Reducing Thermal Noise in Advanced GW Detector Mirror Coatings

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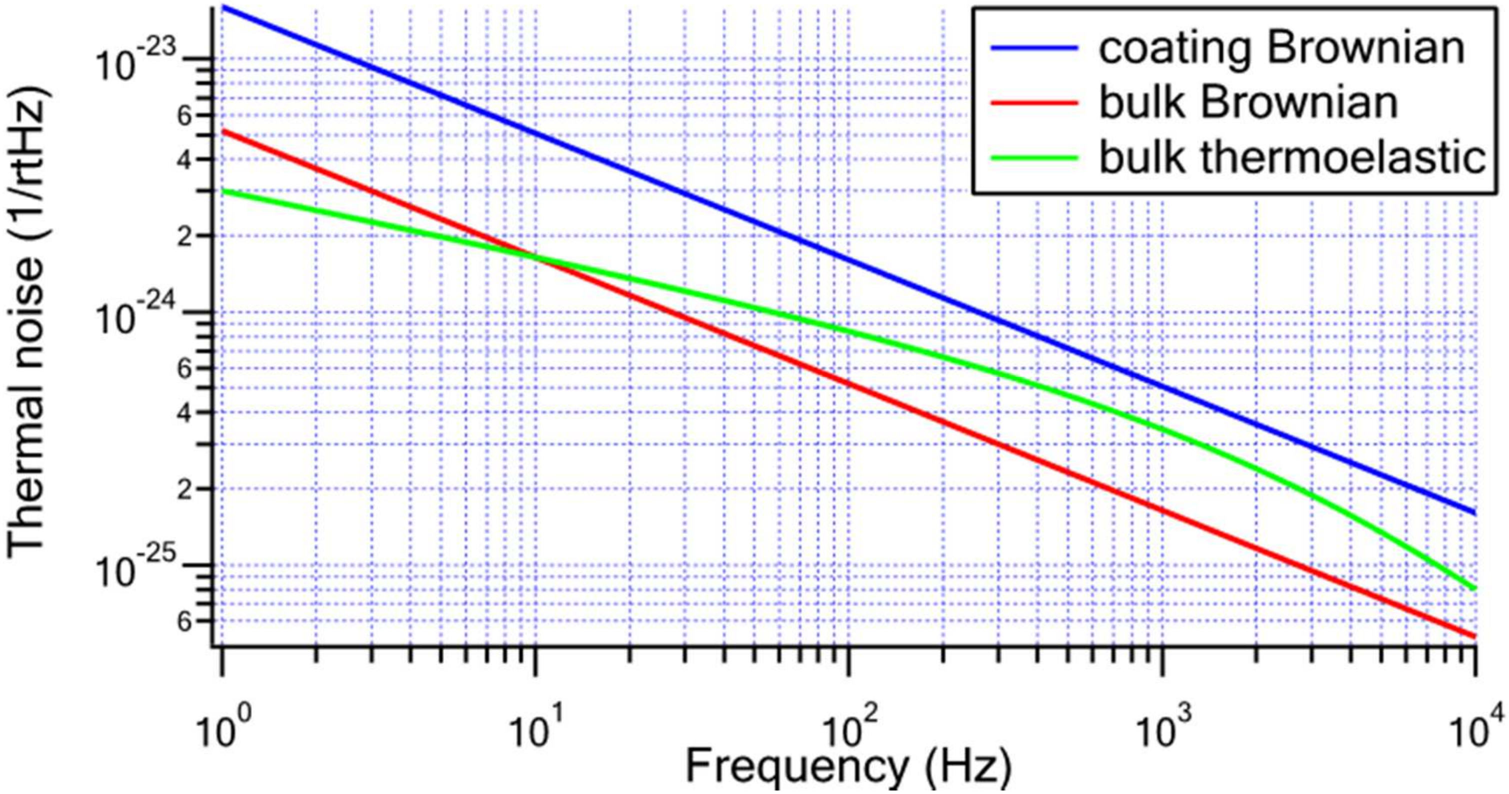
Vincenzo Pierro
Maria Principe

JGW – G12024

Outlook

- b-KAGRA mirror noise budget
  - Reducing coating noise
- Optimizing coating materials
  - Modeling glassy mixtures
- nm-layered SiO2//TiO2 composites
- Optimizing coating geometry
  - Minimum noise dichroic coating

b-KAGRA Mirror Noise Budget



[Courtesy Kentaro Soumiya]

Substrate Thermoelastic Noise PSD

$$S_{sub}^{(\mathrm{TE})}(f) = \frac{4\sqrt{2}}{\pi^2}\alpha^2(1+\sigma)^2\frac{k_B T^2 w_m}{\kappa} J(f)$$

$$J(f) = \int_0^\infty du \int_{-\infty}^\infty dv \frac{u^3 \exp(-u^2/2)}{(u^2+v^2)[(u^2+v^2)^2+4\pi^2 f^2]}$$

α = thermoelastic constant
σ = Poisson modulus
κ = thermal conductivity

of substrate; w_m= spot width

Valid beyond Braginsky's "adiabatic" assumption $(\kappa/\varrho C f)^{1/2} < w_m$

[M. Cerdonio et al., Phys. Rev. D 63 (2001) 082003] (**misprint in their eq. 21 fixed**)

Coating Brownian Noise PSD

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

$$\phi_c = \frac{d_1+d_2}{\sqrt{\pi} w_m} \frac{1}{Y_\perp} \left\{ \left[\frac{Y}{1-\sigma^2} - \frac{2\sigma_\perp^2 Y Y_\parallel}{Y_\perp (1-\sigma^2)(1-\sigma_\parallel)} \right] \phi_\perp + \frac{Y_\parallel \sigma_\perp (1-2\sigma)}{(1-\sigma_\parallel)(1-\sigma)} (\phi_\parallel - \phi_\perp) + \frac{Y_\parallel Y_\perp (1+\sigma)(1-2\sigma)^2}{Y(1-\sigma_\parallel^2)(1-\sigma)} \phi_\parallel \right\}$$

$$Y_\perp = \frac{d_1+d_2}{Y_1^{-1} d_1 + Y_2^{-1} d_2} \; ; \; Y_\parallel = \frac{Y_1 d_1 + Y_2 d_2}{d_1+d_2}$$

$$\phi_\perp = Y_\perp \left(\frac{Y_1^{-1}\phi_1 d_1 + Y_2^{-1}\phi_2 d_2}{d_1+d_2} \right) \; ; \phi_\parallel = Y_\parallel^{-1} \left(\frac{Y_1 \phi_1 d_1 + Y_2 \phi_2 d_2}{d_1+d_2} \right)$$

$$\sigma_\perp = \frac{\sigma_1 Y_1 d_1 + \sigma_2 Y_2 d_2}{Y_1 d_1 + Y_2 d_2}$$

$$\frac{\sigma_1 Y_1 d_1}{(1+\sigma_1)(1-2\sigma_1)} + \frac{\sigma_2 Y_2 d_2}{(1+\sigma_2)(1-2\sigma_2)} = -\frac{Y_\parallel (\sigma_\perp^2 Y_\parallel + \sigma_\parallel Y_\perp)(d_1+d_2)}{(\sigma_\parallel + 1)[2\sigma_\perp^2 Y_\parallel - (1-\sigma_\parallel) Y_\perp]} \Longrightarrow \sigma_\parallel$$

$\Downarrow$ all $\sigma \to 0$

$$\phi_c = \frac{d_1+d_2}{\sqrt{\pi} w_m} \left(\frac{Y}{Y_\perp} \phi_\perp + \frac{Y_\parallel}{Y} \phi_\parallel \right)$$

Reducing Coating Brownian Noise

Decrease T (go cyogenic)

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

Reduce ϕ_c

Increase w_m (mesa beams, HGL modes)

Act on the thicknesses

Act on the materials

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

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

- **Optimizing Coating Materials**

Good Coating Materials

Low mechanical loss-angle per unit thickness (η_H)

Depends ***both*** on complex Young modulus $\tilde{Y} = Y(1 - i\phi)$, ***and*** refractive index n_H;

High dielectric contrast (n_H/n_L)

helps ***reducing the number of layers*** (coating thickness) needed for a prescribed coating transmittance;

Low dielectric losses $(Im[n_H])$

increases power-handling capability.

Titania Doped Tantala

To date, most successful attempt to reduce thermal noise by improving material properties is LMA's “ formula 2 ” TiO_2 - doped Ta_2O_5
[G.M. Harry et al, Class. Quantum Grav. 24 (2007) 405].

How to optimize glassy-mixtures ?

- Extensive Experimental Trial-and-Error (LMA, CSIRO);
- Solid State Modeling/Simulation
  - Glasgow (LIGO)
  - Urbino (Virgo)
- Effective Medium (Mixture) Approach. (Sannio)

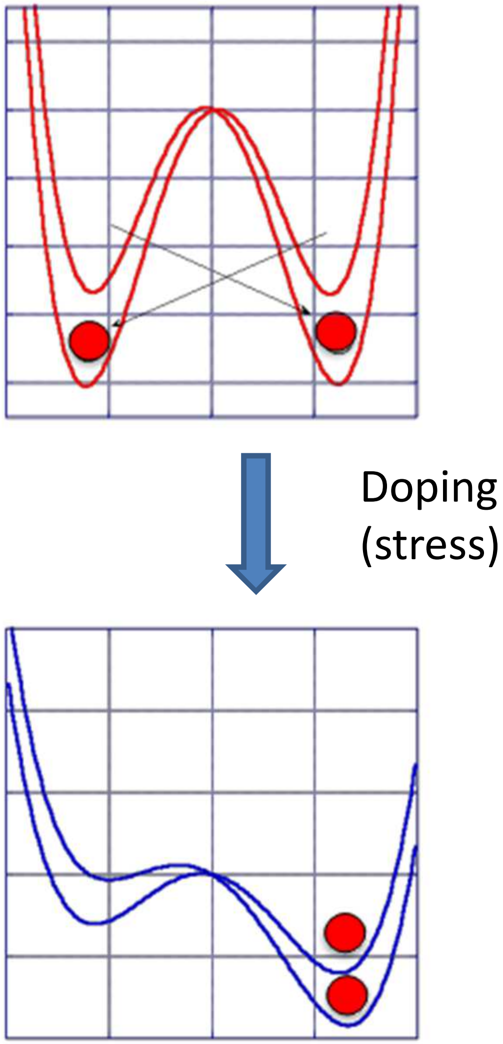
We need reliable values for the material parameters !

Loss Angle Reduction in Doped Glasses

Acoustic oscillations (thermal phonons) in a *symmetric* double-well potential drive well-to-well jumps ➡ dissipation.

Doping (and/or other structural stresses) may destroy the potential symmetry, resulting into *well-trapping* ➡ *reduced* dissipation…

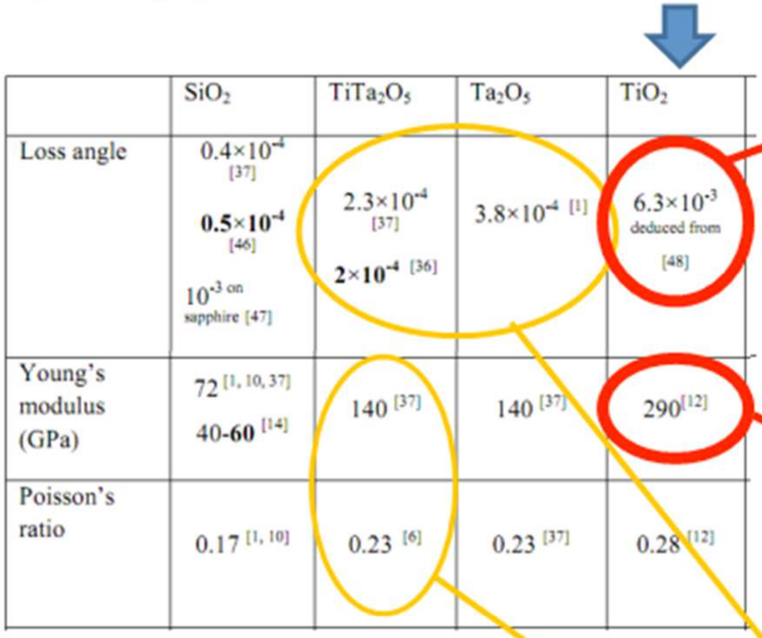
[J.S. Wu and C.C. Yu, “How Stress can Reduce Dissipation in Glasses, ” Phys. Rev. B84 (2011) 174109]



Doping
(stress)

Trustable Numbers Needed

Frequently quoted values must be handled w. care, especially for Titania ...



	SiO_2	$TiTa_2O_5$	Ta_2O_5	TiO_2
Loss angle	0.4×10^{-4} [37] **0.5×10^{-4}** [46] 10^{-3} on sapphire [47]	2.3×10^{-4} [37] **2×10^{-4}** [36]	3.8×10^{-4} [1]	6.3×10^{-3} deduced from [48]
Young's modulus (GPa)	72 [1, 10, 37] 40-60 [14]	140 [37]	140 [37]	290[12]
Poisson's ratio	0.17 [1, 10]	0.23 [6]	0.23 [37]	0.28[12]

J. Franc et al., ET-021-09 (2009).

Values from a *single* experiment: 25-doublets QWL Silica/Titania coating [P. Amico et al., J. Phys. Conf. Ser. 32 (2006) 413]. Thickness of Titania layers was 116nm. Well above limit-thickness for preventing crystallization upon annealing [S. Chao et al., J. Opt. Soc. Am. A16 (1999) 1477]. Reported loss angle most likely due to crystallization.

In the amorphous phase Y_{TiO_2} is 160 - 170 Gpa. [T. Modes et al., Surf. Coat. Technol. 200 (2005) 306]

Quoted Y = 290 Gpa is OK for the *crystalline* (Rutile) phase [O. Zywitzki, et al., Surf. Coat. Technol. 180 (2004) 538].

Large spreads among values obtained from different measurement techniques...

Conjectured values - *No* direct measurements of Y or σ on doped Tantala reported yet.

[I. Pinto et al., LIGO-G1100586]

Material Loss Angles from Coating Noise PSD

Use TNI measurements and results :

Coating	Type	Low Index	High Index	Mftr.	$\phi_c \times 10^4$
1	QWL	Silica	Tantala	REO	8.25 ± 0.3
2	Optimized	Silica	Tantala	LMA	6.85 ± 0.2
3	QWL	Silica	Doped Tantala	LMA	6.0 ± 0.25
4	Dichroic	Silica	Doped Tantala	LMA	5.5 ± 0.5

and G. Harry's mainstream formula for coating noise (vanishing Poisson limit)

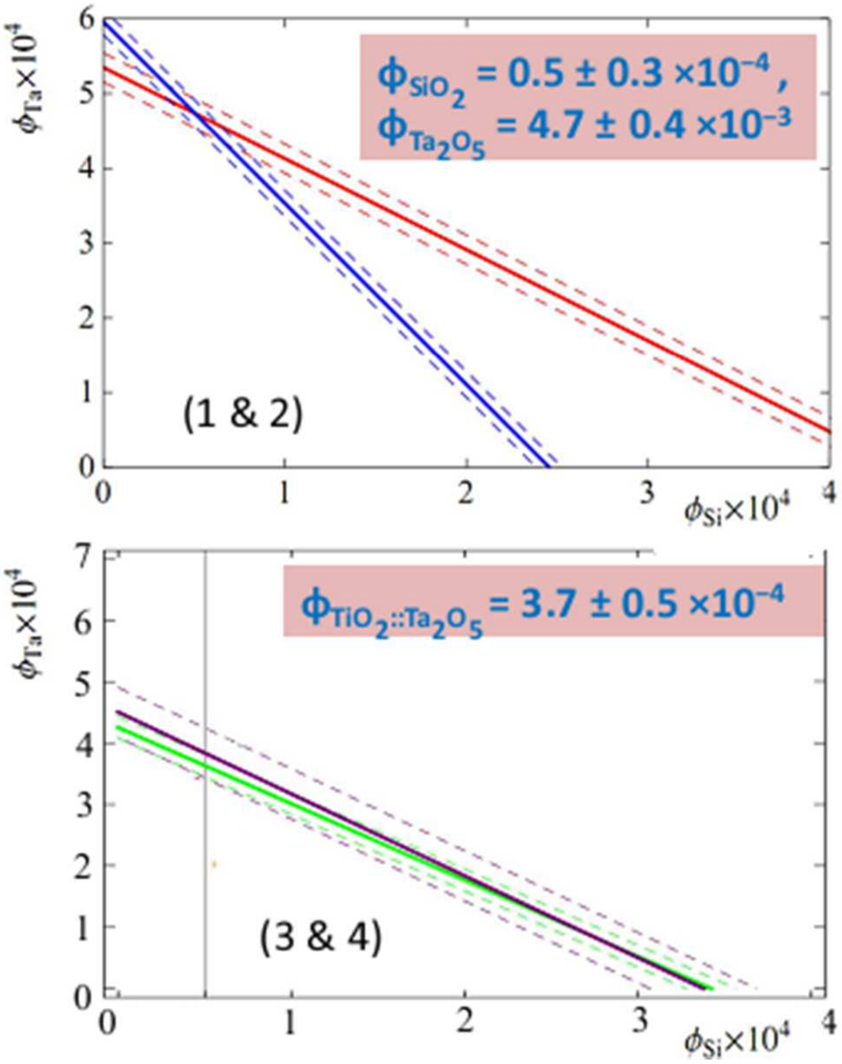
$$\phi_c = b_L d_L \phi_L + b_H d_H \phi_H$$

$$b_{L,H} = (Y_{L,H} / Y_s + Y_s / Y_{L,H}) / (w\sqrt{\pi})$$

to retrieve the loss angles from fiducially known thicknesses etc.

Coating #	d_L	d_H
1	2.72 μm	1.83 μm
2	4.05 μm	1.36 μm
3	2.54 μm	1.67 μm
3	2.36 μm	1.45 μm

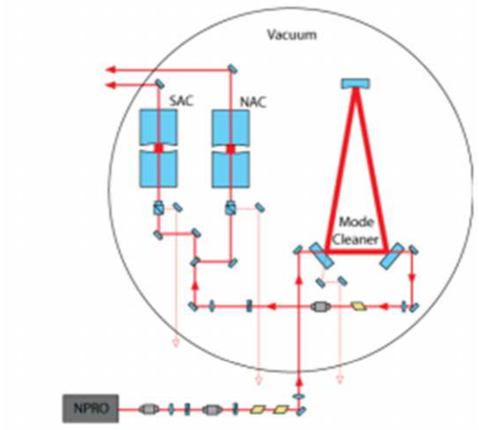
A. Villar et al., LIGO-G1000937 (2010)

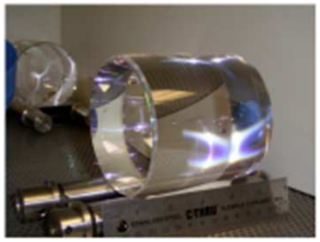


$\phi_{SiO_2} = 0.5 \pm 0.3 \times 10^{-4}$,
$\phi_{Ta_2O_5} = 4.7 \pm 0.4 \times 10^{-3}$

$\phi_{TiO_2::Ta_2O_5} = 3.7 \pm 0.5 \times 10^{-4}$

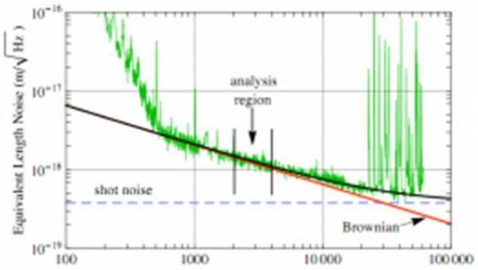
Material Loss Angles from TNI Measurements





Spectrum Analyzer

calibration



fit data to model

[G. Harry et al., CQG 19 (2002) 897]

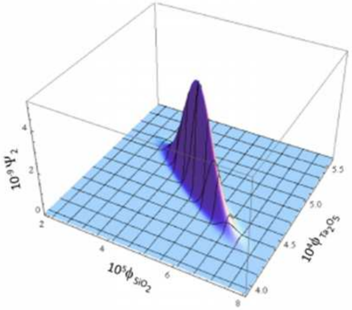
$$S_B(f) = \frac{2k_BT}{\pi^{3/2}f}\frac{(1-\sigma^2)}{wY}\phi_c$$

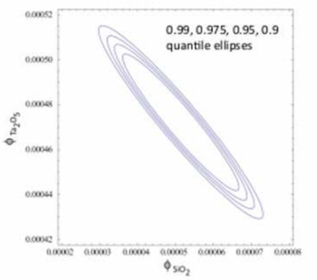
ϕ_c

$$\mathbf{M}\cdot\boxed{\boldsymbol{\phi}} = \mathbf{\Phi_c}$$

Gaussian vector

$$\left\{\begin{array}{l} \mathbf{\Phi_c} = \left\{\Phi_c^{(QWL)}, \Phi_c^{(OPT)}\right\} \\ \boldsymbol{\phi} = \left\{\phi_{SiO_2}, \phi_{Ta_2O_5}\right\} \\ \mathrm{M} = \begin{bmatrix} b_{SiO_2} d_{SiO_2}^{(QWL)} & b_{Ta_2O_5} d_{Ta_2O_5}^{(QWL)} \\ b_{SiO_2} d_{SiO_2}^{(OPT)} & b_{Ta_2O_5} d_{Ta_2O_5}^{(OPT)} \end{bmatrix} \end{array}\right.$$

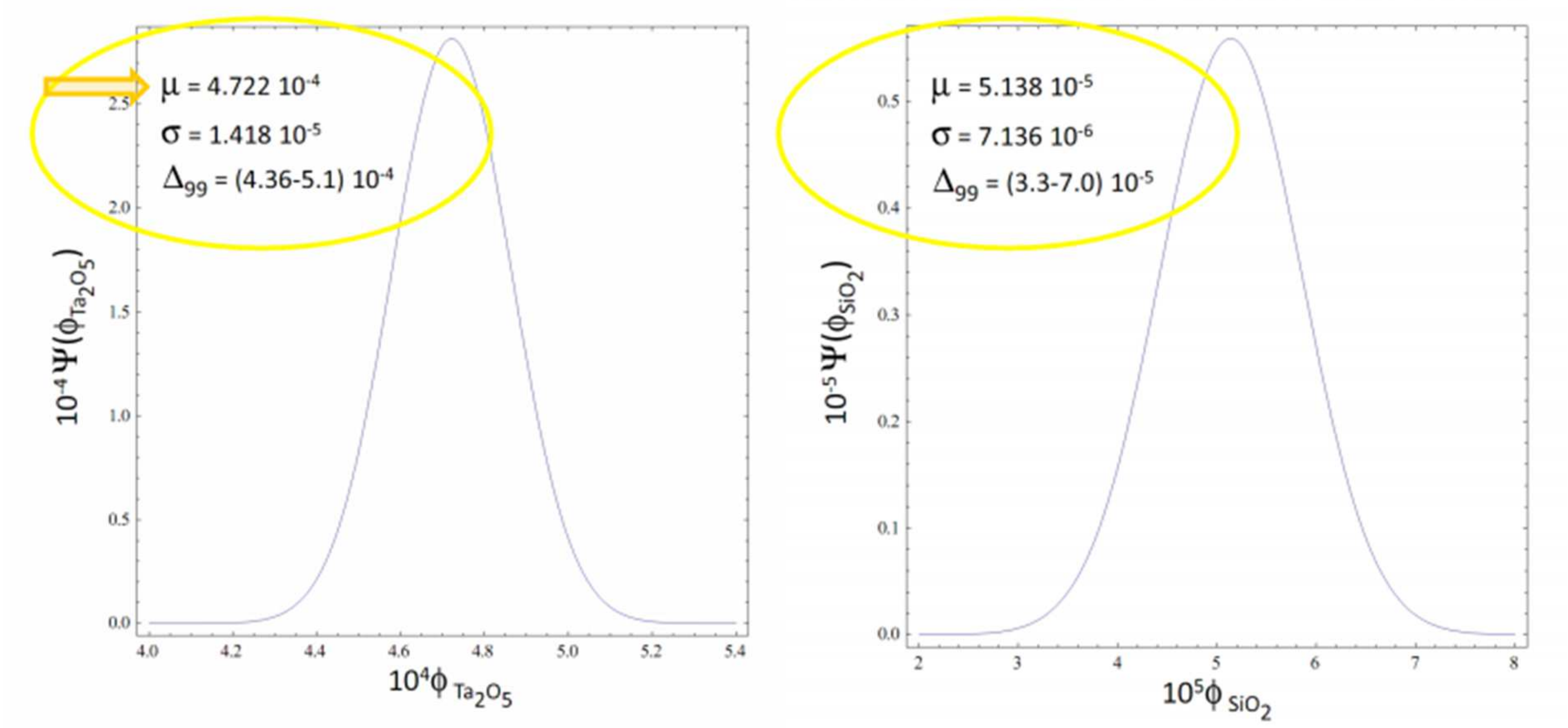




[A. Villar et al., LIGO-G 1101096]

Material Loss Angles from Coating Noise PSD

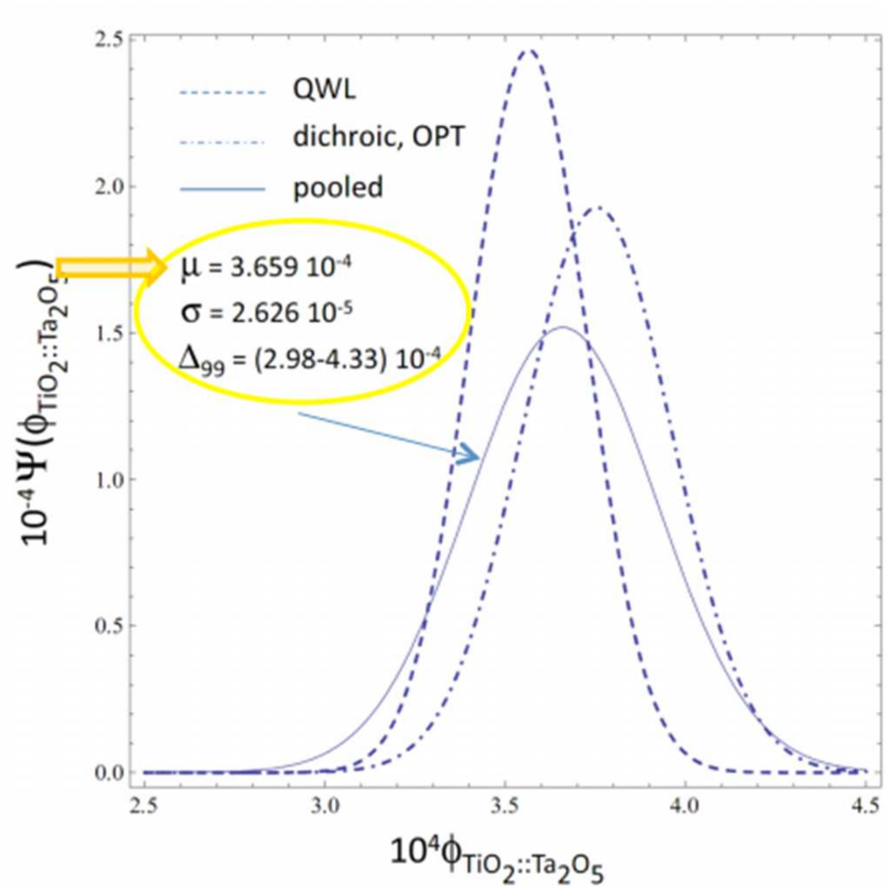
Silica (TiO_2) and plain Tantala (Ta_2O_5)



[A. Villar et al., LIGO-G 1101096]

Loss Angles from Coating Noise PSD, contd.

Doped Tantala ($TiO_2::Ta_2O_5$)



[A. Villar et al., LIGO-G 1101096]

Comparison between TNI and Q-based Material Loss Angle Estimates

Good agreement for Silica;

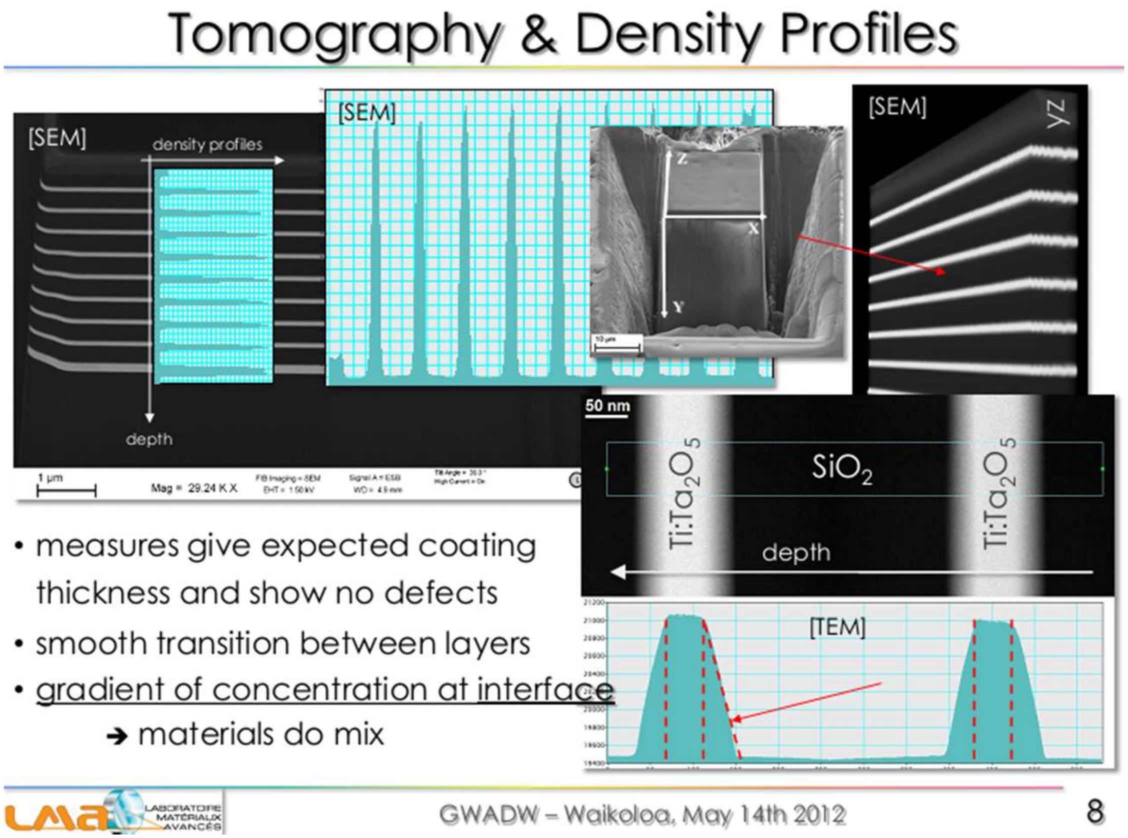
Somewhat larger loss angle for Tantala (plain & doped).

Doped/Undoped loss-angle ratio is the same

Reason of discrepancy yet unclear

[A. Villar et al., LIGO-G 1101096]

Diffusion at Interfaces…


Tomography & Density Profiles

- measures give expected coating thickness and show no defects
- smooth transition between layers
- <u>gradient of concentration at interface</u>

  → materials do mix

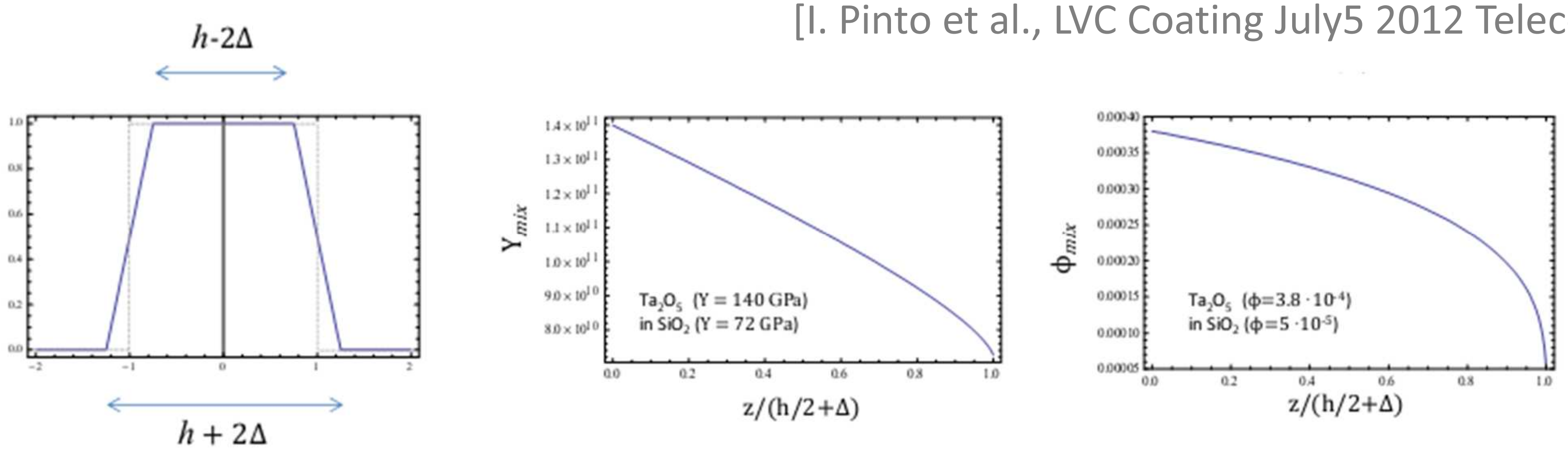
GWADW – Waikoloa, May 14th 2012 8

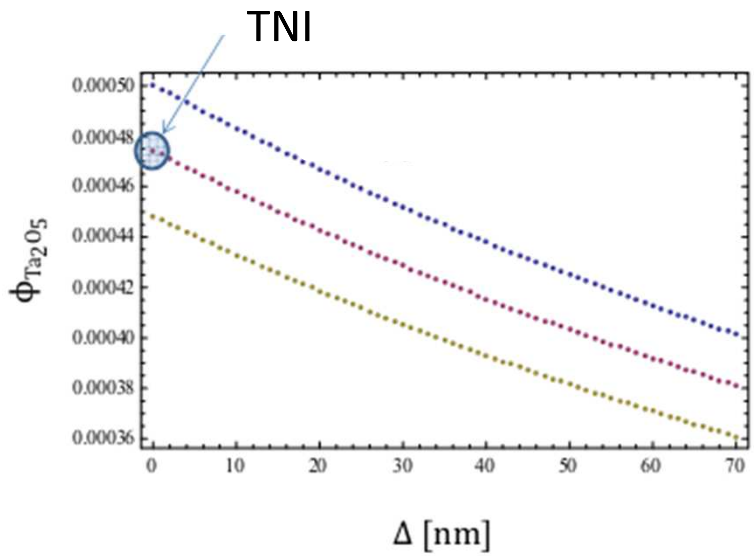
[F. Granata et al. (LMA) , LIGO/G120514]

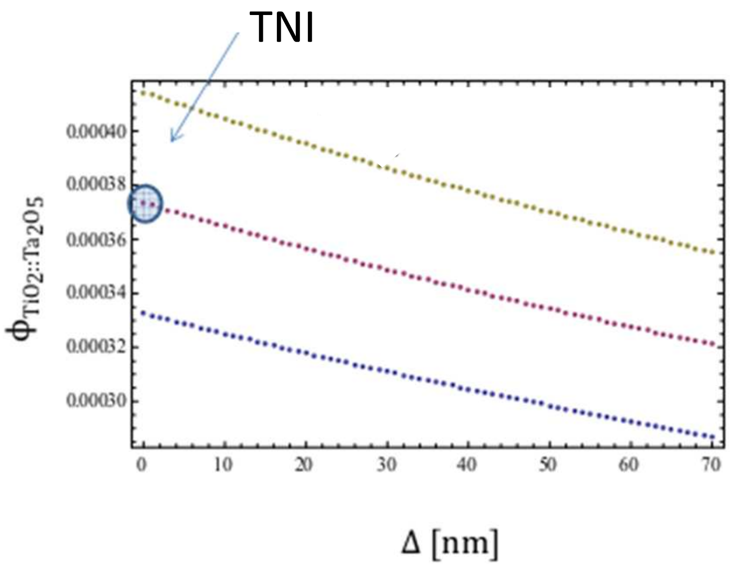
… diffusion length largely annealing-schedule dependent…

… may Explain in part the Discrepancy

[I. Pinto et al., LVC Coating July5 2012 Telecon]

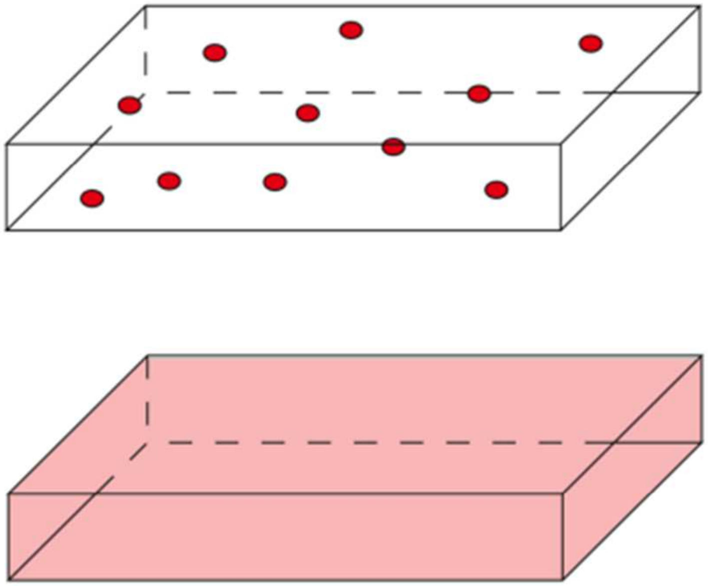






- Simple Mixture Modeling

Simple Mixture Modeling
Effective Medium Theories (EMT)



[A. Villar et al., LIGO-G 1101096]

Composite materials (mixtures) can be modeled by an appropriately-weighted average of macroscopic properties of both components.

Replace actual, “composite” system with a homogeneous, “effective” medium.

Effective for a wide variety of properties

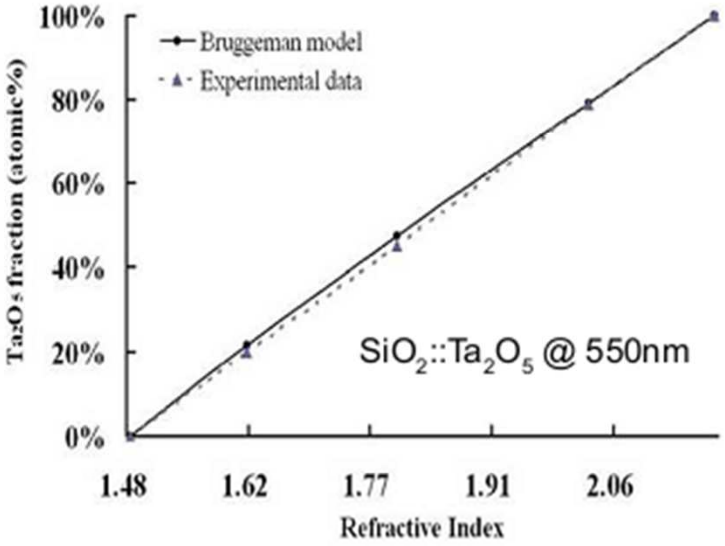
- dielectric constant
- index of refraction
- elastic modulus
- loss angle
- etc.

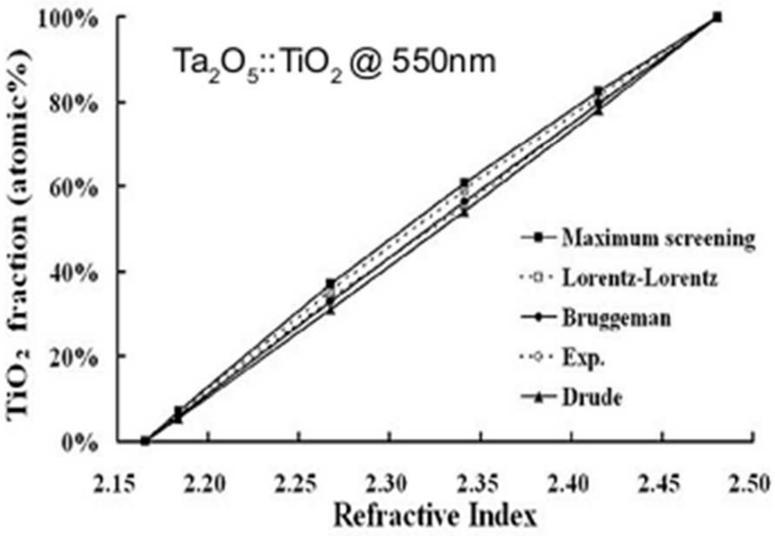
Results depend somewhat on inclusion concentration, morphology, orientation.

EMT for Composite Optical Properties

Bruggemann formula:

$$\eta_2 \frac{\epsilon_2 - \epsilon_{mix}}{\gamma\epsilon_2 + (1-\gamma)\epsilon_{mix}} + (1-\eta_2)\frac{\epsilon_1 - \epsilon_{mix}}{\gamma\epsilon_i + (1-\gamma)\epsilon_{mix}} = 0 \ , \quad \epsilon = n^2$$





Chien-Jen Tang, "Analysis of Ta_2O_5-TiO_2 and Ta_2O_5-SiO_2 Composite Films Prepared by Ion-Beam Sputtering Deposition," PhD Dissertation, Taiwan National Central University (2006).

EMT for Composite Viscoelastic Properties

Barta's microscopic derivation of Bruggemann-like mixture formulas for viscoelastic parameters of a glassy-oxide composite yields

$$\begin{cases} (1-\eta_2)\dfrac{X-X_1}{2X+(X_1/y_1)(\sigma_1+1)}+\eta_2\dfrac{X-X_2}{2X+(X_2/y_2)(\sigma_2+1)}=0 \\ (1-\eta_2)\dfrac{(X/y)-(X_1/y_1)}{2X+(X_1/y_1)(\sigma_1+1)}+\eta_2\dfrac{(X/y)-(X_2/y_2)}{2X+(X_2/y_2)(\sigma_2+1)}=0 \end{cases},$$

$$X=\frac{\sigma Y}{\sigma+1},\ y=\sigma-2$$

System can be solved in closed form . [S. Barta, «Effective Young modulus and Poisson's ratio for the particulate composite," J. Appl. Phys. 75 (1994) 3258].

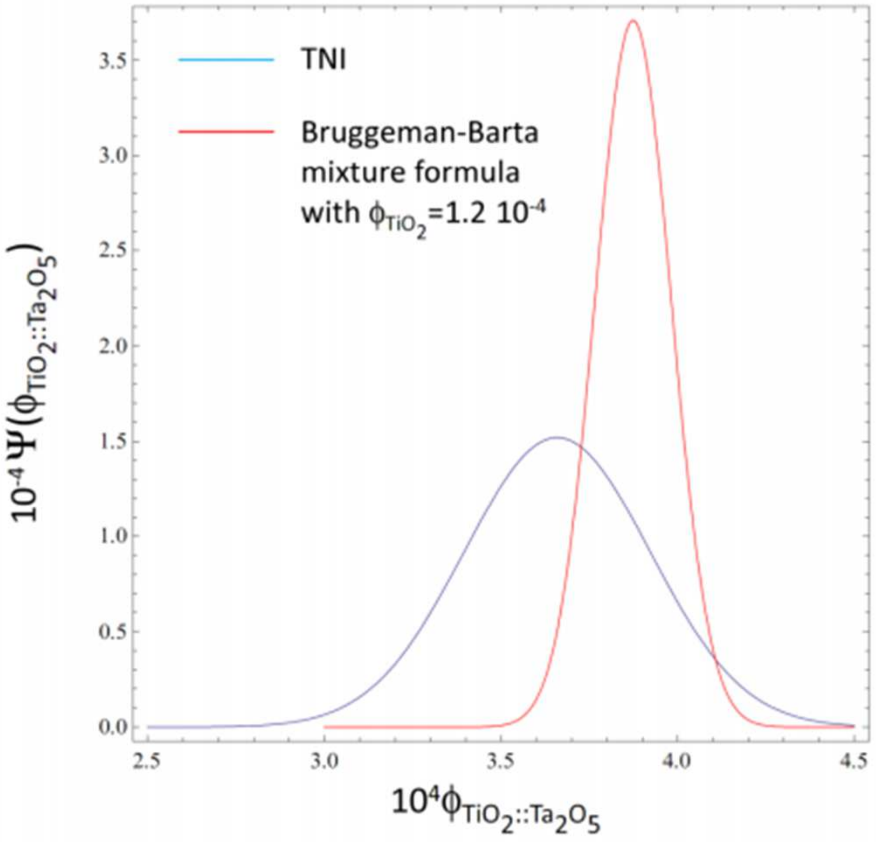
[A. Villar et al., LIGO-G 1101096]

TNI Result vs EMT Prediction

We can compare the doped Tantala loss angle distribution obtained from TNI measurements to the prediction of EMT, using Scott-MacCrone loss angle for Titania, and the TNI result for plain Tantala

TNI : distribution deduced from doped coating measurement, using the marginal distribution of Silica loss angle from the undoped coating measurements.

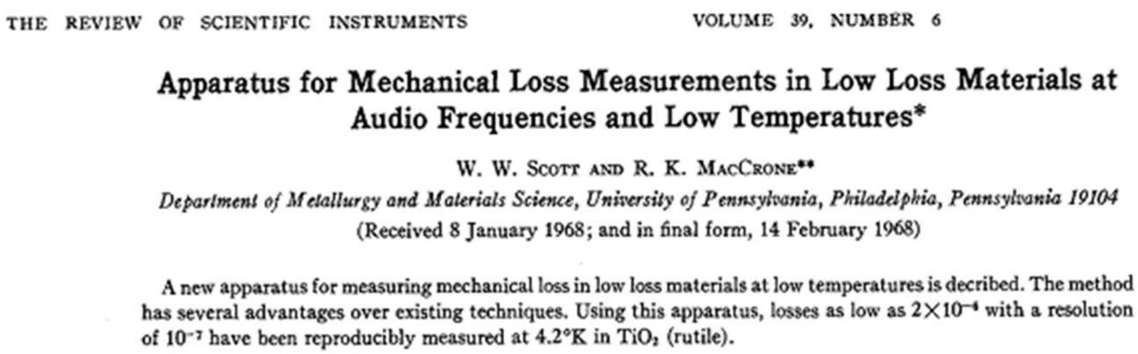
Bruggeman-Barta : distribution deduced using Scott-MacCrone value for Titania loss angle, with plain Tantala loss-angle distribution from un-doped coating measurements.



[A. Villar et al., LIGO-G 1101096]

- **How to do better than TiO2::Ta2O5 ?**

A Direct Measurement of ϕ_{TiO_2}



THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 39, NUMBER 6 JUNE 1968

Apparatus for Mechanical Loss Measurements in Low Loss Materials at Audio Frequencies and Low Temperatures*

W. W. Scott and R. K. MacCrone**

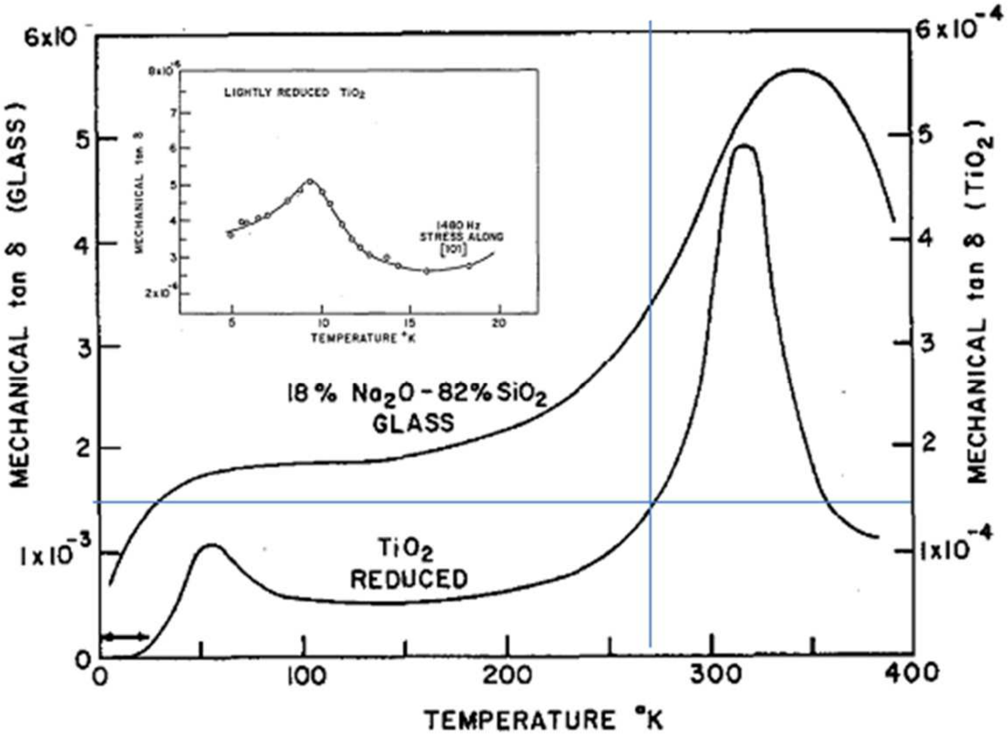
Department of Metallurgy and Materials Science, University of Pennsylvania, Philadelphia, Pennsylvania 19104

(Received 8 January 1968; and in final form, 14 February 1968)

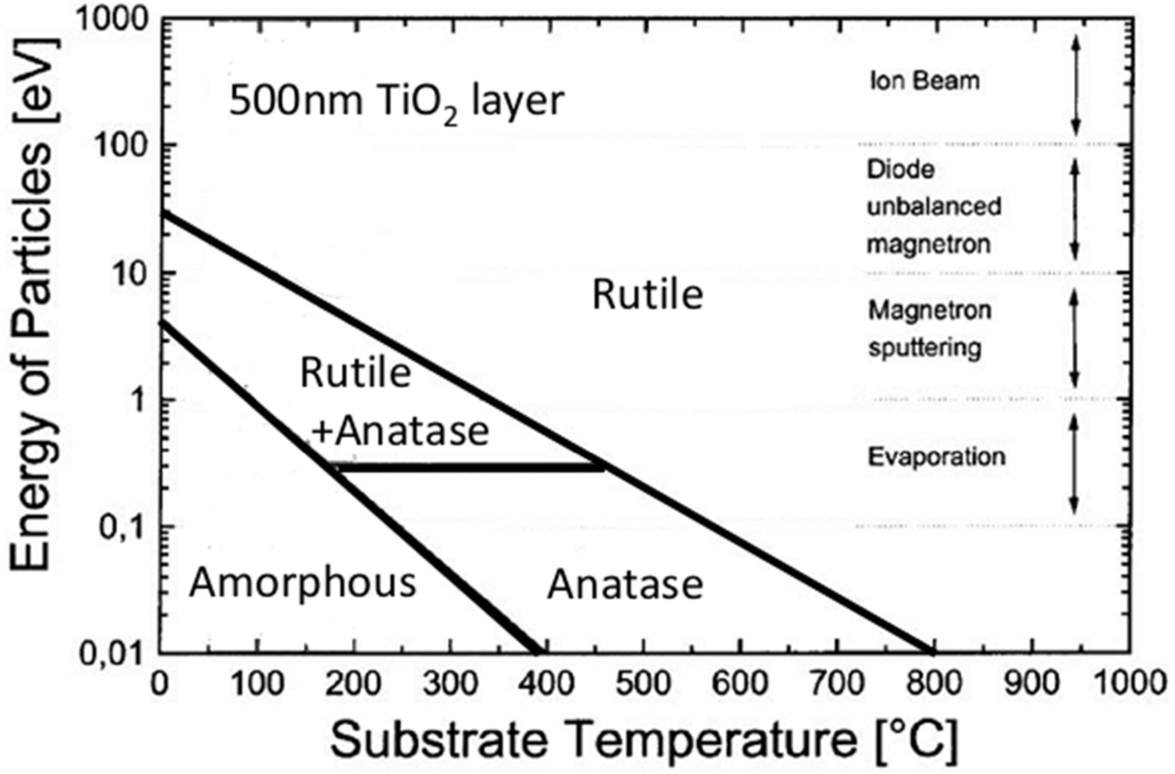
A new apparatus for measuring mechanical loss in low loss materials at low temperatures is decribed. The method has several advantages over existing techniques. Using this apparatus, losses as low as 2×10^{-4} with a resolution of 10^{-7} have been reproducibly measured at 4.2°K in TiO_2 (rutile).

n_{TiO_2}=2.29@1064nm

- Introduces an apparatus *conceptually similar* to the familiar «cantilever».
- Little details about tested materials. Speaks of *lightly reduced TiO2* in the main body, but mentions Rutile in the title;
- Reported results over a wide range of temperatures from 5K to 400K…



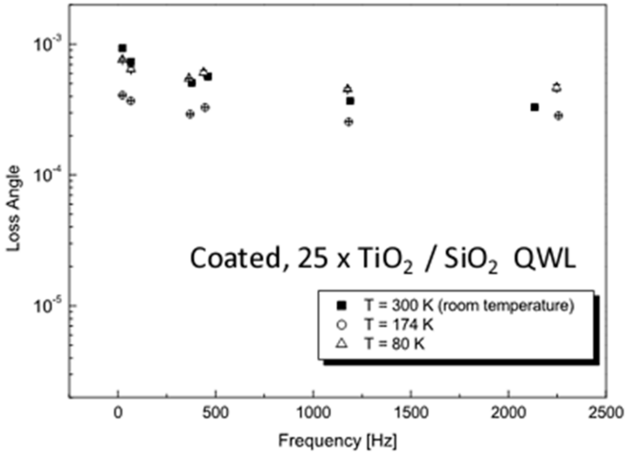
Titania is Nasty

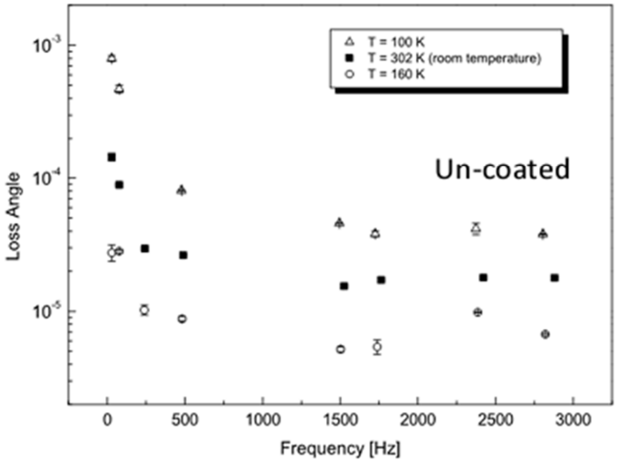


J. Szczyrbowski, Surf. Coat. Technol. 112 (1999) 261–266.

A SiO_2//TiO_2 Coating Prototype

P. Amico et al., J. Phys. Conf. Ser. 32 (2006) 413;
F. Travasso, ILIAS 05 Conference presentation (2005).





[I. Pinto et al., LIGO-G1100586]

1 sq. inch, 50µm thick membranes coated with 25 x TiO_2 (pure) / SiO_2 QWL-doublets.

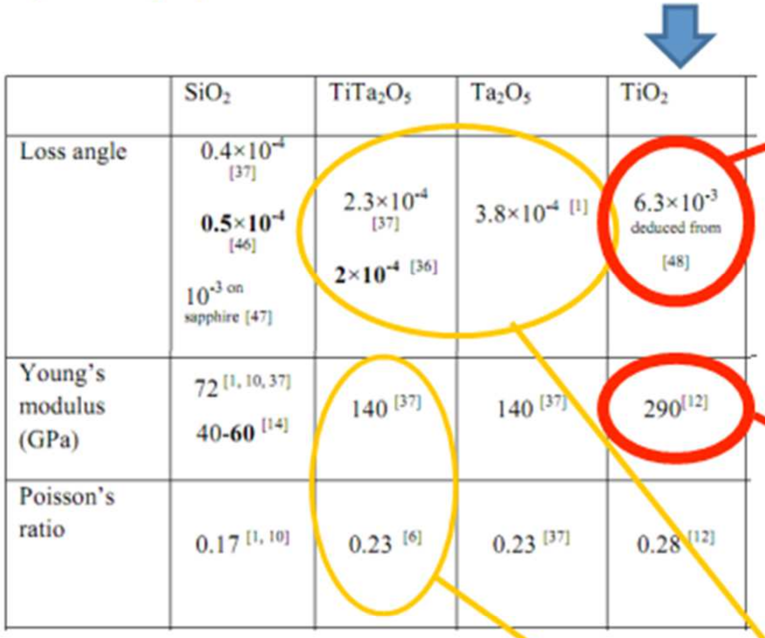
Coatings obtained by e - beam evaporation. Manufactured by italian Company SILO (www.silo.it). ***No* annealing details. *No* TEM images.**

Thickness of **pure** TiO_2 QWL layers ≅ 116nm. **Crystallization expected.**

➡ Used to estimated Titania loss angle in [Franc et al., ET-021-09 (2009)]

Trustable Numbers Needed

Frequently quoted values must be handled w. care, especially for Titania …



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Young's modulus (GPa)	72 [1, 10, 37] **40-60** [14]	140 [37]	140 [37]	290[12]
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J. Franc et al., ET-021-09 (2009).

Values from a *single* experiment: 25-doublets QWL Silica/Titania coating [P. Amico et al., J. Phys. Conf. Ser. 32 (2006) 413]. Thickness of Titania layers was 116nm. Well above limit-thickness for preventing crystallization upon annealing [S. Chao et al., J. Opt. Soc. Am. A16 (1999) 1477]. Reported loss angle most likely due to crystallization.

In the amorphous phase Y_{TiO_2} is 160 - 170 Gpa. [T. Modes et al., Surf. Coat. Technol. 200 (2005) 306]

Quoted Y = 290 Gpa is OK for the *crystalline* (Rutile) phase [O. Zywitzki, et al., Surf. Coat. Technol. 180 (2004) 538].

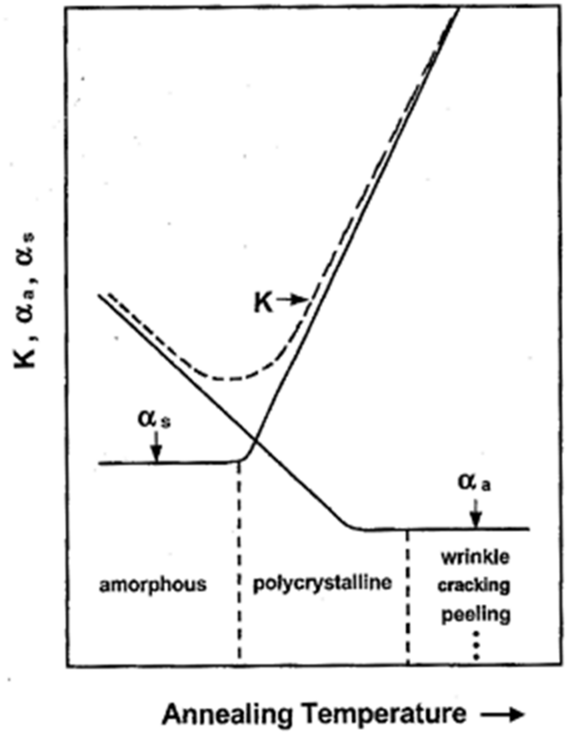
Large spreads among values obtained from different measurement techniques...

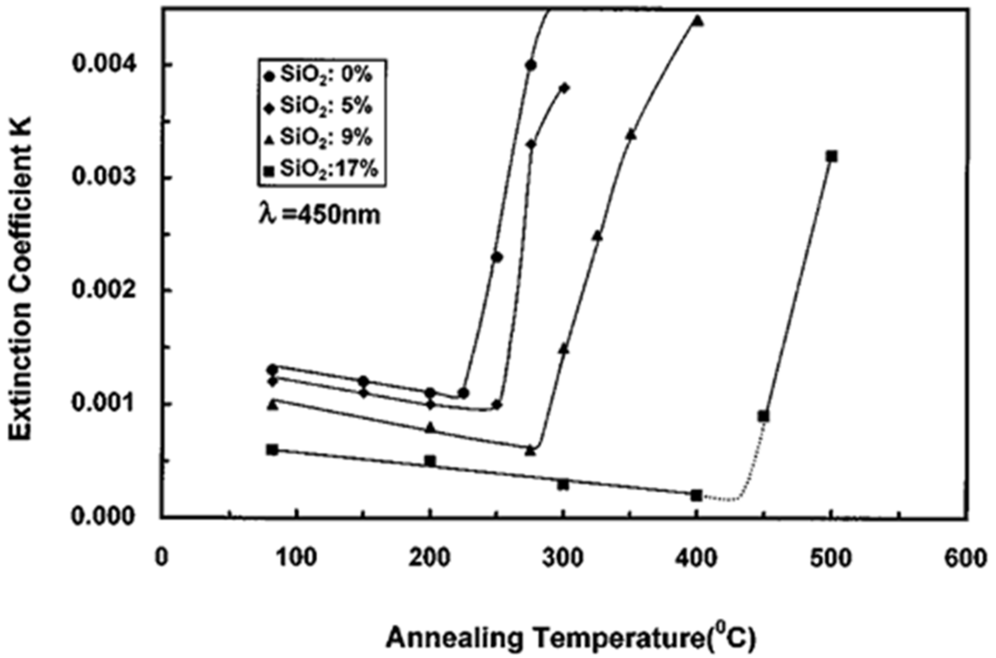
Conjectured values - *No* direct measurements of Y or σ on doped Tantala reported yet.

[I. Pinto et al., LIGO-G1100586]

Silica Doped Titania (SiO_2::TiO_2)

Extinction coefficient, and its absorption and scattering components, vs $T_{annealing}$.



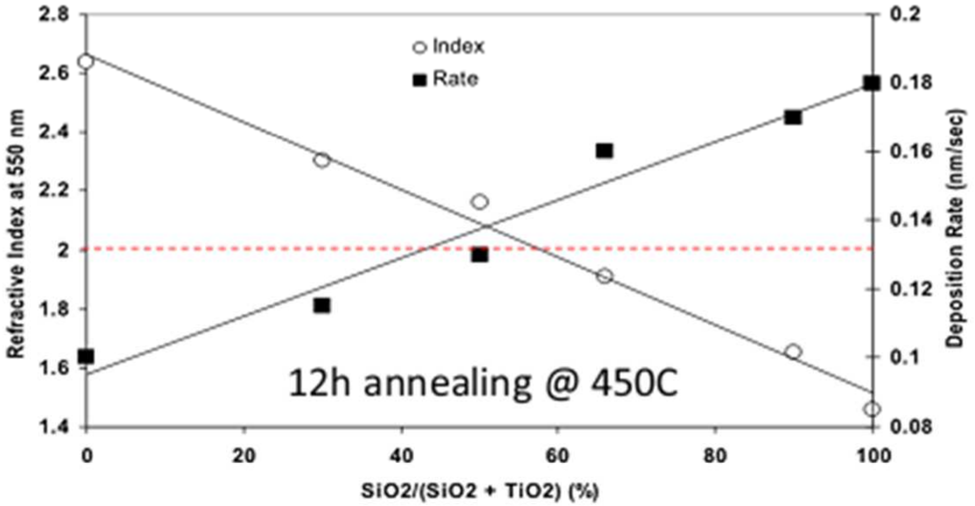


W.H. Wang and S. Chao, Optics Lett., 23 (1998) 1417;
S. Chao, W.H. Wang, M.-Y. Hsu and L.-C. Wang, J. Opt. Soc. Am. A16 (1999) 1477;
S. Chao, W.H. Wang and C.C. Lee, Appl. Opt., 40 (2001) 2177;

[I. Pinto et al., LIGO-G1100586]

A SiO2//TiO2::SiO2 Coating Prototype

R.P. Netterfield and M. Gross, "*Investigation of Ion Beam Sputtered Silica Titania Mixtures for Use in GW Interferometer Optics*," Optical Interference Coatings (OIC) Conference, Tucson AZ, USA, 2007, paper Thd2.



12h annealing @ 450C

Claims: Annealing at 500C did ***not*** produce crystallization

15 QWL doublets SiO_2 / TiO_2::SiO_2 with 35% Titania coating prototype

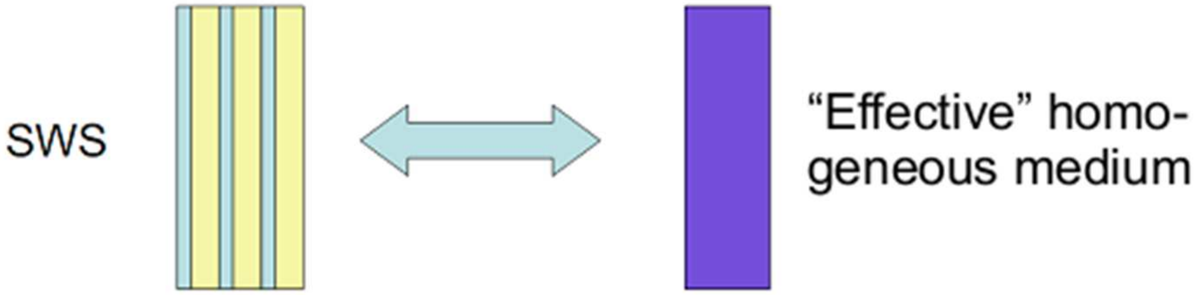
Absorption loss *better* than TiO_2::Ta_2O_5

Optical index slightly *lower* than TiO_2::Ta_2O_5

Mechanical losses slightly *higher* than than TiO_2::Ta_2O_5

No better than LMA no. 5 in terms of noise…

SiO_2//TiO_2 nm-Multilayers - Rationale



Use a *sub-wavelength* layer *stack* (SWS) made of two (or more…) different refractive materials to *synthesize* a *high-index*, *low mechanical loss* material.

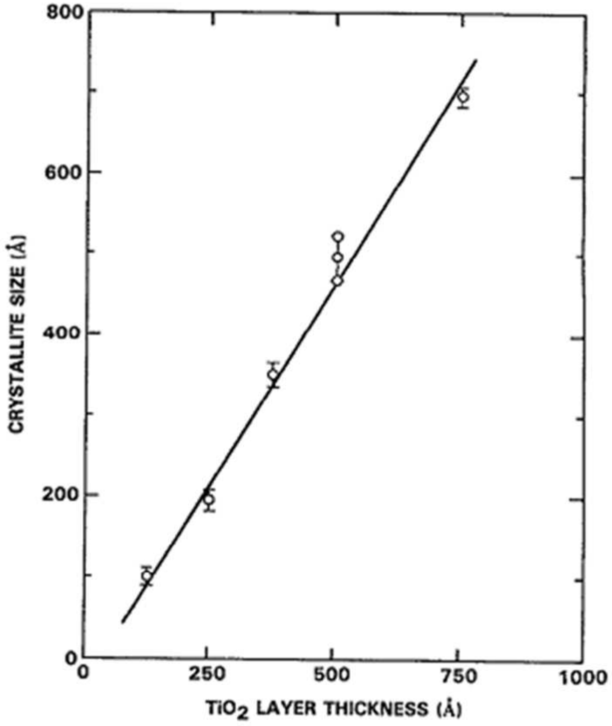
Expect *larger* n_{eff}, *smaller* b_{eff}, compared to “isotropic” mixture With same stoichiometry;

nm – thick TiO_2 layers should *not* crystallize significantly upon annealing. nm-thick silica layers act as separaTors, hopefully preventing Titania from crystallizing

Annealing of TiO2 nm-layers

Anatase *crystallite formation*

→ *affects scattering losses*

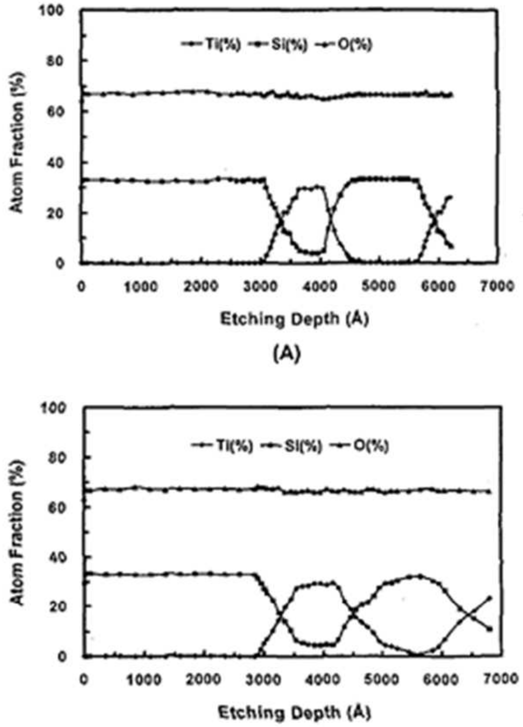


N.S. Gluck et al., J. Appl. Phys., 69 (1991) 3037

Increased *interdiffusion*

before

after



S.Chao, W.-H. Wang and C.-C. Lee, Appl. Optics, 40 (2001) 2177.

Best-tradeoff thickness ?

[I. Pinto et al., LIGO-G1100586]

Modeling nm - Multilayers

Subwavelength Layered Mixture

$$n_{mix} = \sqrt{\sum_i r_i n_i^2}$$

Drude's formula

$$Y_{mix} = \left(\sum_i \frac{r_i}{Y_i} \right)^{-1}$$

Reuss' formula

$$\eta_{mix} = \sum_i r_i \left(\frac{Y_i}{Y_s} + \frac{Y_s}{Y_i} \right) \frac{\phi_i}{n_i}$$

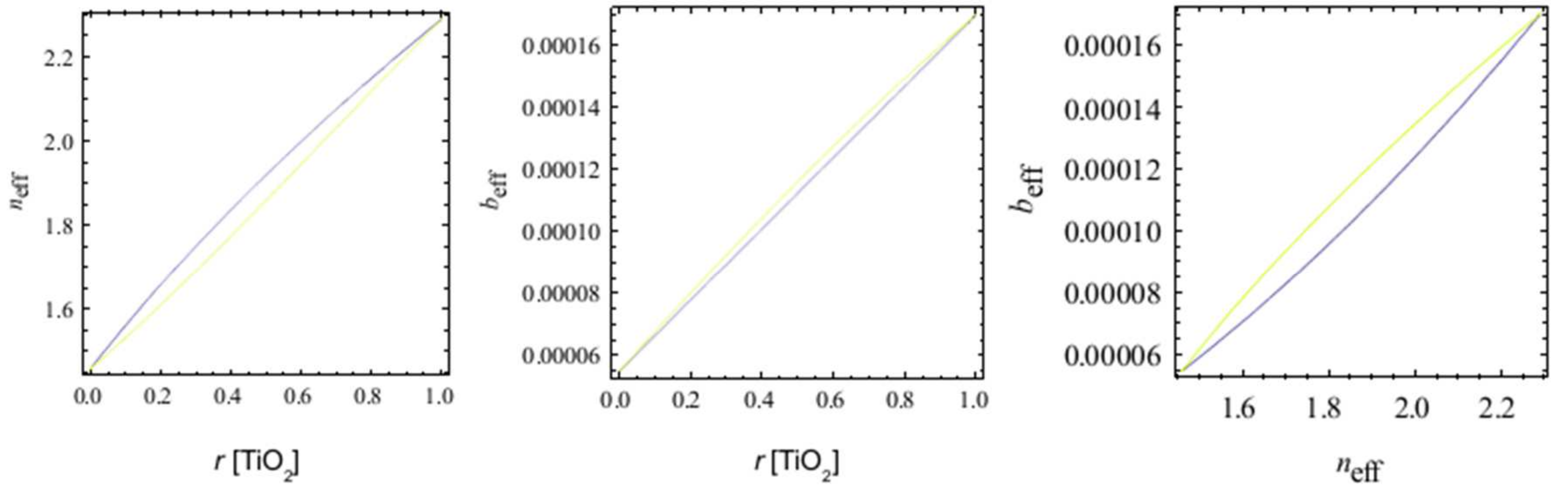
$$\phi_{mix} = \frac{n_{mix} \eta_{mix}}{\left(\frac{Y_{mix}}{Y_s} + \frac{Y_s}{Y_{mix}} \right)}$$

Harry's formula

$$\left(\sum_i r_i = 1 \right)$$

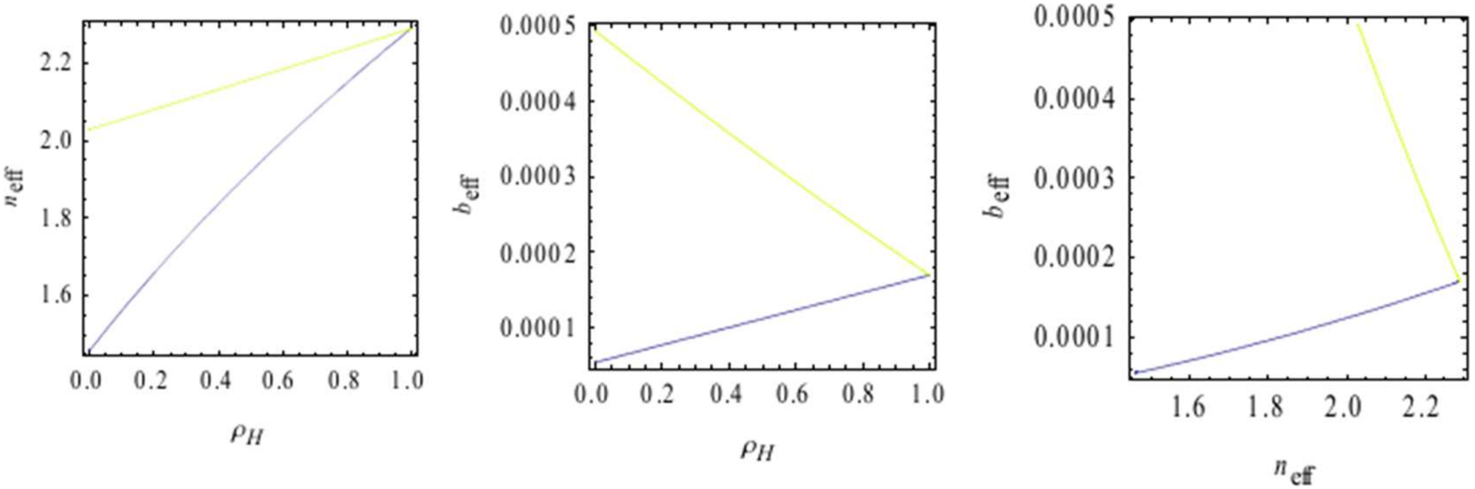
[I. Pinto et al., LIGO-G110372
LIGO-G110537
LIGO-G110586]

Co-sputtered vs nm-layered Silica//Titania



Layered SiO2::TiO2 mixture “bertter” than isotropic mixture at all stoichiometries

Co-sputtered Titania//Tantala vs nm-layered Silica//Titania



Layered $SiO2::TiO2$ outperforms by large isotropic $Ta2O5-TiO2$ mixtures

Technology Challenges

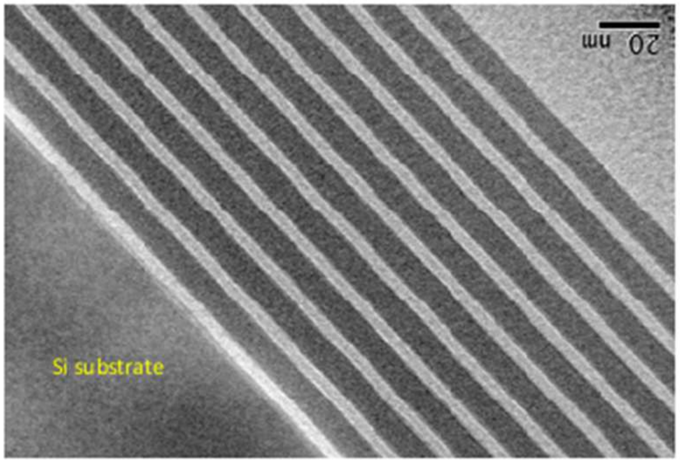
Several alternative sandwich thickness choices possible, yielding *the same* effective medium properties;

Accuracy in *single* layer thickness NOT important, provided
-*Each layer* in sandwich is *subwavelength,*
-The *thickness fraction* of each constituent is *accurate;*

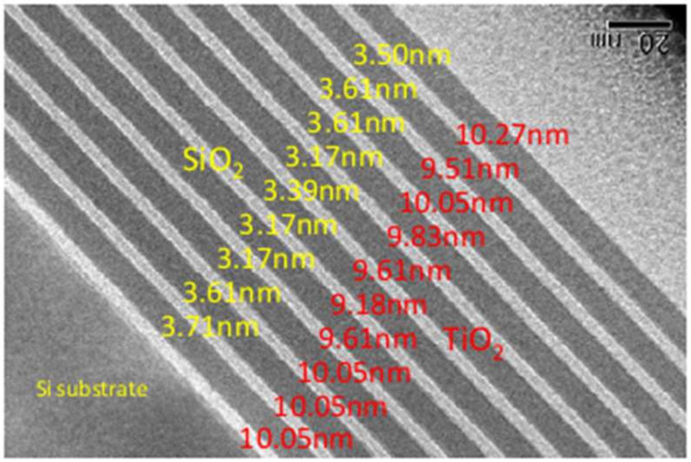
Possibly *mild* technological challenges: layers a few nm thick are currently manufactured for e.g. X-ray mirrors.

nm-Layered Prototypes

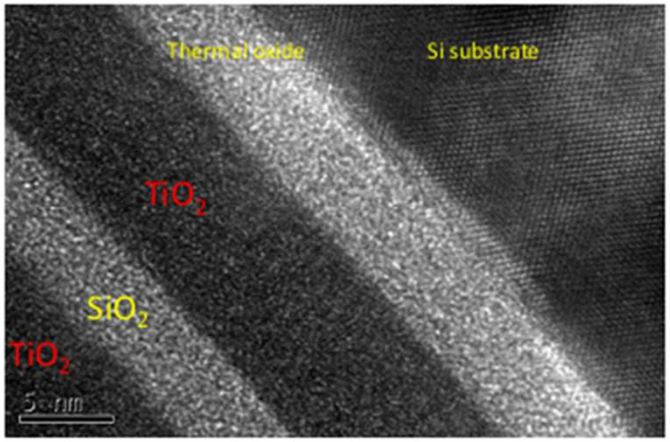
Nano-layer sample #2 TEM pictures



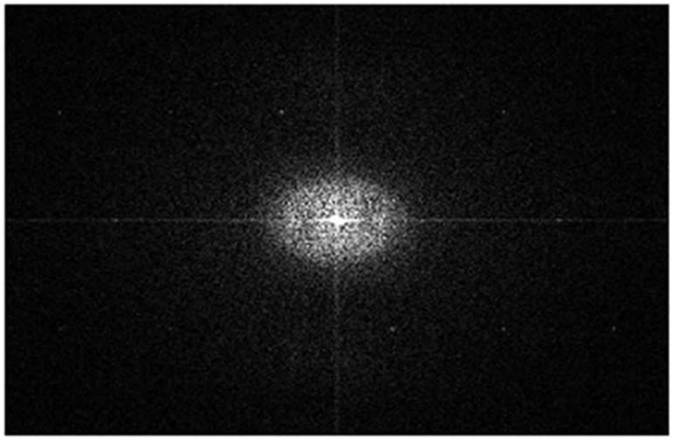
Sample #2



Sample #2 with thickness



close-up view of the layer interfaces

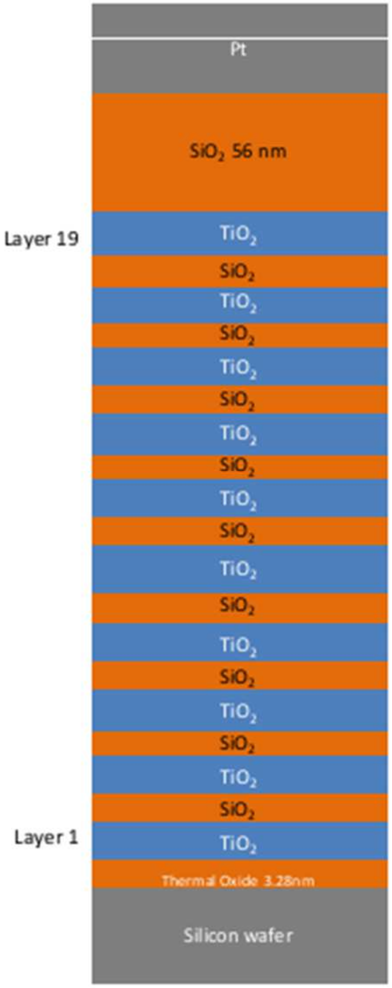


Electron diffraction pattern of the layers (amorphous)

[courtesy S. Chao]

nm-Layered Prototypes

Nano-layer sample #2

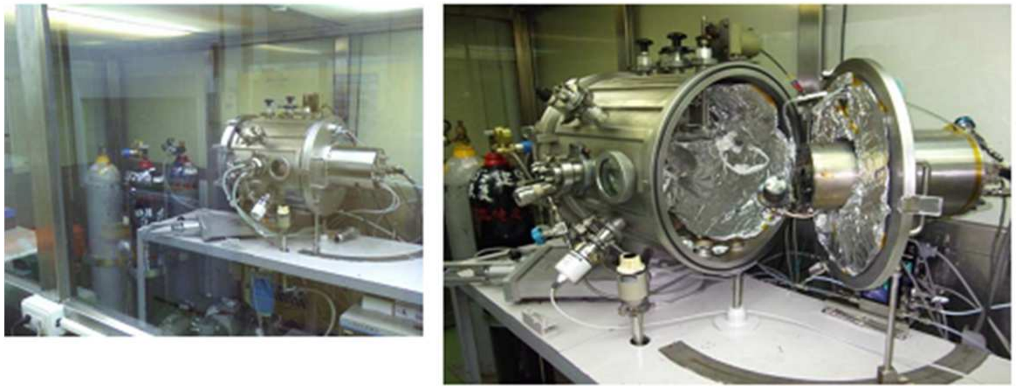


Deposition rate: TiO_2 3.40 nm/min SiO_2 7.79 nm/min

layer	Designed thickness	Deposition time	Measured thickness (TEM)	Thickness error	Measured thickness (Ellipsometry)	Thickness error
19	8.51nm	2'30"	10.27 nm	20.7%	Not Available	
18	4.68nm	36"	3.5 nm	-25.2%		
17	8.51nm	2'30"	9.51 nm	11.8%		
16	4.68nm	36"	3.39 nm	-27.6%		
15	8.51nm	2'30"	10,05 nm	18.1%		
14	4.68nm	36"	3.61 nm	-22.8%		
13	8.51nm	2'30"	9.83 nm	15.5%		
12	4.68nm	36"	3.17 nm	-32.2%		
11	8.51nm	2'30"	9.61 nm	12.9%		
10	4.68nm	36"	3.39 nm	-27.6%		
9	8.51nm	2'30"	9.18 nm	7.8%		
8	4.68nm	36"	3.17 nm	-32.3%		
7	8.51nm	2'30"	9.61nm	12.9%		
6	4.68nm	36"	3.17 nm	-32.3%		
5	8.51nm	2'30"	10.05 nm	18.1%		
4	4.68nm	36"	3.61nm	-22.9%		
3	8.51nm	2'30"	10.05 nm	18.1%		
2	4.68nm	36"	3.71 nm	-20.7%		
1	8.51nm	2'30"	10.05 nm	18.2%		

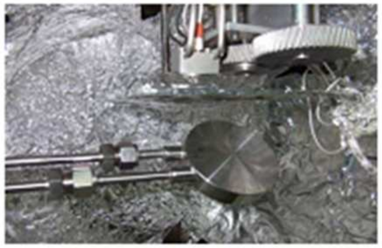
[courtesy S. Chao]

Chao’s Lab, Tsing Hua Univ., Taiwan

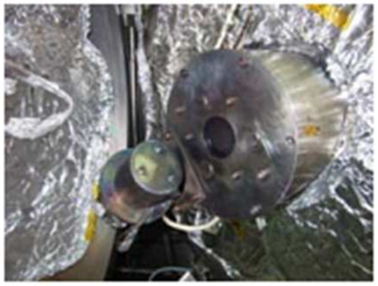


Kaufman-type ion beam sputter system in a class 100 clean compartment within a class 10,000 clean room, used to coat low loss mirror for ring-laser gyroscope

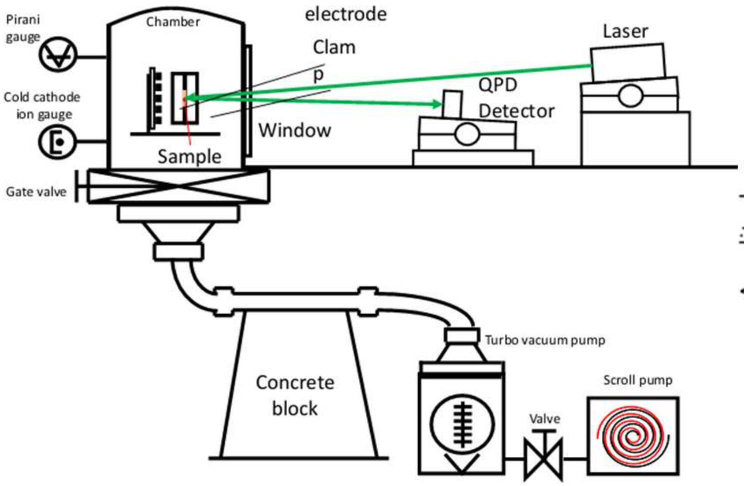
Three sets of exchangable target holder, each holding two sputter targets



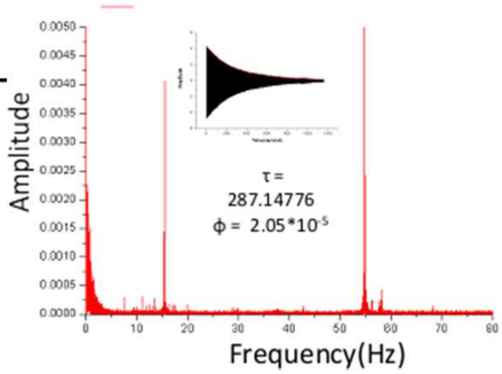
Sputter target and single axis substrate rotation



Kaufman ion gun with plasma bridge neutralizer

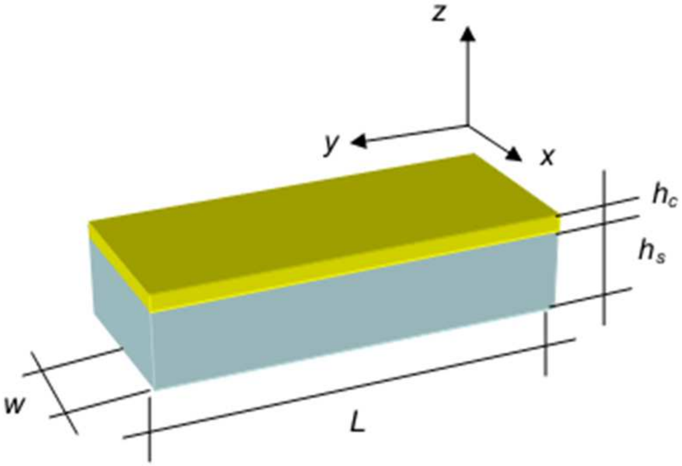


Clamped cantilever Q mesurement setup



[courtesy S. Chao]

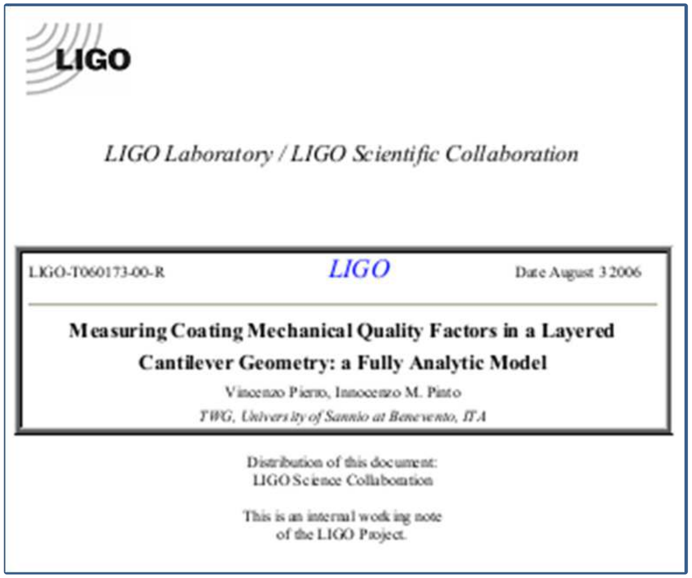
The Clamped Coated Cantilever



$$Q_c^{-1} = Q^{-1} + \frac{<W_s>}{<W_c>}\left(Q^{-1} - Q_s^{-1}\right)$$

$$\frac{<W_c>}{<W_s>} = \frac{\int_{h_s}^{h_s+h_c} (z-z_0)^2 \frac{E(z)}{\left(1-\sigma(z)^2\right)} dz}{\int_{0}^{h_s} (z-z_0)^2 \frac{E(z)}{\left(1-\sigma(z)^2\right)} dz} \approx \frac{E_s h_s}{3E_c h_c}$$

LIGO –T060173



LIGO

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T060173-00-R LIGO Date August 3 2006

Measuring Coating Mechanical Quality Factors in a Layered Cantilever Geometry: a Fully Analytic Model

Vincenzo Pierro, Innocenzo M. Pinto

TWG, University of Sannio at Benevento, ITA

Distribution of this document:
LIGO Science Collaboration

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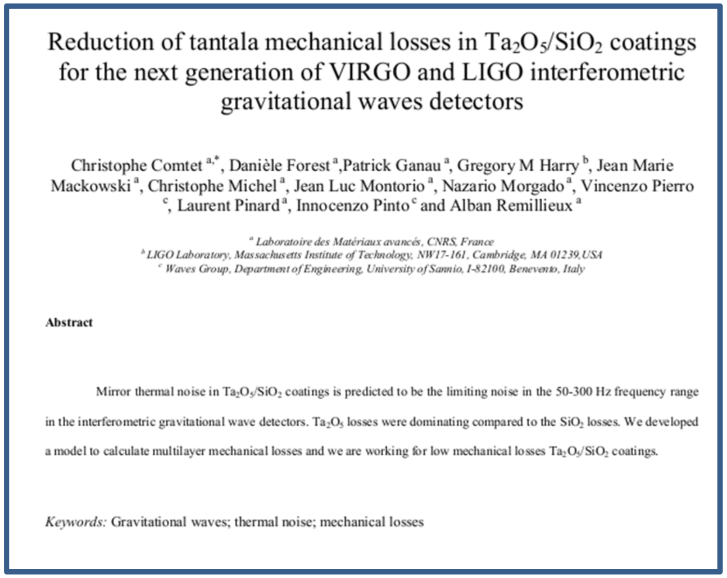
of the LIGO Project.



Reduction of tantala mechanical losses in Ta_2O_5/SiO_2 coatings for the next generation of VIRGO and LIGO interferometric gravitational waves detectors

Christophe Comtet [a,*], Danièle Forest [a],Patrick Ganau [a], Gregory M Harry [b], Jean Marie Mackowski [a], Christophe Michel [a], Jean Luc Montorio [a], Nazario Morgado [a], Vincenzo Pierro [c], Laurent Pinard [a], Innocenzo Pinto [c] and Alban Remillieux [a]

[a] *Laboratoire des Matériaux avancés, CNRS, France*
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[c] *Waves Group, Department of Engineering, University of Sannio, I-82100, Benevento, Italy*

Abstract

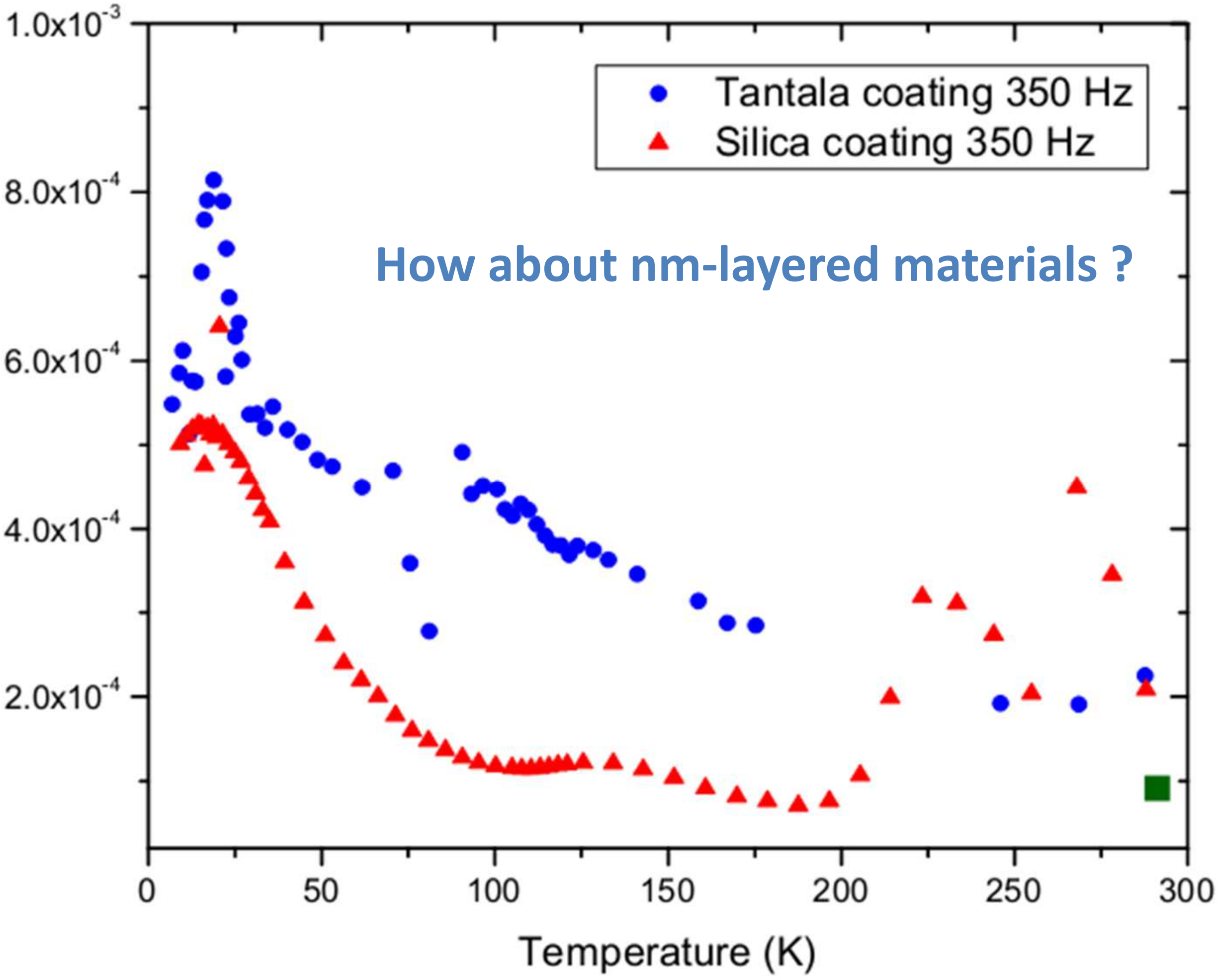
Mirror thermal noise in Ta_2O_5/SiO_2 coatings is predicted to be the limiting noise in the 50-300 Hz frequency range in the interferometric gravitational wave detectors. Ta_2O_5 losses were dominating compared to the SiO_2 losses. We developed a model to calculate multilayer mechanical losses and we are working for low mechanical losses Ta_2O_5/SiO_2 coatings.

Keywords: Gravitational waves; thermal noise; mechanical losses

[*in 42th Rencontres de Moriond : Gravitational Waves and Experimental Gravity, 2007*]

➡ **Chao's Q measurements will yield *both* composite and pure TiO2 loss angle estimates**

Cryogenic Peak

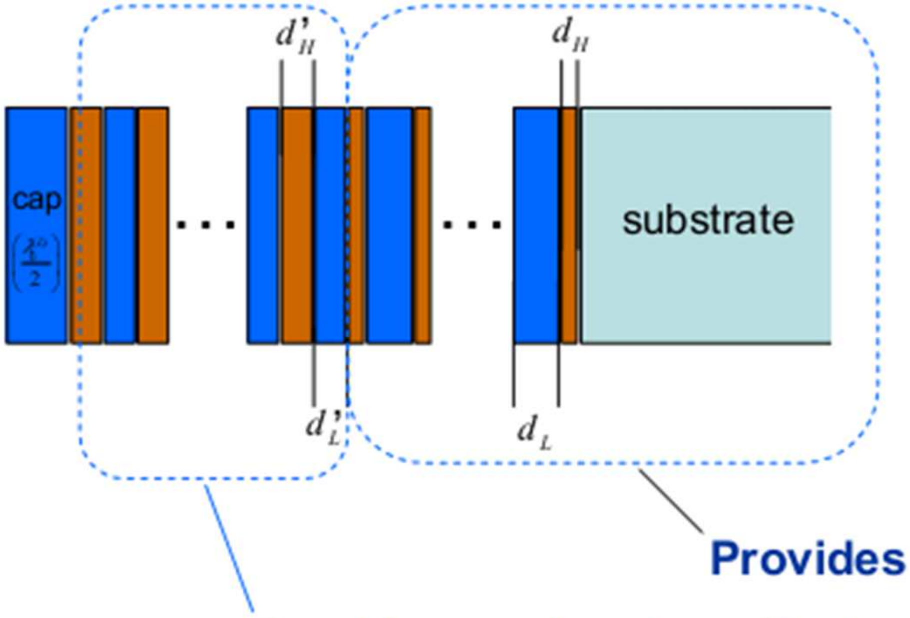


How about nm-layered materials ?

- # Optimizing Coating Geometry

Minimal Noise Dichroic Design

"Naive" Reference Dichroic Design



$$d_H = \frac{\lambda_0^{(H)}}{8} = \frac{\lambda_0^{(H)}/2}{4}$$

$$d_L = \frac{3\lambda_0^{(L)}}{8} = \frac{\lambda_0^{(H)}/2}{4} + \frac{\lambda_0^{(H)}/2}{2}$$

$$\lambda_0^{(L,H)} = \lambda_0 / n_{L,H}$$

$$d'_{L,H} = \frac{\lambda_0^{(L,H)}}{4} = \frac{\lambda_0^{(L,H)}/2}{2}$$

Provides reqd. reflectance at $\lambda_0/2$

Provides reqd. extra reflectance at λ_0

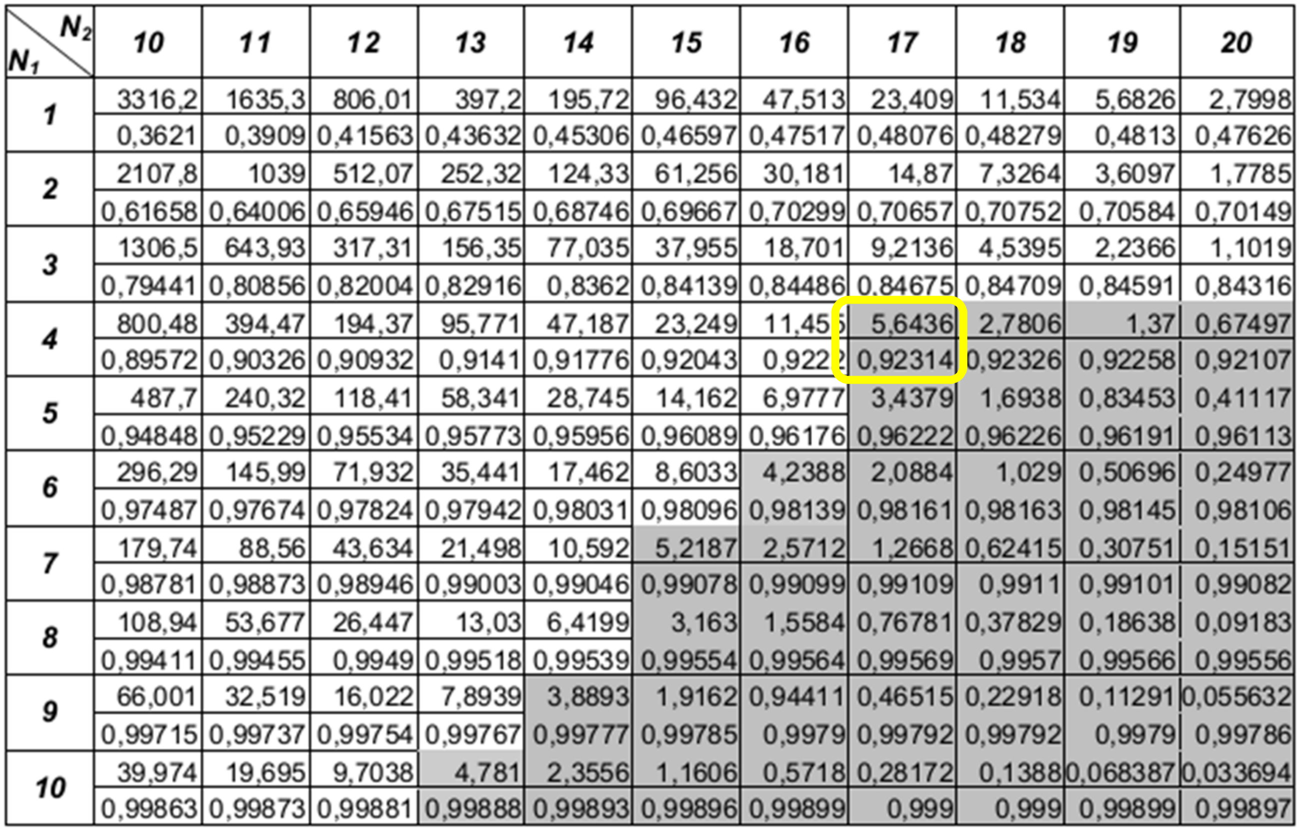
…this simple argument *ignores material dispersion*, e.g.

wavelength material	532	670	946	1064	1319
Silica	1.47809	1.47337	1.47044	1.46995	1.46937
Doped Tantala	2.13890	2.10980	2.09570	2.09418	2.09238

(courtesy
M.Gross,
CSIRO)

“Naive” Reference Dichroic Design, contd.

Design goal compliant and minimal noise designs (dispersion included)



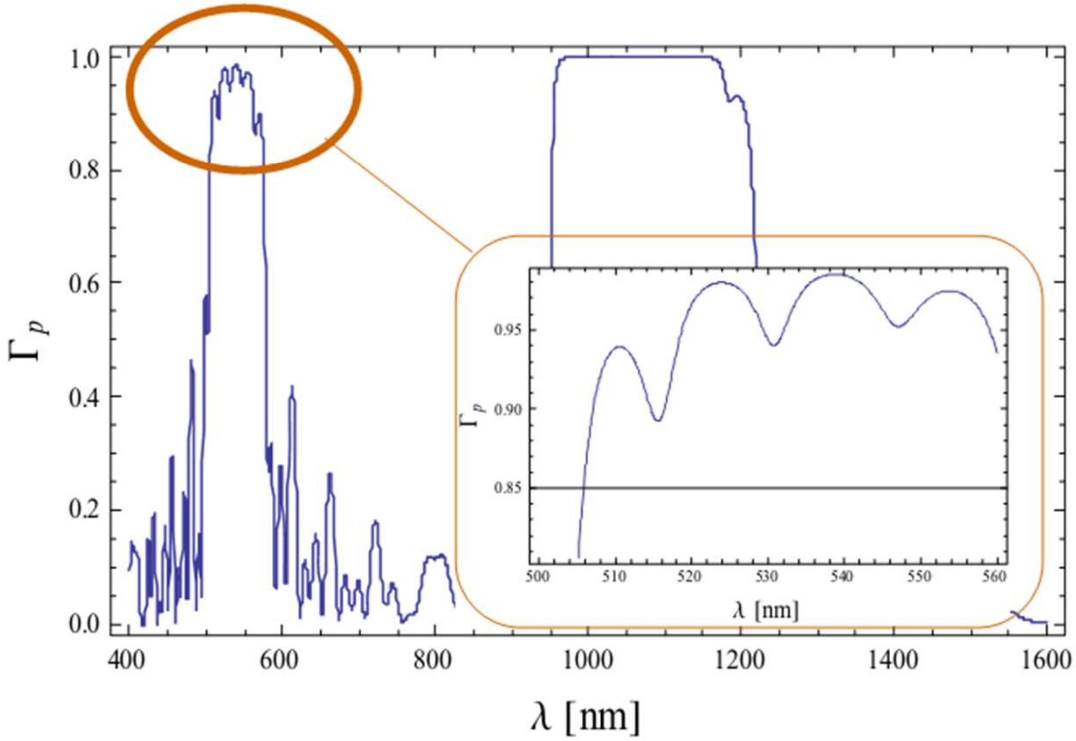
N_2 N_1	10	11	12	13	14	15	16	17	18	19	20
1	3316,2	1635,3	806,01	397,2	195,72	96,432	47,513	23,409	11,534	5,6826	2,7998
	0,3621	0,3909	0,41563	0,43632	0,45306	0,46597	0,47517	0,48076	0,48279	0,4813	0,47626
2	2107,8	1039	512,07	252,32	124,33	61,256	30,181	14,87	7,3264	3,6097	1,7785
	0,61658	0,64006	0,65946	0,67515	0,68746	0,69667	0,70299	0,70657	0,70752	0,70584	0,70149
3	1306,5	643,93	317,31	156,35	77,035	37,955	18,701	9,2136	4,5395	2,2366	1,1019
	0,79441	0,80856	0,82004	0,82916	0,8362	0,84139	0,84486	0,84675	0,84709	0,84591	0,84316
4	800,48	394,47	194,37	95,771	47,187	23,249	11,45	5,6436	2,7806	1,37	0,67497
	0,89572	0,90326	0,90932	0,9141	0,91776	0,92043	0,922	0,92314	0,92326	0,92258	0,92107
5	487,7	240,32	118,41	58,341	28,745	14,162	6,9777	3,4379	1,6938	0,83453	0,41117
	0,94848	0,95229	0,95534	0,95773	0,95956	0,96089	0,96176	0,96222	0,96226	0,96191	0,96113
6	296,29	145,99	71,932	35,441	17,462	8,6033	4,2388	2,0884	1,029	0,50696	0,24977
	0,97487	0,97674	0,97824	0,97942	0,98031	0,98096	0,98139	0,98161	0,98163	0,98145	0,98106
7	179,74	88,56	43,634	21,498	10,592	5,2187	2,5712	1,2668	0,62415	0,30751	0,15151
	0,98781	0,98873	0,98946	0,99003	0,99046	0,99078	0,99099	0,99109	0,9911	0,99101	0,99082
8	108,94	53,677	26,447	13,03	6,4199	3,163	1,5584	0,76781	0,37829	0,18638	0,09183
	0,99411	0,99455	0,9949	0,99518	0,99539	0,99554	0,99564	0,99569	0,9957	0,99566	0,99556
9	66,001	32,519	16,022	7,8939	3,8893	1,9162	0,94411	0,46515	0,22918	0,11291	0,055632
	0,99715	0,99737	0,99754	0,99767	0,99777	0,99785	0,9979	0,99792	0,99792	0,9979	0,99786
10	39,974	19,695	9,7038	4,781	2,3556	1,1606	0,5718	0,28172	0,1388	0,068387	0,033694
	0,99863	0,99873	0,99881	0,99888	0,99893	0,99896	0,99899	0,999	0,999	0,99899	0,99897

Table 1 – ETM reference “hybrid” SD design. In each cell: ETM power transmission coefficient @1064 nm [ppm] (1st line) and power reflection coefficient @532 nm (2nd line) for different values of N_1 and N_2

[M. Principe and I. Pinto, LIGO-T080337]

“Naive” Reference Dichroic Design, contd.

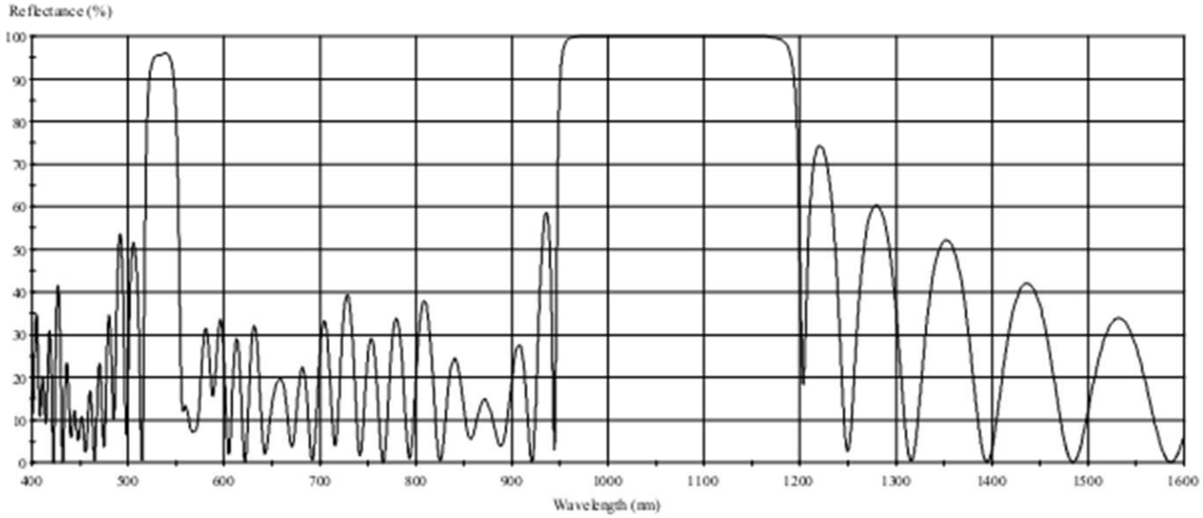
$$|cap|\left(|\lambda_0^{(H)}/4|\lambda_0^{(L)}/4|\right)^{14}(|\lambda_0^{(H)}/8|3\lambda_0^{(L)}/8|)^{6}|\lambda_0^{(H)}/8|substrate$$



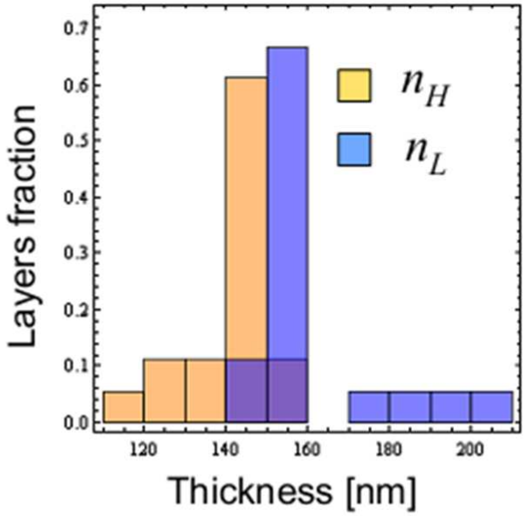
λ [nm]		
1064	4.44893	τ_p [ppm]
532	0.948927	Γ_p
670	0.0642971	
946	0.14197	
980	0.999696	
1319	0.0949941	
1550	0.0229077	

Genetically Engineered Dichroic Design

(… controlled ignorance attitude…)



λ [nm]		
1064	5.97	τ_p [ppm]
532	0.9551	
670	0.0406	
946	0.3125	
980	0.9998	Γ_p
1319	0.9736	
1550	0.7286	



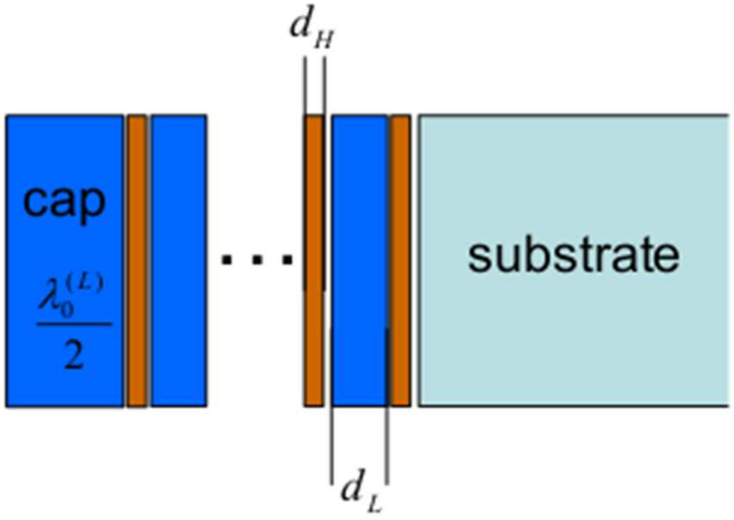
(50 iterations, 25 cycles, other settings default;
layers rescaled modulo $\lambda/2$;
layers below $5\lambda/1000$ deleted. 38 layers left.

Neat trend toward a *stacked-doublet core* …

[I. Pinto et al., LIGO-G0900205]

Simplest SD-Core Dichroic Design

$$|\,cap\,|\left(|\,d_H\,|\,d_L\,|\right)^N|\,d_H\,|\,substrate$$



$$d_L = \frac{\lambda_0}{n_L}\left(\frac{1}{4}+\xi_L\right), d_H = \frac{\lambda_0}{n_H}\left(\frac{1}{4}-\xi_H\right)$$

Three constraints:

$\tau_p \in (\tau_{min}, \tau_{max}\,)$ @ 1064nm
$\tau_p \in (\tau_{min}, \tau_{max}\,)$@ 532nm
ϕ_c as small as possible

Three design parameters:

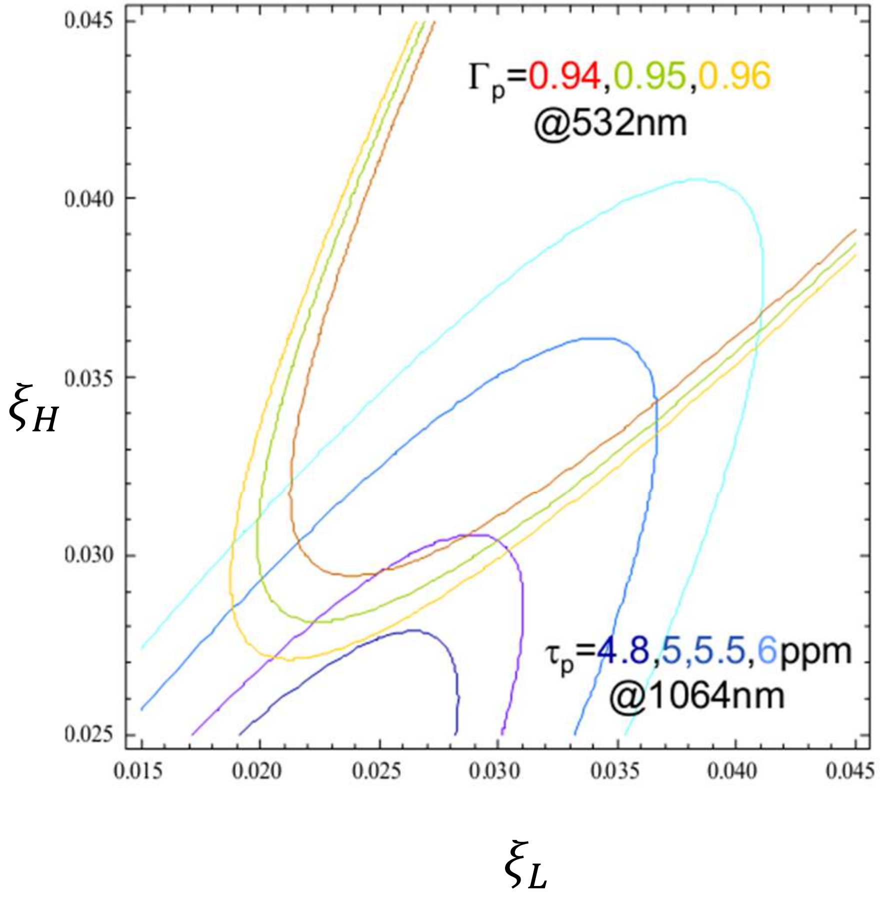
$$\xi_h, \xi_h\,, N$$

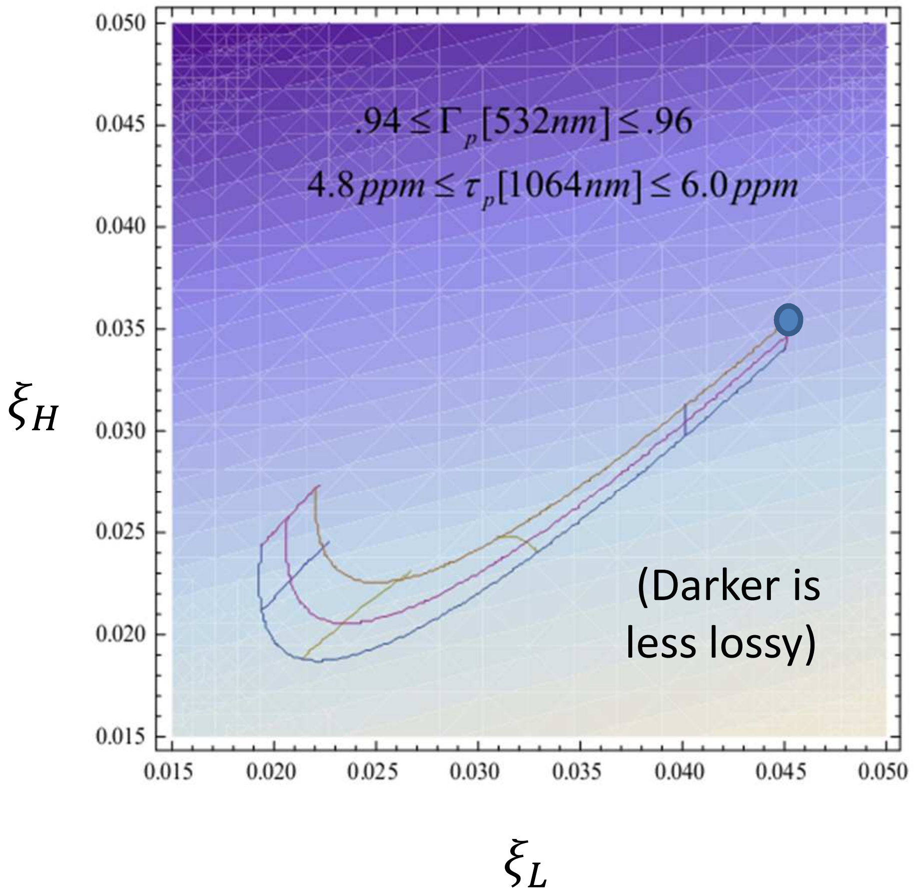
…

[I. Pinto et al., LIGO-G0900205]

Isoreflective Contours (N=18)

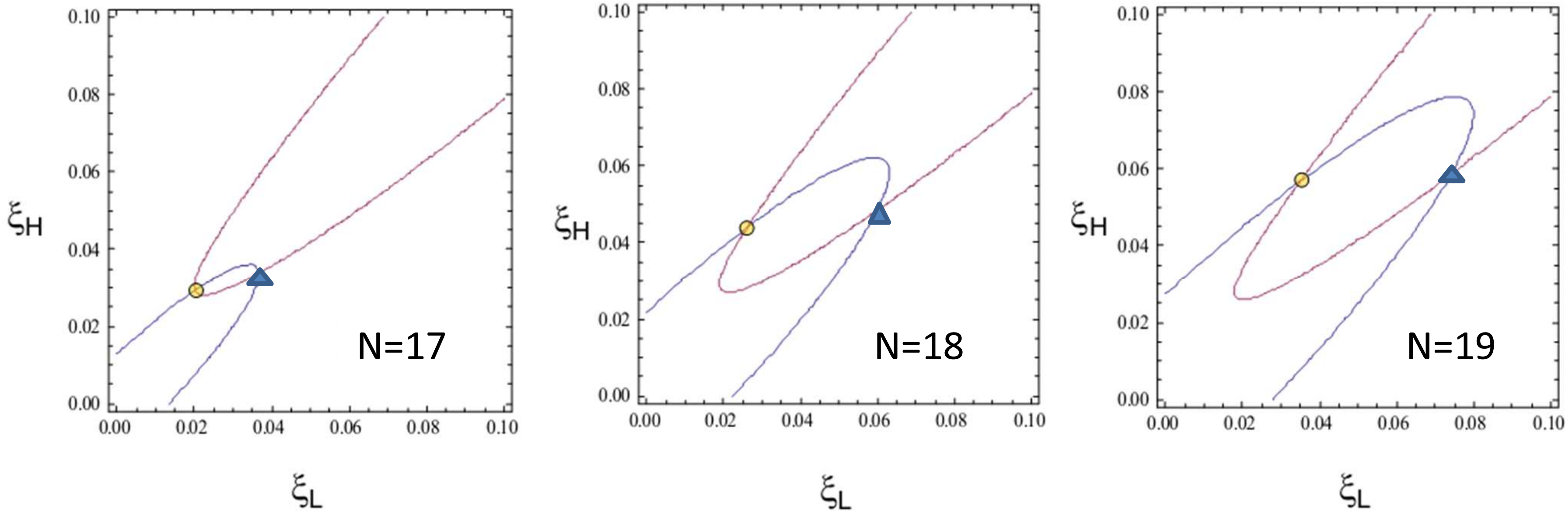
$$|cap|\left(|d_H|d_L|\right)^{18}|d_H|substrate$$

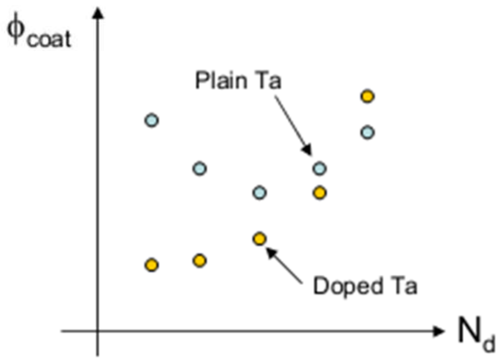




Minimal Noise SD Dichroic Design

Require, e.g., τ_p = 5.5ppm @ 1064nm and Γ_p = 0.95 @ 532nm

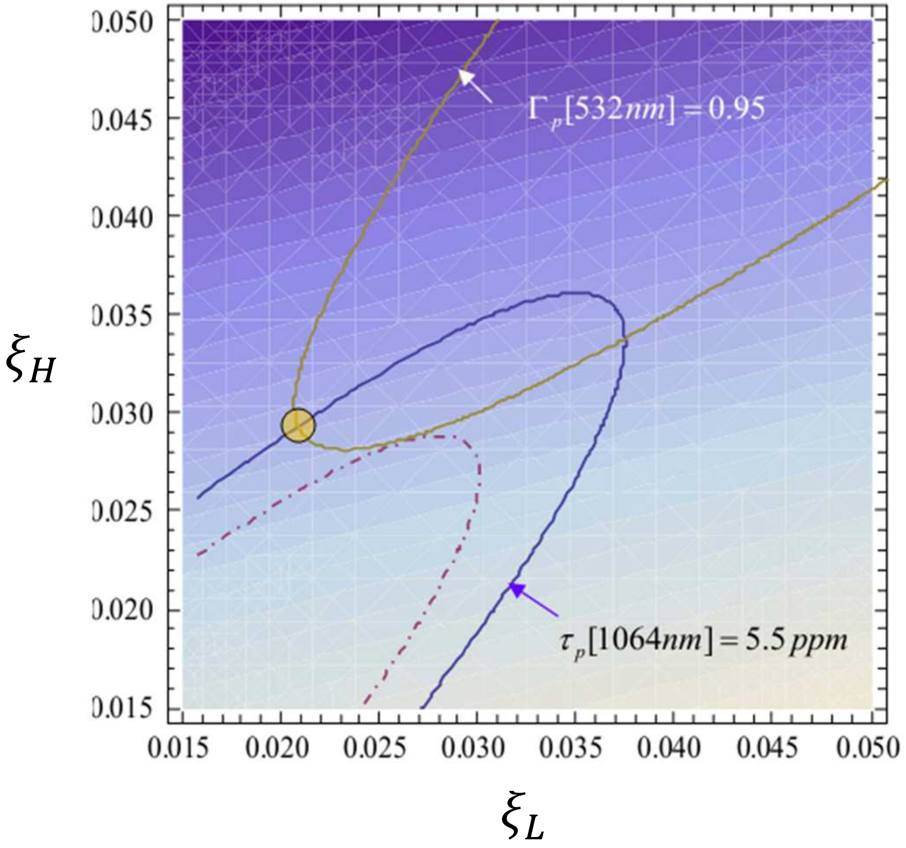




identify N for which ϕ_c is minimum

Minimal Noise SD Design

$$|cap|(|d_H|d_L|)^N|d_H|substrate$$



$\xi_L=0.02008,\ \xi_H=0.029362$

$d_L=195.493nm,\ d_H=112.1nm$

$N=18$

λ [nm]		
1064	5.5	τ_p [ppm]
532	0.949261	Γ_p
670	0.0889853	
946	0.994795	
980	0.999955	
1319	0.181319	
1550	0.0347272	

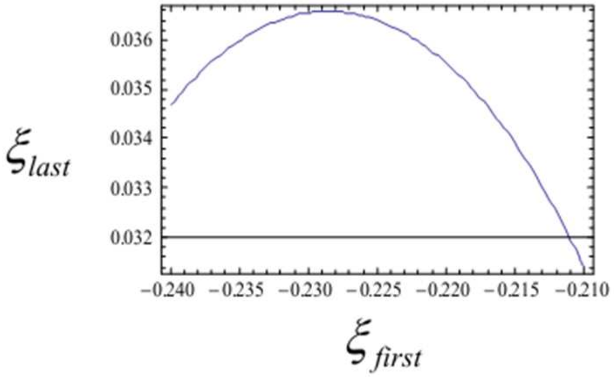
Tweaked Minimal Noise Design

Tweak (adjust) the thicknesses of the *outermost* (first, last) layers, e.g.

Let:

$$d_{first}^{(H)} = \frac{\lambda_0}{n_H}\left(\frac{1}{4} - \xi_{first}\right), d_{last}^{(L)} = \frac{\lambda_0}{n_L}\left(\frac{1}{4} + \xi_{last}\right)$$

Keep τ_p@1064nm, Γ_p@532nm unchanged



Tweak so that peak electric field at coating face achieves its *infimum*,

$$|E| = |E^{inc}||1+\Gamma| =$$

$$= |E^{inc}|(1-|\Gamma|) \cong |E^{inc}|\frac{\tau_p}{2}$$

For our N=18 SD-ETM design, get

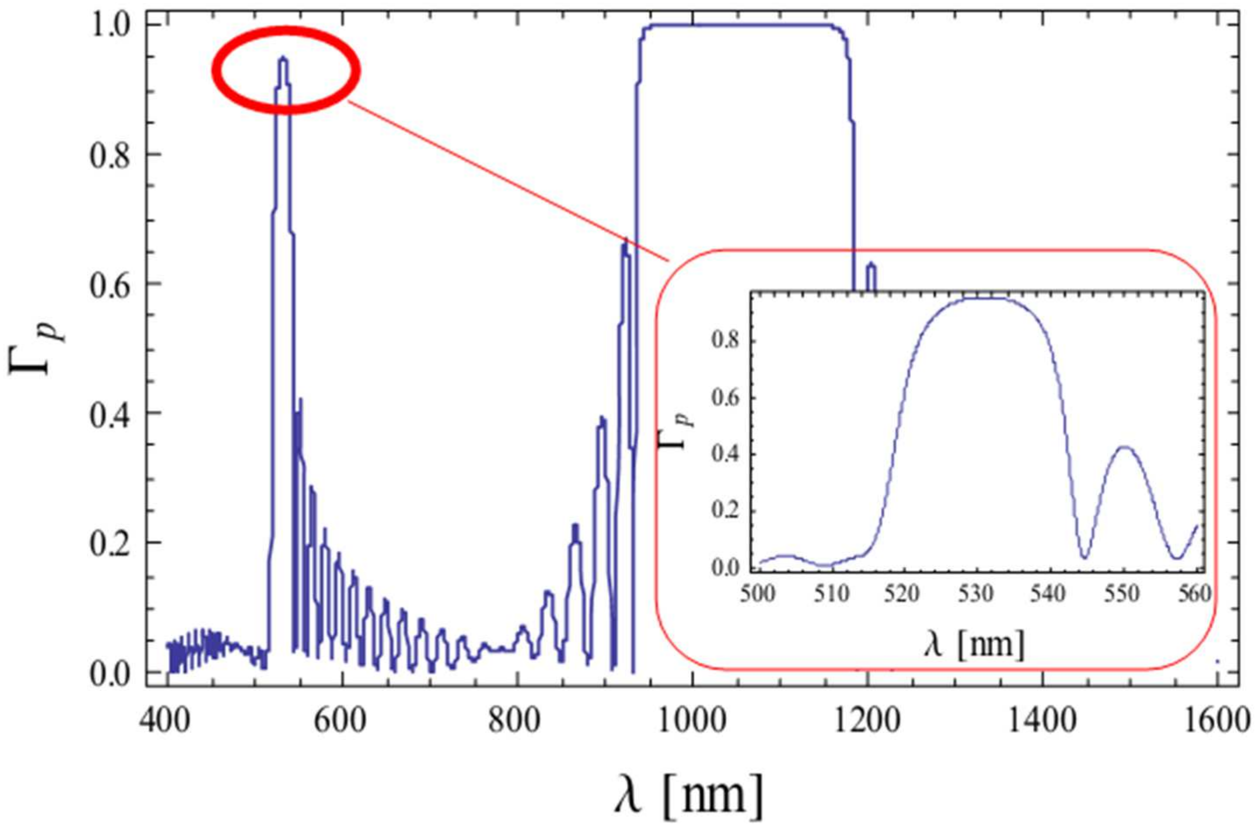
$$\xi_{last} = -0.22862, \ \xi_{first} = 0.030761$$

$$d_{last} = 111.389nm, \ d_{first} = 15.4765nm$$

$$|E_{face}| \cong 2.7 \cdot 10^{-6} |E^{inc}|$$

… additional constraints (e.g., flatness) can be accommodated by tweaking additional (outermost) layers …

SD-Core, Tweaked Optimal Design



LMA started from this to engineer the current AdvLIGO ETM and ITM coatings. They enforced further band-centering tweaks . Details are covered by secret .

Conclusions

Several tools have been developed in the LVC (and the Scientific Community at large) which may suit the specific mirror noise issue of b-KAGRA, including

-EMT modeling of glassy mixtures

-The idea of nm-layered composites

-A simple systematic procedure for coating thickness optimization