R&D activity at LMA

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LABORATOIRE MATÉRIAUX AVANCÉS

GWADW – May 28th 2014, Takayama

outline

- thermo-elastic damping of Si disks

- direct measurement of coating thermal noise
- coating structure and mechanical loss

thermo-elastic damping of Si disks

unexpected results

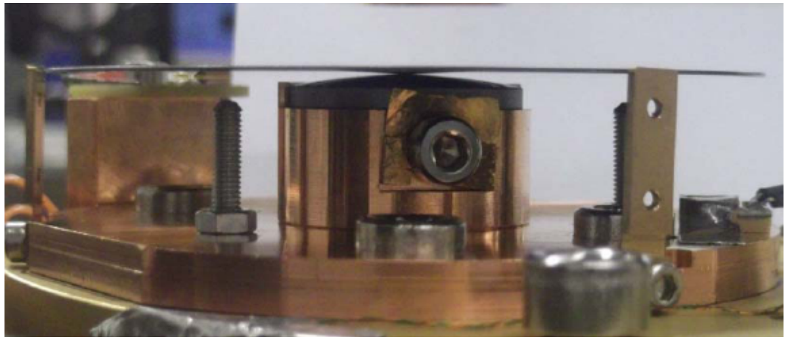
Si disks used for coating characterization

- Gentle Nodal Suspension (GeNS)

  Cesarini & al., *Rev. Sci. Instrum.* 80, 2009

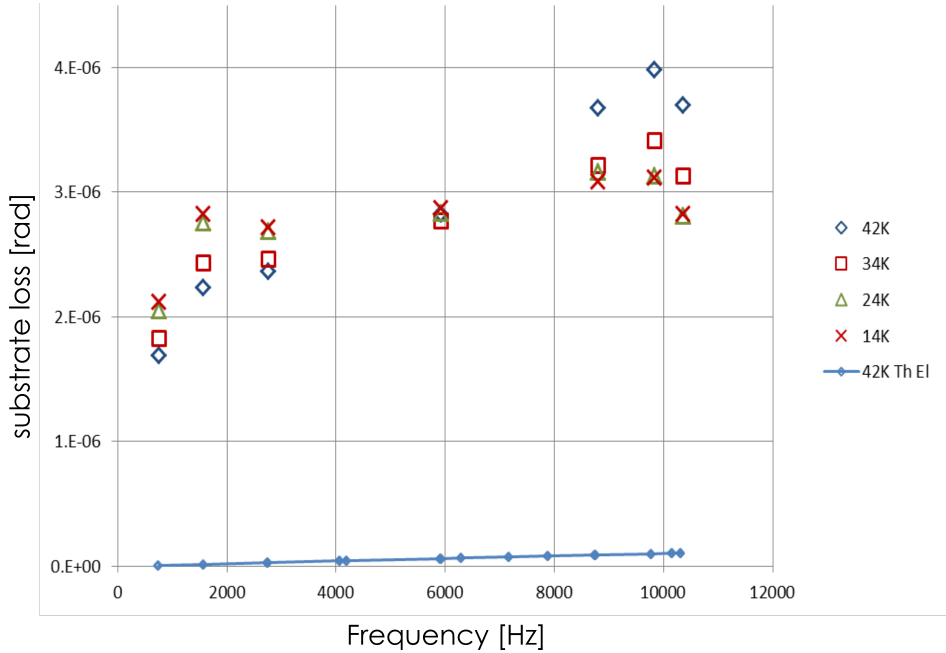
  Cesarini & al., *Class. Quantum Grav.* 27, 2010

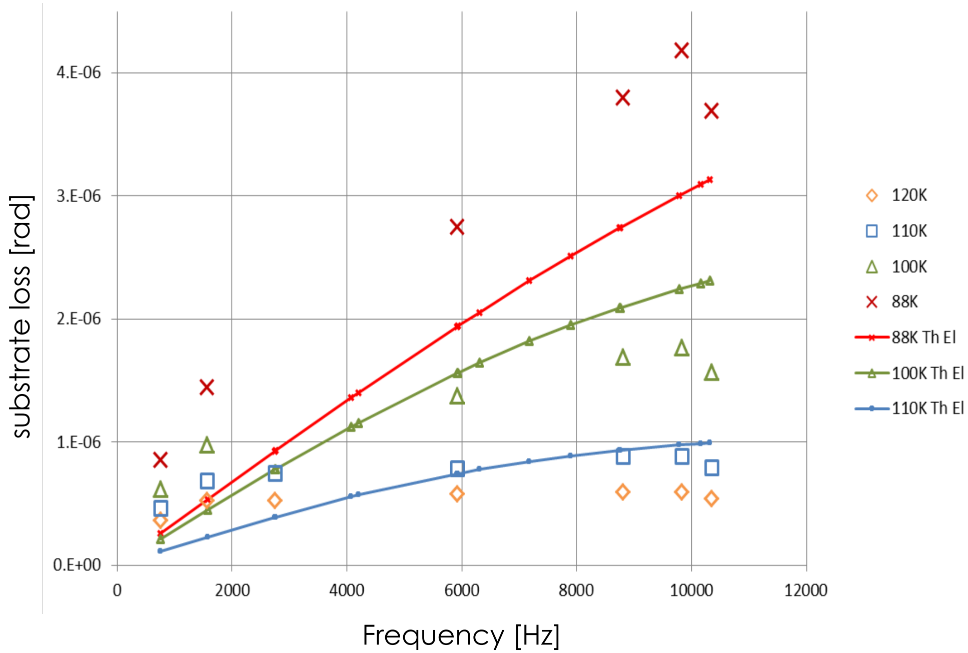
  R. Flaminio & al., *GWADW*, Elba, 2013



- isotropic thermoelastic loss does not explain the measured loss

  M. Granata & al., *GWADW*, Elba, 2013



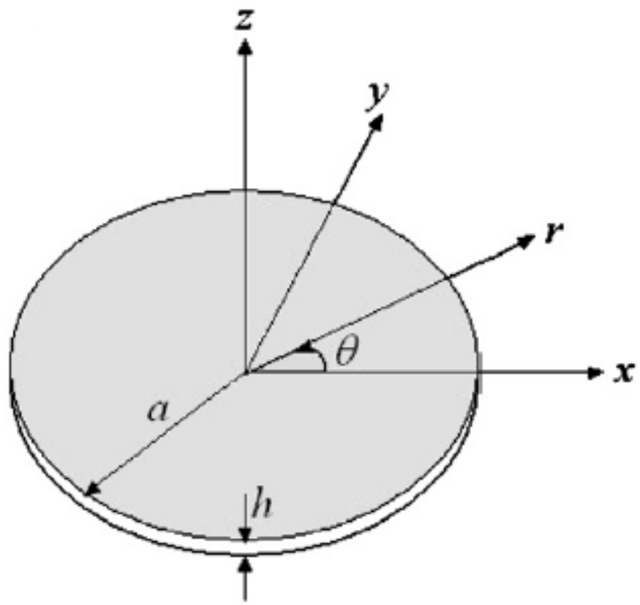


models

- isotropic material
- developed mainly for MEMS
- from beams to disks

Lifshitz & Roukes, *Phys. Rev. B* 61, 2000

Sun & Tohmyoh, *J. Sound Vib.* 319, 2009



$$Q^{-1} = 2\left|\frac{\mathrm{Im}(\omega)}{\mathrm{Re}(\omega)}\right|$$

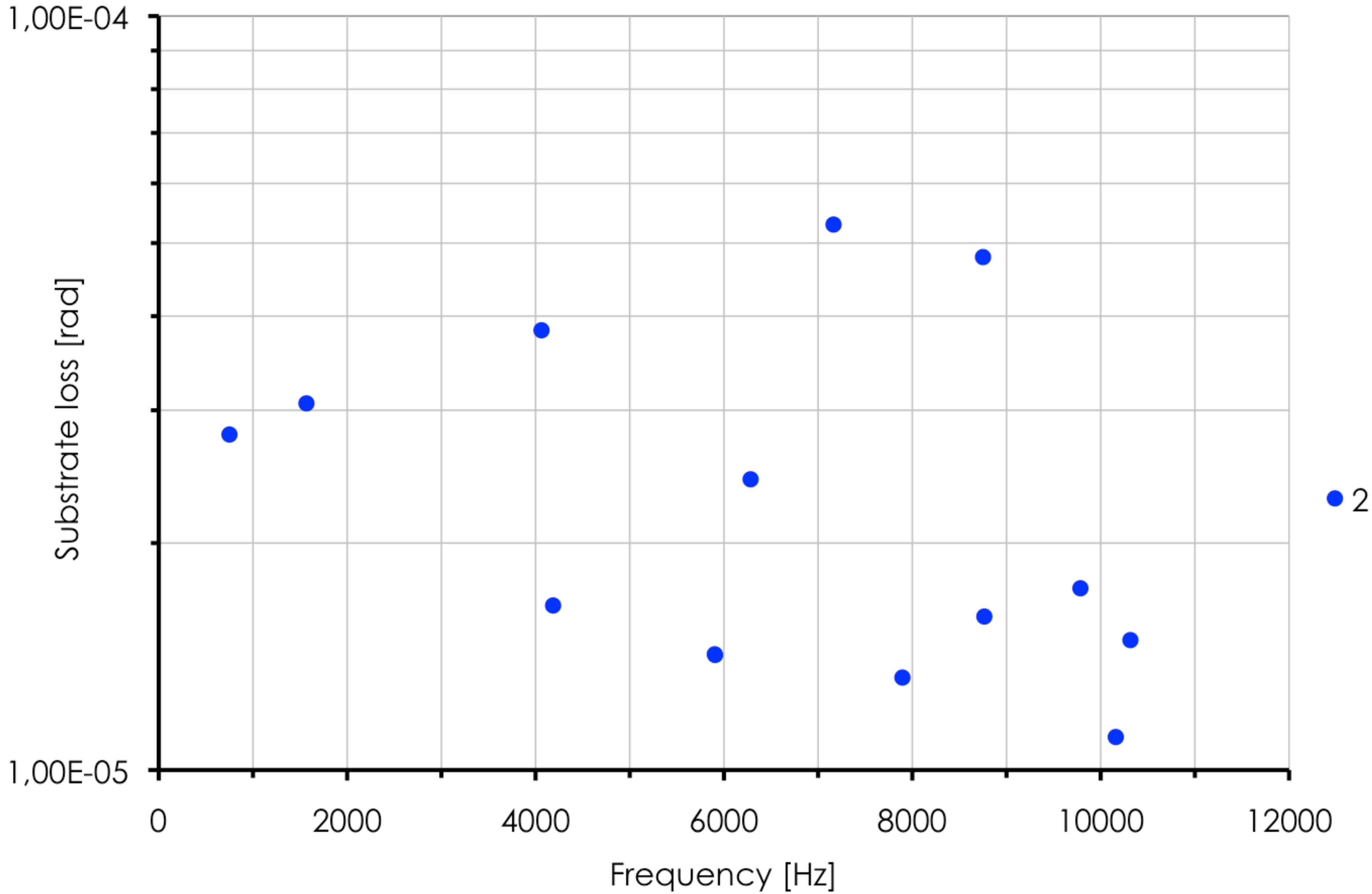
$$D\nabla^2\nabla^2 w_0 + D(1+\nu)\alpha_T \nabla^2 M_{T0} - \rho h \omega^2 w_0 = 0$$

$$\kappa \frac{\partial^2 \vartheta_0}{\partial z^2} = \mathrm{i}\omega\rho c_v \vartheta_0 - \mathrm{i}\omega\beta T_0 z \nabla^2 w_0$$

$$M_{T0} = \frac{12}{h^3}\int_{-h/2}^{h/2} \vartheta_0 z \, \mathrm{d}z$$

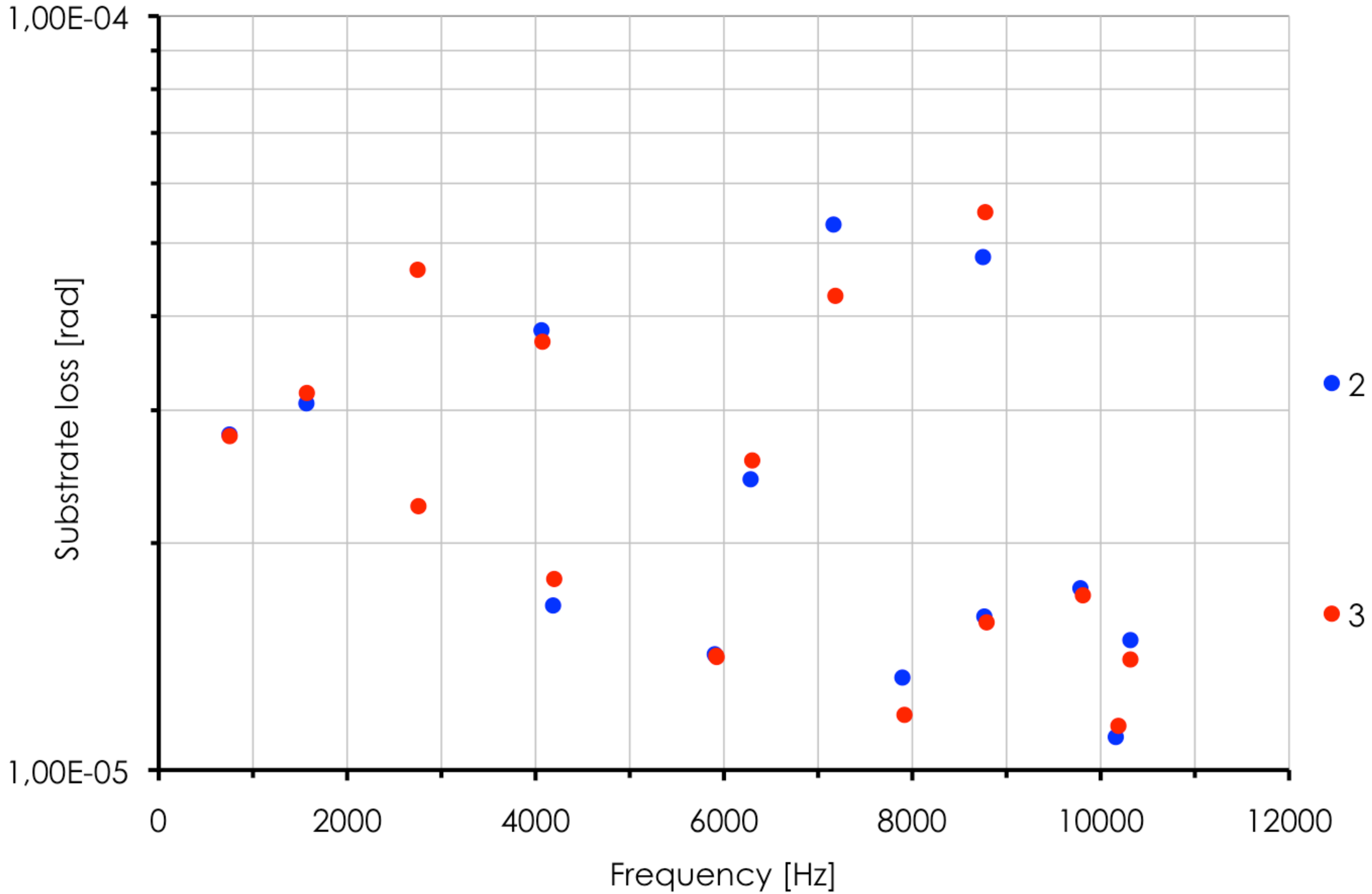
→ thermoelastic damping only depends on frequency

patterns



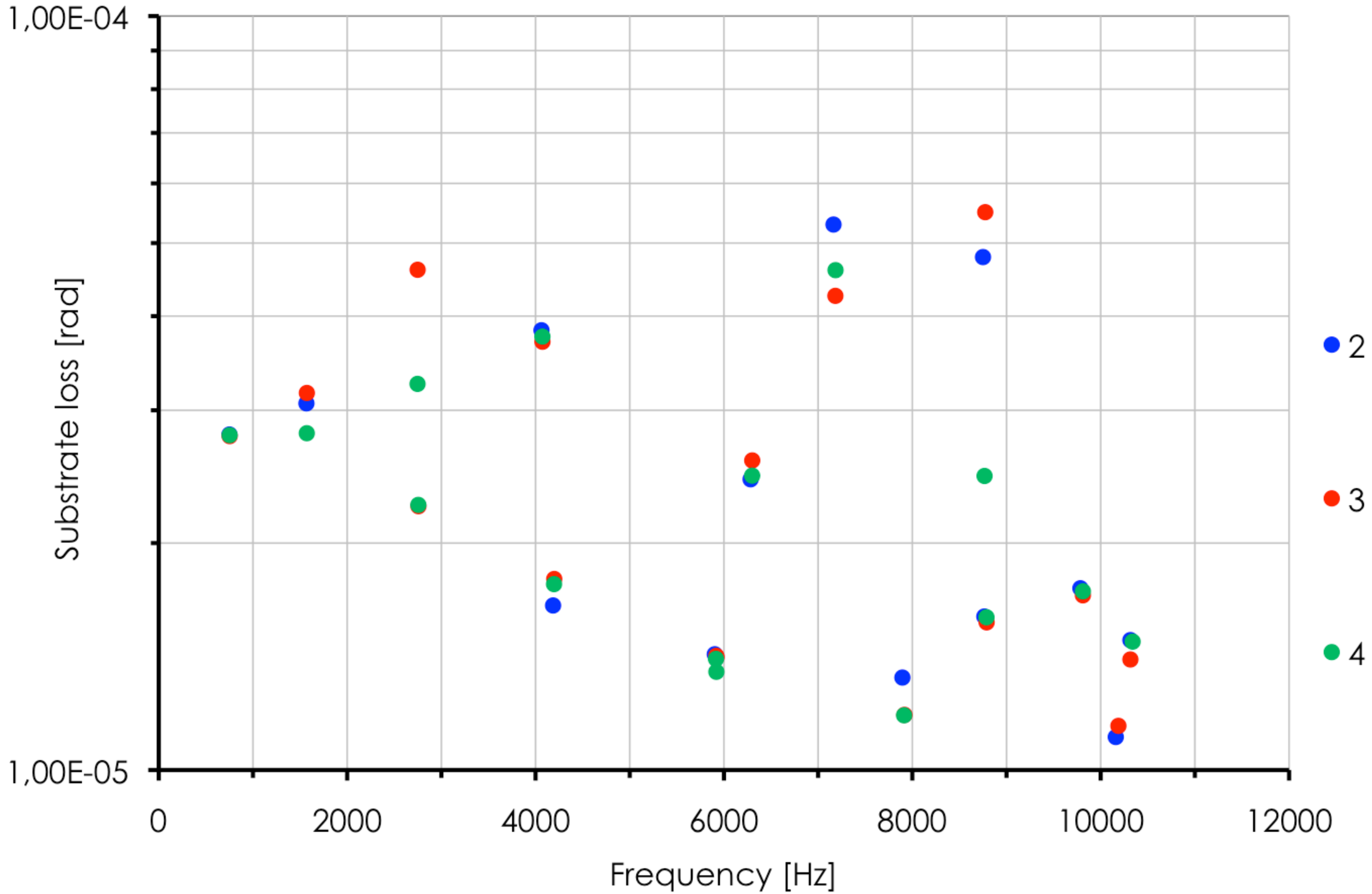
1,00E-04
1,00E-05
Substrate loss [rad]
0
2000
4000
6000
8000
10000
12000
Frequency [Hz]
2

patterns



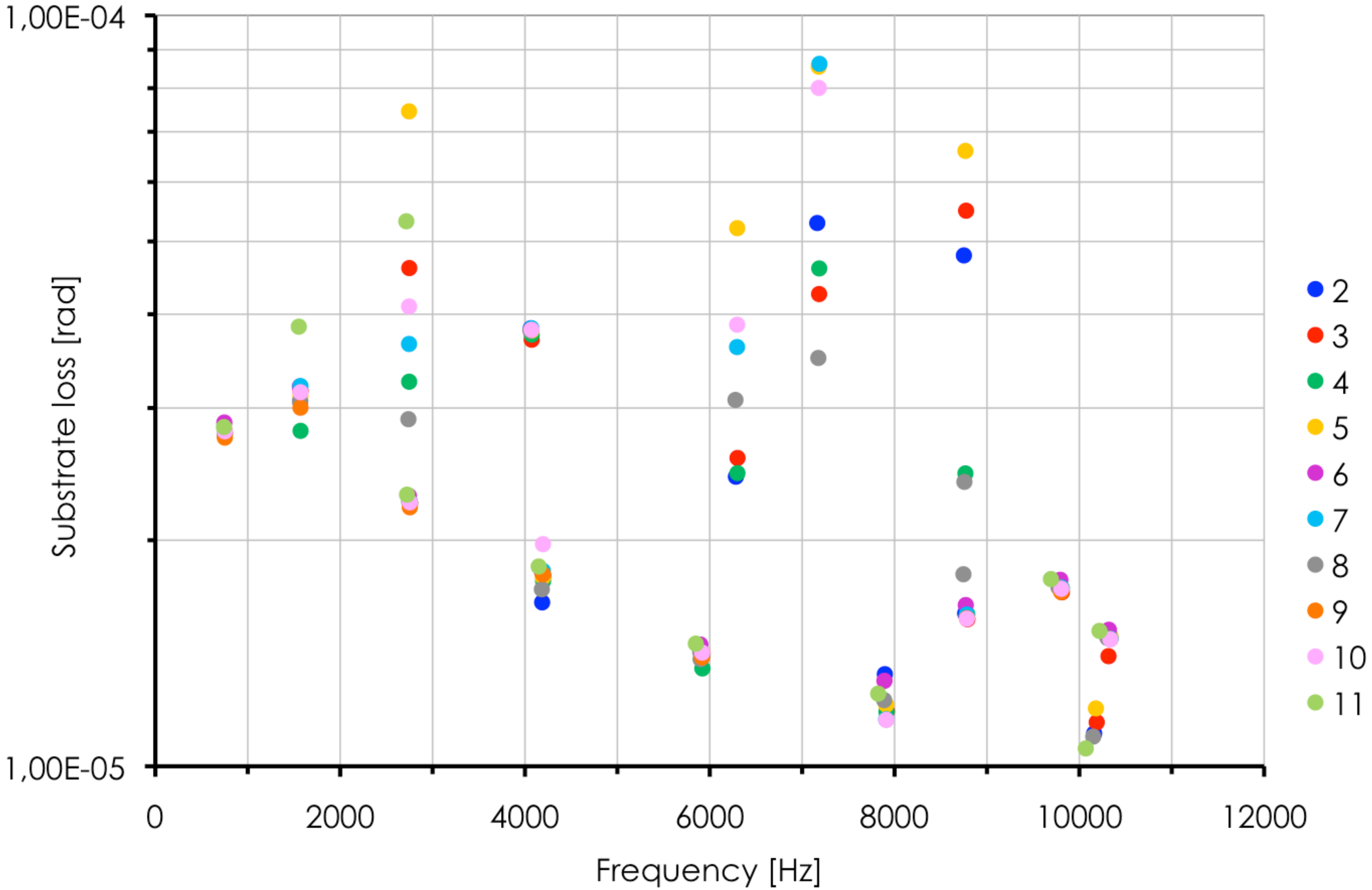
1,00E-04
1,00E-05
Substrate loss [rad]
0
2000
4000
6000
8000
10000
12000
Frequency [Hz]
2
3

patterns



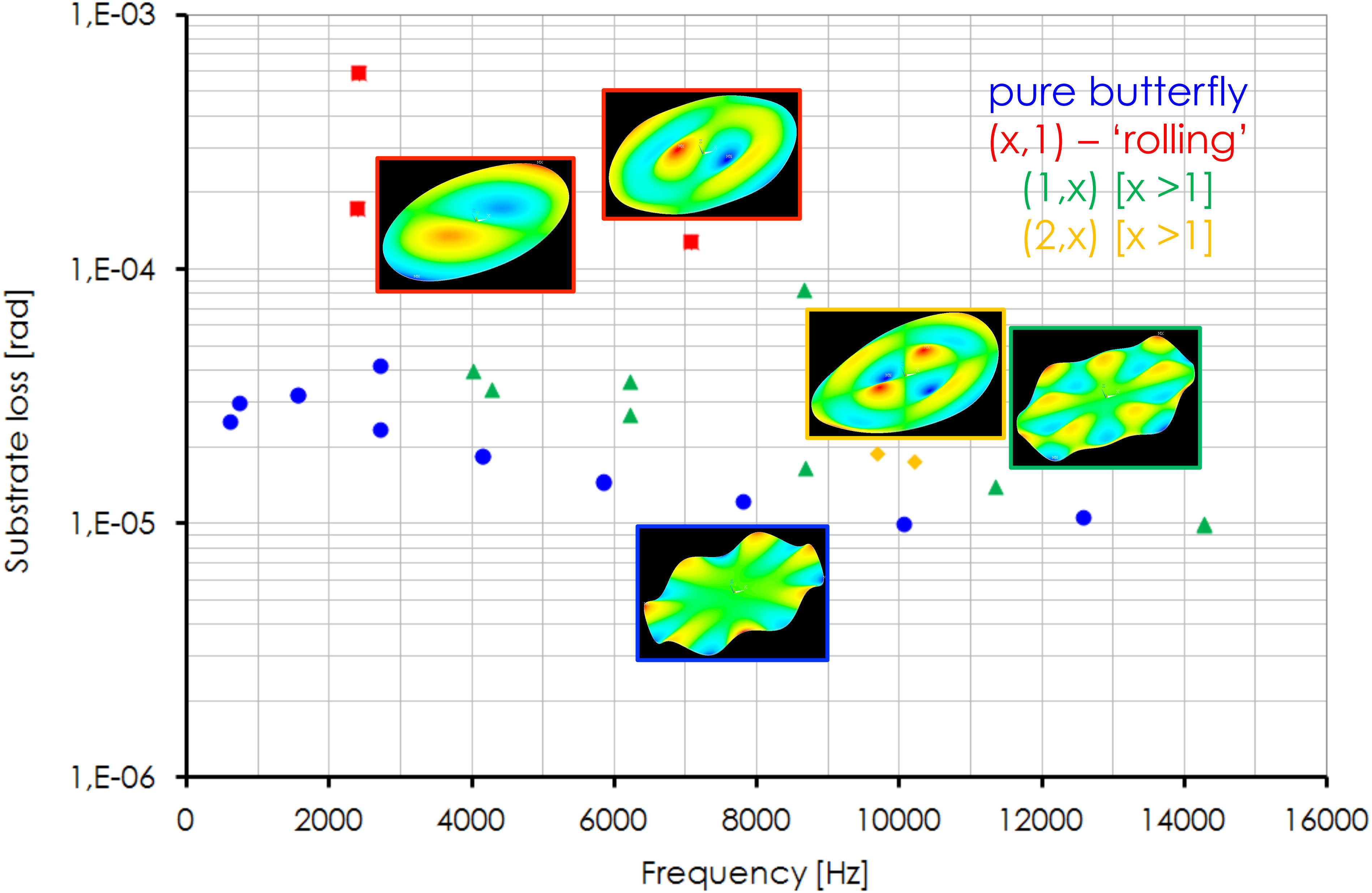
1,00E-04
1,00E-05
Substrate loss [rad]
0
2000
4000
6000
8000
10000
12000
Frequency [Hz]
2
3
4

patterns

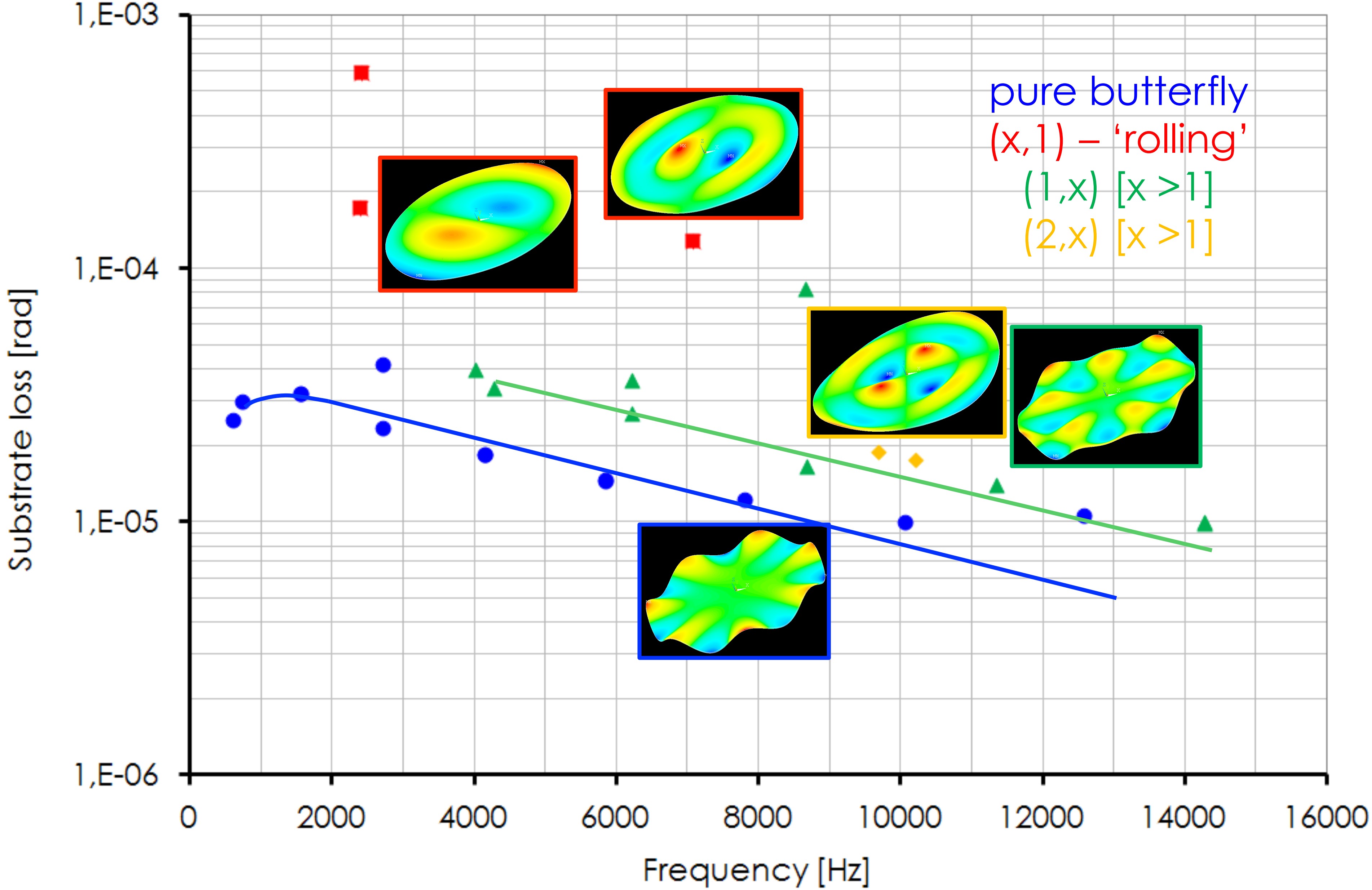


1,00E-04
1,00E-05
Substrate loss [rad]
0
2000
4000
6000
8000
10000
12000
Frequency [Hz]
2
3
4
5
6
7
8
9
10
11

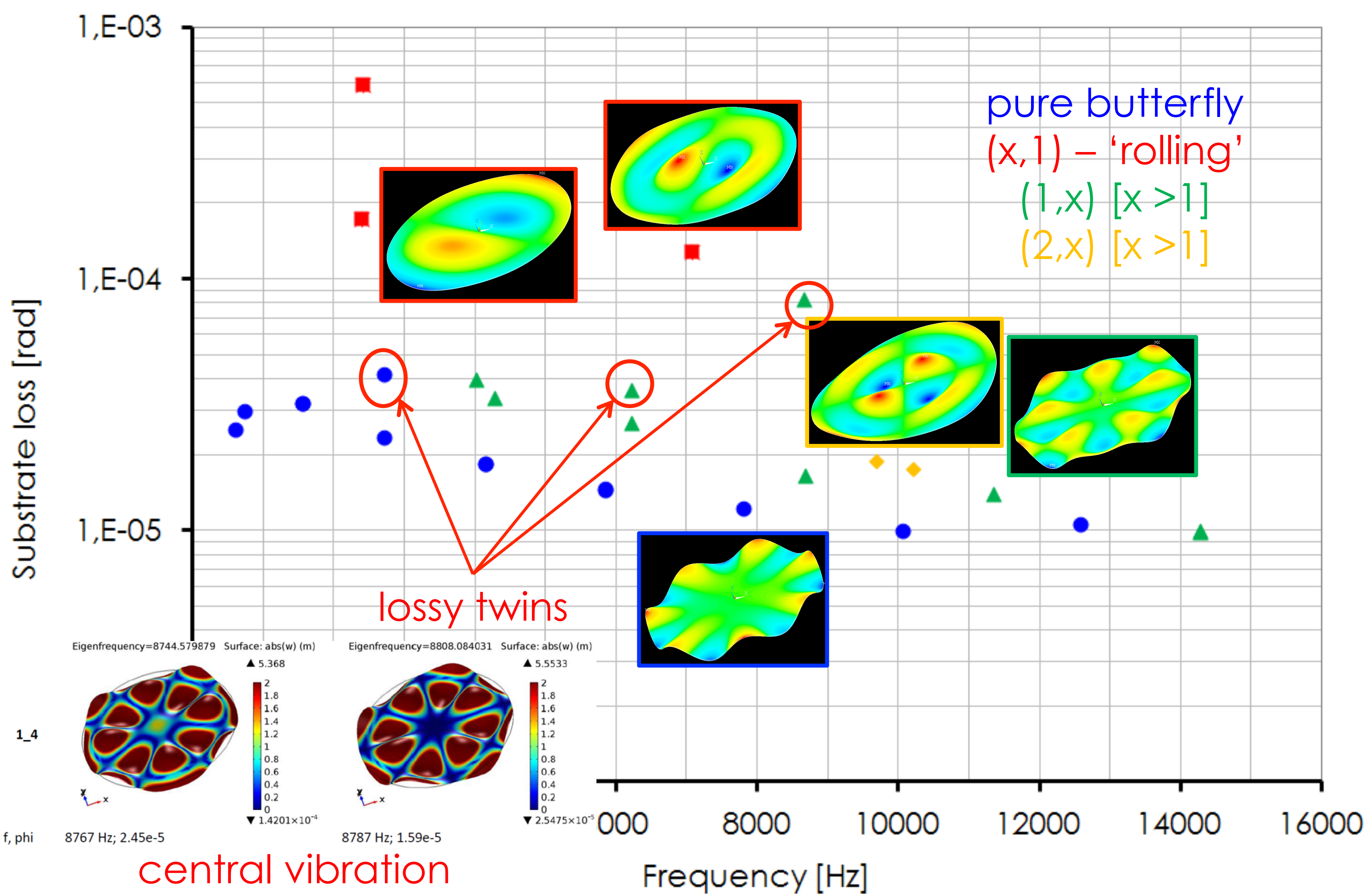
mode families



mode families



mode families



evidences

GeNS

- high repeatability
- high reproducibility

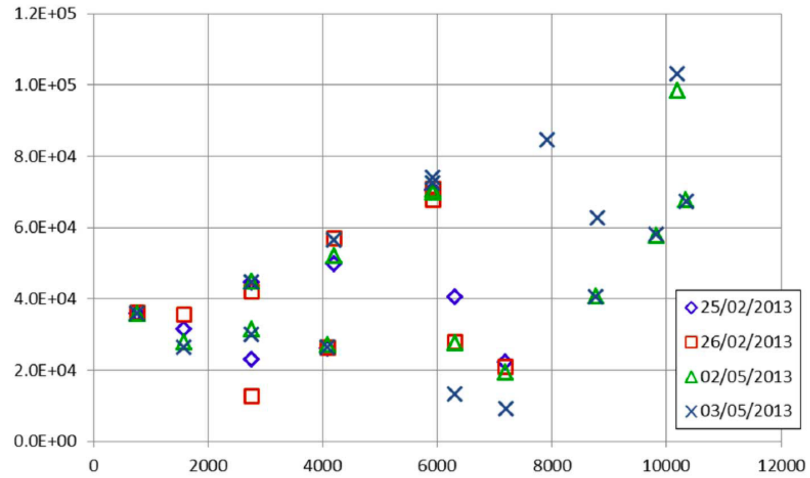
  $\Delta f/f \sim 10^{-4}$

  $\Delta Q/Q < 10\%$
- very low excess loss at low temperature

  $Q_{0,2} = 2.2 \times 10^8$

  $Q_{1,4} = 8.3 \times 10^7$

  $Q_{2,2} = 1.1 \times 10^8$



evidences

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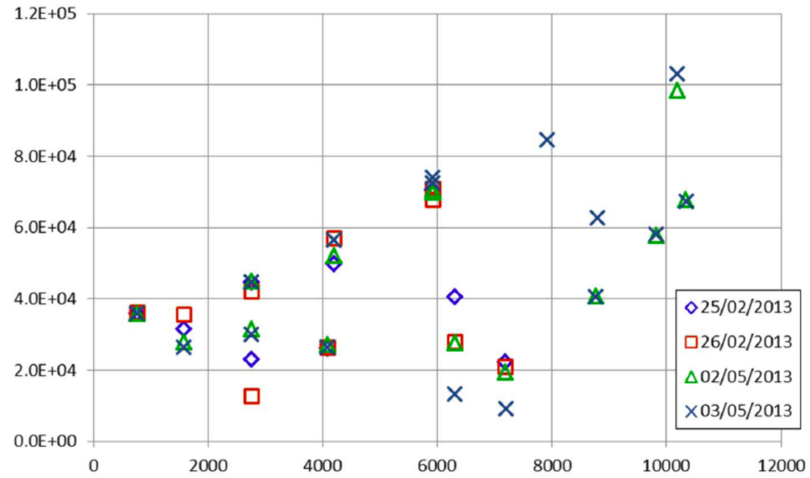


- very low excess loss at low temperature

  $Q_{0,2} = 2.2 \times 10^8$

  $Q_{1,4} = 8.3 \times 10^7$

  $Q_{2,2} = 1.1 \times 10^8$

- indipendent simulations

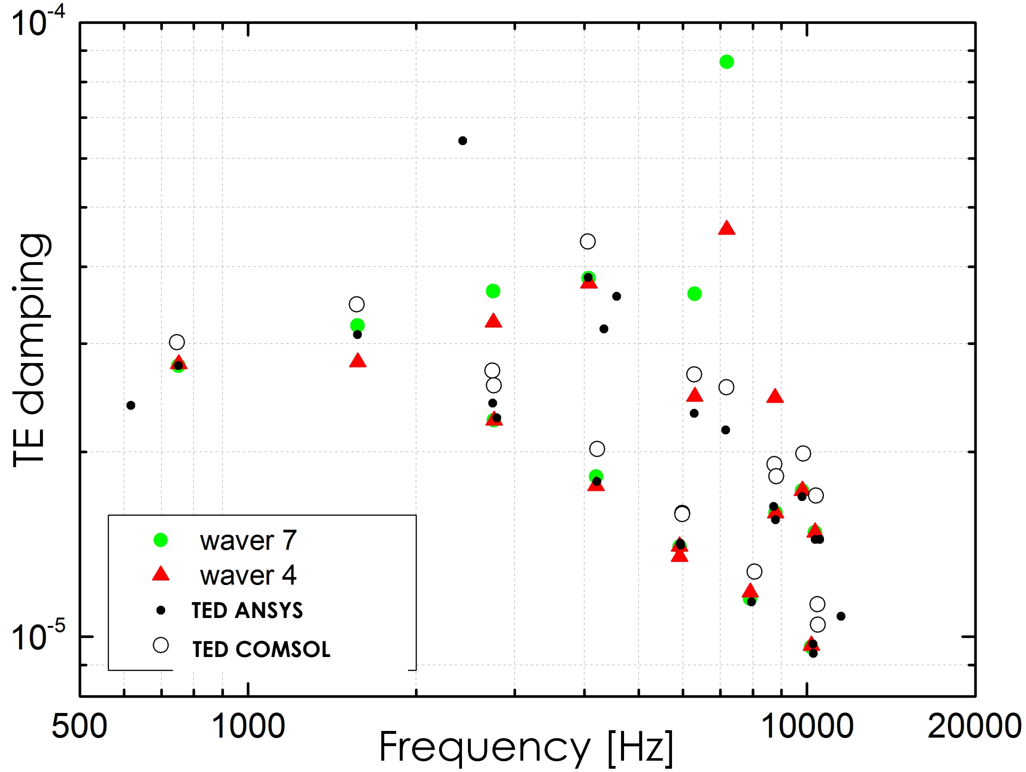
  ANSYS + analytical

  COMSOL

  modes and loss confirmed

→ mode families are for real

crystalline nature of Si ?



CuBe

- 3" isotropic sample – t = 1 mm
- simulations predict mode families
- discrepancy with measurements

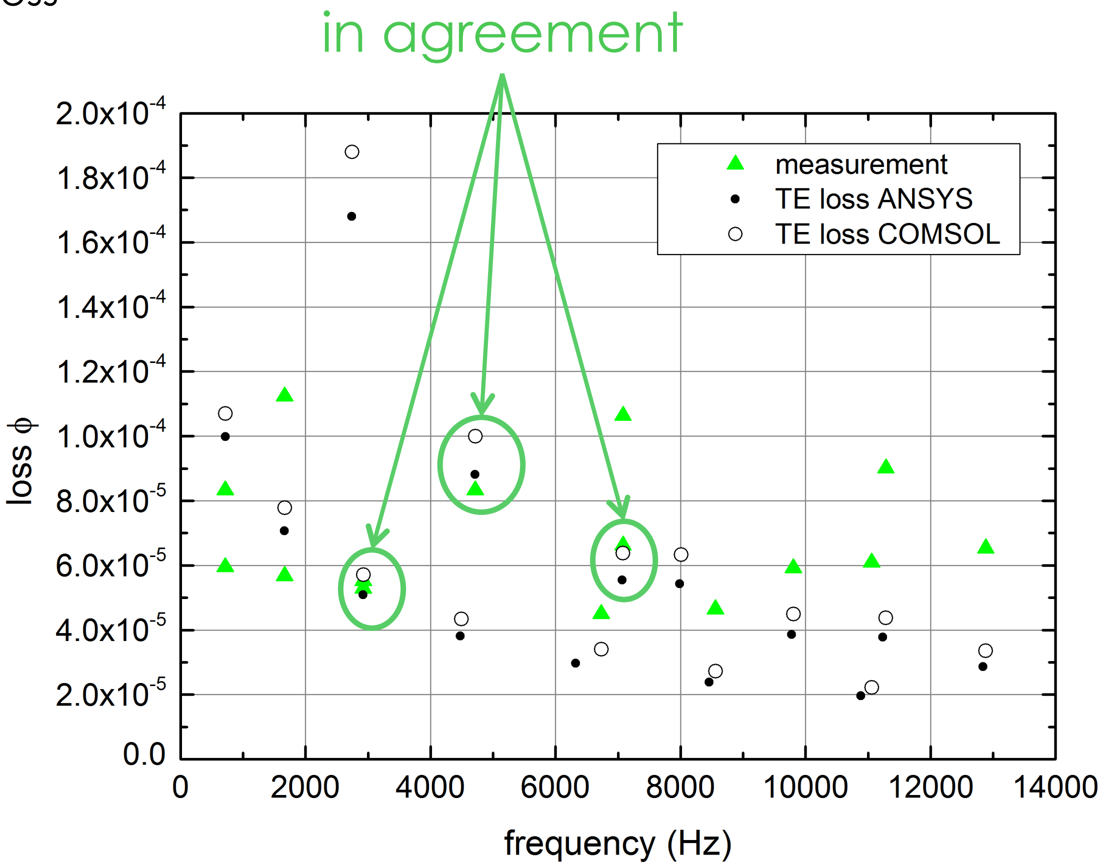
  lower frequency → lower measured loss

  higher frequency → higher measured loss

→ tune simulations ?

→ thinner sample ?

→ new material ?



next steps

- thin Si disks show mode-dependent thermoelastic damping
- analytical models do not predict mode families
  → new model is under developement
- no clear outcome from CuBe disk → new samples and simulations
  → 0.5-mm thick CuBe disk
  → 0.5-mm thick α-brass disk

direct measurement of coating thermal noise

technique

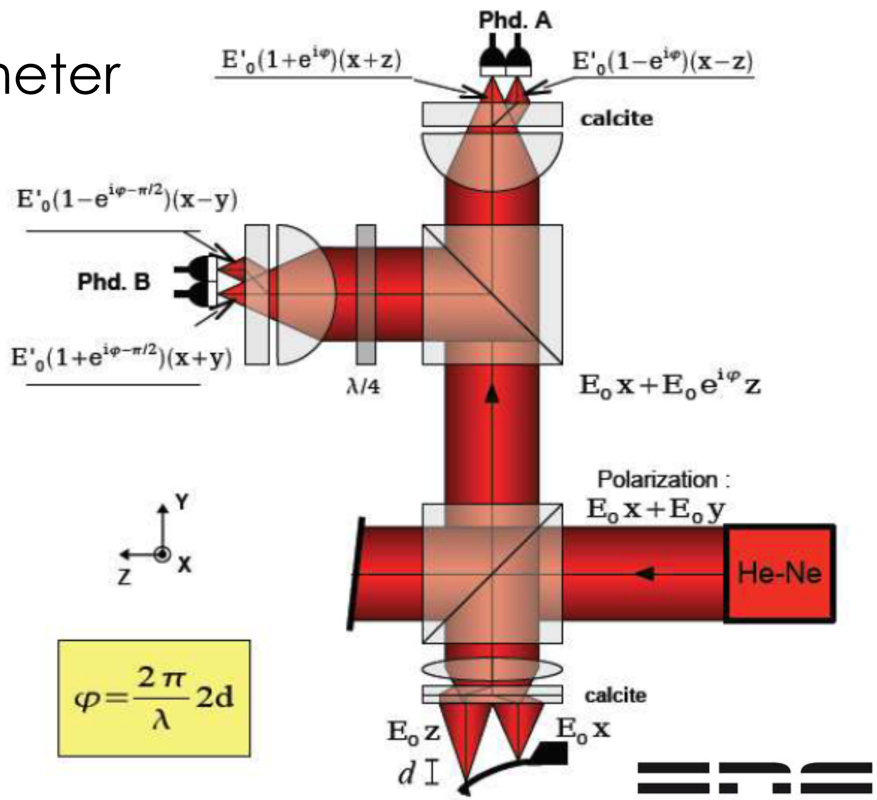
quadrature-phase differential interferometer

Bellon et al., *Opt. Commun.* 207, 2002

Paolino et al., *Rev. Sci. Instrum.* 84, 2013

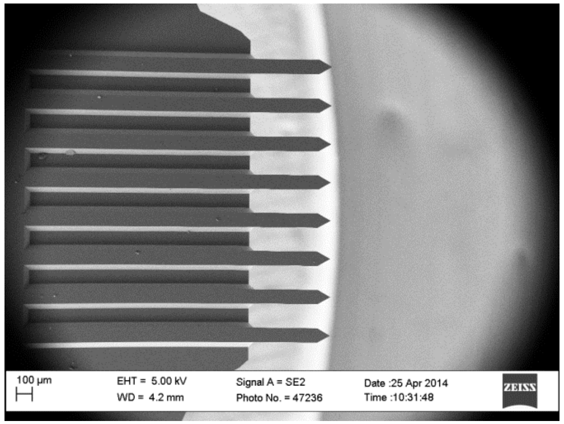
- suitable to study coating thermal noise
  - ✓ direct measurement
  - ✓ simple setup
- key point 1 – micro-cantilevers
  - low rigidity $k \leq 1$ N/m
  - high resonances $f_0 > 14$ kHz
  - low dilution factor $t_c \sim t_s$
  - → thermal noise ~ 10^{-13} m/√Hz
- key point 2 – polarization
  - linear response of several µm

nearly-common-path Michelson
high noise rejection
very low drift



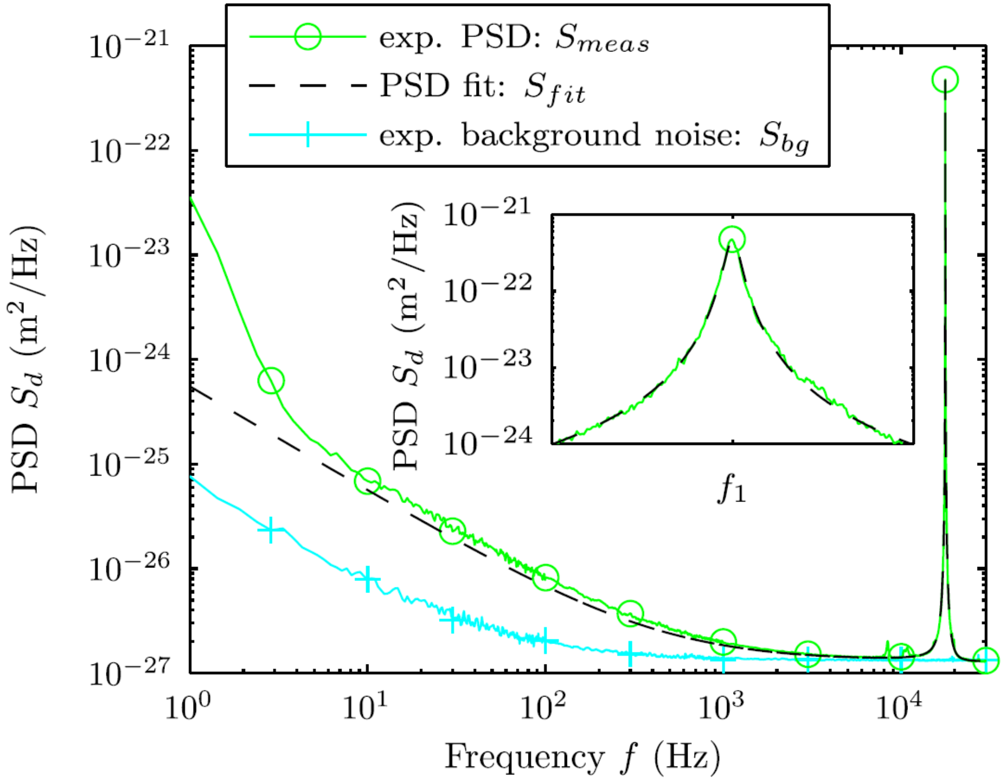
Bellon, Ciliberto et autres, Opt. Comm. (2002).

ENS DE LYON



results

- measure
  - average of 10^2 spectra of ~10 s
- band from 10 Hz to 20 kHz
- analysis
  - fit of resonance
  - background subtraction
  - *measured* dilution factor D
  - → $\Phi_C(\omega)$



- metallic coatings
  - Paolino & Bellon, *Nanotechnology* 20, 2009
  - Li & Bellon, *Europhys. Lett.* 98, 2012
- optical dielectric mono-layer coatings
  - Cagnoli et al., *22nd ICNF*, IEEE, 2013
  - Li et al., *Phys. Rev. D* 89, 2014

$1-D \sim (f_s/f_{C})^2\, \mu_s/(\mu_s+\mu_C)$

Sample	$\mathcal{D}$	$\mathcal{D}^{calc}$
Sample **Si**	0.40 ± 0.02	0.40 ± 0.02
Sample **Si**$_A$	0.41 ± 0.02	0.41 ± 0.02
Sample **Ta**$_A$	0.45 ± 0.02	0.54 ± 0.02

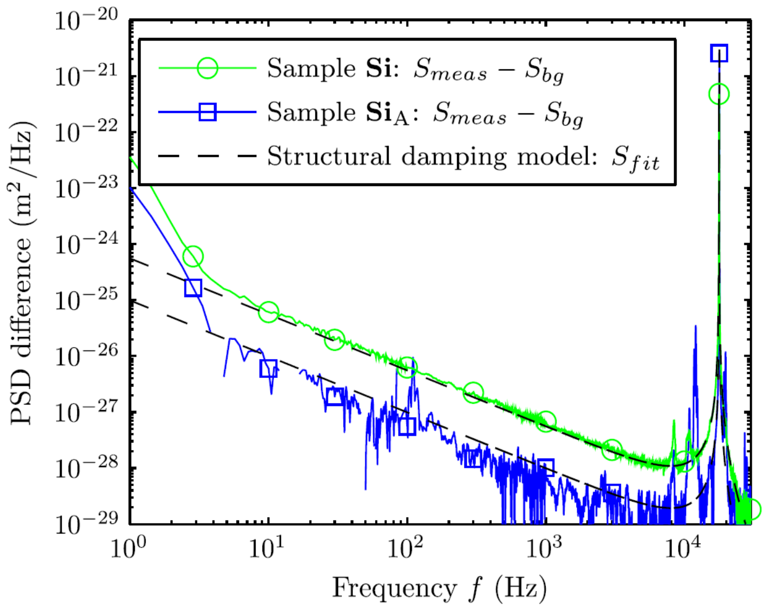
Y_{Ta2O5} ?

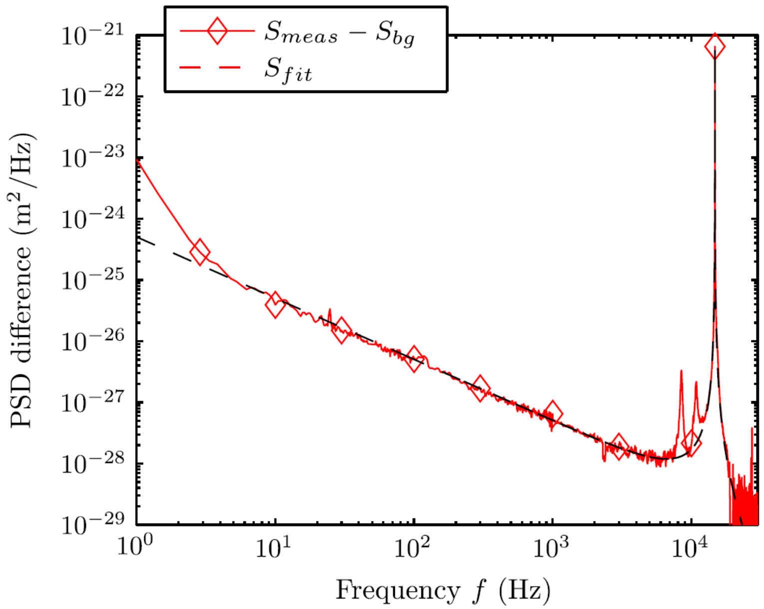
SiO2 and Ta2O5

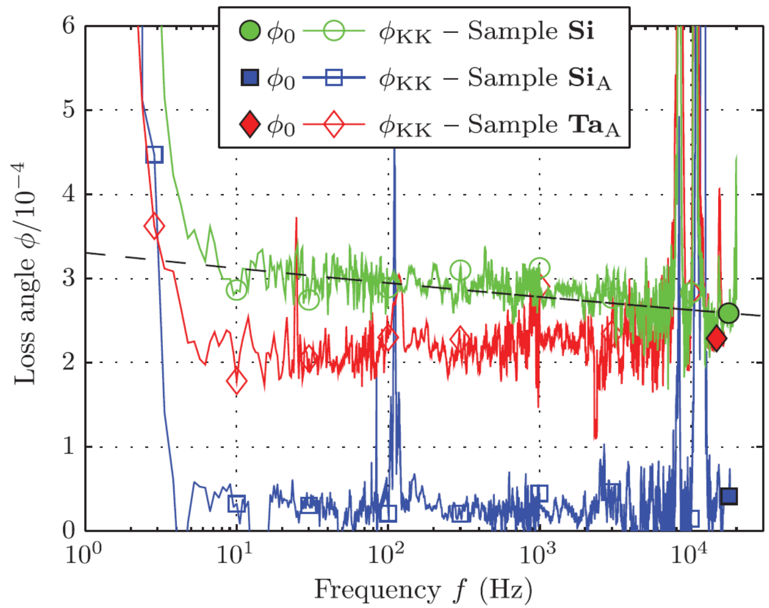
- 1/*f* noise – Saulson model confirmed
- *f*-independent loss after annealing

Coating	$\mathcal{D}$	$\phi_c \times 10^4$
SiO_2 as coated	0.40 ± 0.02	$6.0 \pm 0.3 (\pm 0.5)$
SiO_2 annealed	0.41 ± 0.02	$0.62 \pm 0.05 (\pm 0.43)$
Ta_2O_5 annealed	0.45 ± 0.02	$4.7 \pm 0.2 (\pm 0.4)$

in agreement with resonant method
– GeNS –





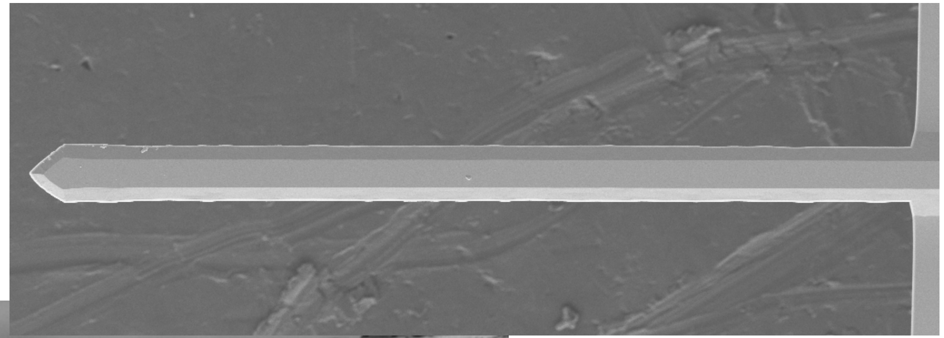


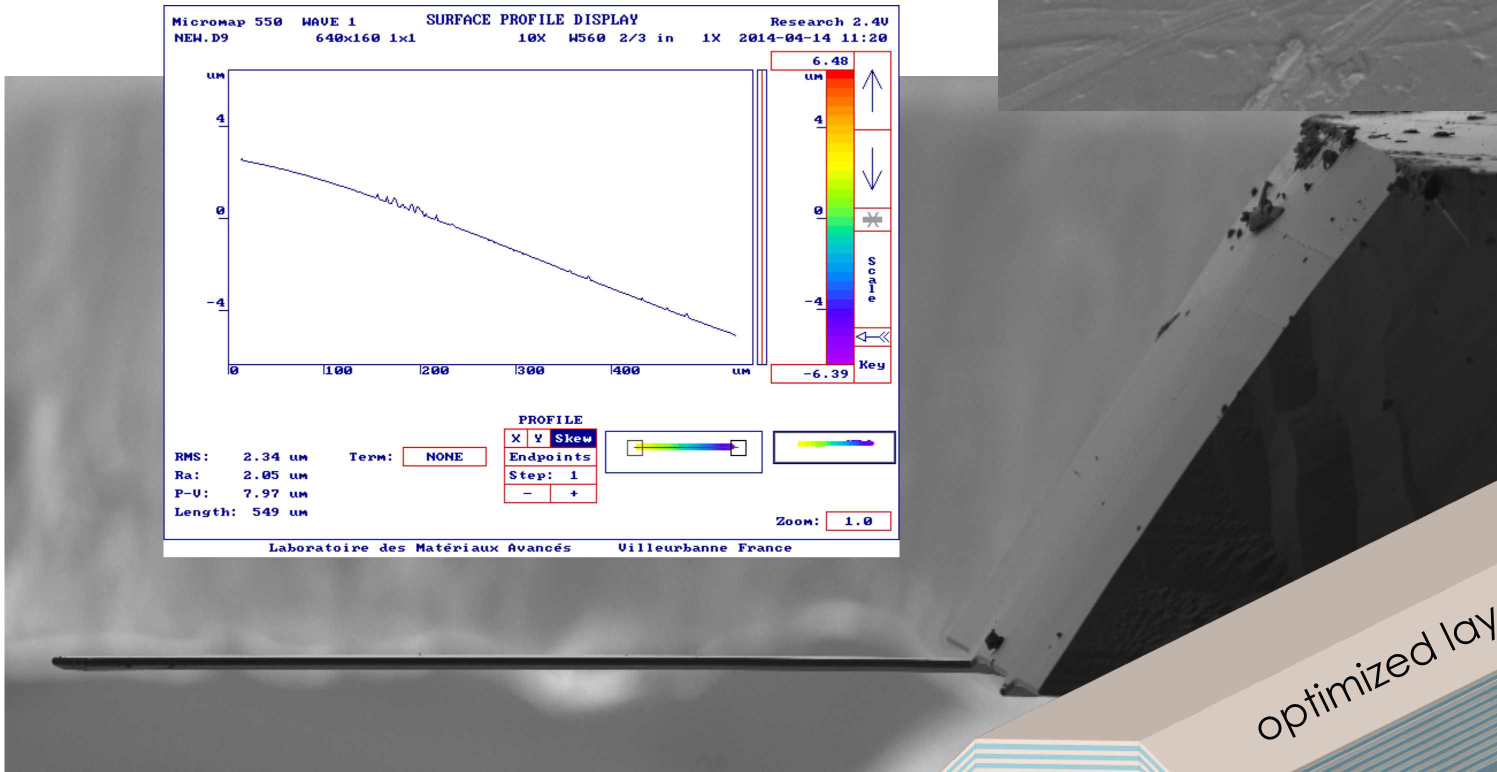
stack

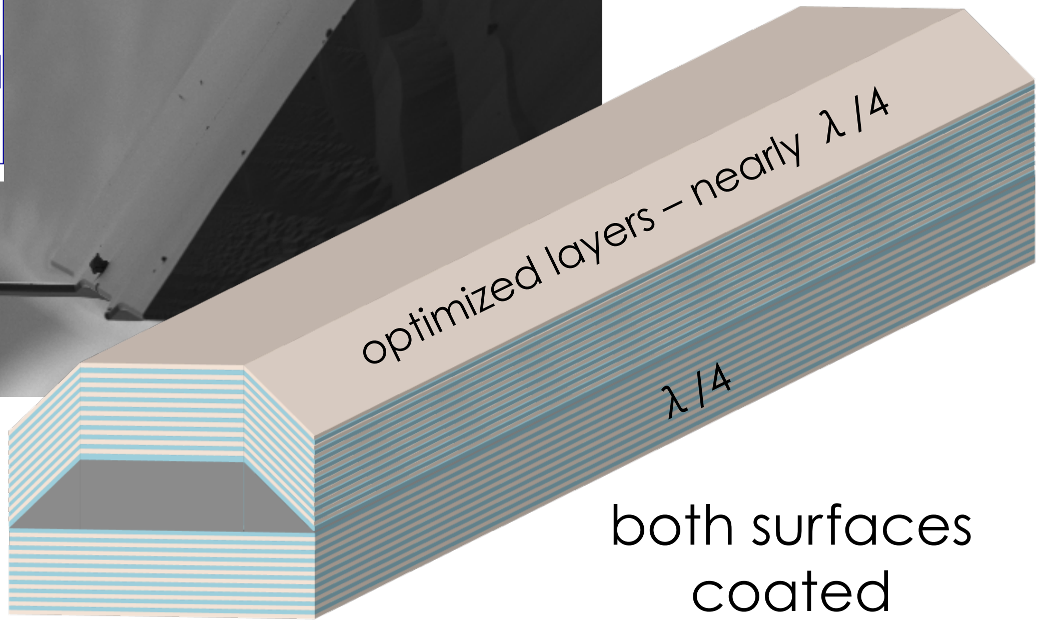
• quarter-wavelength coating

plain Ta2O5 and SiO2 layers

λ = 1064 nm, 10 doublets







– straight coated cantilever –
technique developed at LMA

results

• before coating

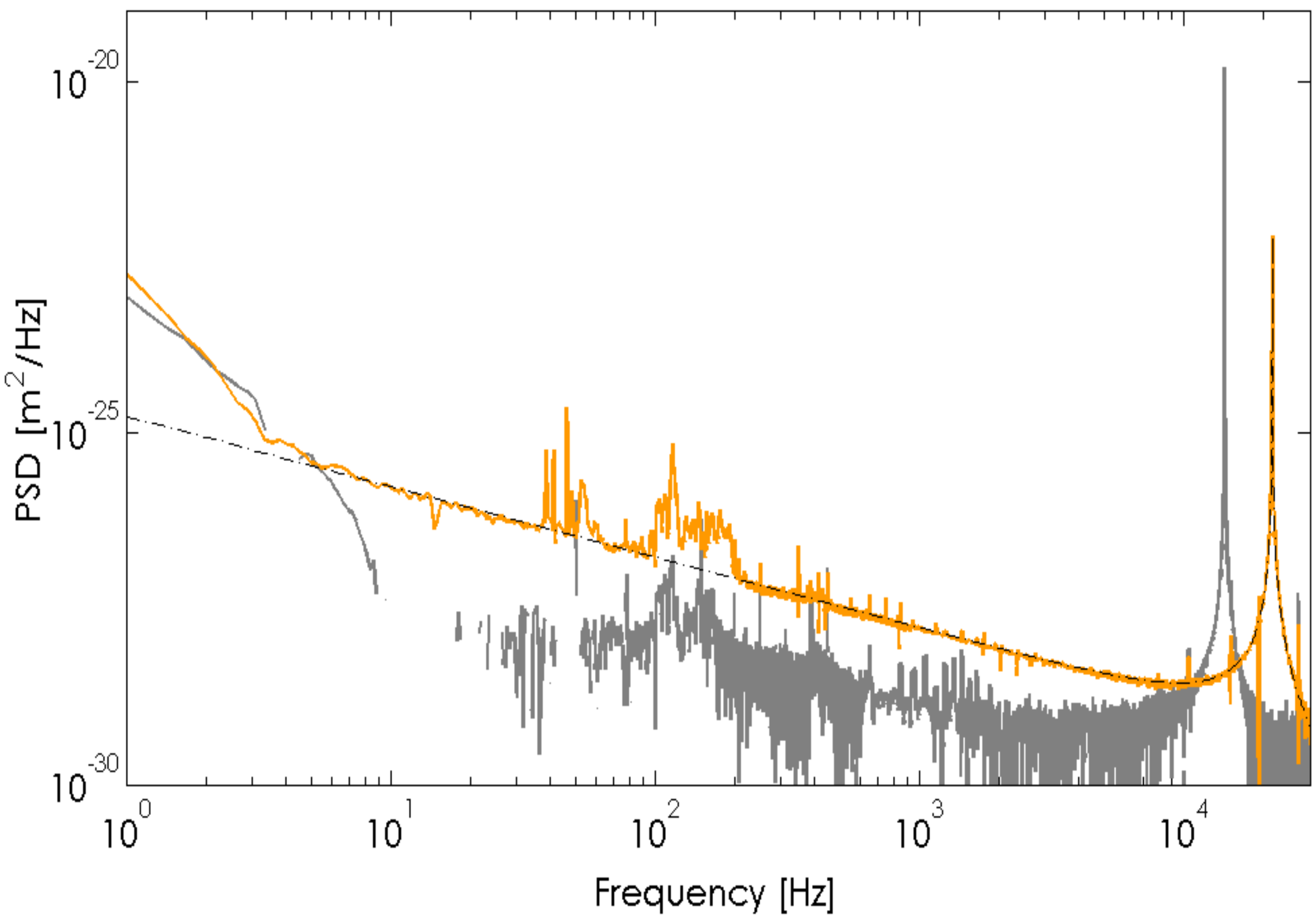
f_0 = 14280.33 ± 0.01 Hz

• after coating

f_0 = 21619.79 ± 0.03 Hz

measured loss
$\Phi_C = 3.86 \times 10^{-4}$

expected loss
$\Phi_C = 2.73 \times 10^{-4}$
[linear combination of mono-layer loss]



loss higher than expected

same phenomenon observed with macro-cantilevers ?

M. Granata & al., *GWADW*, Waikoloa, 2012

next steps

• quadrature-phase differential interferometer

very powerful tool to study out-of-resonance coating thermal noise

→ additional informations on present optical coatings

→ enhance R&D programs on new materials

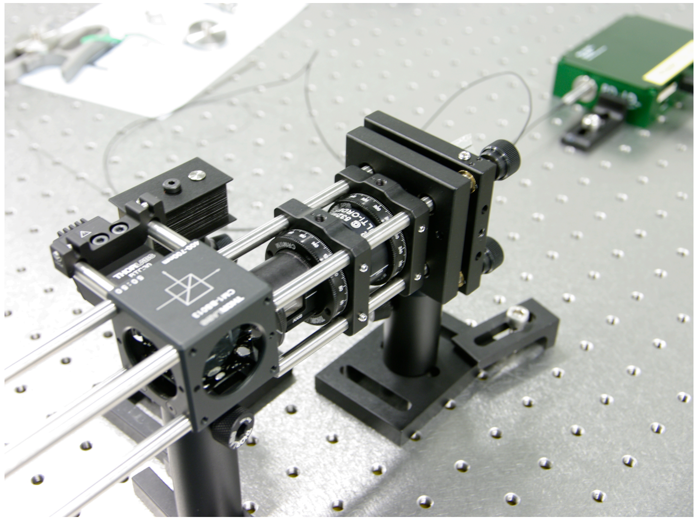
• mono-layer dielectric optical coatings characterized

• LMA developed a technique to deposit stacks on micro-cantilevers

→ multi-layer coatings under study

• 2nd setup being assembled at LMA

to be coupled to a cryostat



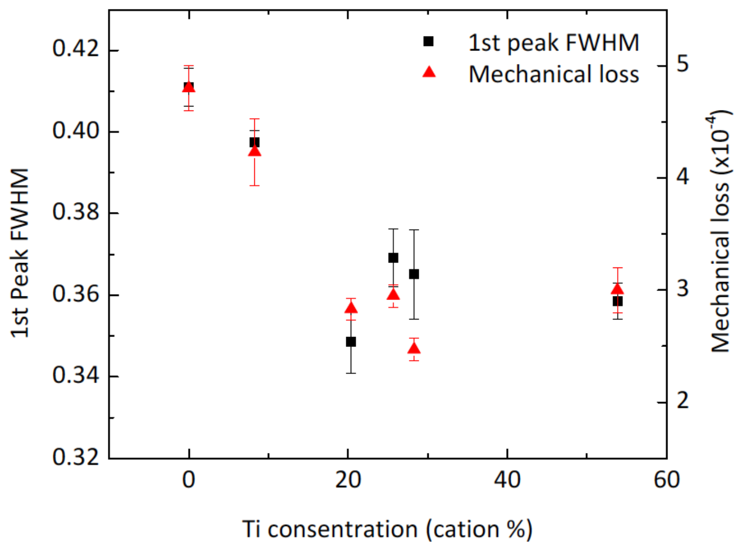
coating structure and mechanical loss

mechanical loss

due to structural relaxation of materials

→ investigation of microscopic structure

- $TiO_2Ta_2O_5$



reduced density functions

Bassiri & al., *Acta Mater.* 61, 2013

Bassiri & al., *LIGO-G1400271*, 2014

talk in this session

- Ta_2O_5

→ Raman spectroscopy at Institut Lumière Matière

- SiO_2

iLM
INSTITUT LUMIÈRE MATIÈRE

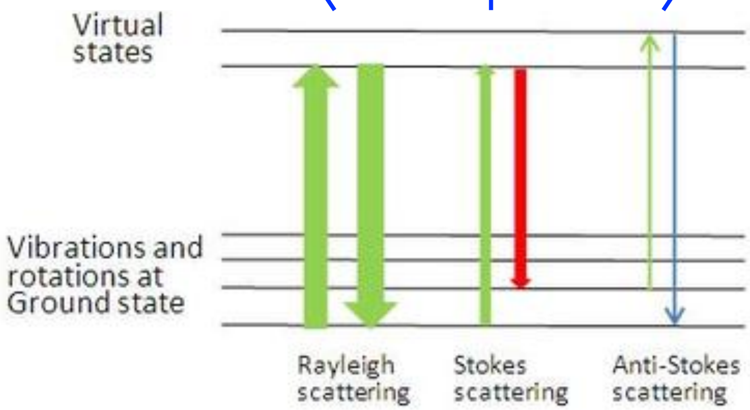
Raman in a nutshell

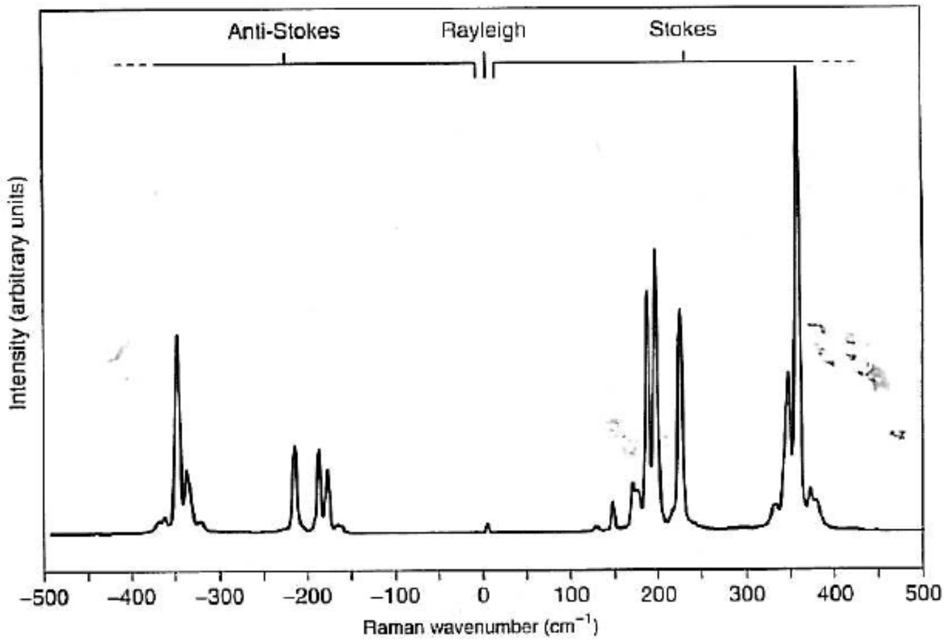
laser $\mathbf{E} = \mathbf{E}_0 \cos(2\pi f_0 t)$ → dipole $\mathbf{p} = \alpha \mathbf{E}$

polarizability & normal coordinates $\alpha(Q_k) \sim \alpha_0 + Q_k \, \partial\alpha/\partial Q_k$

~ harmonic vibration of atoms $Q_k = Q_{k0} \cos(2\pi f_k t)$

→ $\mathbf{p} = \mathbf{p}(f_0) + \mathbf{p}(f_0 - f_k) + \mathbf{p}(f_0 + f_k)$





→ spectrum of vibrational transitions

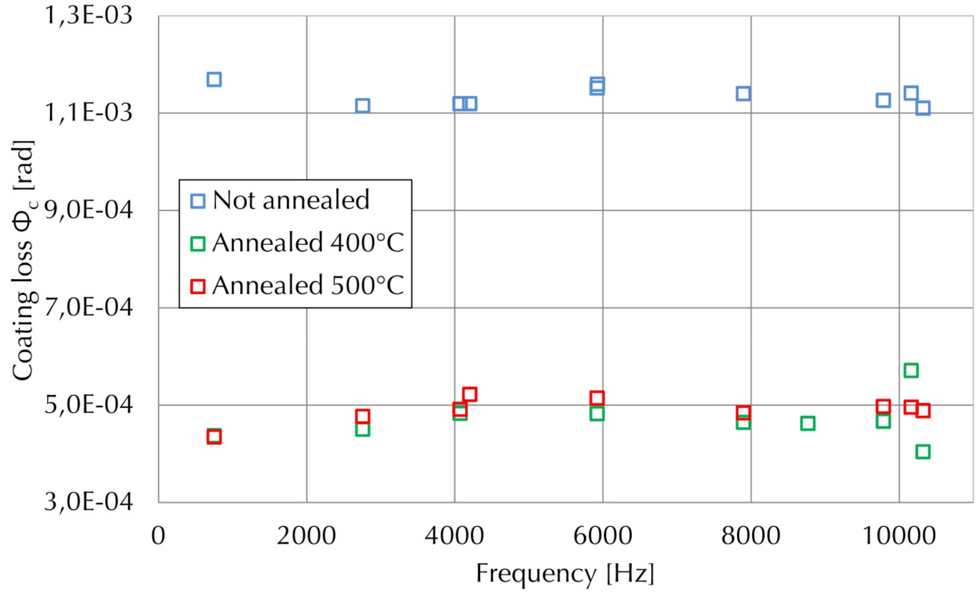
wavenumber $\omega = (f_0 - f)/c$

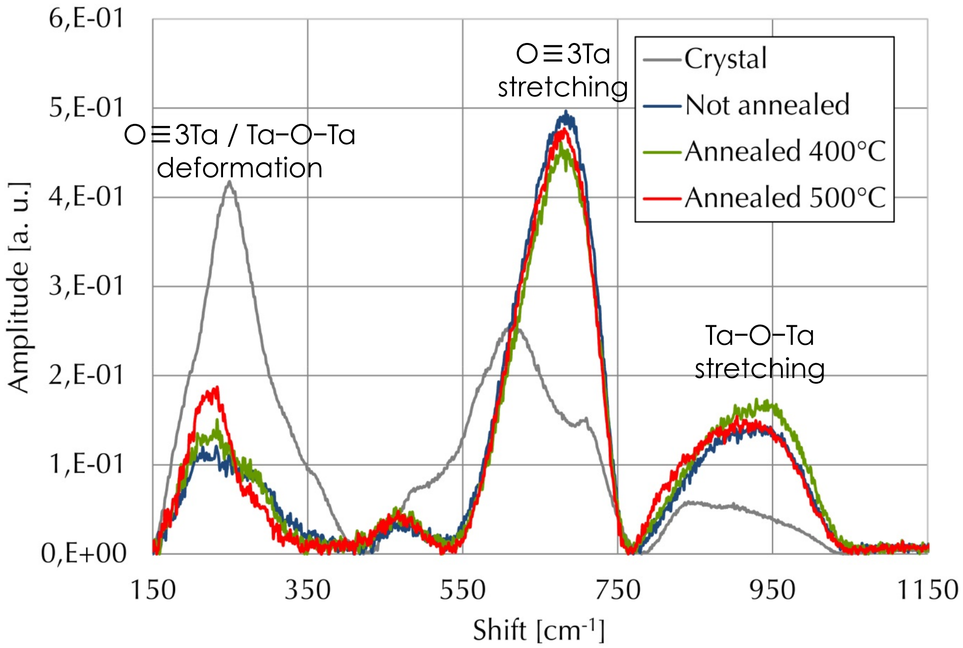
$[\omega] = \text{cm}^{-1}$

P. Vandenabeele, *Practical Raman Spectroscopy*, Wiley, 2013

Ta2O5

• annealing decreases losses by a factor 2





• little evolution of spectra wrt annealing

M. Granata & al., *Amaldi10*, Warsaw, 2013

peak identification

Ono & al., *Thin Solid Films* 381, 2001

• problem of samples?

warning

ion-beam-sputtered SiO_2 used in this study
is not the same
as that of detector mirrors

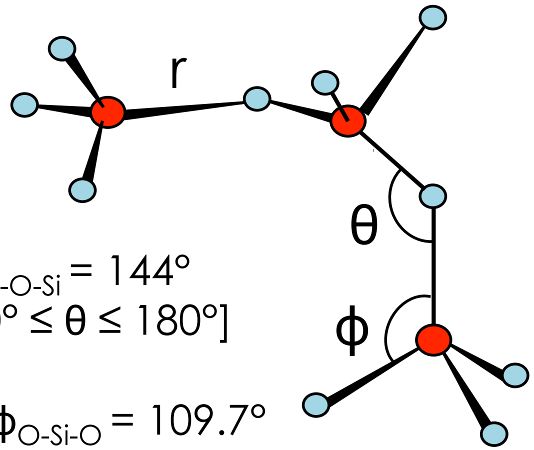
golden rule:

different deposition parameters give different coatings

SiO2

- bulk

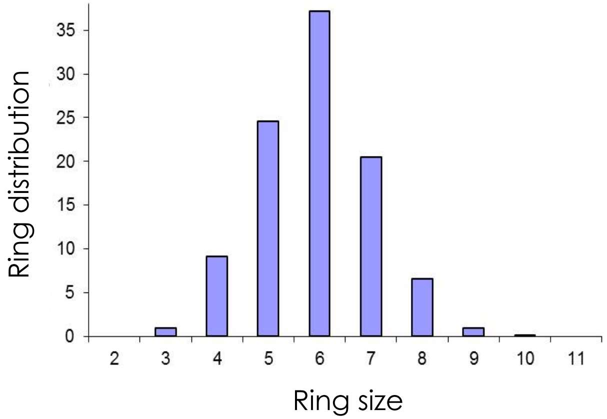
$r_{Si\text{-}O} = 1.62$ Å

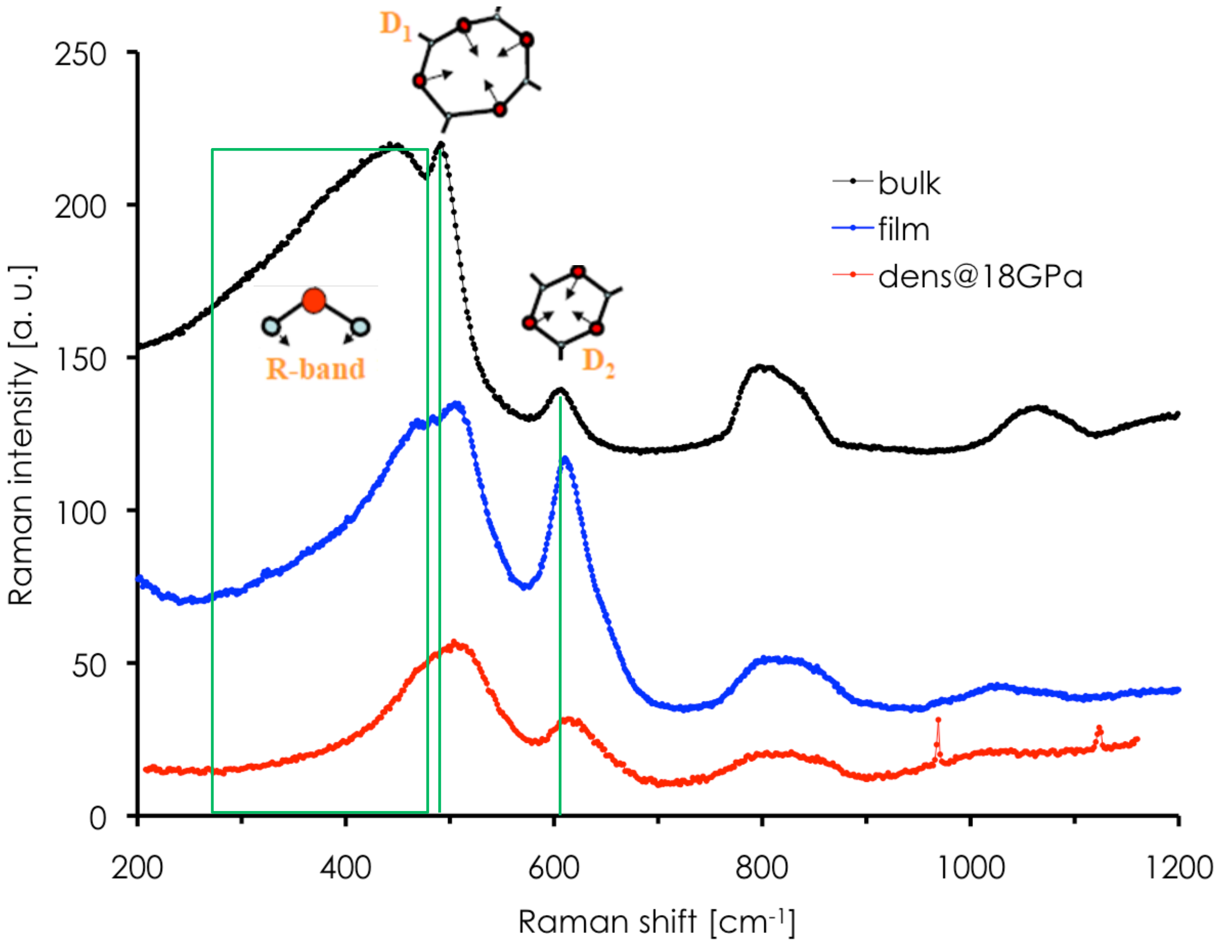


$\theta_{Si\text{-}O\text{-}Si} = 144°$
$[120° \leq \theta \leq 180°]$

$\phi_{O\text{-}Si\text{-}O} = 109.7°$

Jin & al., *Phys. Rev B* 50, 1994





- peak identification
  Galeener, *J. Non-Cryst. Solids* 71, 1985

SiO2

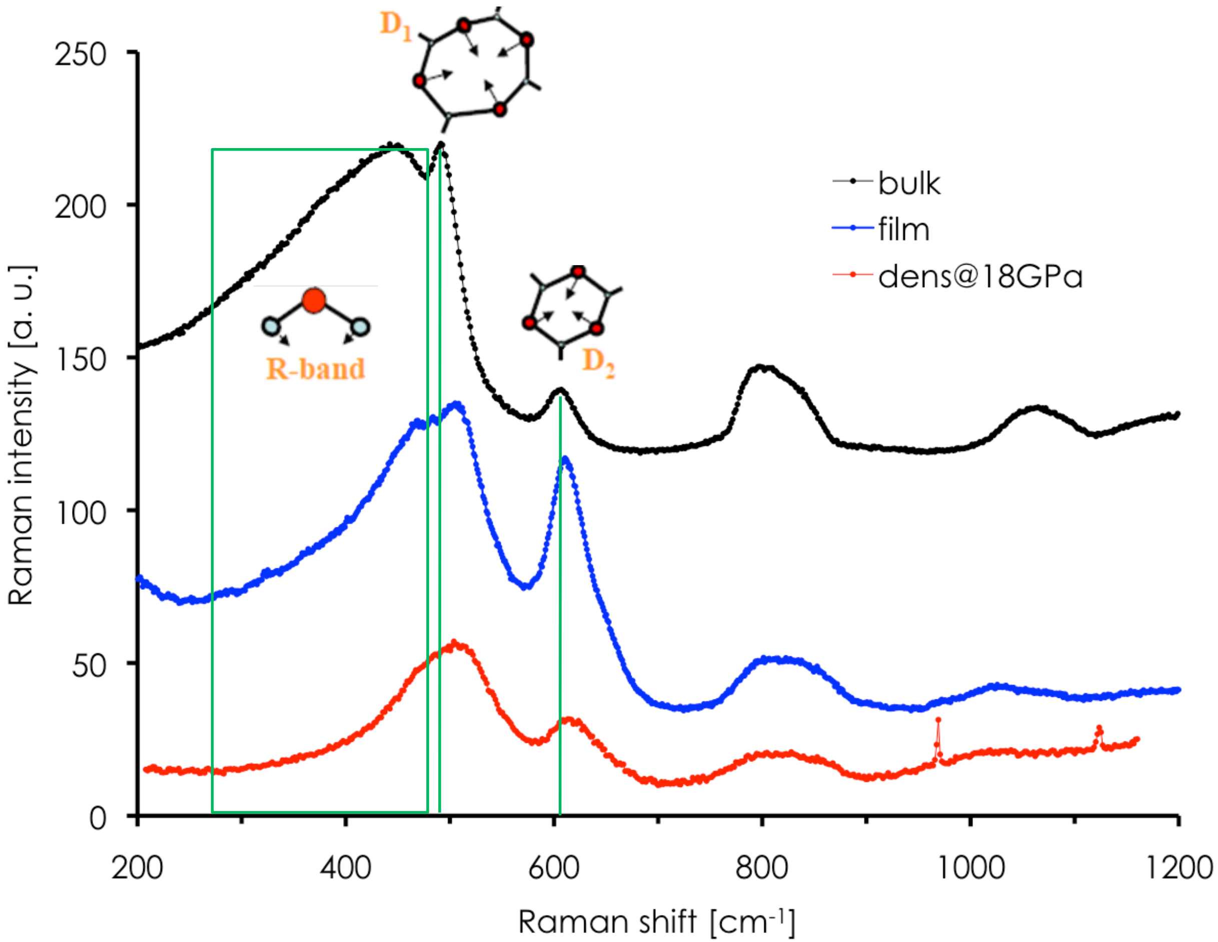
- film
  - different R-band → different θ distribution
  - shifted peaks
  - higher D2 intensity

→ similar to densified bulk

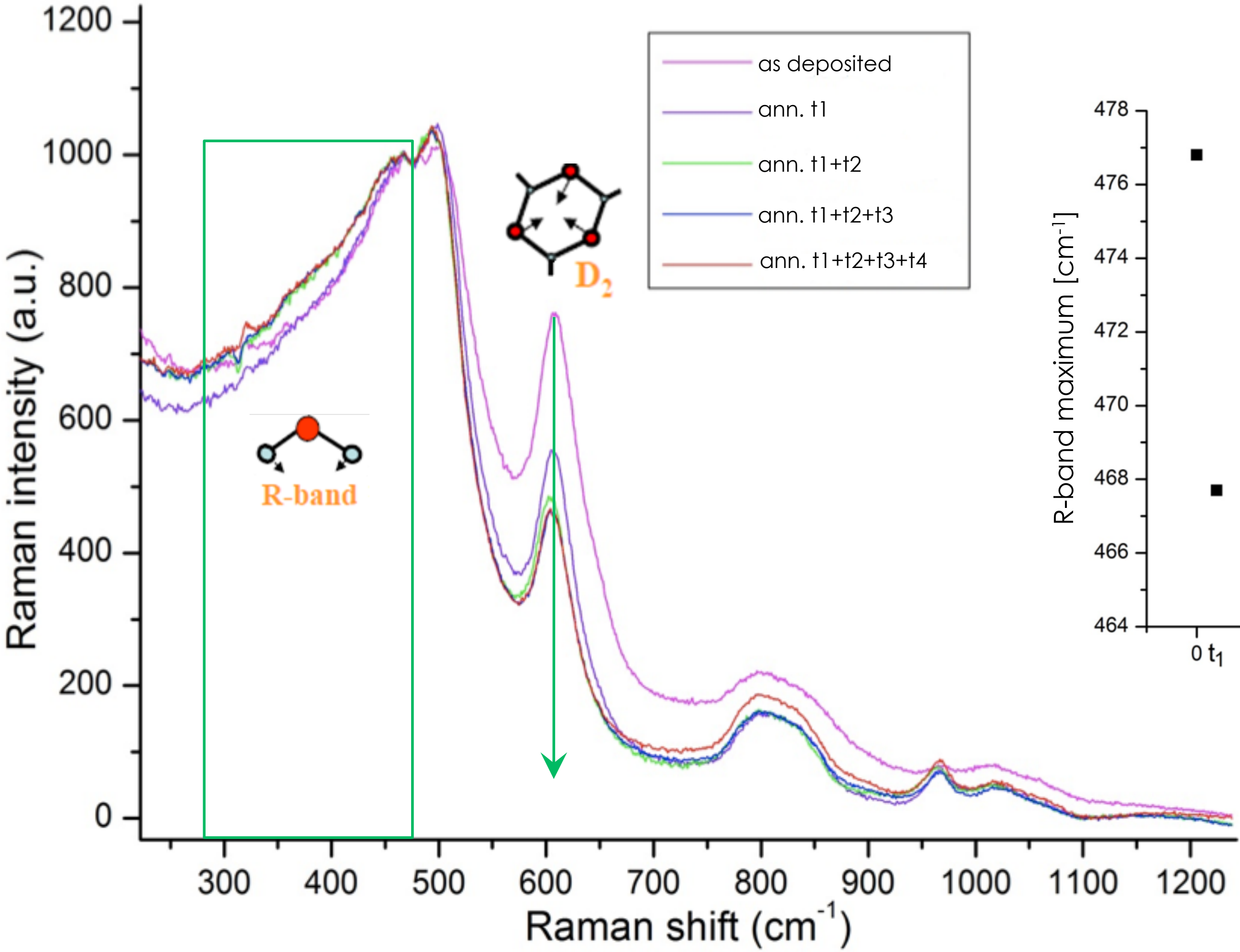
- in agreement with density measurements

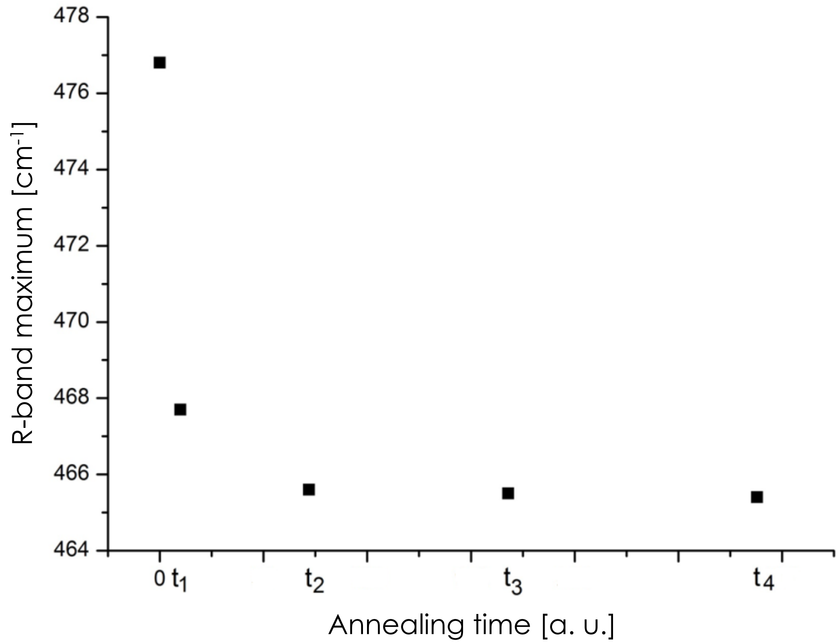
  $\rho_{\text{bulk}} = 2.20\ \text{g/cm}^3$

  $\rho_{\text{film}} = 2.47\ \text{g/cm}^3$



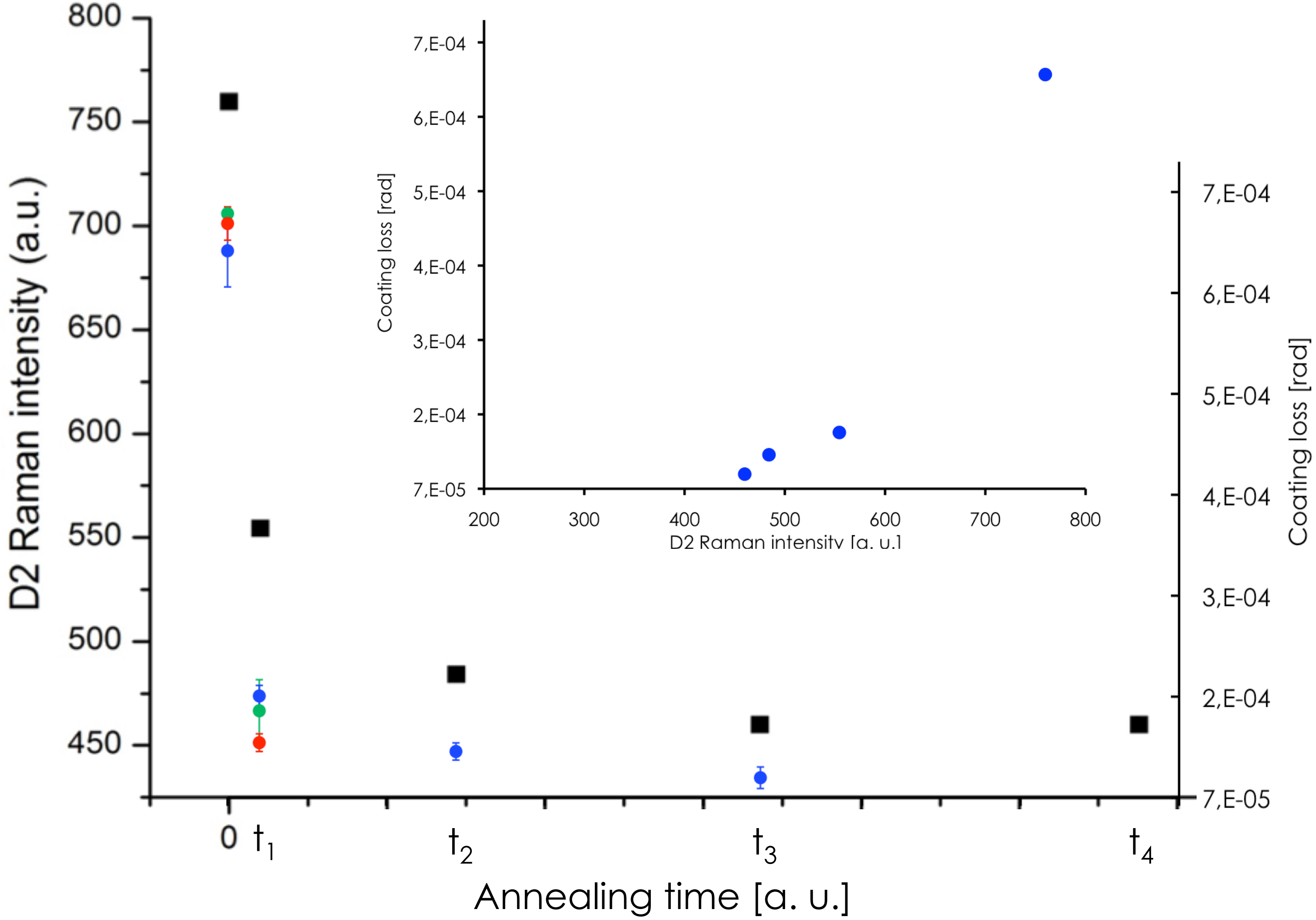
annealing





- remarkable differences wrt to cumulated annealing time
  - evolution of the R-band → different θ distribution
  - clear reduction of D2 peak

SiO2 structure and loss



- loss measured on 3 cantilever blades
- close correlation between D2 spectral evolution and loss

next steps

- Raman spectroscopy used to investigate Ta_2O_5 and SiO_2 coatings
  - ➢ no clear outcome from Ta_2O_5 → new set of samples
  - ✓ first observation of structure/loss correlation in SiO_2

    → repeat with advanced-detector SiO_2

conclusions

conclusions

• mode-dependent thermoelastic damping observed on Si disks

→ new model under developement

relevant for other planar structures (ribbons and blades)

• simple out-of-resonance measurement of thermal noise is now possible

→ optical mono-layer coatings characterized

→ first results from high-reflectivity coatings (stacks)

excess mechanical loss observed, study ongoing

→ additional cryogenic setup being assembled for R&D

• Raman spectroscopy used to investigate coating structure

→ measured SiO2 relaxation wrt annealing time

→ first observation of SiO2 structure/loss correlation