
- bandwidth → MHz
- non-contact, compact, robust, cheap



Lang-Kobayashi equations



Linewidth enhancement factor

Modal gain

Carrier density @transparency

$$\frac{dE(t)}{dt} = \frac{1}{2}(1+i\alpha)[G_N(N(t)-N_0)-\frac{1}{\tau_p}]E(t)$$

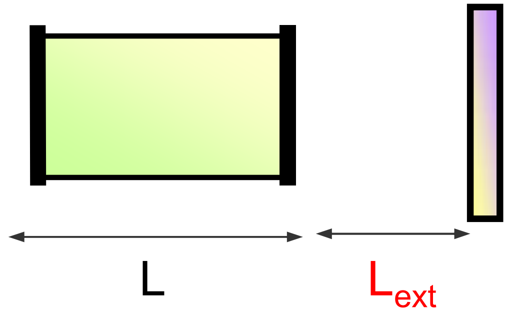
Photon lifetime

$$\frac{dN(t)}{dt} = R_P - \frac{N(t)}{\tau_e} - G_N[N(t)-N_0]\left|E(t)\right|^2$$

Pump rate (injection)

Carrier lifetime

Lang-Kobayashi equations



Attenuation factor due to mode mismatch

Feedback coefficient

$$k = \varepsilon \sqrt{\frac{R_{ext}}{R}}(1-R)$$

Solitary laser frequency

$$\frac{dE(t)}{dt} = \frac{1}{2}(1+i\alpha)[G_N(N(t)-N_0) - \frac{1}{\tau_p}]E(t) + \frac{k}{\tau_C}E(t-\tau)e^{-i\omega_0\tau}$$

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

Laser cavity round trip time (2L/v)

External cavity round trip Time ($2L_{ext}/c$)

Typical values: $\tau_C = 8ps; \tau_p = 1.6ps; \quad \alpha = 5; \quad N_0 = 1.4x10^{18}cm^{-3}; \quad G_n = 8x10^7 cm^3 s^{-1}$

Lang-Kobayashi equations

writing $E(t) = E_0(t)e^{i\phi(t)}$ one gets equations for the field amplitude and phase

$$\frac{dE_0(t)}{dt} = \frac{1}{2}[G_N(N(t) - N_0) - \frac{1}{\tau_p}]E_0(t) + \frac{k}{\tau_C}E_0(t-\tau)\cos[\omega_0\tau + \phi(t) - \phi(t-\tau)]$$

$$\frac{d\phi(t)}{dt} = \frac{1}{2}\alpha G_N(N(t) - N_T) - \frac{k}{\tau_C}\frac{E_0(t-\tau)}{E_0(t)}\sin[\omega_0\tau + \phi(t) - \phi(t-\tau)]$$

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

Lang-Kobayashi equations

Looking for steady-state plane-wave solutions

$$\omega = \omega_F, \quad E_0(t) = E_s, \quad \phi(t) = (\omega_F - \omega_0)t, \quad N(t) = N_s$$

- From the eq. for the phase $\Phi = \omega_F \tau$

$$\omega_F = \omega_0 - \frac{k}{\tau_c}\sqrt{1+\alpha^2}\left[\sin(\omega_F \tau + arctg(\alpha))\right] \longrightarrow$$ Laser frequency

- Numerically solving the last trascendental equation in the weak-moderate feedback limit ($k << \tau_c/2\tau_p$)

$$N_s = N_{th} - \frac{2k}{G_n \tau_c}\cos(\omega_F \tau) \longrightarrow$$ Carrier density and gain

$$|E_s|^2 = \frac{(R_p - \frac{N_s}{\tau_e})}{G_n (N_s - N_0)} \longrightarrow$$ Optical power

periodic dependence from:
- feedback coefficient
- target position

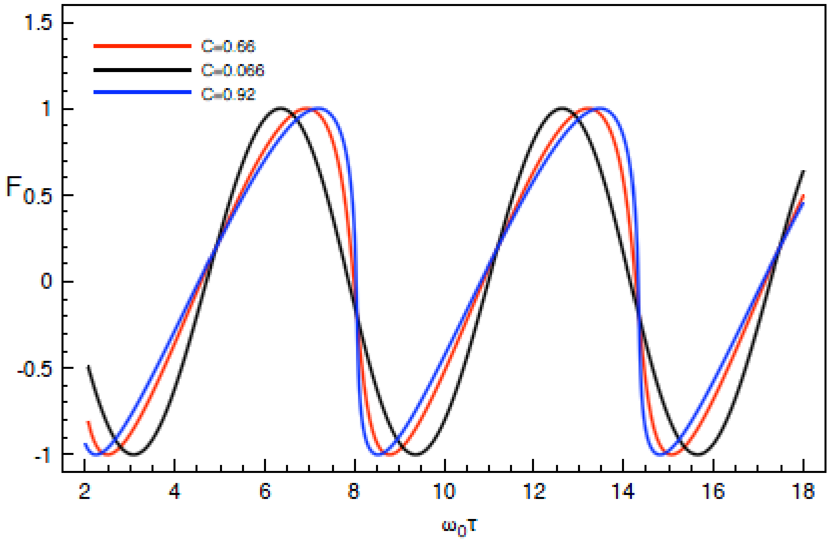
Optical power modulation

$$P^2 = P_0^2(1 + mF(\phi))$$

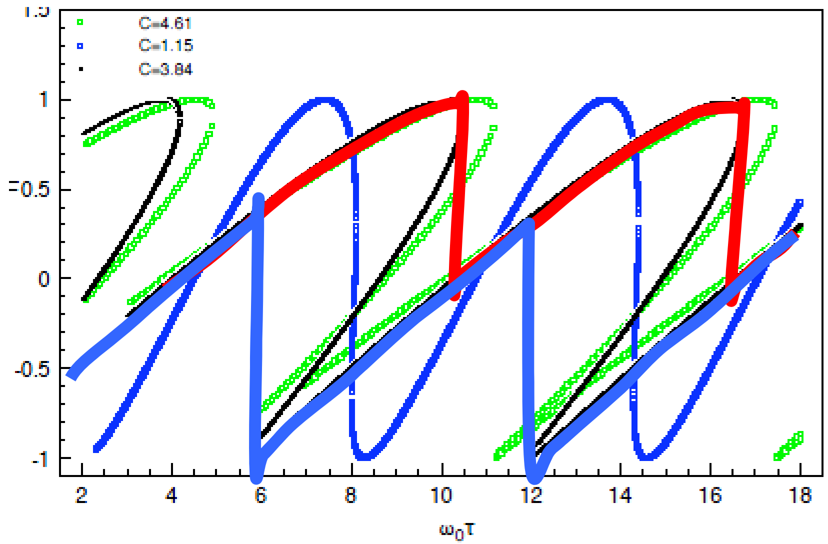
$m = 2k\tau_p / \tau_C$ Modulation index

$F(\phi) = \cos(\omega_F \tau)$ Feedback function

- F is periodic as a function of $\phi = \omega_F \tau = 4\pi L_{ext} / \lambda$



$\alpha = 5,\ \gamma = 0.001,\ I_p = 1.05,\ R = 0.4,\ R_{ext} = 0.7,\ \omega_0 = 2000$

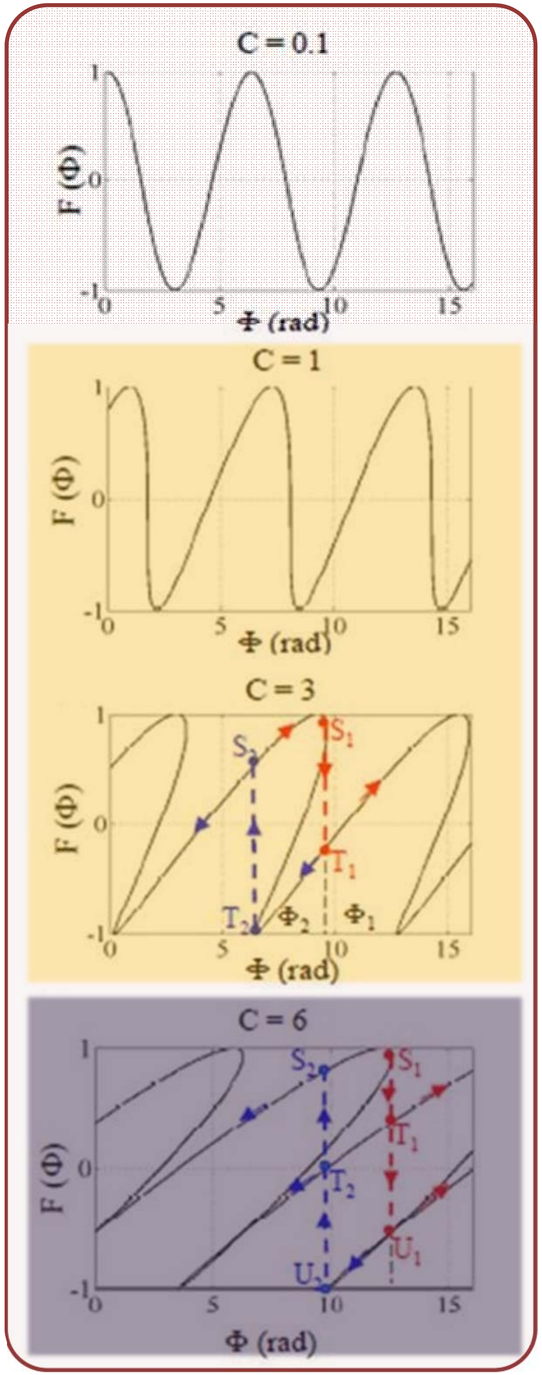


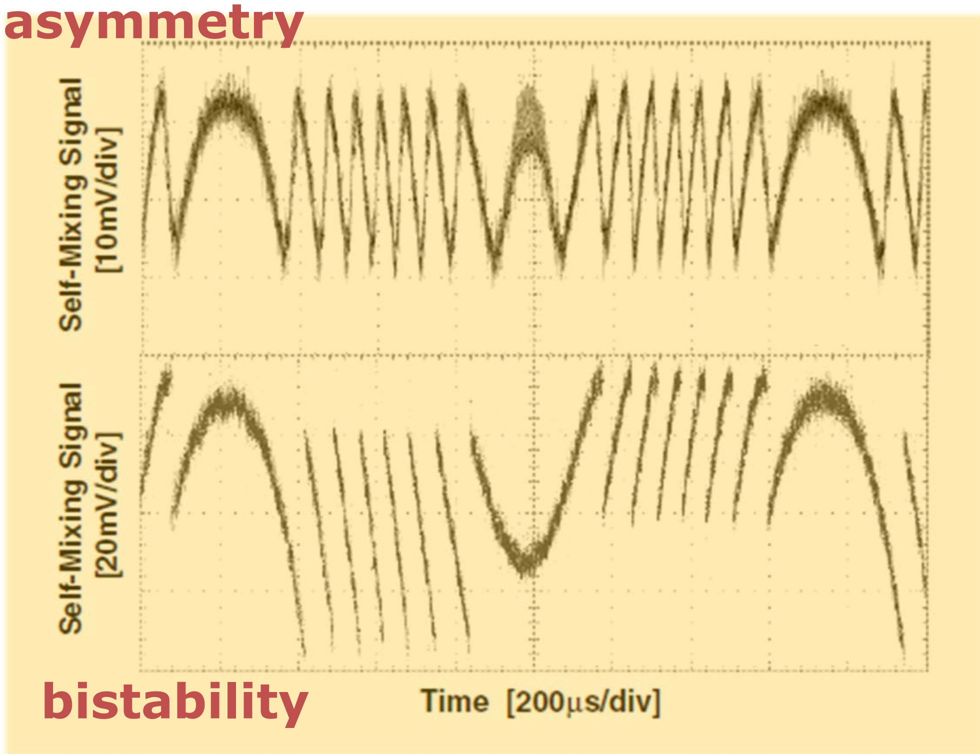
Feedback parameter

$$C = k\frac{\tau}{\tau_C}\sqrt{1 + \alpha^2}$$

- C < 1 → single solution
- 1 < C < 4.6 → three solutions sawtooth asymmetric fringes

Self-mixing regimes





$\Delta\omega/\omega = 5\text{x}10^{-9} – 5\text{x}10^{-7}$ (typical)

$\Delta\omega$ ~ 1 GHz (max value in THz QCLs)

C > 4.6 → multistability

C > 30 → coherence collapse→ chaos

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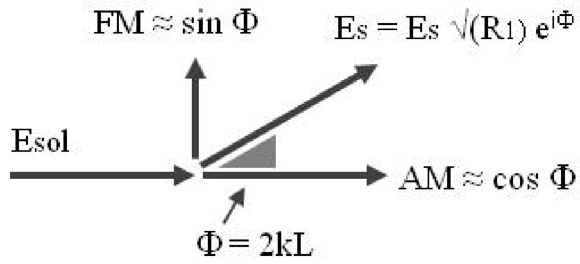
Laser self-mixing interferometry: metrology

$$\Phi = \vec{k} \cdot \vec{r} = \frac{n\omega r}{c} \hat{u}_k \cdot \hat{u}_r$$



$d\Phi \propto dn$	filled cavity spectroscopy (gas concentration, temperature)
$d\omega$	Doppler shift (velocity), phase noise (linewidth)
dr	displacement, vibration
$d(\hat{u}_k \cdot \hat{u}_r)$	orientation, alignment

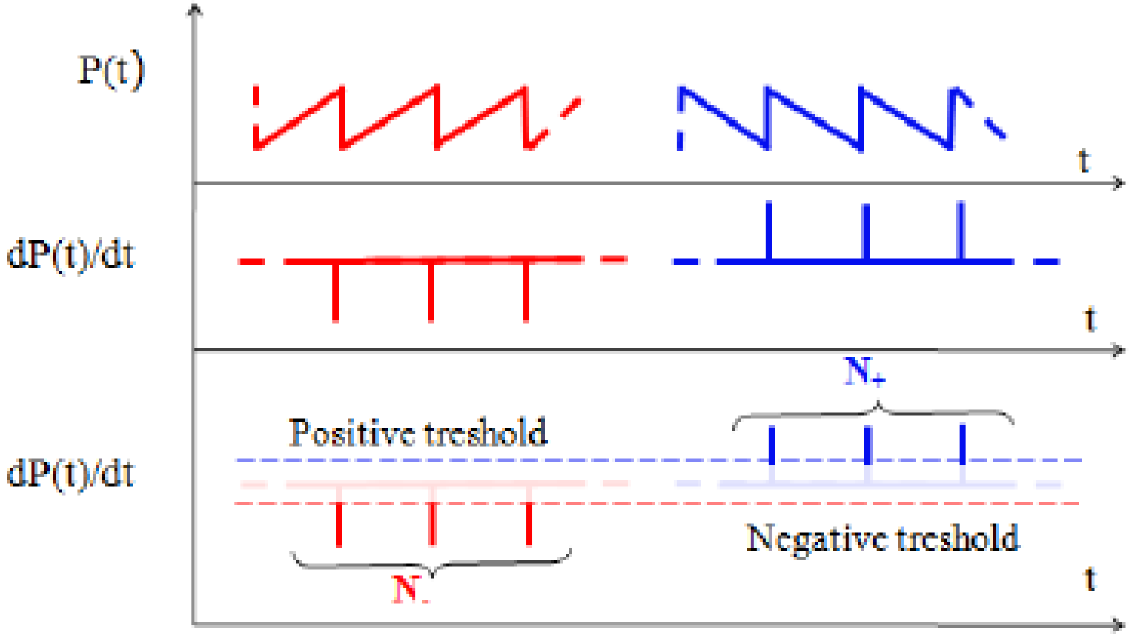
limiting factors

mode matching $\varepsilon = \varepsilon(L)$

coherence length $\tau\gamma_\perp < 1 \rightarrow L < c / \delta\nu$

relaxation oscillation frequency $\pi / \tau > \omega_r = \sqrt{2(\alpha - 1) / \gamma_\parallel}$

Linear displacement



$$\Delta x = \Delta N \times \frac{\lambda}{2}$$

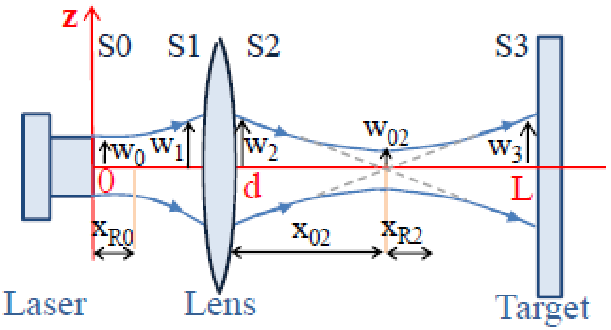
- Fringe counting in the moderate regime: 1.0 < C < 4.6
- The feedback coefficient $C \propto L_{ext}$ → displacement range: $L_{MAX}/L_{min} \leq 4.6$
- Reported continuous linear range with no change in the experimental conditions (e.g. alignment, attenuation) → $L_{min} \sim 30$ *cm* - $L_{MAX} \sim 1.4$ *m*
- Applications in mechatronics demand sub-µm control over > 10 m

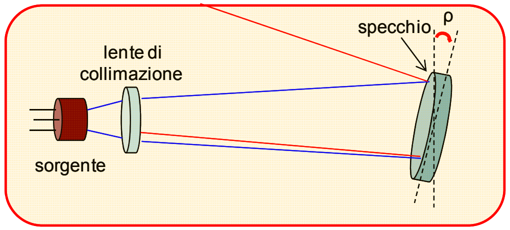
  (e.g. aerospace, remote alignment in hostile spaces, particle physics experiments, …)

Effective feedback coefficient

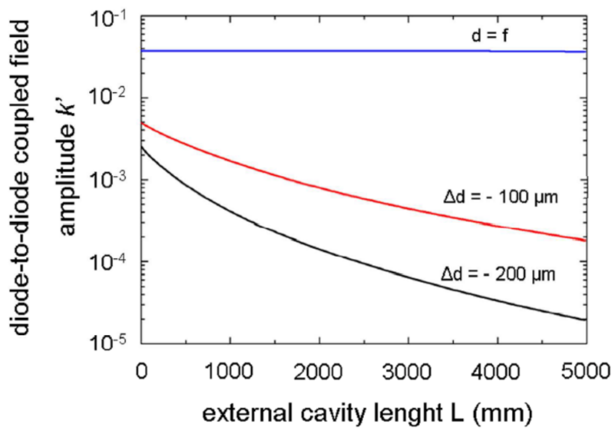
[De Lucia, Putignano, Ottonelli, di Vietro, Dabbicco, Scamarcio, Opt. Exp. 2010]

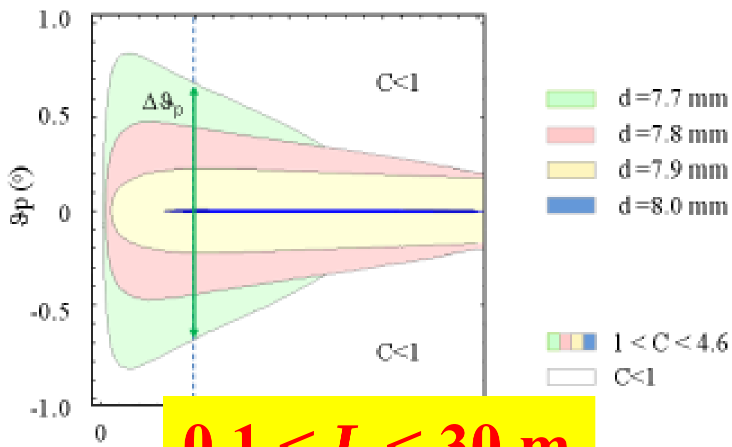
- LK model assumes plane waves and mirrors → Gaussian beams
- Accurate mode feedback mismatch modeling





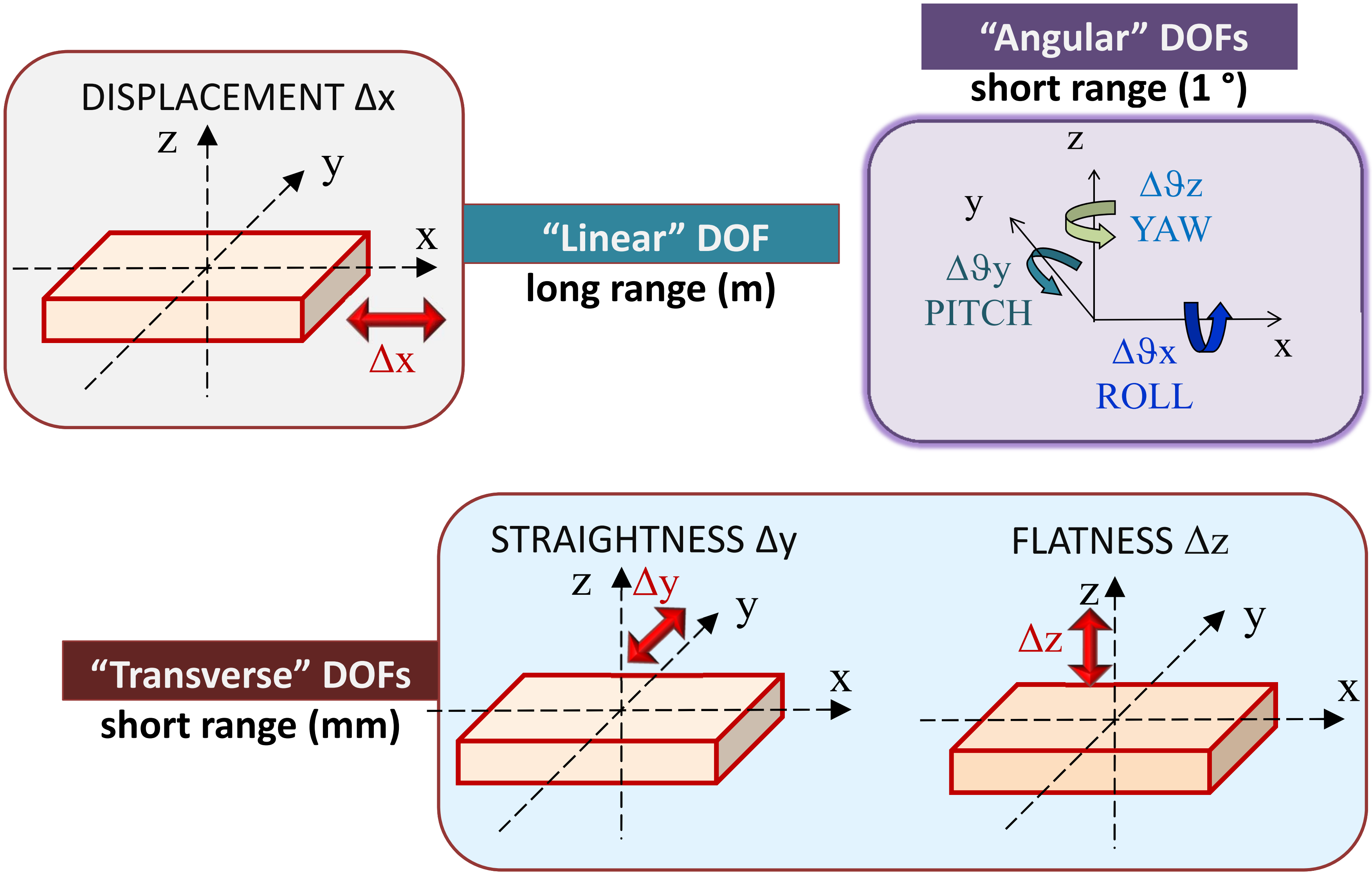
- Partial defocusing → i) compensates for C↑ with L; ii) tolerant for $\Delta\theta$





0.1 < *L* < 30 m

6 DOFs MEASUREMENT

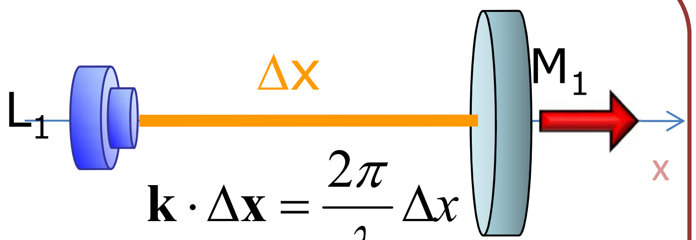


Motivation

- Central problem in precision manufacturing and micro-machining: *real-time measurement of the* ***tool-center-point position***
- Vibrations, mechanical defects, thermal expansion → all 6 DoF must be monitored
- Standard approach for linear motion: mechanical/optical encoders, hybrids
- An all-optical, compact, simple, cheap system is highly desirable
- Possibly based on a single technique

Experimental method

LINEAR DISPLACEMENT Δx

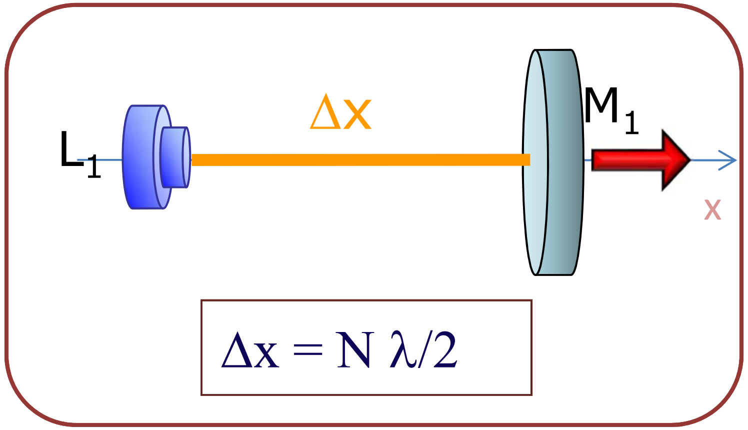


$$\mathbf{k} \cdot \Delta \mathbf{x} = \frac{2\pi}{\lambda} \Delta x$$

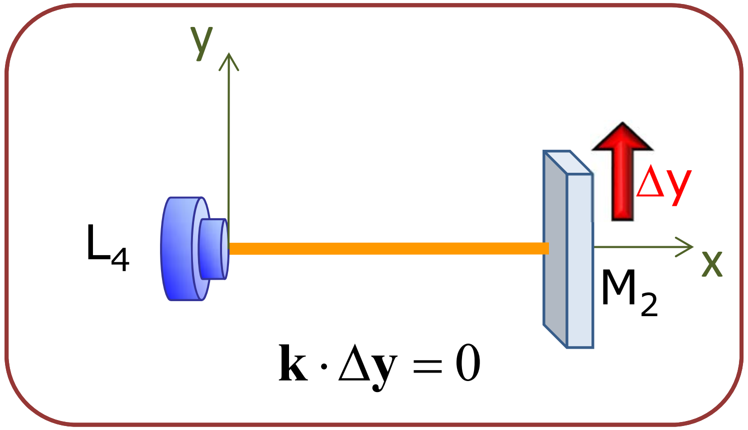
$$\Delta x = N\, \lambda/2$$

Experimental method

LINEAR DISPLACEMENT Δx

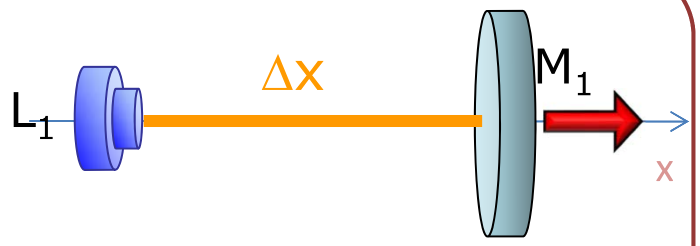


TRANSVERSE DISPLACEMENT Δy, Δz



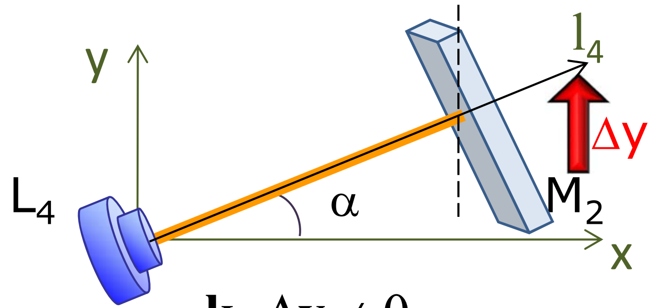
Experimental method

LINEAR DISPLACEMENT Δx



$$\Delta x = N\,\lambda/2$$

TRANSVERSE DISPLACEMENT Δy, Δz

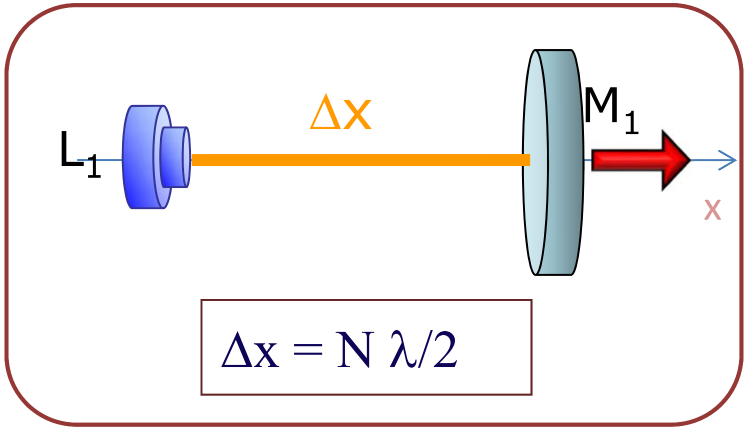


$$\mathbf{k}\cdot\mathbf{\Delta y} \neq 0$$

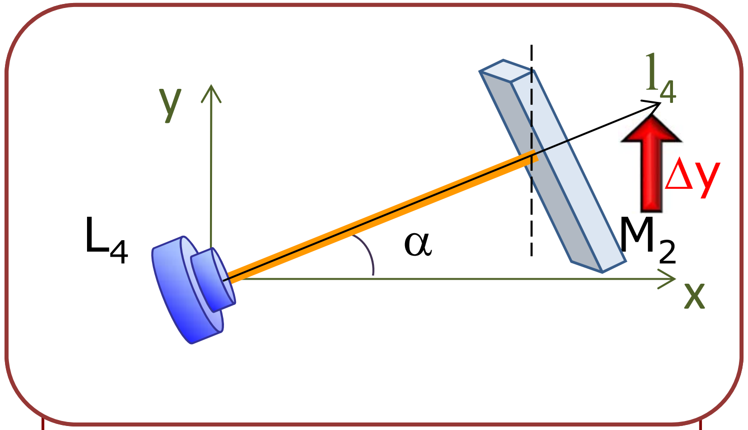
$$\Delta y \cong \Delta l_2 / \sin(\alpha) - \Delta x / \tan(\alpha)$$

Experimental method

LINEAR DISPLACEMENT Δx

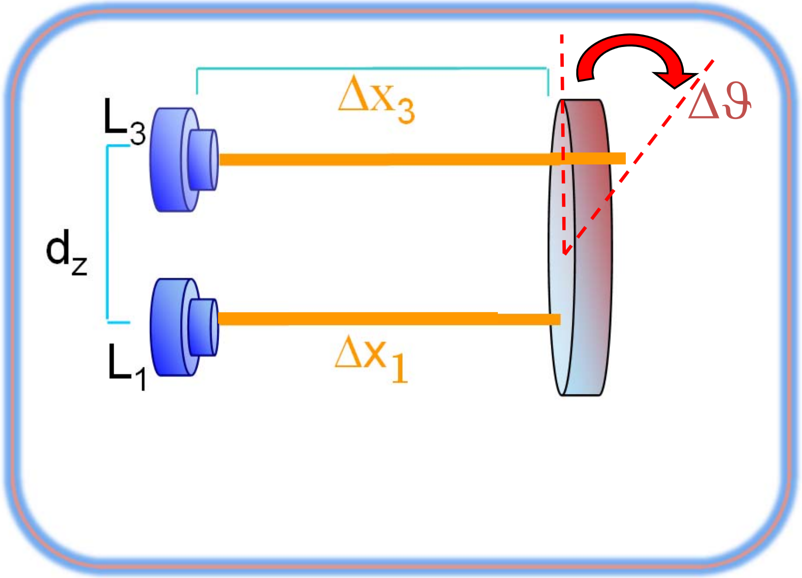


TRANSVERSE DISPLACEMENT Δy, Δz



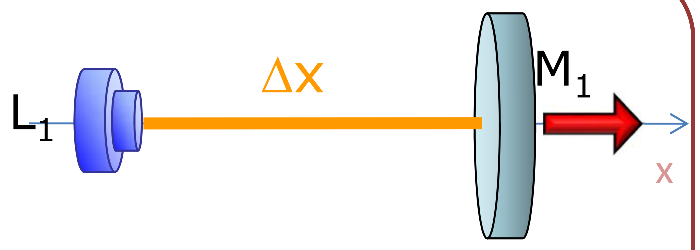
$$\Delta y \cong \Delta l_2 / \sin(\alpha) - \Delta x / \tan(\alpha)$$

OFF-AXIS ROTATIONS $\Delta\vartheta y$, $\Delta\vartheta z$



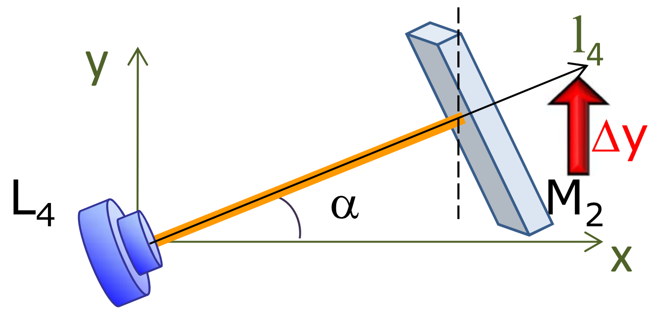
Experimental method

LINEAR DISPLACEMENT Δx



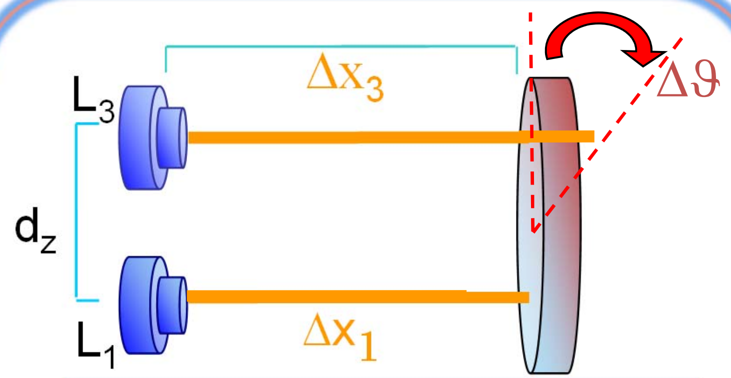
$$\Delta x = N\,\lambda/2$$

TRANSVERSE DISPLACEMENT Δy, Δz



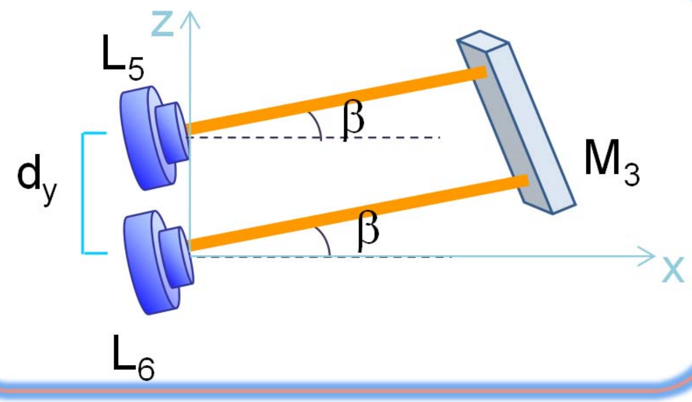
$$\Delta y \cong \Delta l_2 \,/\, \sin(\alpha) - \Delta x \,/\, \tan(\alpha)$$

OFF-AXIS ROTATIONS Δϑy, Δϑz

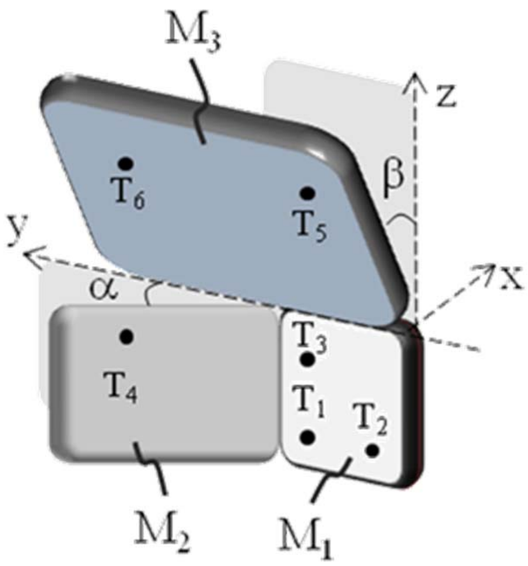


$$\Delta\vartheta = (\Delta x_3 - \Delta x_1)/d_z = (N_3\,\lambda_3 - N_1\,\lambda_1)/2\,d_z$$

ON-AXIS ROTATIONS Δϑx



LASER INTERFEROMETRY: 6DoF



"Collaborative" target

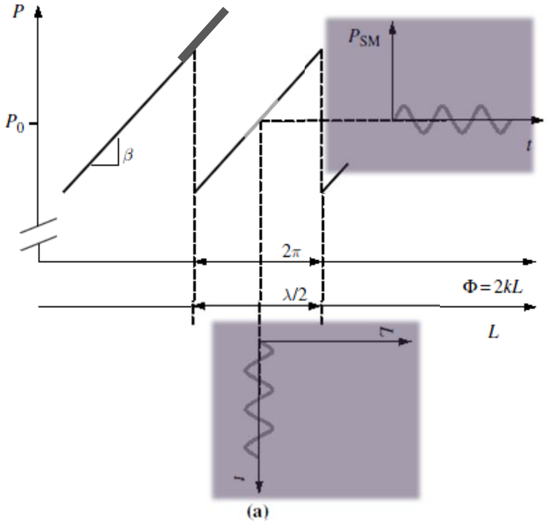
	Longitudinal	Transverse	Yaw, Pitch	Roll
Resolution	0.7 μm	20 μm	$10^{-3°}$ (3'')	0.016° (58'')
Range	± 1 m	± 1 mm	± 0.5 (°) (± 1800'')	± 0.5 (°) (± 1800'')
Accuracy	±7 μm @ 1 m	± 80 μm @ 1 mm	3 × $10^{-3°}$ (11'')@ 0.5°	± 0.05 ° @ 0.5 °

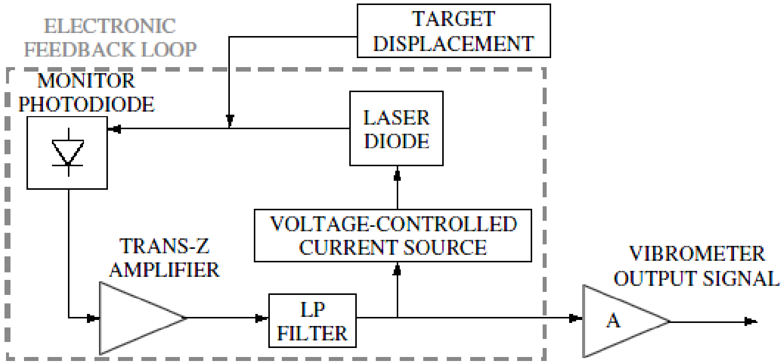
S.Ottonelli, F. De Lucia, M. Di Vietro; M. Dabbicco, G.Scamarcio , F. Mezzapesa, IEEE-PTL, 20, 1360 (2008)
S.Ottonelli, M.Dabbicco,F. De Lucia, and G.Scamarcio , Appl. Opt. 48, 1784 (2009)
S.Ottonelli, M.Dabbicco, F. De Lucia, M.di Vietro and G. Scamarcio, Sensors, 9, 3528 (2009)

Vibrometry

- Vibration amplitudes >> λ → fringe counting technique
- Vibration amplitudes << λ → closed loop fringe locking technique
- Ultimate sensitivity for vibration measurement set by quantum noise
- Noise equivalent displacement NED = $(\lambda/2\pi)/(SNR)$ = 10 pm/√Hz

[G. Giuliani, S. Bozzi-Pietra and S. Donati, Meas. Sci. Technol .4, S283(2002)]





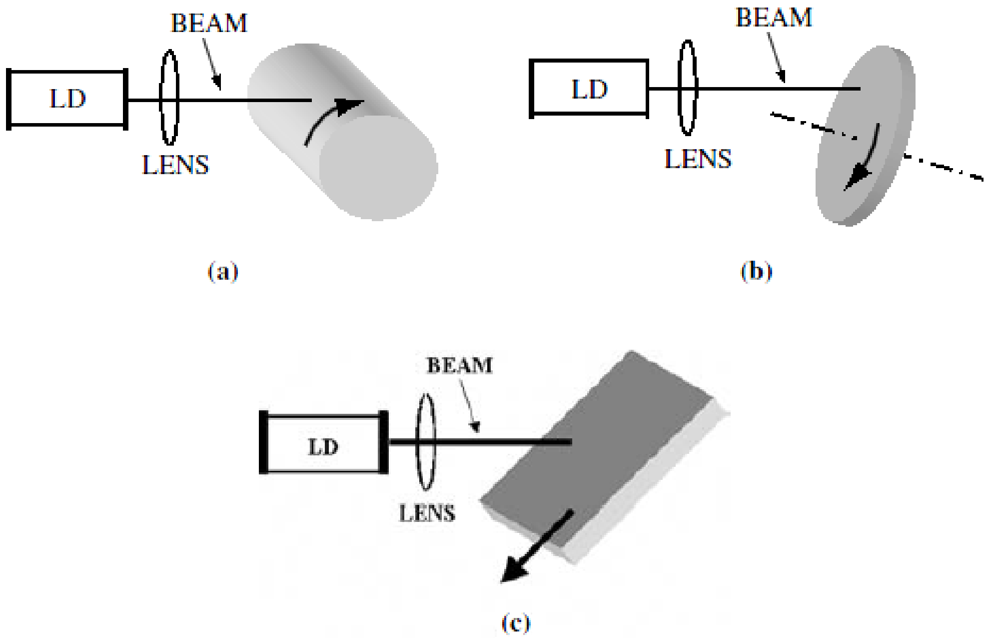
Locking to half-fringe

$\lambda/100 < \Delta L < 100\ \lambda$

Velocimetry

$$I_{SM}(t) = I_0\{1 + m \cdot F\,[\phi(t)]\} = I_0\{1 + m \cdot F\,[2k \cdot L(t)]\}$$

$$= I_0\{1 + m \cdot F\,[2\pi \cdot (2v/c) \cdot t]\}$$



- Doppler shift
- Interest for rotating targets and moving scattering fuids (in vitro + in vivo)

Fiber strain sensors

Monitoring deformations in static structures

Deformations in manufacturing systems and processed specimens

- Immune to electromagnetic noise
- Adaptable to any shape
- Suitable for hostile hambients

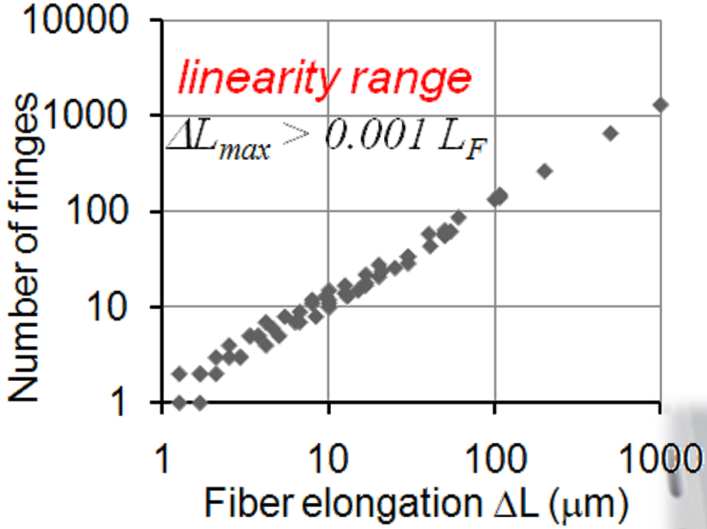
Conventional Bragg gratings fiber sensors exploits strain induced λshift

- Local strain in selected spots at the BG

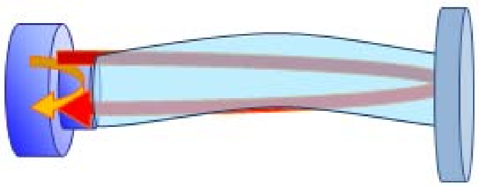
- Small shifts (pm/$\mu\varepsilon$) require demanding and costly detection

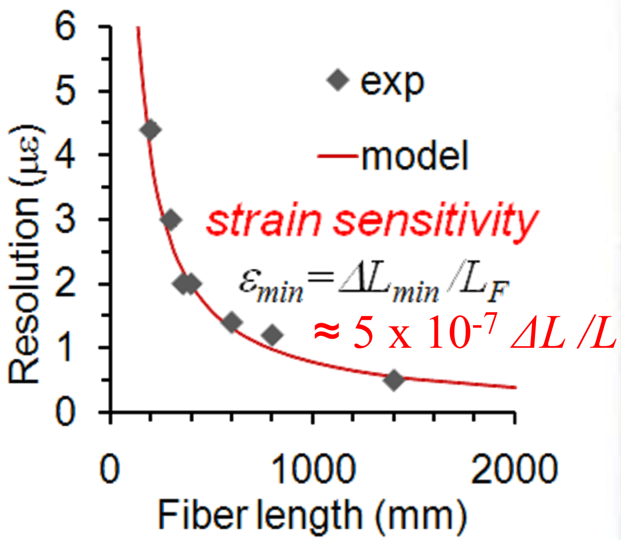
Self-mixing fiber sensors for integral strain measurement

[Dabbicco, Scamarcio, Ottonelli, Intermite, Bradisalijevic, Int. patent (2010), J. Lightw. Technol., (2011)]



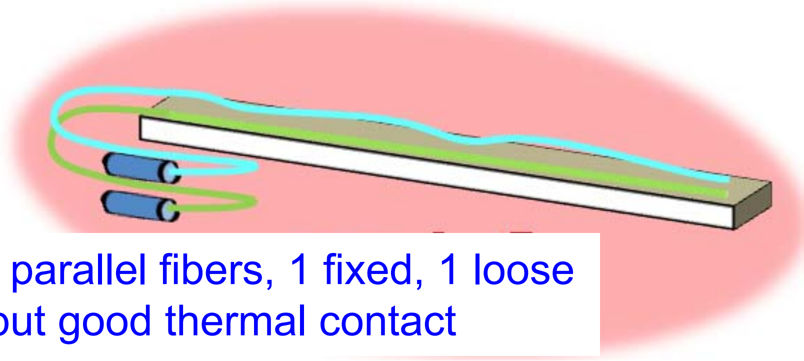
- Pigtailed diode laser
- Fiber fixed to the stressed object
- Feedback by back reflection from fiber free end



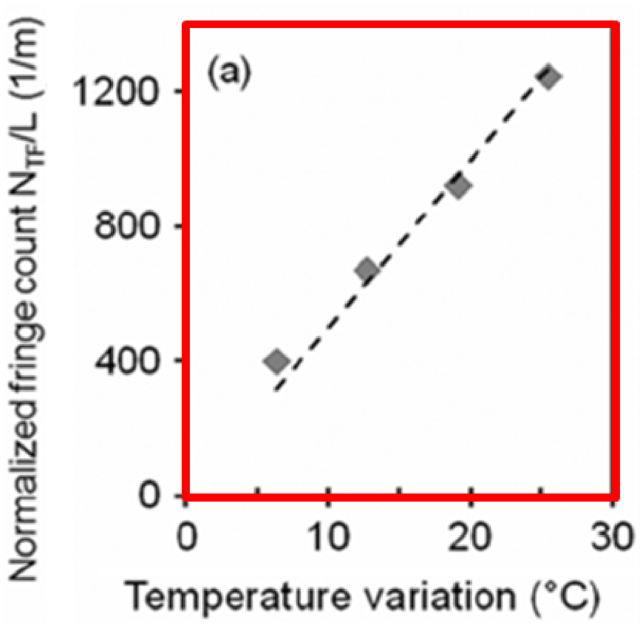


Thermal effects

$$N = N_\varepsilon + N_T = \frac{1}{2\pi}(\Delta\phi_\varepsilon + \Delta\phi_T)$$
$$\approx \frac{2}{\lambda}\left[1 - \frac{n_{\text{eff}}^2}{2}[(1-\mu)p_{12} - \mu p_{11}]\right]\Delta L$$
$$+ \frac{2}{\lambda}\left[\frac{1}{n_{\text{eff}}}\frac{dn_{\text{eff}}}{dT}\right]L\Delta T$$



2 parallel fibers, 1 fixed, 1 loose
but good thermal contact



mechanical and
thermal deformation

⇩

all-purpose
integral strain
fiber sensor
Complementary to
fiber Bragg local
Strain sensors

- Strain resolution = 5×10^{-7} $\Delta L/L$ in a continuous range spanning 3 orders of magnitude.
- A calibrated fiber to correct phase drift in case of thermal deformations.

Outline

- optical feedback interferometry
  - self-mixing effect in semiconductor lasers
  - Lang-Kobayashi model
- applications in metrology
  - linear displacement (single channel)
  - Translations and rotations (multiple channels): 6 DoF
  - absolute distance
  - displacement or rotation velocity
  - vibrations
  - longitudinal and volume deformations (strain fiber sensor)
- laser ablation sensor
  - *in-situ* characterization of laser ablation process
  - study of the ablation dynamics in the thermal regime
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  - Terahertz imaging

Laser ablation sensors

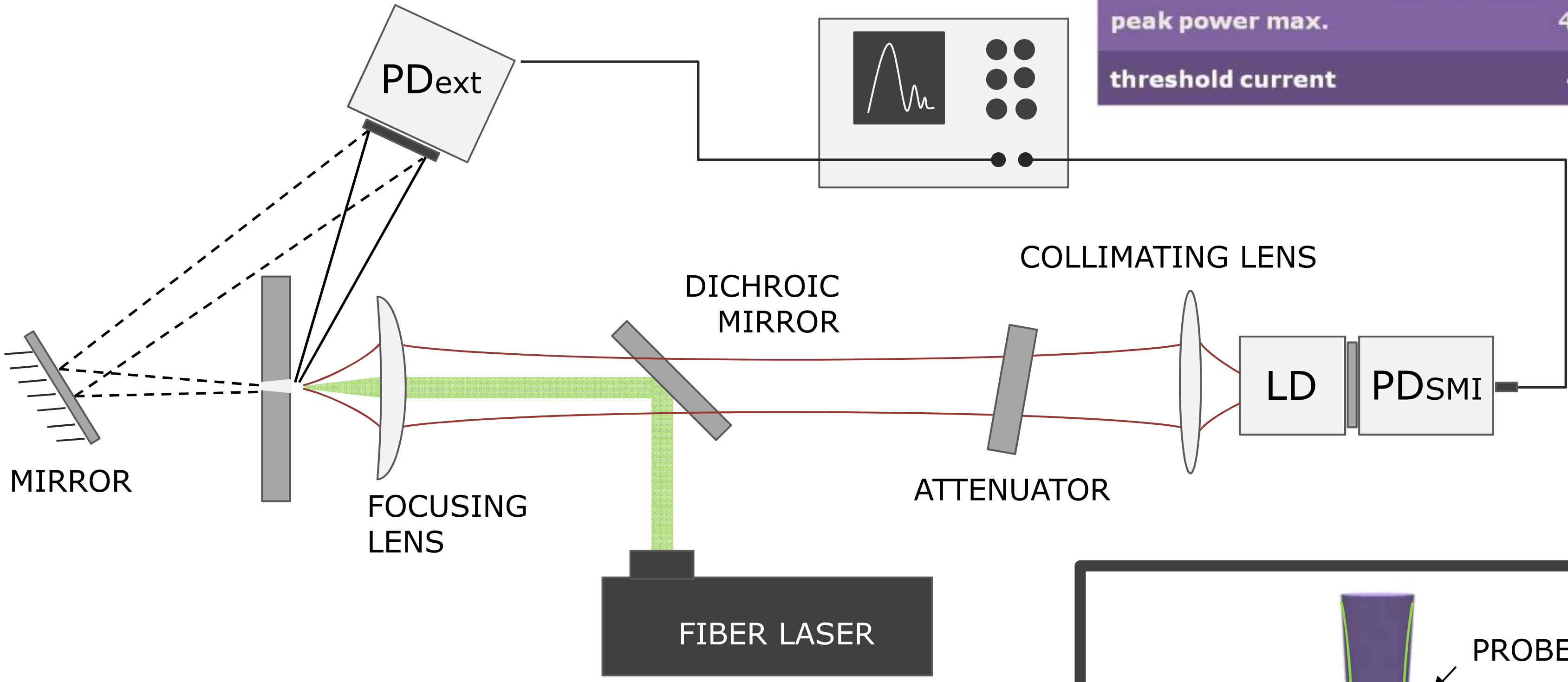
- Pulsed laser ablation is a key process in precision micromachining of solids
- Countless industrial applications (manufacturing; medical …)
  - cutting, drilling, engraving, scribing a large variety of soft and hard materials.
- Full characterization of ultrafast (ps, fs) laser ablation requires knowledge of
  - hole penetration depth (μm resolution or better)
  - laser ablation rate (up to MHz rep rate)
- *Real-time* experimental techniques needed
- In semiconductors, imaging of the hole shape evolution during laser drilling exploit the transparency of the material at the laser wavelength.
- In opaque materials (e.g. metals) optical coherence tomography or confocal imaging
  - low hole depth resolution (10-20 μm)
  - Low repetition rate (< 100 Hz).

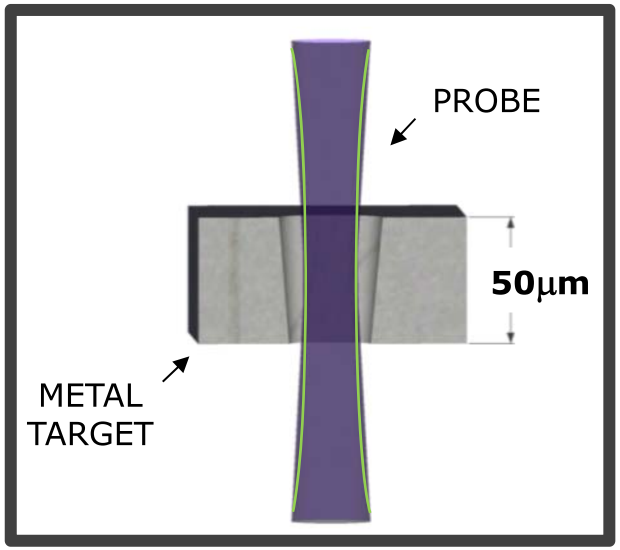
Q: What if the surface of a static surface is ablated (not just moved)?

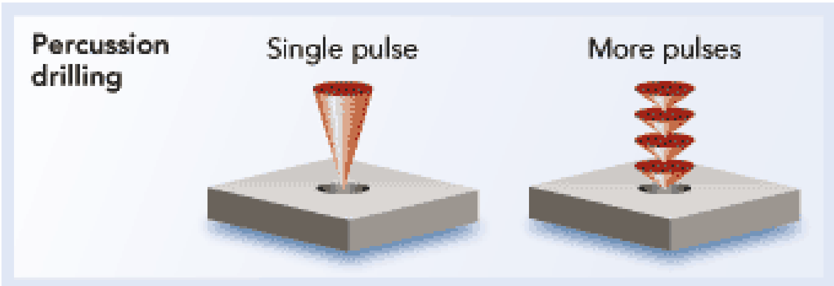
→ SMI can monitor the propagation of the laser ablation front during ultrafast laser drilling of metal plates w/resolution of 0.4 μm *(patent pending)*

Real-time monitoring of laser ablation

laser diode (LD)	Hitachi HL8325G
wavelength (@50mA)	832 nm
peak power max.	40 mW
threshold current	40 mA

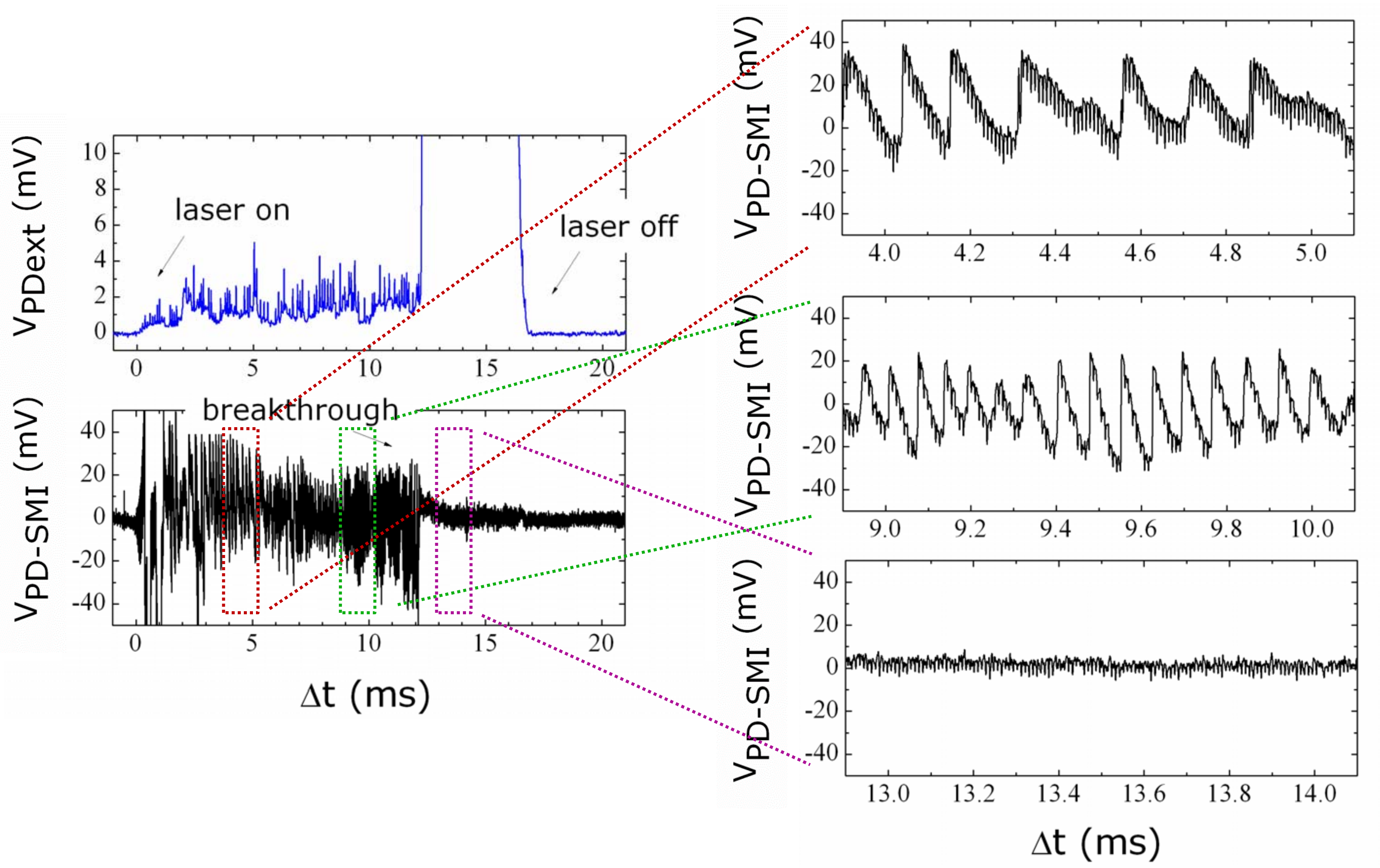






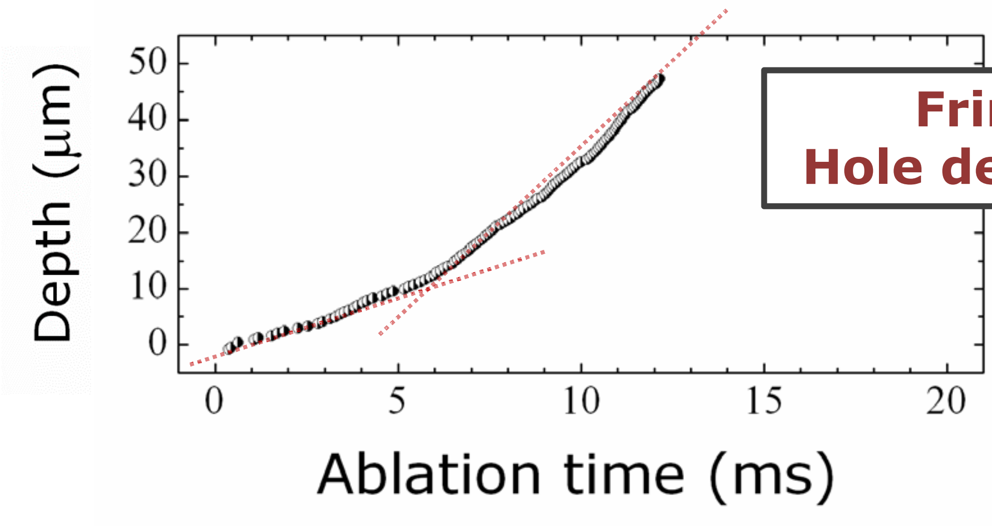
Self-mixing signal during laser ablation

[Mezzapesa, Ancona, *Sibillano, De Lucia, Dabbicco, Lugarà, Scamarcio* Opt. Lett. **36**, 824 (2011)]



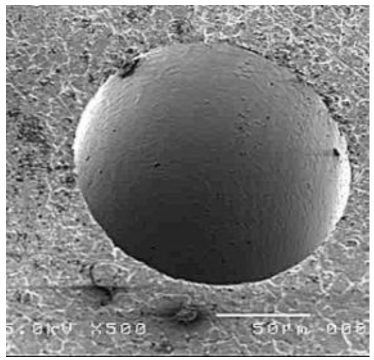
Self-mixing signal during laser ablation

[*Scamarcio, Mezzapesa, Sibillano, Ancona, Lugarà, Dabbicco, De Lucia, Patent pending*]



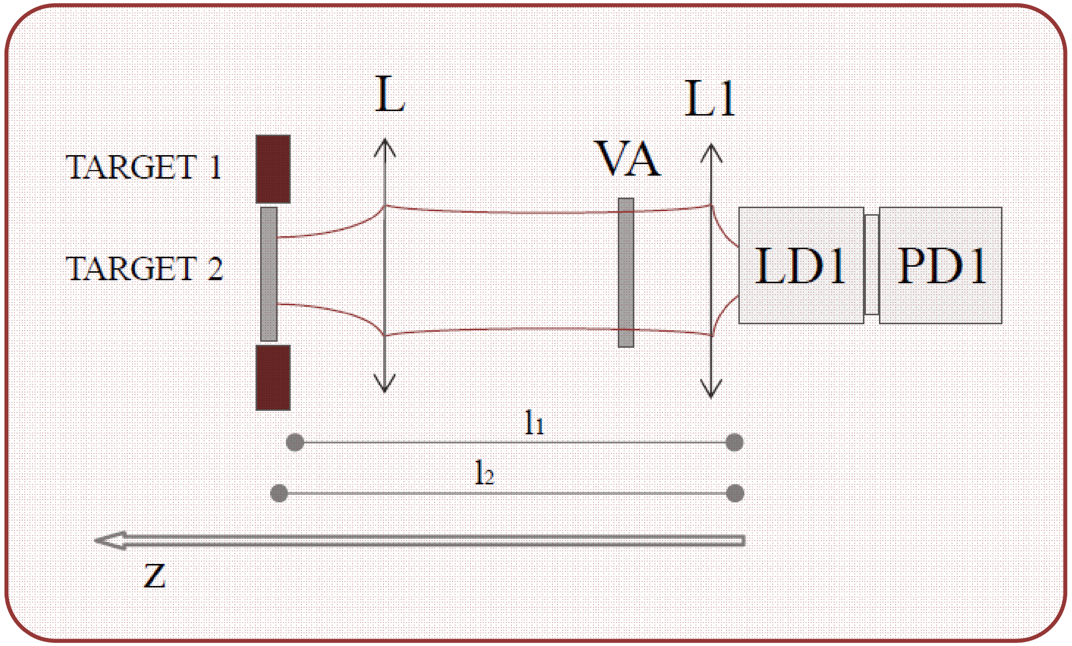
Fringes No. = 116 ± 1
Hole depth = 47.74 ± 0.41 μm

- On-line monitoring of the ablation depth
- Pulse-by-pulse monitoring feasible
- Easy integration in laser micromachining systems



- Ablation rate measurement during the process
- Systematic investigation of ultrafast laser-matter interaction physics made possible

Simultaneous measurement of multiple target displacements with a single diode laser



- Similar to wavefront split interferometry employed in astronomy
- Demonstrated using ultrafast percussion drilling of a moving target

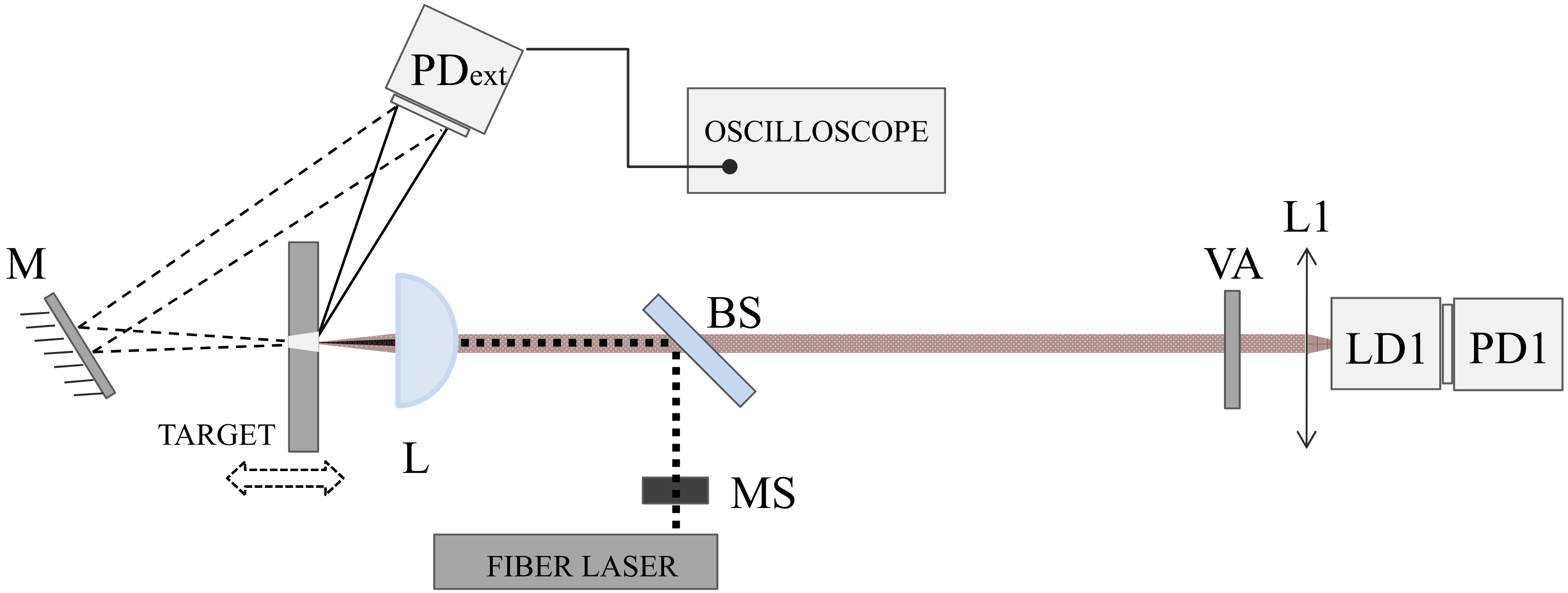
Modified Lang-Kobayashi equations:

$$\frac{dE(t)}{dt} = \frac{1}{2}(1+\alpha)\left(G(N(t)-N_0) - \frac{1}{\tau_p}\right)E(t) + \frac{k_1}{\tau_c}E(t-\tau_1)e^{-i\omega_0\tau_1} + \frac{k_2}{\tau_c}E(t-\tau_2)e^{-i\omega_0\tau_2}$$

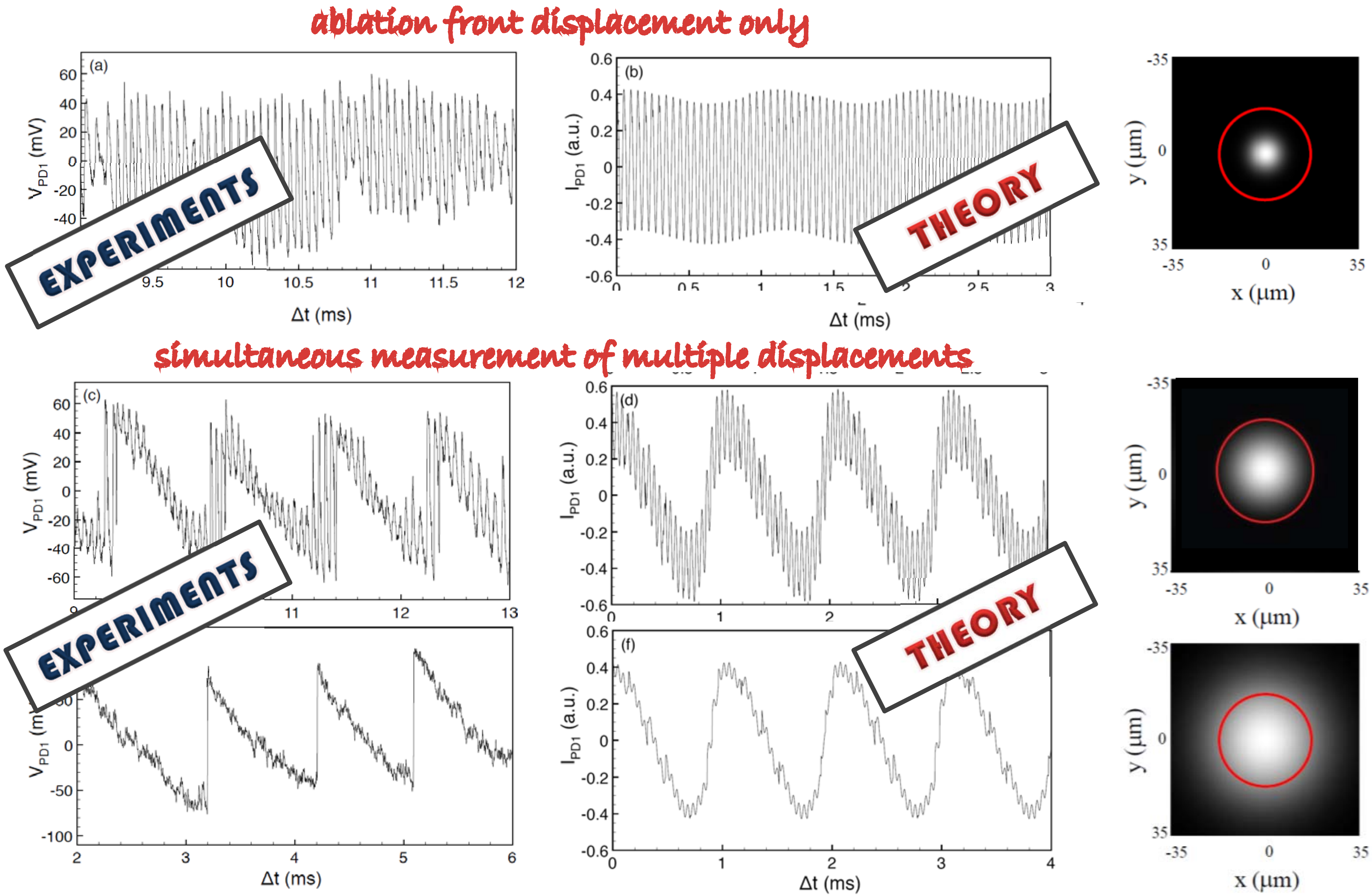
$$\frac{dN(t)}{dt} = \mu - \frac{N(t)}{\tau_e} - G(N(t)-N_0)\,|E(t)|^2$$

[Mezzapesa, Columbo, Brambilla, Dabbicco, Ancona, Sibillano, De Lucia, Lugarà, Scamarcio, Opt. Exp. ***19****, 16160 (2011)]*

Multi detection SM interferometry in a single diode laser



1 laser can simultaneously detects the displacement of 2 surfaces



[Mezzapesa, Columbo, Brambilla, Dabbicco, Ancona, Sibillano, De Lucia, Lugarà, Scamarcio, Opt. Exp. ***19****, 16160 (2011)]*

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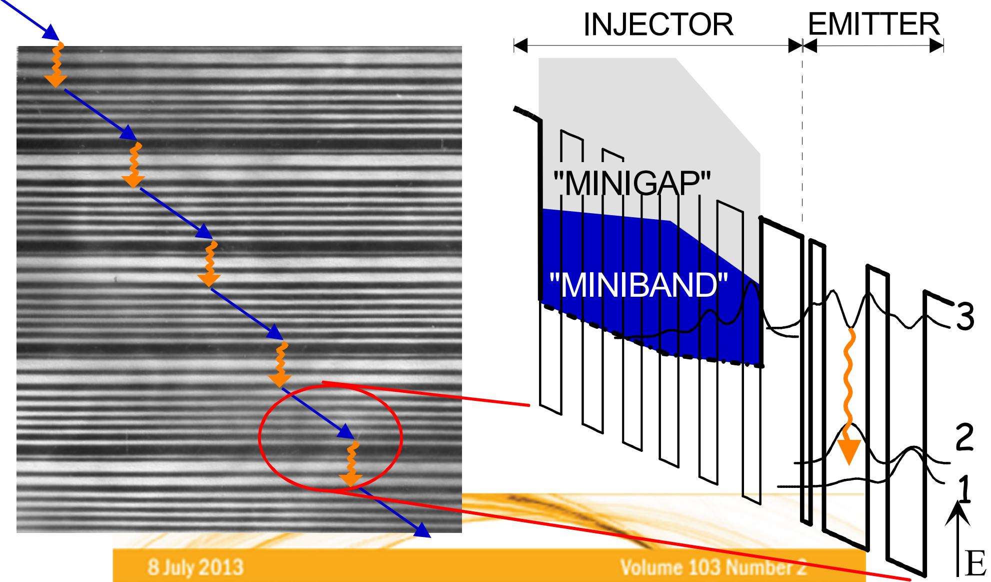
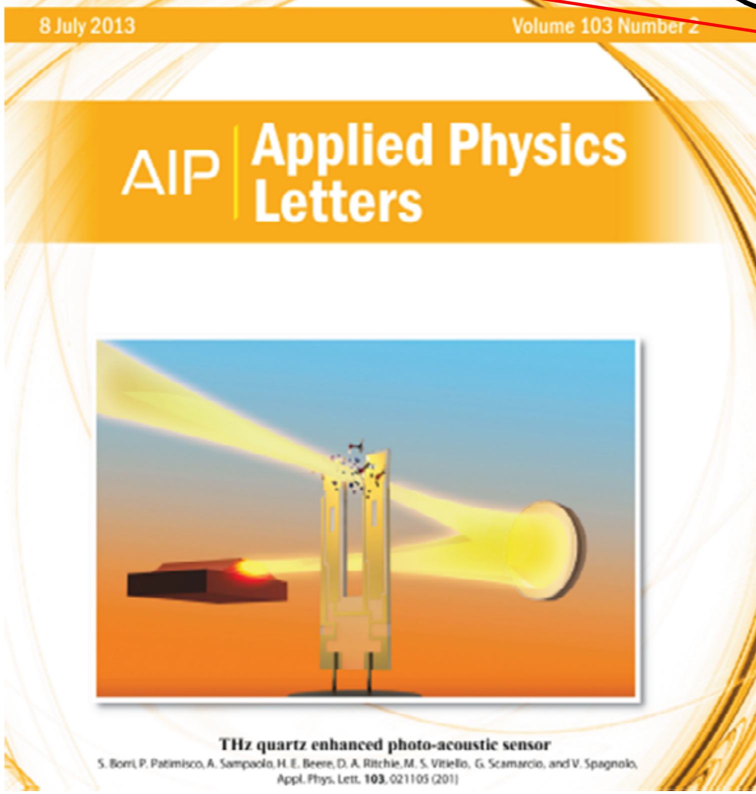
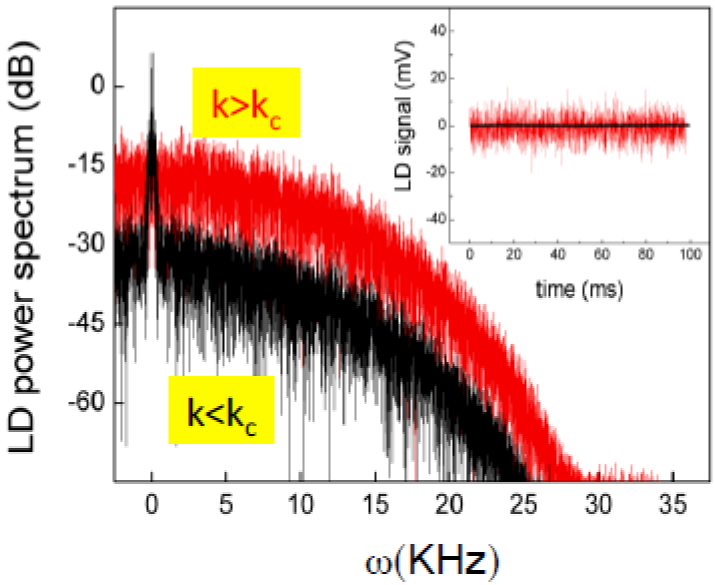
Quantum Cascade Laser

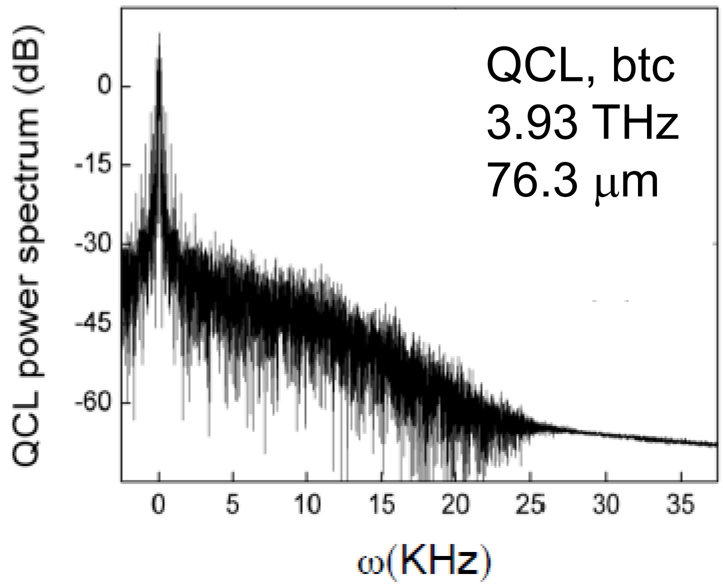
- unipolarity
  - intersubband transitions
- cascading
  - N photons/injected electron
  - high optical power
- wavelength agility
  - mid-IR and beyond (3.5 - 150 μm) via MBE thickness control
- materials by design
  - wavefunctions, population inversion, optical gain, transport
  - Auger effect negligible (no holes!)
- applications
  - trace gas sensing for environmental monitoring and atmospheric chemistry
  - industrial process control
  - combustion diagnostics
  - breath analysis in medicine
  - explosive detection
  - infrared countermeasures





diode laser vs THz QCL (CW emission)





A radically different behavior!

- **Laser diode**
  The laser emission becomes unstable (coherence collapse) for a feedback strength $k > k_c \sim 10^{-3}$, where $k \propto$ reinjected power/input power
  (k_c = critical value)
- **THz-QCL**
  The laser emission remains stable up to $k \sim 10^2 k_c$. Theoretical estimations show that this is the maximum value achievable
  No instabilities (e.g. mode-hopping, coherence collapse) are observed by continuously increasing k

[Mezzapesa, Columbo, Brambilla, Dabbicco, Borri, Vitiello, Beere, Ritchie, Scamarcio, Opt. Exp. (2013)]

ultra-stability of QCLs

experimental evidence

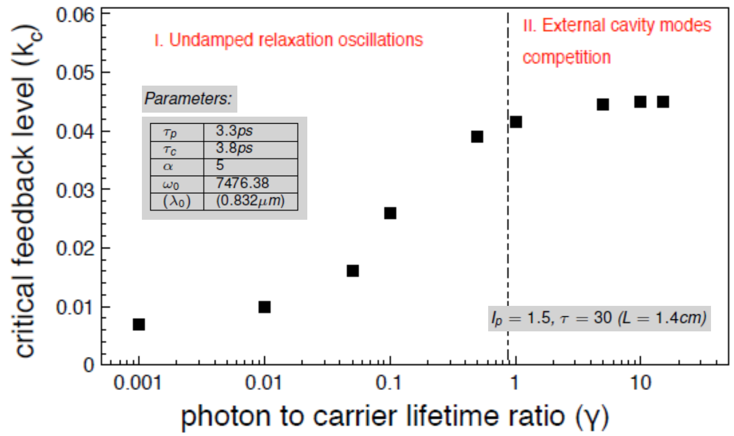
stable continuous wave (CW) emission of MIR and THz-QCLs against strong optical injection

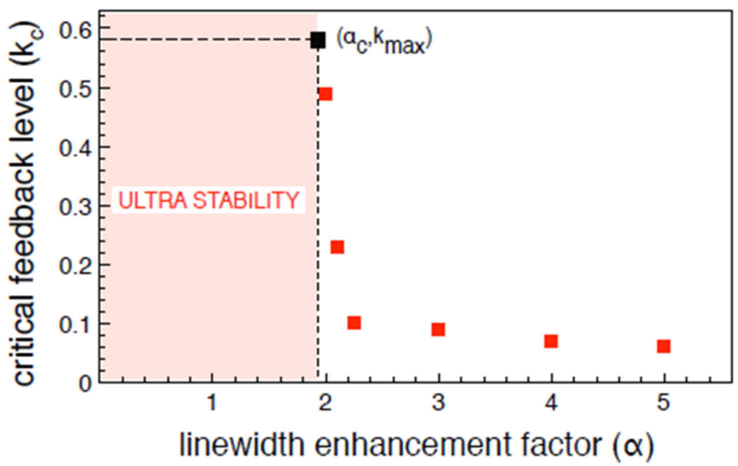
interpretation

- **high photon to carrier lifetime ratio** $\gamma > 1$
  suppresses instabilities due to undamped relaxation oscillations (*class A*-laser)
- **low *alpha*-factor** $\alpha \leq 2$
  suppresses multimode instabilities due to external cavity modes competition

the critical feedback level calculated as the **minimum feedback strength** causing CW instability (e.g. mode-hopping, coherence collapse)

Linear stability analysis of the CW solutions

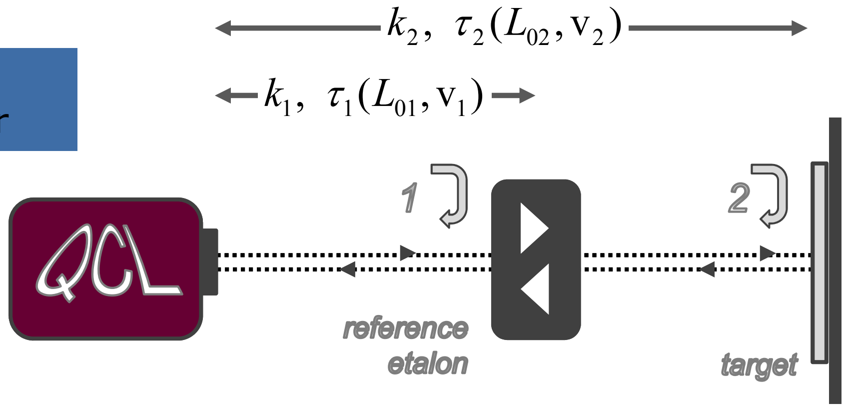




Mezzapesa *et al.*, Optics Express 21 (11), 13748-13757 (2013)

nonlinear mixing in mid-IR QCLs

dynamic reference arm
in a dual-cavity interferometer



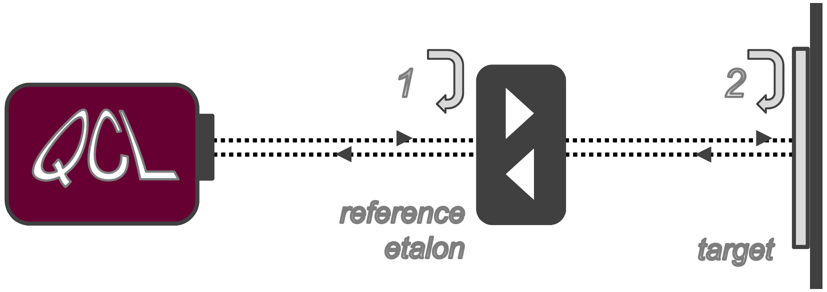
$$\Delta N = G\tau_c(N - N_{sol}) = -2\left[k_1 \cos(\omega_F \tau_1) + k_2 \cos(\omega_F \tau_2)\right]$$

$$\omega_F \tau_i = \omega_F \frac{2(L_{0i} \pm |v_i|t)}{c} = \frac{2L_{0i}\omega_F}{c} \pm \frac{2\omega_F |v_i|}{c} t \quad \Leftrightarrow \quad \omega_F \tau_i = A \pm \omega_i t$$

$$\omega_F = \omega_0 - \frac{k_1}{\tau_c}\left[\alpha \cos(\omega_F \tau_1) + \sin(\omega_F \tau_1)\right] - \frac{k_2}{\tau_c}\left[\alpha \cos(\omega_F \tau_2) + \sin(\omega_F \tau_2)\right]$$

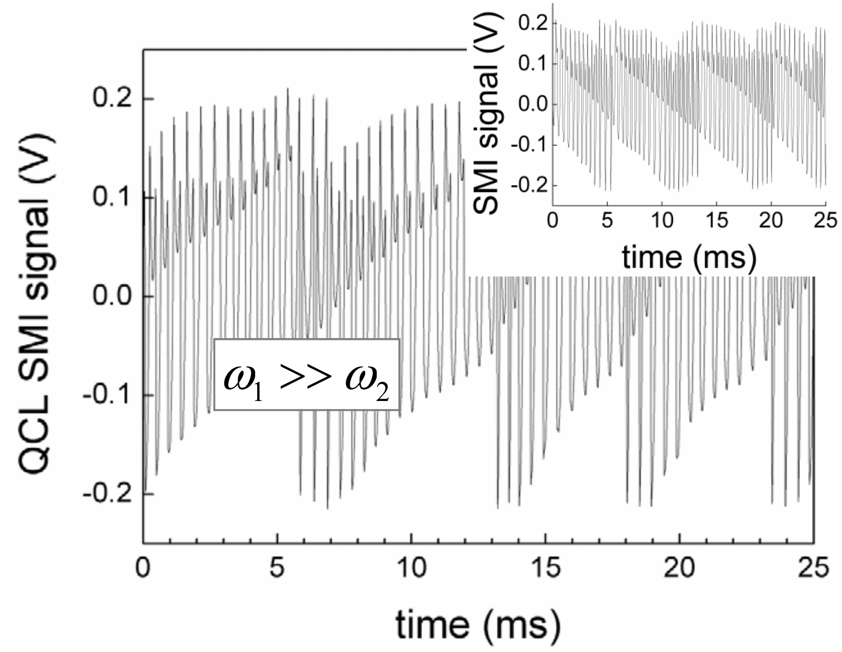
nonlinear frequency mixing due to the implicit and transcendental character of last Eq. (1) → spectral components at ω1 ± ω2

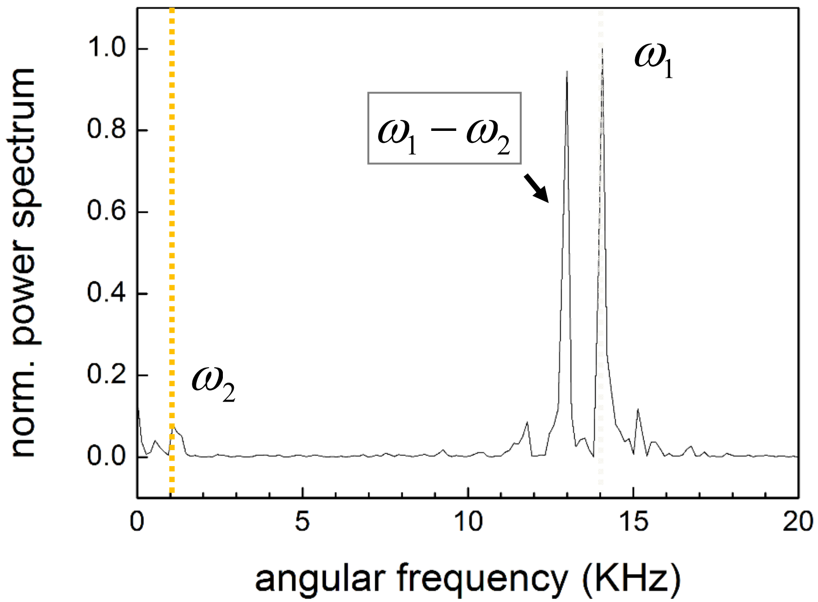
nonlinear frequency mixing



$$\omega_i = \frac{2\omega_F \,|\mathrm{v}_i|}{c} = \frac{4\pi\,|\mathrm{v}_i|}{\lambda}$$

$$\lambda = 6.2\ \mu m;\ \ \mathrm{v}_1 = 7\ \ mm/s;\ \ \mathrm{v}_2 = 0.5\ \ mm/s$$



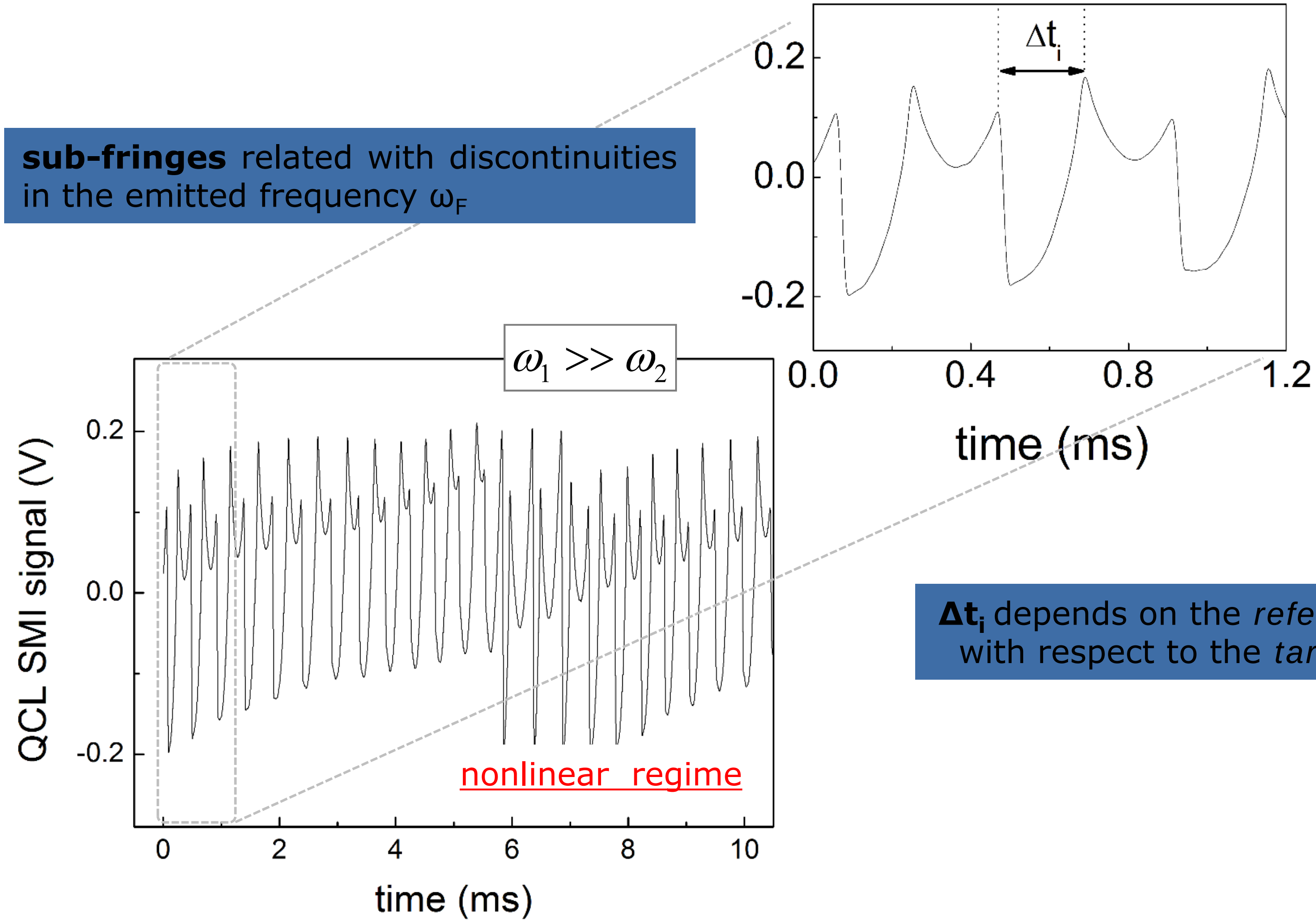


Mezzapesa *et al.*, IEEE Journal of Selected Topics in Quantum Electronic, submitted (2015)

Stroboscope-like effect

for resolution enhancement

sub-fringes related with discontinuities in the emitted frequency ω_F



Δt_i depends on the *reference motion* with respect to the *target position*

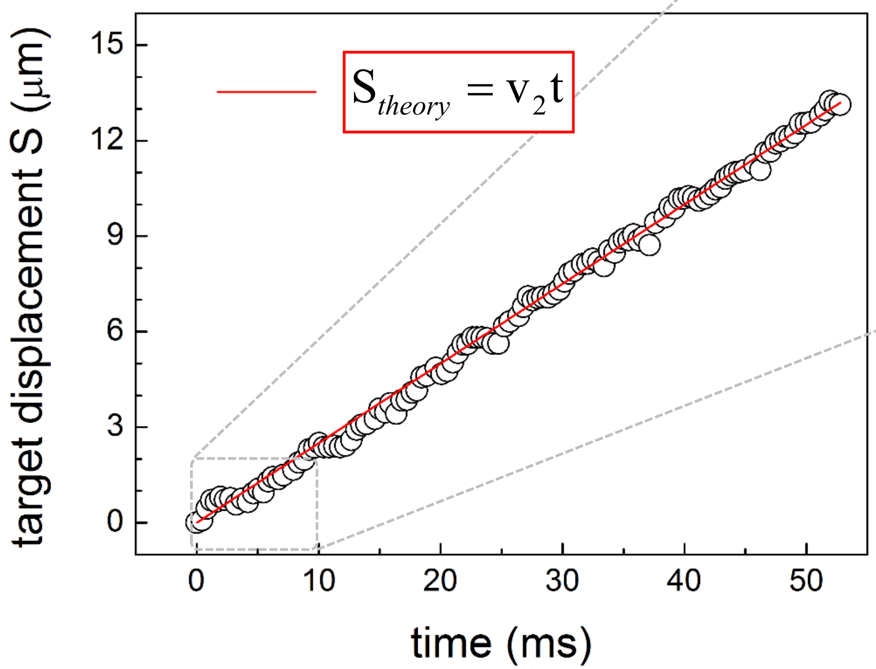
F. P. Mezzapesa, L. L. Columbo, G. De Risi, M. Brambilla, M. Dabbicco, V. Spagnolo and G. Scamarcio, IEEE Journal of Selected Topics in Quantum Electronic, in press (2015)

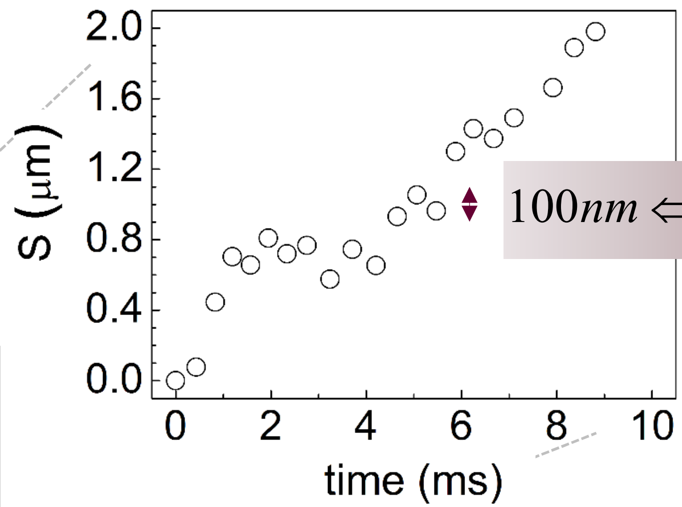
nanoscale displacement sensor

Best fit of the expected displacement $\mathbf{S}_{theory}$:

$$S = -\gamma_2 \frac{v_1^2}{\lambda}\Delta t_i^2 - \gamma_1 v_1 \Delta t_i + \gamma_0 \frac{\lambda}{2}$$

$\gamma_2 = 1.06 \pm 0.03$
$\gamma_1 = 0.64 \pm 0.01$
$\gamma_0 = 0.94 \pm 0.01$





$$100nm \Leftrightarrow \lambda/60$$

$$\Delta S_{min} = \frac{v_2}{2v_1}\lambda << \frac{\lambda}{2}$$

the minimum displacement $\Delta \mathbf{S}_{min}$ depends on the *relative velocity* between *reference* $\mathbf{v}_1$ and *target* $\mathbf{v}_2$, thus potentially scalable to the **nanometer range!!**

Mezzapesa *et al.*, IEEE Journal of Selected Topics in Quantum Electronic, submitted (2015)

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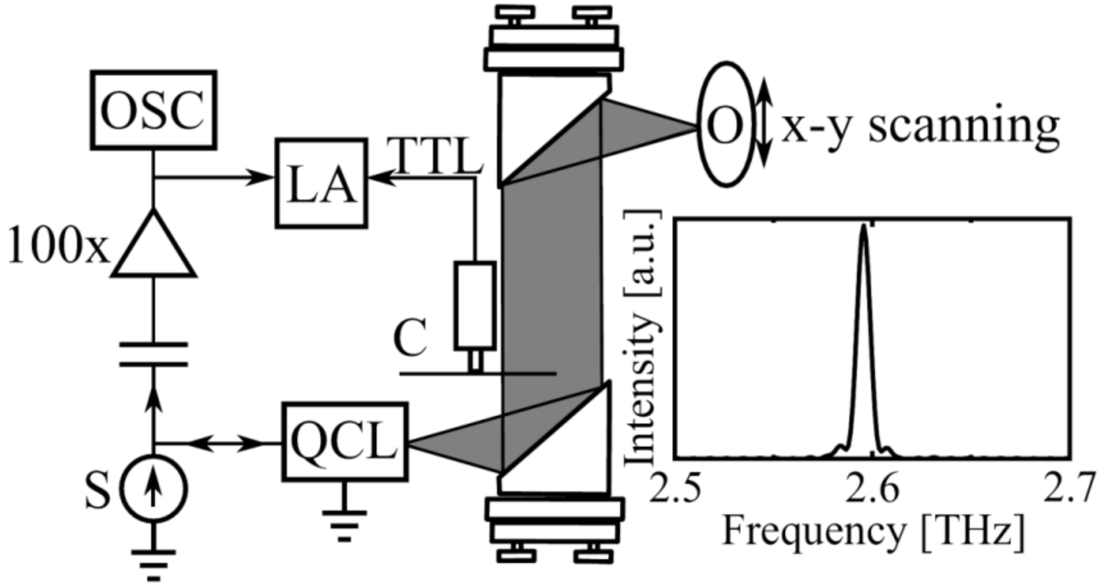
Terahertz imaging through self-mixing in a QCL

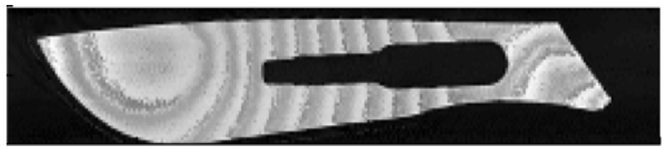
*[Dean et al., Opt. Lett. **36**, 2587(2011)]*



T = 25 K

L_{ext} = 65 cm

P = 0.24 mW

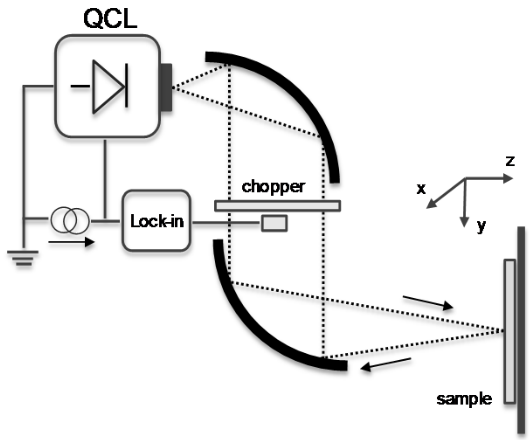


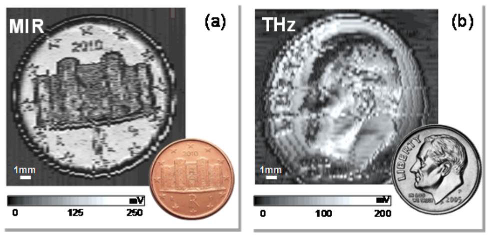
Blade hidden in a paper envelope sensitivity to surface morphology (fringes at ~ 58 μm)

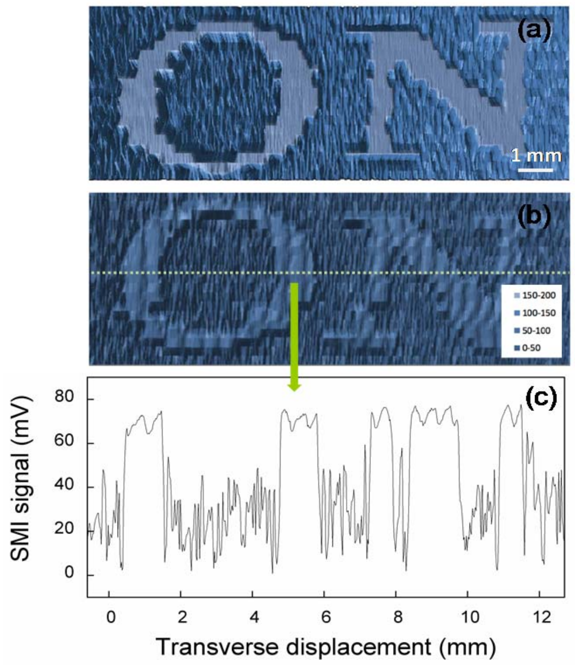
- No need for external detector, simple, compact, fast modulation (→ 100 GHz)
- Homodyne (coherent) nature of self-mixing → very high-sensitivity, potentially at the quantum noise limit
- High signal-to-noise ratio
- Still cryogenic …

Coherent imaging in mid-IR and THz QCLs

[Mezzapesa, Petruzzella, Dabbicco, Beere, Ritchie, Vitiello, and Scamarcio, IEEE Trans. THz Sci. and Technol. (2014)]







amplitude

phase

Imaging of free carriers density distribution through self-mixing in THz QCLs

Free carriers density modulation in a semiconductor target →
strong variations of the **complex reflectivity in the THz spectral region**
as accounted by the **Drude model** [R. Ulbricht,

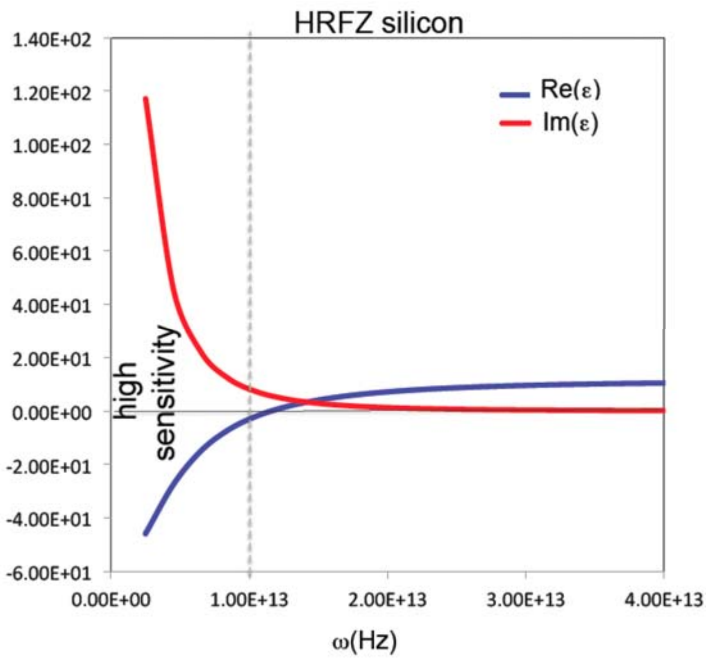
(Fresnel relations) $\sqrt{R_{ext}} = \frac{n_{air} - n}{n_{air} + n}$

<u>THz complex permittivity</u>

$$n^2 = \varepsilon\,(\omega_{TH}) = \varepsilon_\infty(\omega_{TH}) - \frac{\omega_P^2\tau^2}{\left(1+(\omega_{TH}\tau)^2\right)} + i\frac{\omega_P^2\tau}{\omega_{TH}\left(1+(\omega_{TH}\tau)^2\right)}$$

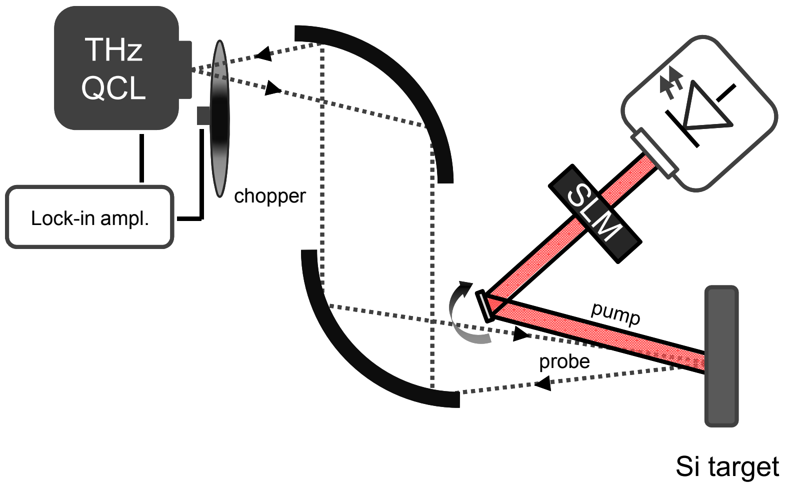
m^* = electron reduced mass , τ = average collision time,
ε_∞= background dielectric contribution

PLASMA FREQUENCY $\omega_p = \sqrt{\frac{N e^2}{\varepsilon_0 m^*}}$

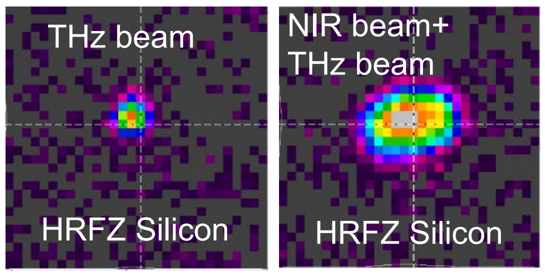


Proof-of-principle experiment

- A CW THz beam emitted by a THz-QCL "probes" a Si target in which free carriers are optically generated by a spatially modulated near-IR "pump" beam
- The photo-induced variations in the Si reflectivity produces voltage modulations at the laser terminals (V_{QCL}) in the self-mixing configuration



- **probe**: THz QCL
  λ_{THz} = 76.3 μm
  CW @ I = 700 mA
  resonant phonon
  single mode
  working temperature = 7 K
- **pump**: diode laser
  λ_{NIR} = 0.832 μm
  CW @ J = 40 mW/cm^2

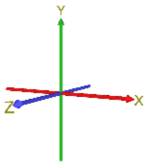


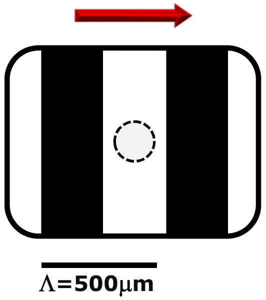
Spot size by Pyrocam (pixel size 85 μm)

F. Mezzapesa et al., Appl. Phys. Lett. 104, 041112 (2014)

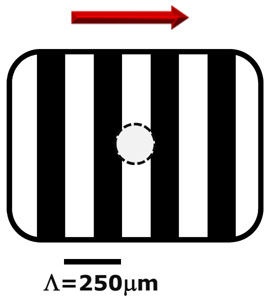
free carrier profile @ 4THz

SLM mask
2 stripes

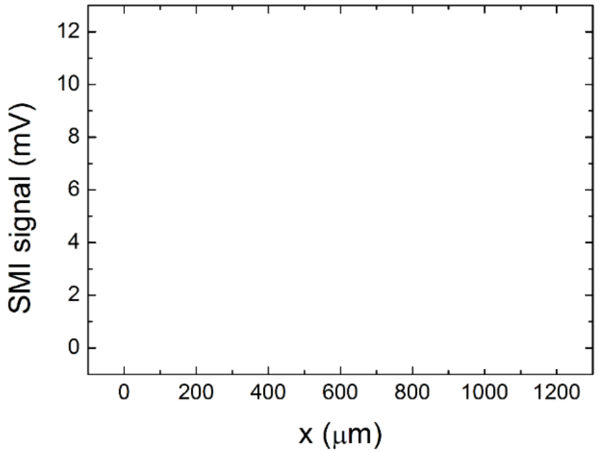


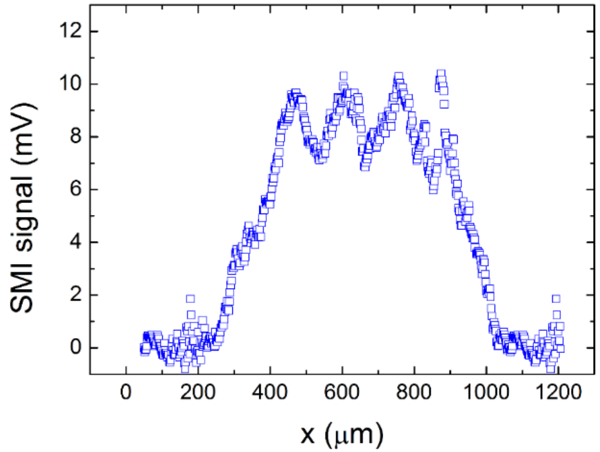


SLM mask
4 stripes

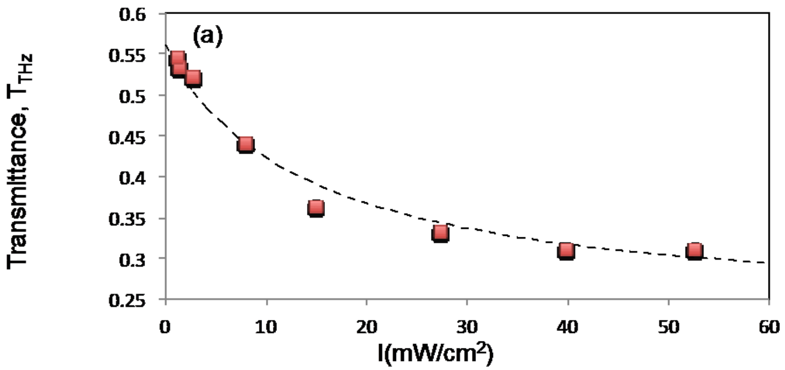


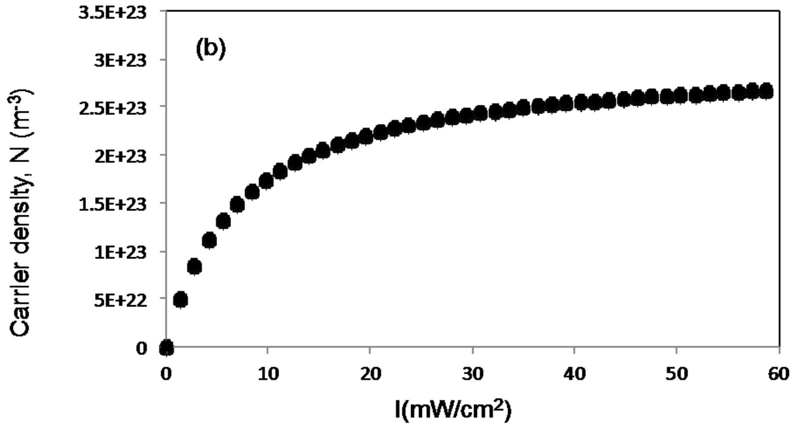
Phase sensitivity:
profiling the *change in refractive index* using the self-mixing effect in THz QCL





charge carrier density by THz-QCL



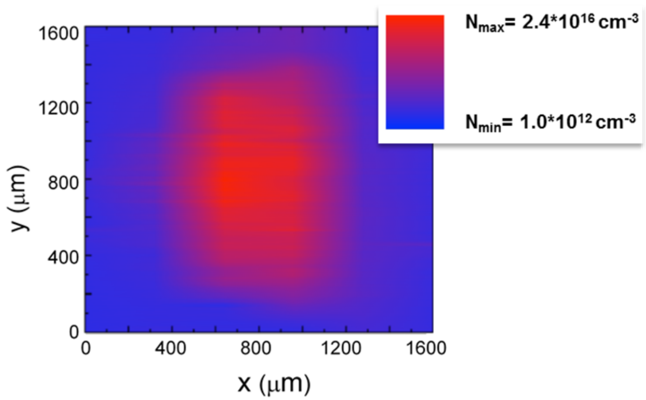


Carrier density (no pump)

$$N = \frac{N^* + \frac{N_0 J}{J_{sat}}}{1 + \frac{J}{J_{sat}}} = N^* + \left(\frac{J\alpha^{IR}}{\hbar\omega^{IR}}\right)\tau_R$$

Pump power density

Carrier lifetime (non radiative)



[Mezzapesa, Columbo, Brambilla, Dabbicco, Vitiello, Scamarcio, Appl. Phys. Lett. 104, 041112 (2014)]

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  - Terahertz imaging / optically induced optical metamaterials

The team


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Thank you !