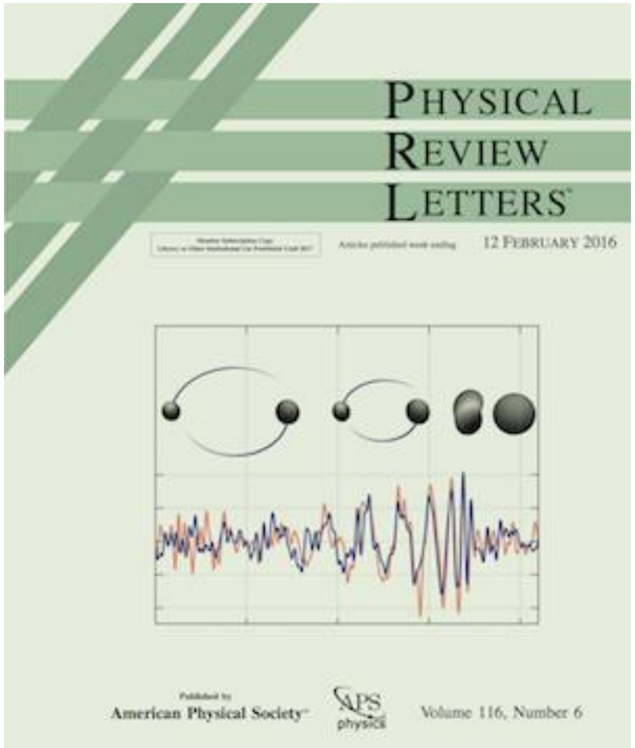
i-CoRe

(**i**nnovative **Co**ating **Re**search)

Innocenzo M. Pinto

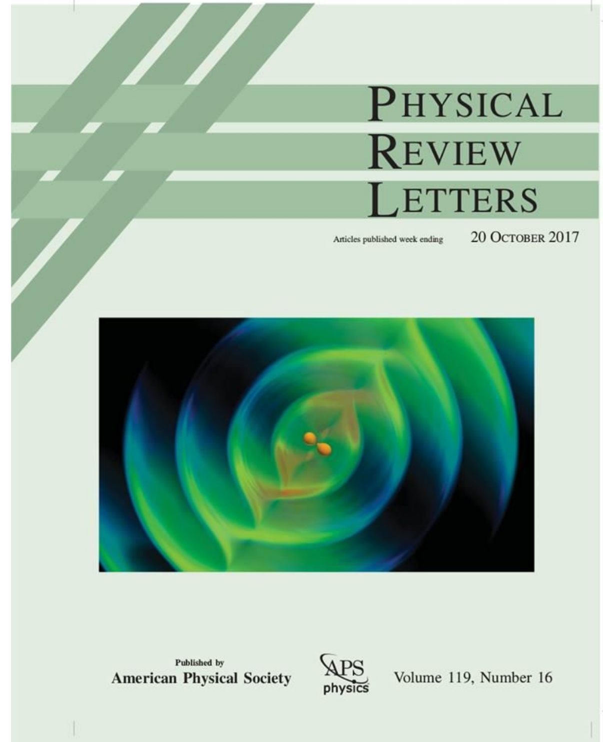
New Eyes / Ears !

GW150914 (2015)



birth of Gravitational Wave Astronomy

GW170817 (2017)

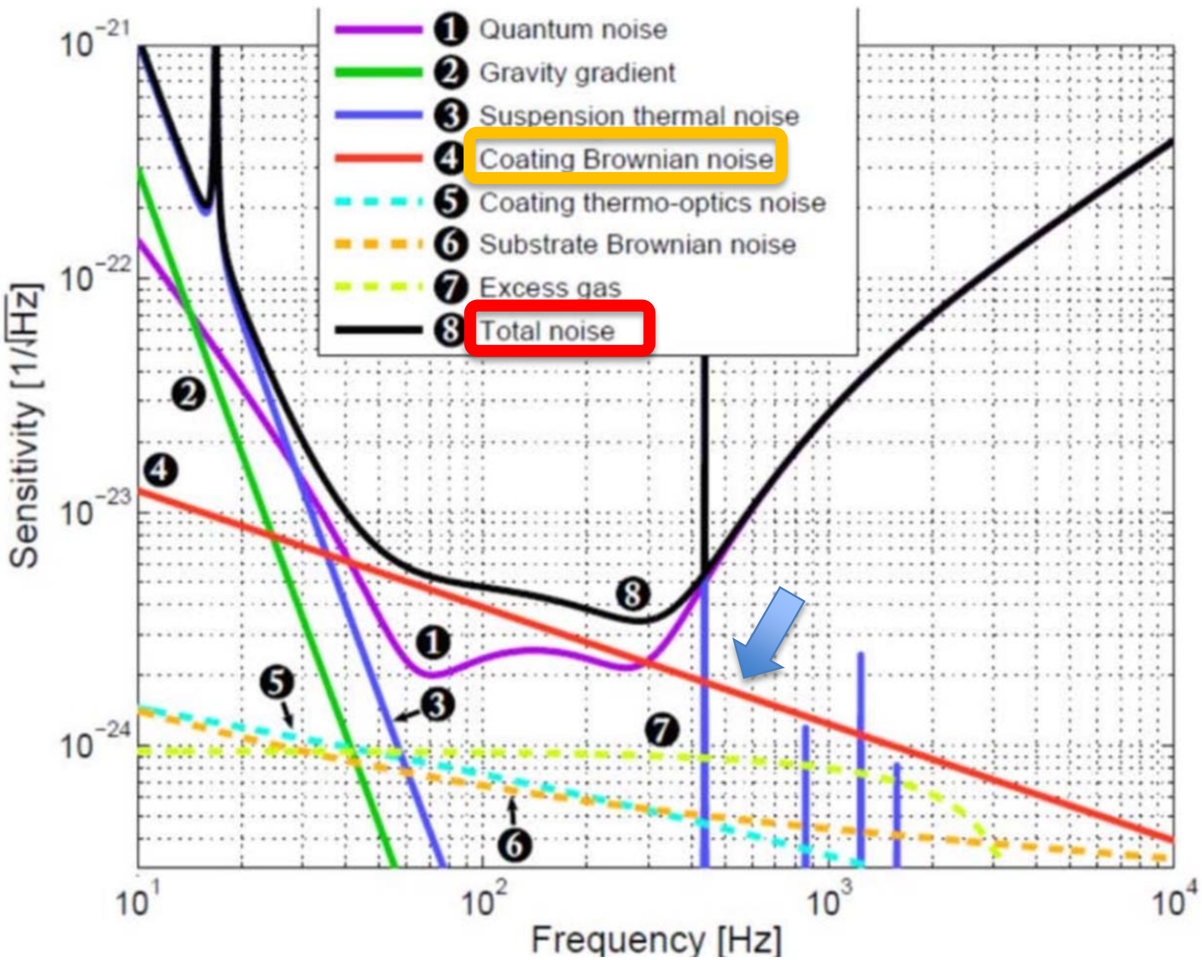


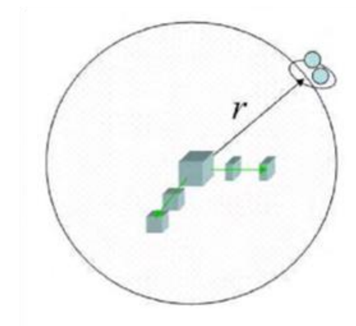
birth of multi-messenger Astronomy

Visibility distance (aLIGO, 2017) : 130Mpc gor BNS coalescence

i-CoRe – Science Case

Advanced Virgo Noise Budget





Visibility volume & event rate $\} \propto PSD_{floor}^{-3/2}$

… a 5μ thick film sets the sensitivity of a 5 Km scale instrument ! …

Coating (Brownian) Noise

HR coatings consist of cascaded doublets of high/low index material. Each doublet is $\lambda/2$ thick (Bragg) ; the *total number of doublets depends on the prescribed transmittance and the optical contrast*...

$$S^{(B)}_{coat}(f) = \frac{2k_B T}{\sqrt{\pi^3} f}\,\frac{1-\sigma^2}{w_m Y}\,\phi_c$$

Temperature

Coating loss angle (mechanical, F/D theorem)

Beam spot-size

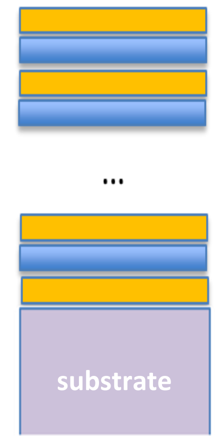
Act on the thicknesses

Act on the materials

$$\phi_c = \frac{\lambda_0}{w\sqrt{\pi}}\left(\eta_L d_L + \eta_H d_H\right), \qquad \eta_{L,H} = \frac{\phi_{L,H}}{n_{L,H}}\left(\frac{Y_{L,H}}{Y_s} + \frac{Y_s}{Y_{L,H}}\right)$$

total *(H,L)*-index material thickness, in units of local wavelength

L,H material noisyness per unit thickness



2nd Generation Coatings (aLIGO, AdvVirgo 2018)

Material downselection

SiO_2 and Ta_2O_5::Ti where chosen as coating materials after extensive trial and error experiments …

500nm thick films

	Refraction index	Absorption (ppm)	Mechanical losses
Ta_2O_5	2.035	1.22	$3 \cdot 10^{-4}$
Ta_2O_5 : Co	2.11	5000	$11 \cdot 10^{-4}$
Ta_2O_5 : W	2.07	2.45	$7.5 \cdot 10^{-4}$
Ta_2O_5 : W+Ti	2.06	1.65	$3.3 \cdot 10^{-4}$
Ta_2O_5 : Ti	2.07	0.5	$2.4 \cdot 10^{-4}$

Coating	Refraction index	Absorption (ppm)	Mechanical losses
ZrO_2	2.10	11	$2.3 \cdot 10^{-4}$
ZrO_2 : Ti	2.15	37	$6.8 \cdot 10^{-4}$
ZrO_2 : W	2.12	10	$2.8 \cdot 10^{-4}$

…

[Flaminio et al., CQG 27 (2010) 84030]

2^{nd} Generation Coatings (aLIGO, AdvVirgo 2018)

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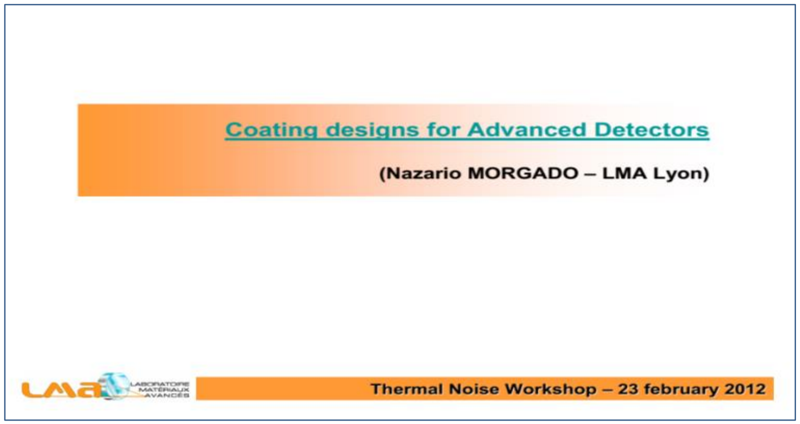
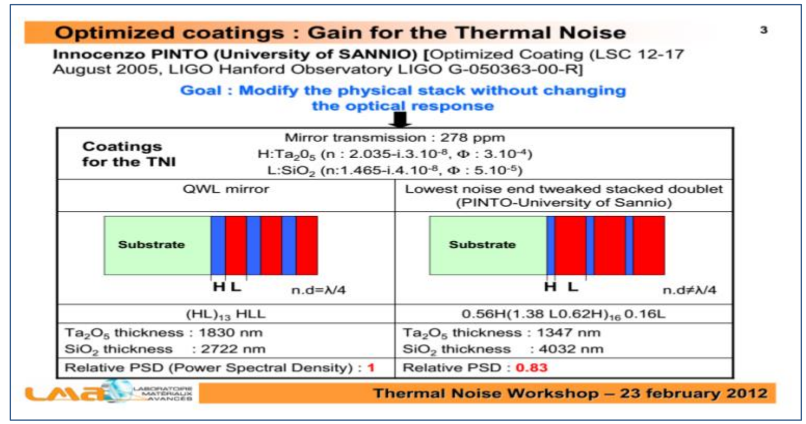
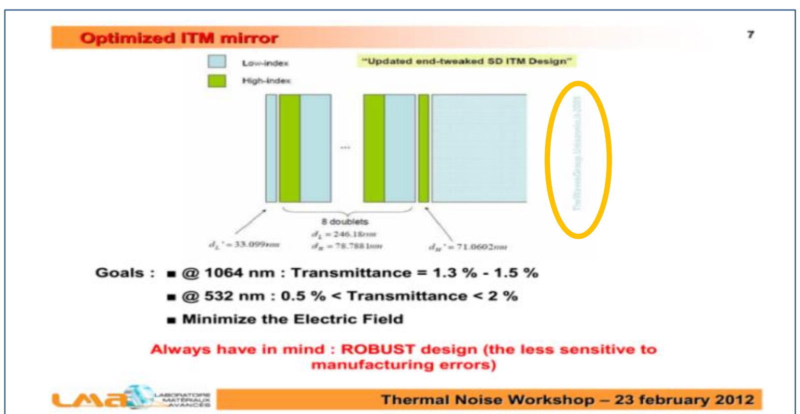
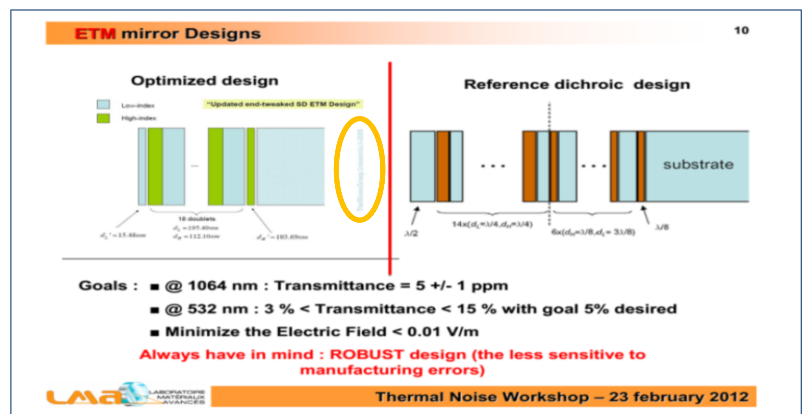
Multilayer Optimization

(I.M. Pinto, M. Principe, R. DeSalvo, Ch. 12 in, *"Optical Coatings and Thermal Noise in Precision Measurements,"* Cambridge Un Press, 2012)









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i-CoRe – Global R&D Scenario (2018)

GOALS

- "Better" materials (2) : ***high contrast, low optical absorption, low mechanical losses***
- **Cryo – compatibility (→ Einstein Telescope; KAGRA)**
- **"Easy" technology, scalable**

R&D LINES (see I. Pinto, LIGO-G1700171)

- **Microscopic/molecular modeling** (dangling bonds, TLS models - *UFL, Stanford, Glasgow*)
- **High-temperature deposition** (enhanced surface mobility, ultrastable glasses - *Stanford*)
- **Ion Plating** (*Glasgow, Jena*)
- **More glassy oxides and glassy oxide mixtures** (*H&WSC, LMA, CSIRO*)
- **Multimaterial (m-ary) coatings** (*Glasgow, MIT*)
- **Nanolayered composite materials** (*USannio, NTHU, UFL*)
- **Crystalline (GaAlAs, GaAlP) materials** (*CMS & LLC, Stanford, Glasgow, LMA*)
- **Silicon Nitrides** (*NTHU, H&WSC, USannio*)
- **Diffractive & Metamaterials** *(Mie, gratings - USannio, Braunschweig)*

FUNDING

US NSF (3M US$, 3 years collaborative plan) - LIGO-LSC

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i-CoRe R&D

GOALS

- "Better" materials (2) : *high contrast, low optical absorption, low mechanical losses*
- Cryo – compatibility (→ Einstein Telescope; KAGRA)
- "Easy" technology, scalable to meter-size mirrors

RESEARCH LINES (as of 2017-2018 – see I. Pinto, LIGO-G1700171)

- Microscopic/molecular modeling (dangling bonds, TLS models - *UFL, Stanford, Glasgow*)
- High-temperature deposition (enhanced surface mobility, ultrastable glasses - *Stanford*)
- Ion Plating (*Glasgow, Jena*)
- More glassy oxides and glassy oxide mixtures (*H&WSC, LMA, CSIRO*)
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FUNDING

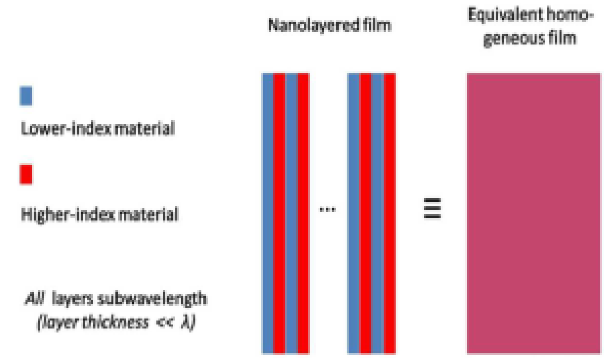
US NSF (3M US$, 3 years collaborative plan) - LIGO-LSC

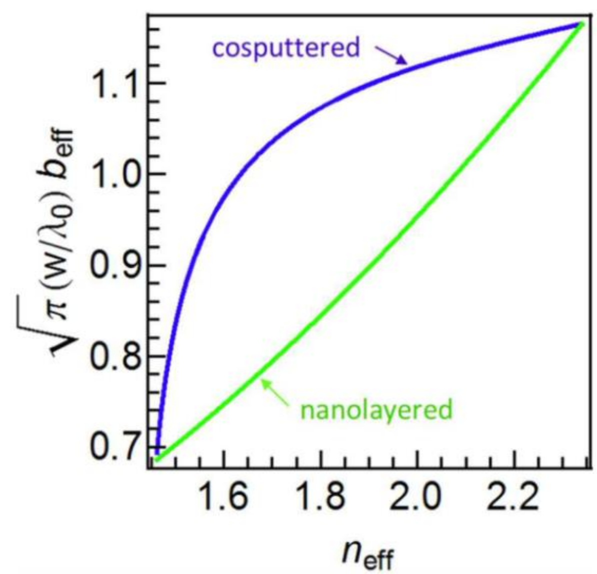
nm-Layered Composites

- Thin layers of a glass-former (e.g. Silica) alternated to a crystallization-prone material (e.g., Titania) hinder crystallite formation during the annealing phase, that spoils mechanical and optical losses

  [Sankur et al., J Appl Phys 66, 4747 (1989);
  Pan, Principe et al., Opt. Expr. 22, 29857 (2014)]

- Amenable to simple modeling (*effective medium theory*) ➡ easily engineerable;
  [Principe, Opt; Expr. 23, 10938 (2015)]
- Less noisy than amorphous mixtures w. the same (effective) refrative index
  [Principe, Opt. Expr. 23, 10938 (2015)]





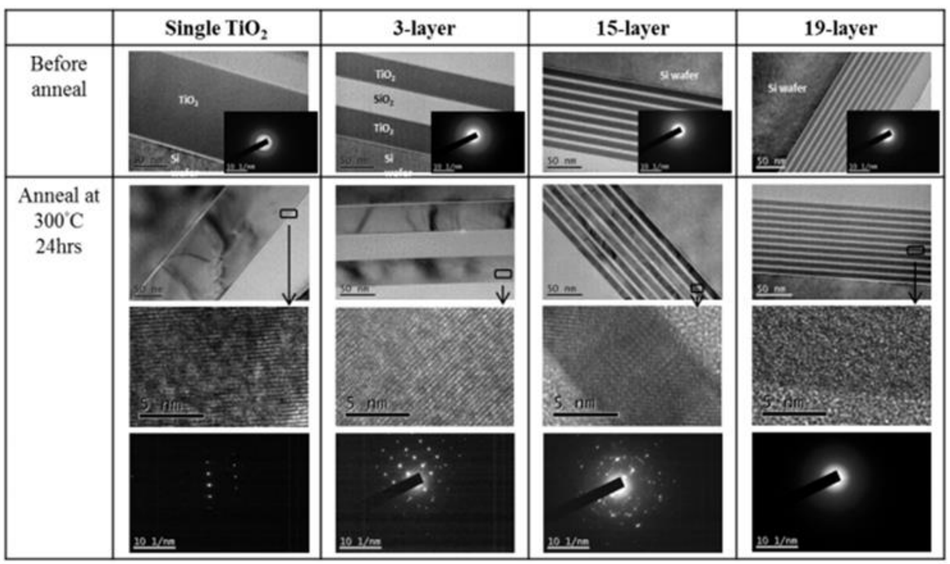
Hindering Crystalization

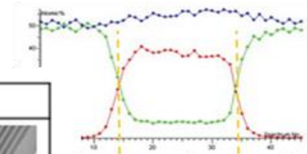
All nanolayered composite prototype films :
$n_{eff} = 2.065$, QWL thick @1064nm

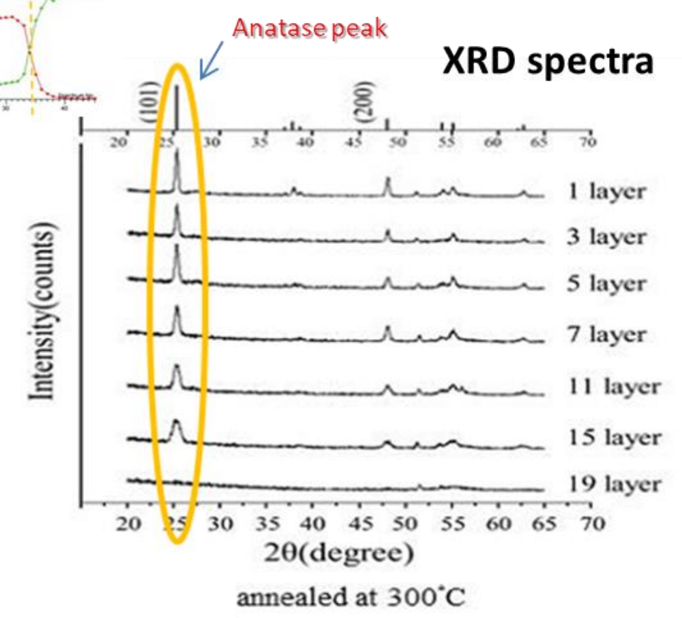
EDXRD investigation of interfacial diffusion before/after annealing (negligible)

(S. Chao, I. Pinto et al., Opt. Expr. **22** (2014) 29847)

TEM & electron diffraction







- **Glass-former (silica, alumina) nanolayers inhibit crystallite growth upon annealing;**
- **Allows using cryofriendly materials, like Titania or Hafnia, that otherwise crystallize;**
- **The nanolayered composites exhibit very low mechanical losses, and no cryopeak**

i-CoRe - People

Coordinator: *Innocenzo M Pinto (CF associate, LVC PI)*

OSA Fellow (2017) "For fundamental contribution to the thermal noise reduction in the mirror coatings of the LIGO interferometric gravitational wave detectors and for diverse contributions to the science of Electromagnetics."

Participants (CF related):

Elisabetta Cesarini (CF postdoc fellow 2017)
Maria Principe (CF associate - postdoc at UniSA; former Fulbright Scholar)

Places of Work & Collaborations:

Virgo:

- University of Sannio *(Coating Deposition Laboratory, M. Principe, I. Pinto, J. Neilson)*
- University of Salerno *(AFM, SFM, TEM, STM, XRD – F. Bobba, C. DiGiorgio, R. Fittipaldi)*
- University of Rome "Tor Vergata" *(GeNS System – M. Lorenzini, E. Cesarini, D. Lumaca)*
- University of Genoa *(Ellipsometric characterization – M. Canepa)*
- University of Perugia *(cryo-GeNS 'H. Vocca, F. Travasso)*

LMA – CNRS [Lyon, FR] *(IBS deposition and testing; glassy oxide mixture; film metrology)*

CNR IMM [Na-Le] *(Ellipsometry; MM; SiN_xH_y PECVD – F. Quaranta, E. De Tommasi)*

National Tsing-Hua University (NTHU) Optics and Photonics Lab [Taiwan]
(IBS nanofilms; PECVD - SiN_xH_y; cryo characterization - S. Chao)

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i-CoRe Activity 2016-2017

- **New coating prototyping facility (IAD) set up at USannio**
  (OAC75-F custom configured; 700KEUR funding from "Regione Campania" - POR 2007-2013; delivered 2016; fully operational 2017)

- **New Salerno/Benevento Virgo group established (formerly in LIGO); collabs wih other Virgo coating R&D groups fostered**
  (MOU with Virgo approved ; INFN funding approved)

- **Work on mechanical (loss) characterization of of nm-layered Silica/Titania films based on GeNS** *(Rome-TV ; published, Int. J. Chem. Mol. Eng. 10 (2016) 1)*

- **Work on optical (ellipsometric) characterization of nm-layered Silica/Titania films** *(Genoa; published, Opt. Materials 75 (2018) 94101)*

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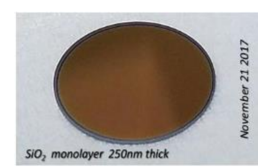
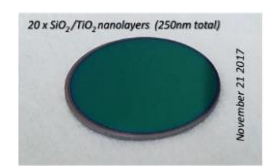
i-CORE Activity 2016-2017

New Coating Deposition facility @ USannio

(Optotech OAC75-F custom configured; 700KEUR funding from "Regione Campania" - POR 2007-2013; delivered 2016; fully operational 2017)

- High vacuum chamber (cryo + rotative pumps)
- 1 EB-gun with 6 pockets (a second source will be installed)
- Plasma source (IAD)
- Argon and Oxygen in chamber feeds
- Fully controllable from GUI
- Rotating substrate support to ehnance uniformity
- Ceramic lamps to heat the substrate





(courtesy Maria Principe, Josh Neilson)

i-CoRe Activities 2016-2017

GeNS Facility @ Rome "Tor Vergata"

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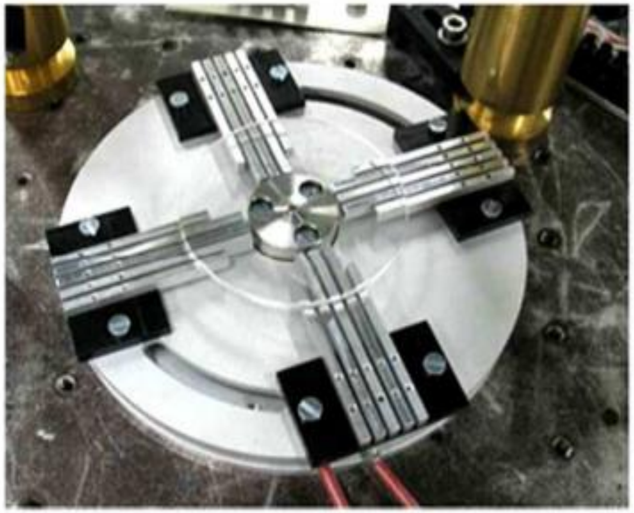
(courtesy Viviana Fafone, Elisabetta Cesarini)

The Gentle nodal Suspension (GeNS) is to date the most reliable mechanical loss estimation setup based on ringdown measurement.

Several improvements compared to clamped cantilever systems;

Designed to be exempt from re-clamping issues, yields nicely repeatable results.

Multimode operation should allow measurement of bulk/shear loss angles (TBD).



GeNS facilities (2018)

- LMA (G. Cagnoli)
- Rome-TV (E. Cesarini)
- Caltech (G. Vajente)
- Perugia (cryo, H. Vocca)

[Cesarini et al., Rev. Sci. Instrum. 80 (2009) 053904.]

i-CORE Activities 2016-2017

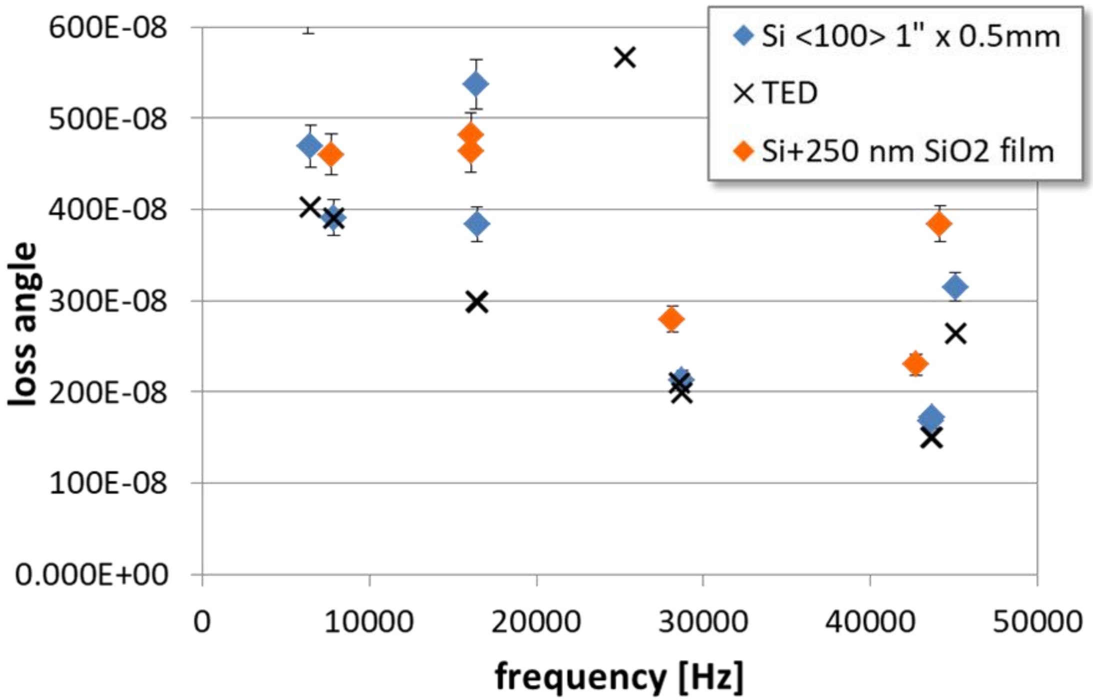
Loss angle Measurements using GeNS

Film deposited @ USannio

Y_{Si}	Y_{SiO2}
1,60E+10	7,3E+10
t_{Si}	t_{SiO2}
5,00E-04	2,50E-07

$$\varphi_{film} = \frac{Y_{Si} t_{Si}}{3 Y_{SiO_2} t_{SiO_2}} \cdot \Delta\varphi$$

(courtesy Elisabetta Cesarini, Daria Lumaca)



$\phi_{film} = (1.02 \pm 0.10) \cdot 10^{-4}$ (as deposited)

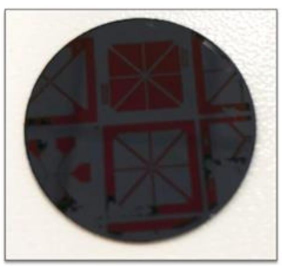
i-CORE Activities 2016-2017

Prototype Morphology @ UniSA

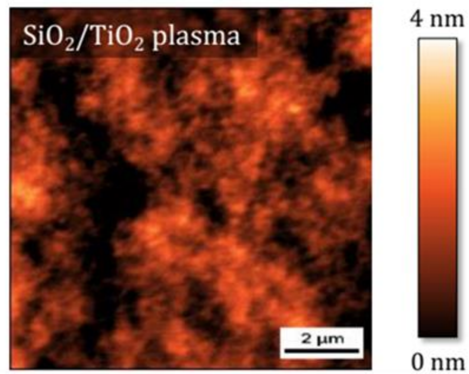
(courtesy Cinzia DiGiorgio, Giovanni Carapella)

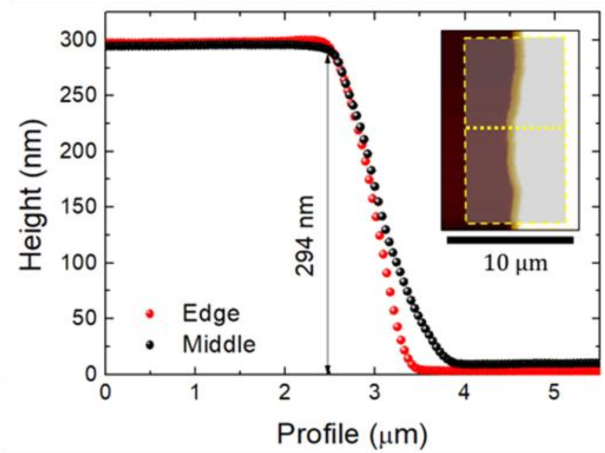
USannio deposited nm-layered SiO_2/TiO_2 Film (19nanolayers)

After selective etching

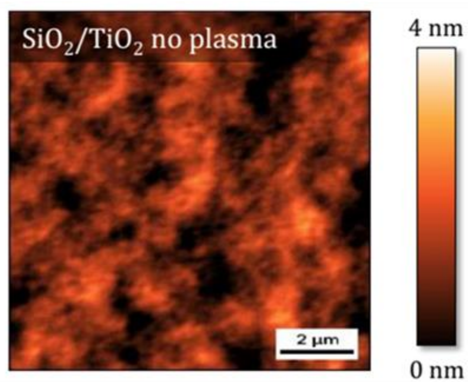


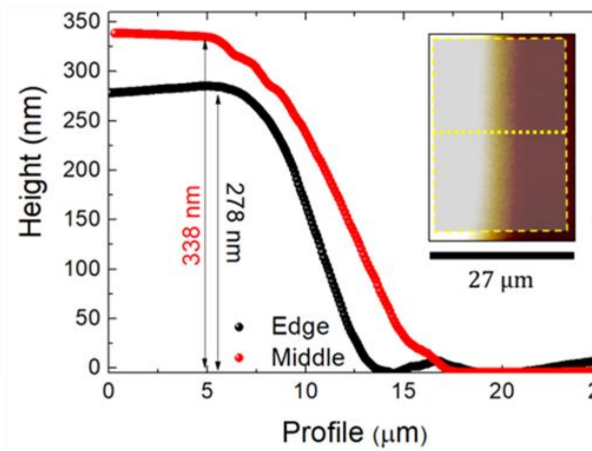
With IAD:





Without IAD:





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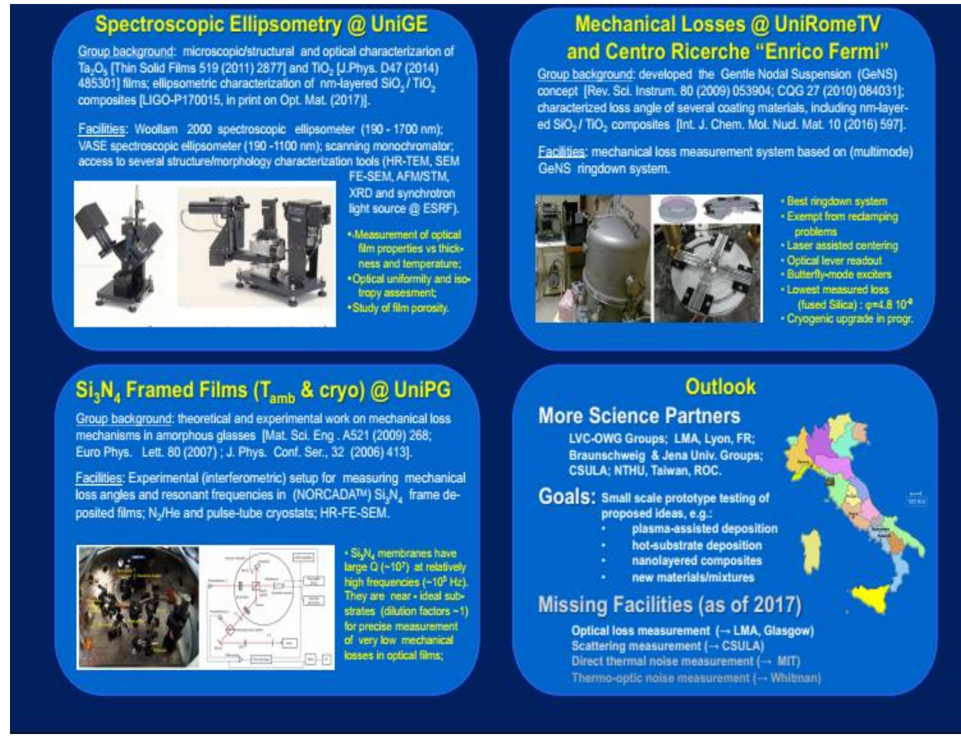
i-CORE Activities 2016-2017

Creating a “distributed” Coating Lab in Italy



Ligo-Virgo Collaboration Meeting (2017)

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i-CoRe – Planned Work (2018-2020)

Milestones 2018

-Steady operation of our deposition and characterization chains
-Characterization of IAD nm-layered SiO_2/TiO_2 film prototypes
-Formulation of process/design optimization criteria

Plan of activities 2018 - 2020

Deposition (IAD) & Characterization of nm-layered SiO_2/TiO_2 composites
(morphological, optical, viscoelastic properties, down to T=10K)

Optimization of nm-layered composites *design*
(optimum thickness and number of nanolayers for fixed n and d/λ)

Optimization of *deposition & annealing parameters/schedule*
(IAD tuning; substrate temperature; annealing protocol and T_{max})

SiN_x development
(comparison with optimized doped [LMA] and nanolayered composites)

Preliminary study/prototyping of Mie Metalayers

New measurement facilities in Italy (CTN, PCI) ?

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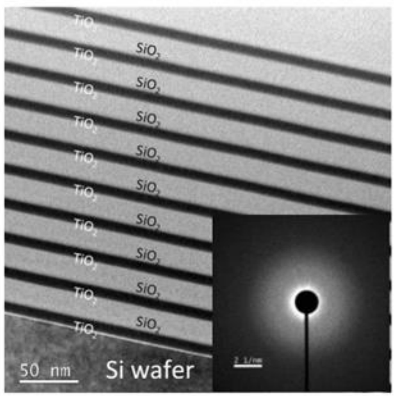
i-CoRe Activity Plan (2018-2020)
Preliminary (new) results

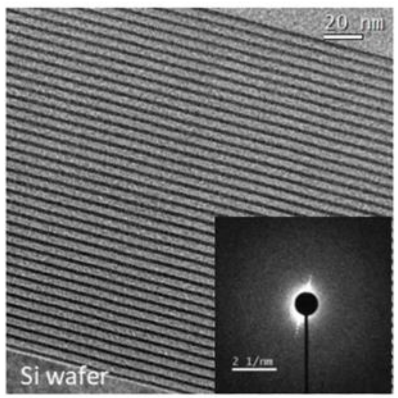
2nd generation nm-layered Silica/Titania composites (collab. w. NTHU)

(2014)
19-layers



	thickness (nm)
SiO_2	19.3 ± 0.1 (x9)
TiO_2	8.3 ± 0.2 (x10)
$r = 0.32$	

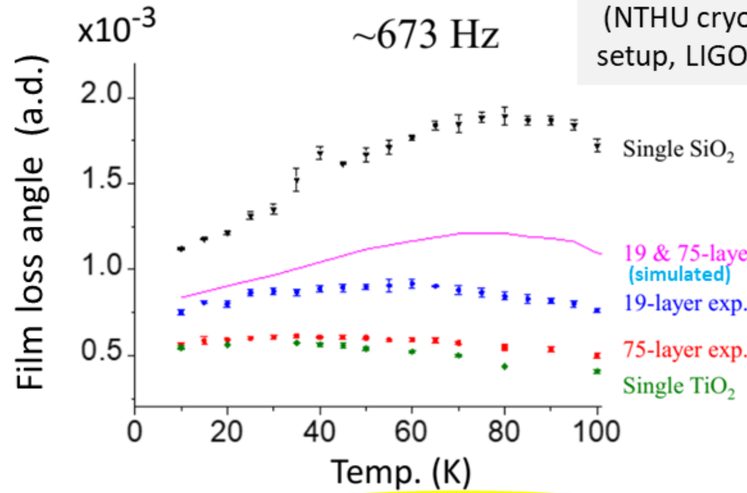
(2018)
75-layers



	thickness (nm)
SiO_2	3.6 ± 0.1 (x37)
TiO_2	1.8 ± 0.1 (x38)
$r = 0.33$	

Both films QWL, with n=2.16

(NTHU cryo-cantilever setup, LIGO-G1501048)

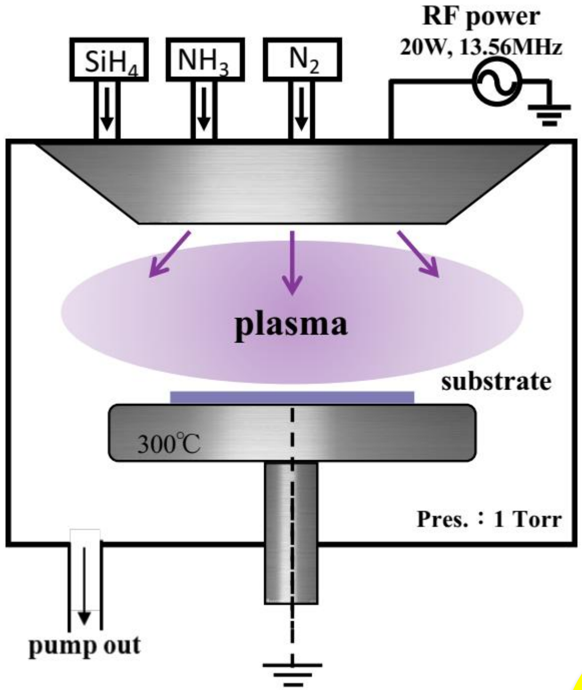


… as nanolayers become thinner and thinner:
1. losses *decrease*;
2. loss peak *shifts to lower temperature*

(courtesy S. Chao, feb. 2018)

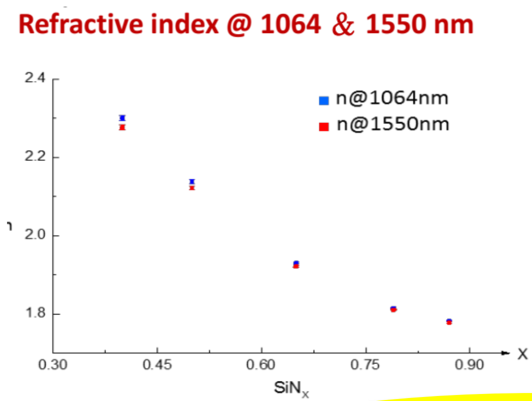
i-CoRe Activity Plan (2018-2020)
Preliminary (new) results

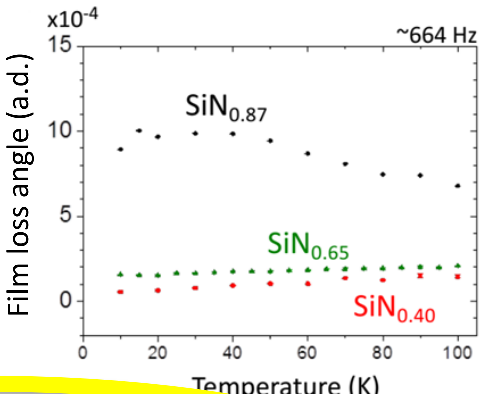
PECVD Silicon Nitrides (SiN_xH_y) films - collab. w. NTHU



S. Chao et al., LIGO-G1701790

Different reactant pressures yield *different stoichimetries*





PECVD Silicon Nitrides:

- **flexible stoichiometry -> index tunability**
- **mechanical losses on a par with SiO_2**
- **no cryo peak (for several x)**
- ***scalability* poses no problem**

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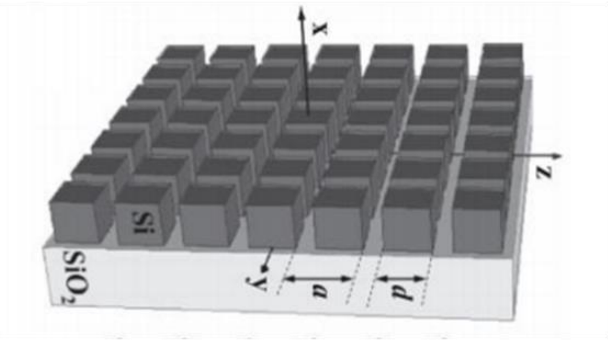
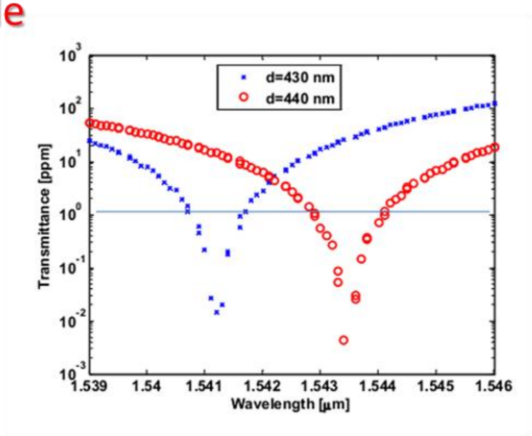
i-CoRe Activity Plan (2018-2020)
Preliminary (new) results

Mie Metalayers (collab. w. Braunschweig Univ)

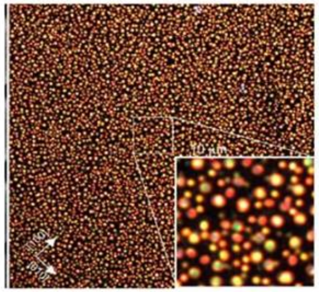
Very thin, monolayer, fully scalable





Trade reflectance (exceeding our needs) for band-width (insufficient for our needs).

Introduce randomness (or multiple periodicity) in the Mie inclusion pattern …



Use colloidal self assembly ?

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i-CoRe - Fundings

Expected fundings (2018-2020) :

- ***Funding from Centro Fermi*: 1 postdoc grant (renewal)**

- ***External funding* : INFN Virgo (2017 given; 2018-2020 expected)**

- ***Potential external funding* : MIUR-PRIN 2017 (South Line) € 1M**

"Toward the Next Generation of Optical Coatings for Advanced Virgo: Consolidating a Distributed Research Laboratory Network in South Italy"

Participating Institutions: University of Sannio at Benevento
University of Salerno
CNR-IMM (Naples and Lecce)

Partners: Virgo (Genoa, Rome-TV, Perugia)
LMA-CNRS (Lyon, FR)
Centro Fermi
University Braunschweig (GER)
NTHU (Taiwan, ROC)