Low Noise Optical Coatings For Advanced GW Detectors

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*** University of Sannio, INFN, LVC and KAGRA***

Outlook

Coating Noise(s)

Wide Beams

Optimizing Thicknesses

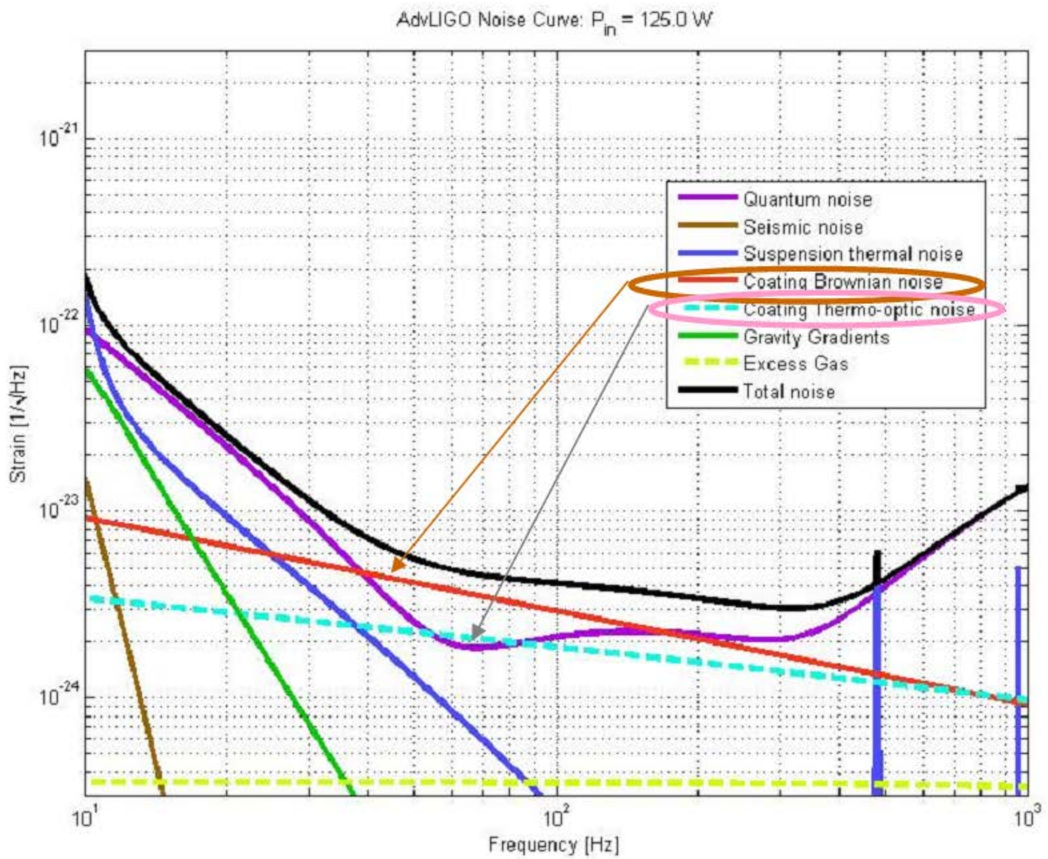
Optimizing Materials

Going Cryogenic

Alternative R&D

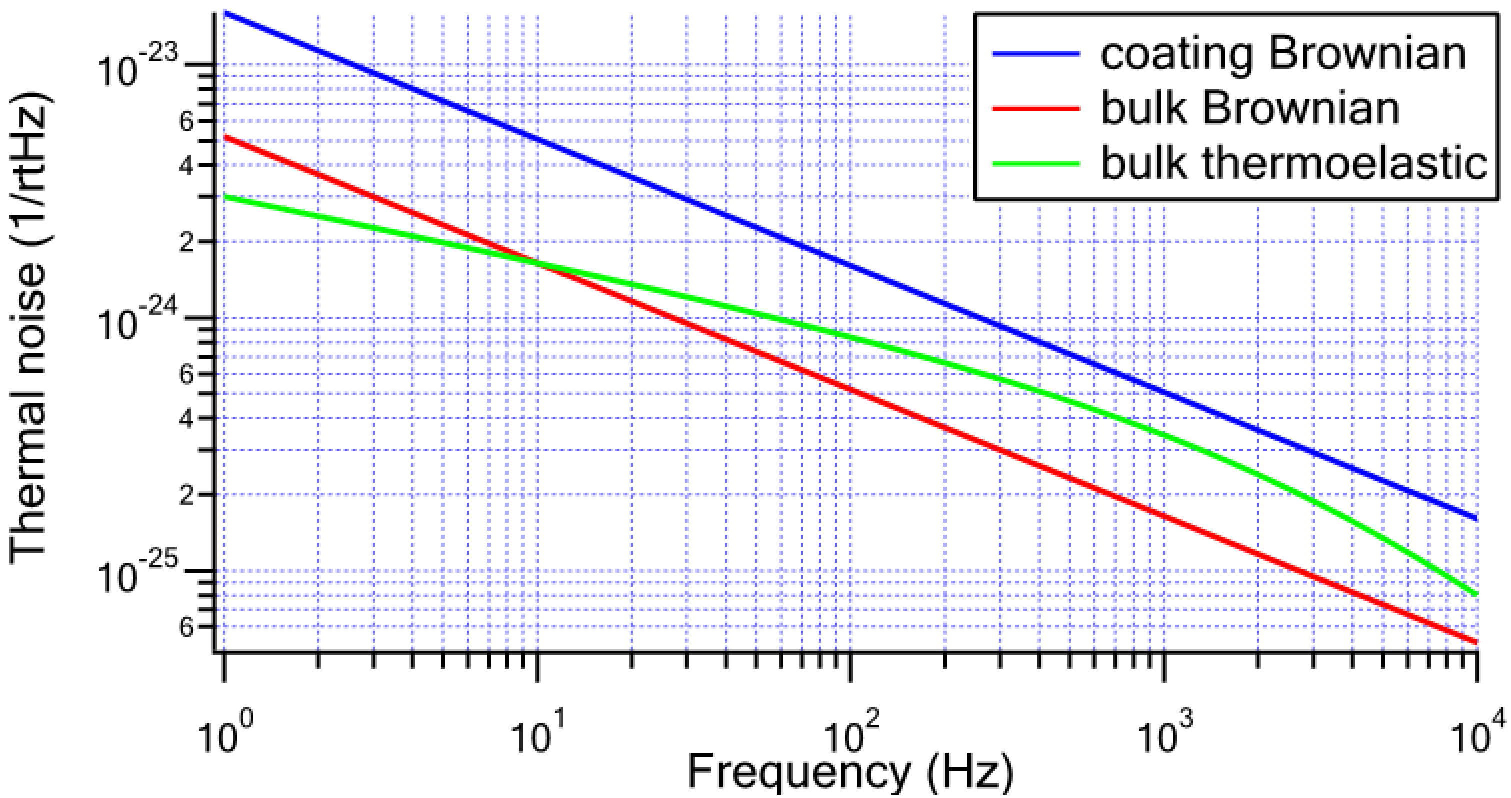
Conclusions

Adv LIGO Noise Budget



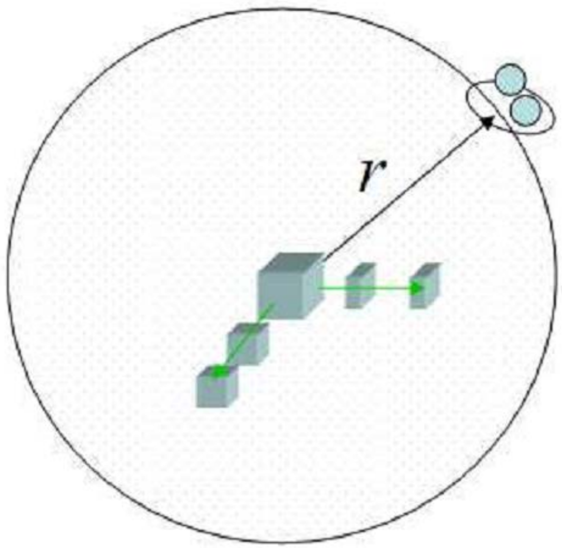
Coating Brownian noise largely dominant in setting noise PSD floor level

KAGRA Mirror Noise Budget



[Courtesy Kentaro Soumiya]

Detector's Range vs Noise PSD



$$r_{max} \propto 1/h_{min}$$

$$h_{min} \propto PSD_{floor}^{1/2}$$

$$r_{max} \propto PSD_{floor}^{-1/2}$$

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

30% less noise PSD means 70% larger visibility volume (& event rate)

Coating (Brownian) Noise PSD

[G. Harry, LIGO-T040029-00-R, 2004]

Boltzmann constant

Absolute temperature

Poisson ratio of substrate

$$S_{\Delta x}^{(B)}(f) = \frac{2k_B T}{\pi^{3/2} f} \frac{(1-\sigma^2)}{wY} \phi_{eff}$$

Beam half-width

Young modulus of substrate

Effective loss - angle of mirror (complicated function of layers' thicknesses, loss-angles, Young moduli & Poisson coeff.s)

Coating (Brownian) Noise PSD

[G. Harry, LIGO-T040029-00-R, 2004]

Boltzmann constant

Reduce temperature
(go cryogenic)

Absolute temperature

Reduce coating loss-angle
(materials & geometry)

Poisson ratio of substrate

$$S_{\Delta x}^{(B)}(f) = \frac{2k_B T}{\pi^{3/2} f} \frac{(1-\sigma^2)}{wY} \phi_{eff}$$

Increase spot size
(mesa beams)

Half-width

Young modulus of substrate

Effective loss - angle of mirror (complicated function of layers' thicknesses, loss-angles, Young moduli & Poisson coeff.s)

Coating Noise PSD, contd.

In the limit of vanishingly small Poisson ratios, the complicated formula for ϕ_c [G. Harry, LIGO-T040029] boils down to a simple linear combination

Optimize the thicknesses

Optimize the materials

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

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

Loss-angle per unit wavelength

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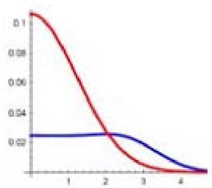
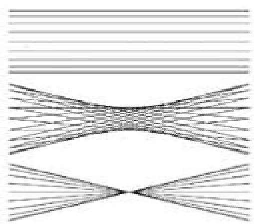


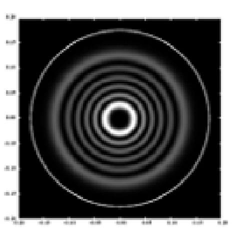
- Mesa-Beams (MB) - Mexican Hat (MH) mirrors

[E. D'Ambrosio, PRD67 (2003) 102004, etc.]. Nearly flat wavefront; **tilt instability** [P. Savov, PRD74 (2006) 082002] ;



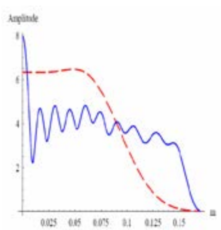
- Hyperboloidal-Beams (& their GL representations)

Family including flat and spherical mirror as limiting cases. [M. Bondarescu and K. Thorne, PRD74 (2006) 082003; V. Galdi et al., PRD73 (2006) 127101; A. Lundgren et al., PRD77 (2008) 042003, etc] ; **no prototype yet ;**



- Higher Order Gauss-Laguerre Modes (HOGL)

[B. Mours et al., CQG 23 (2006) 5777, etc.] spherical mirrors; degeneracy; **strict surface tolerances** [see e.g., C. Bond et al., PRD84, 102002 (2011)] ;



- Bessel Beams (conical mirrors)

[M. Bondarescu et al., PRD78 (2008) 082002], alignment issues expected; **no prototype yet .**

Wide Beams – Bounds

Absolute (exact, variational closed-form) *lower bounds* for coating & substrate noise PSDs obtained (from the unphysical no-diffraction-loss case) via Shough-nessy [CQG 24 (2007) 4491] - Lovelace [CQG 23 (2006) 7627] formalism, and compared to proposed wide beams in [V. Pierro et al., PRD76 (2007) 122003, LIGO-G070308]

.

	$\bar{S}_{SLP} / \bar{S}_{\min}$	$\bar{S}_{MB} / \bar{S}_{\min}$	$\bar{S}_{GB} / \bar{S}_{\min}$
Substrate (Br)	1.145	2.044	2.97
Coating (Br+TE)	1.225	3.227	6.92
Substrate (TE)	1.381	4.455	13.66

Design details

$a = 16cm$

$N_d = \frac{a^2}{L\lambda} = 14$

$\mathcal{L}_T = 1ppm$

$w_{MB} = (N_D)^{-1/2}$

Slepian - Landau - Pollack (SLP) synthetized beam (closest to Bessel beam)

Mesa Beam

Gaussian Beam

... *large* margin for noise reduction !!!

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From QWL to Optimized

Educated ignorance attitude

- *no a-priori assumption* on structure;
- easy inclusion of heterogeneous design constraints;

GA - engineered minimum noise *binary* coatings show trend toward non - QWL quasi - Bragg ($z_L + z_H = 0.5$) stacked-doublet (SD) configurations;

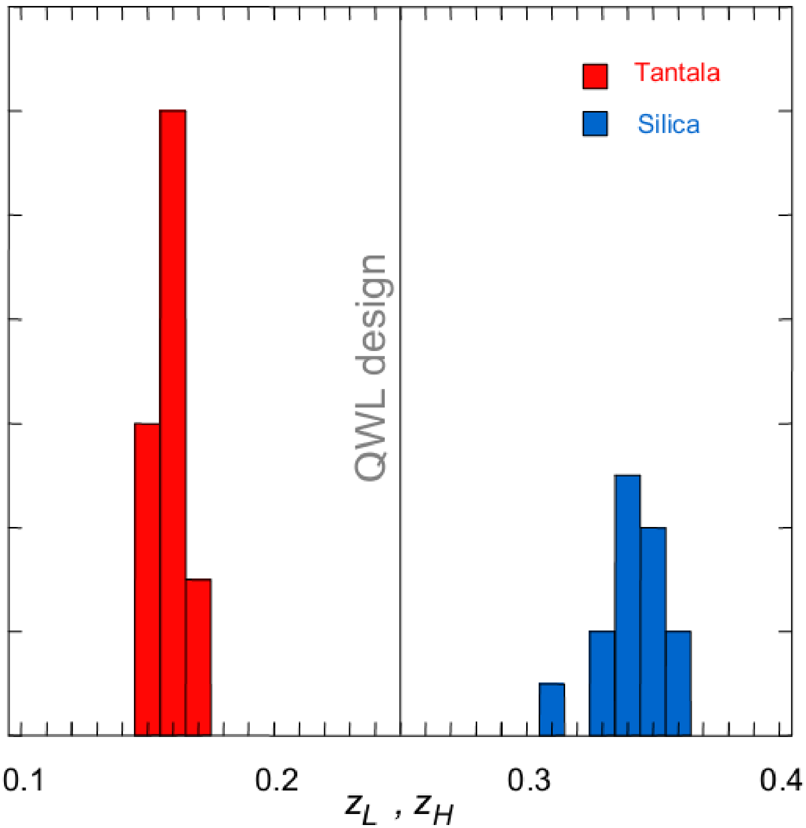
Deviations from trend are confined to fewest end - layers (first, last);

Suggests sequential design recipe :

a) Design minimum-noise SD;
b) Tweak terminal layers;

[I. Pinto et al., LIGO-G080082]

GA-optimized 20ppm transmittance prototype. z_L and z_H histograms after 10^4 generations.



Thickness Optimization Recipe

1) Start with the standard QWL design with reflectance R, consisting of N_0 QWL doublets, and featuring a loss angle ϕ_{QWL};

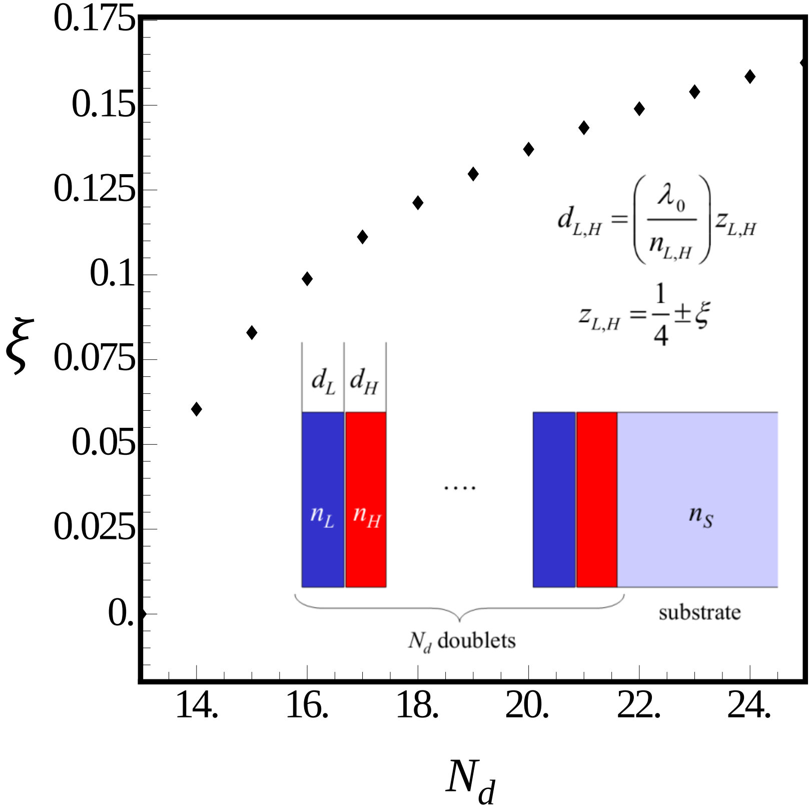
2) Add one doublet to the coating, and reduce the thickness of the Tantala layers while increasing the thickness of the Silica layers, so as to keep $z_L + z_H = 1/2$, until the prescribed R is recovered. Calculate the loss angle of the coating;

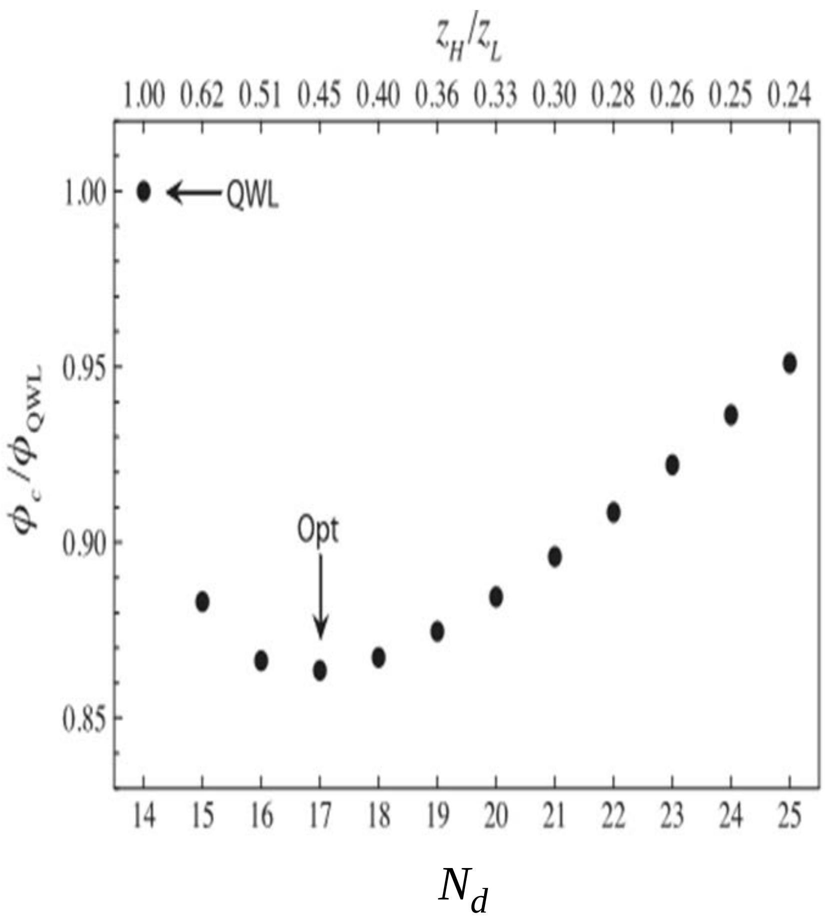
3) Repeat step 2 until the minimal loss angle is reached (stop when the loss angle starts to grow);

4) Tweak the top (silica) layer to maximize reflectance; tweak the bottom (Tantala) layer to bring back R to its prescribed value.

[A. Villar et al., PRD 81 (2008) 122001]

Optimized Stacked Doublets





[I Pinto et al., Ch. 12 in *Optical Coatings for Precision Measurements,* G. Harry et al. Eds., Cambridge Univ. Press, 2012]

Thickness Optimization Results

- Generalization to *dichroic* mirror relatively straightforward, yielding non-HWL stacked doublet designs. [M. Principe and I. Pinto, LIGO-T080337].

- Thickness-optimized coating prototypes using both plain (single wavelength) and TiO_2 doped Tantala (dichroic) were manufactured by LMA and tested at Caltech TNI. Measured coating loss was in excellent agreement with model. [A. Villar et al., PRD81 (2010) 122001]

- Optimized design nicely robust against uncertainties in the η_H/η_H ratio and layer deposition tolerances [I. Pinto, LIGO-G080082].

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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.

Optimizing Coating Materials

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].

Glassy Mixture Modeling and optimization:

Microscopic approach (reduced density function, molecular modeling, asymmetric double well potentials) – link between atomic structure, doping/annealing treatments , and viscoelastic properties [H.P. Cheng, LIGO-G1300390, R. Bassiri et al., LIGO-G1300379]

Mesoscopic approach based on effective medium theories [D.E. Aspnes, Am. J.Phys., 50 (1982) 707] – composite material properties [I.M. Pinto et al., LIGO-G1100372]

EMT: Bruggemann Formula

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

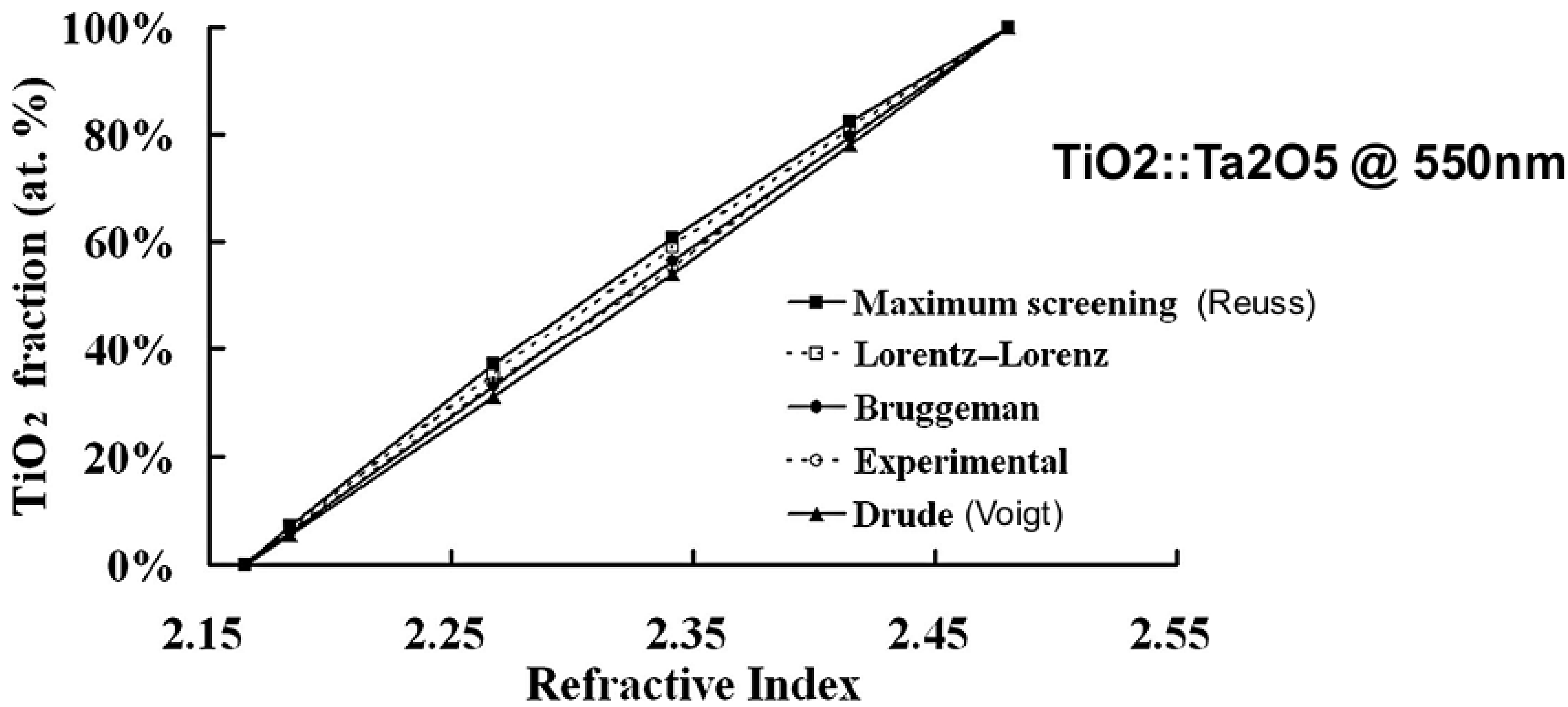
$$\left\{\begin{array}{l} (1-\eta_2)\dfrac{X-X_1}{2X+(X_1/y_1)(\sigma_1+1)}+\eta_2\dfrac{X-X_2}{2X+(X_2/y_2)(\sigma_2+1)}=0 \\ \\ (1-\eta_2)\dfrac{(X/y)-(X_1/y_1)}{2X+(X_1/y_1)(\sigma_1+1)}+\eta_2\dfrac{(X/y)-(X_2/y_2)}{2X+(X_2/y_2)(\sigma_2+1)}=0 \end{array}\right. ,$$

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

System can be solved in closed form . [S. Barta, J. Appl. Phys. 75 (1994) 3258]

[I. Pinto et al., LIGO-G1100372]

Bruggemann Formula for n

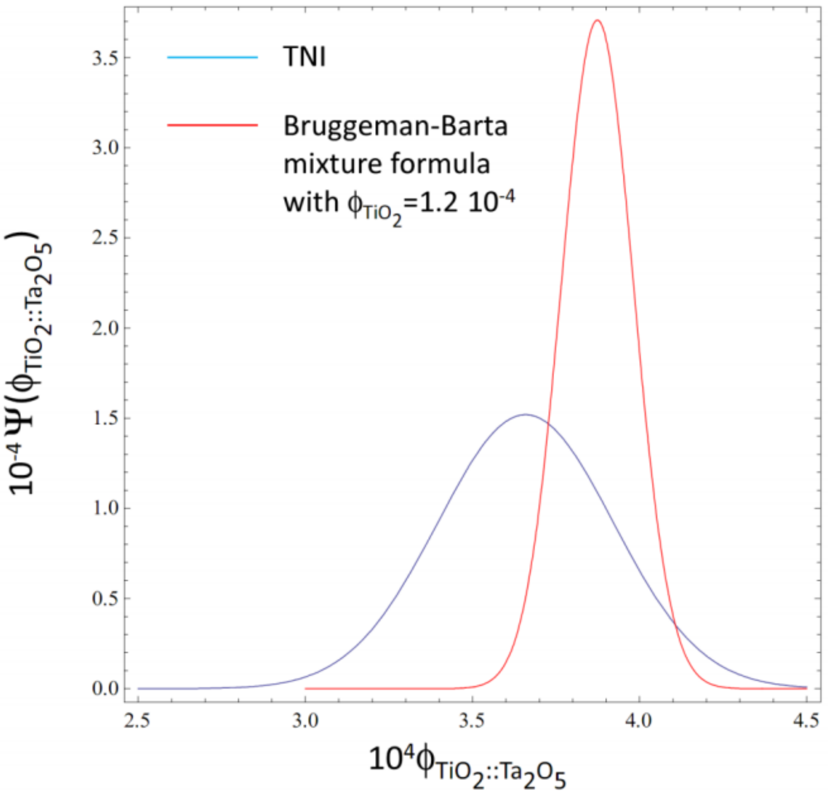


C.C. Lee, C.J. Tang, Appl. Opt., 45, 9125 [2006]

EMT Prediction vs TNI Data

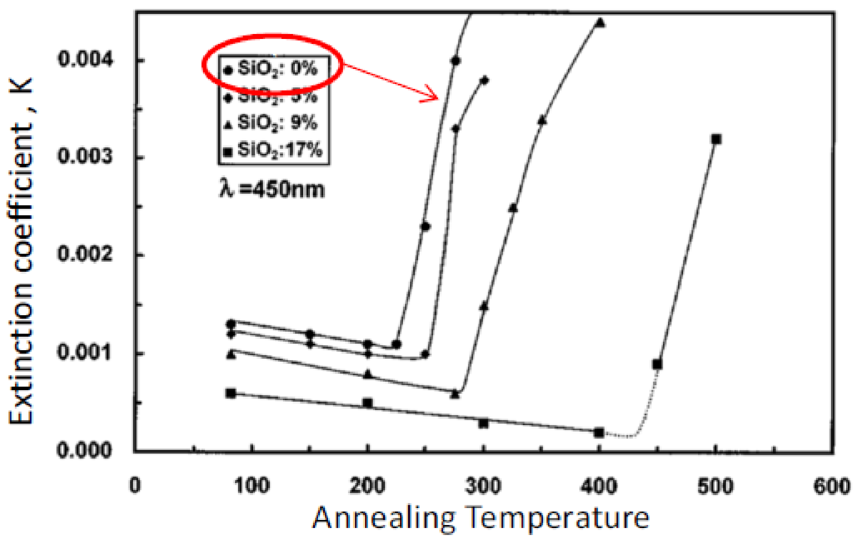
TNI : distribution of doped Tantala loss angle deduced from TNI measurements on doped Tantala prototype coatings;

Bruggemann-Barta: distribution of doped Tantala loss angle obtained from EMT using Scott-MacCrone value for Titania loss angle ($1.4\ 10^{-4}$) and the distribution of plain Tantala loss angle deduced from TNI measurements on plain Tantala prototype coatings.



Silica Doped Titania

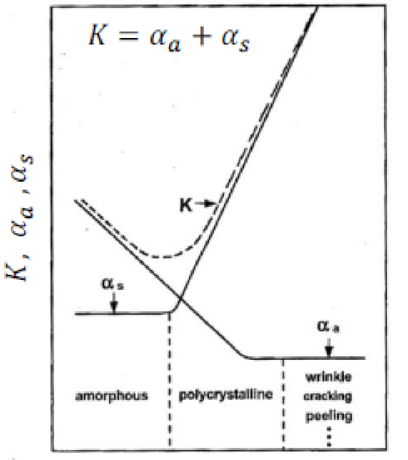
QWL TiO2 film



[W.H. Wang and S. Chao, Opt. Lett. 23 (1998) 1417.
S. Chao et al., JOSA A16 (1999) 1477
S. Chao, W.H. Wang, C.C. Lee, Appl. Opt 40(2001) 2177]

- *Thick* TiO_2 *crystallizes* upon annealing above ~ 200ºC, signaled by blow-up of optical extinction coefficient;
- *Mechanical losses* blow up in parallel;
- *Can be mitigated doping* TiO_2 w. SiO_2 (cosputtered);
- Related to *growth of crystallites* formed during deposition...

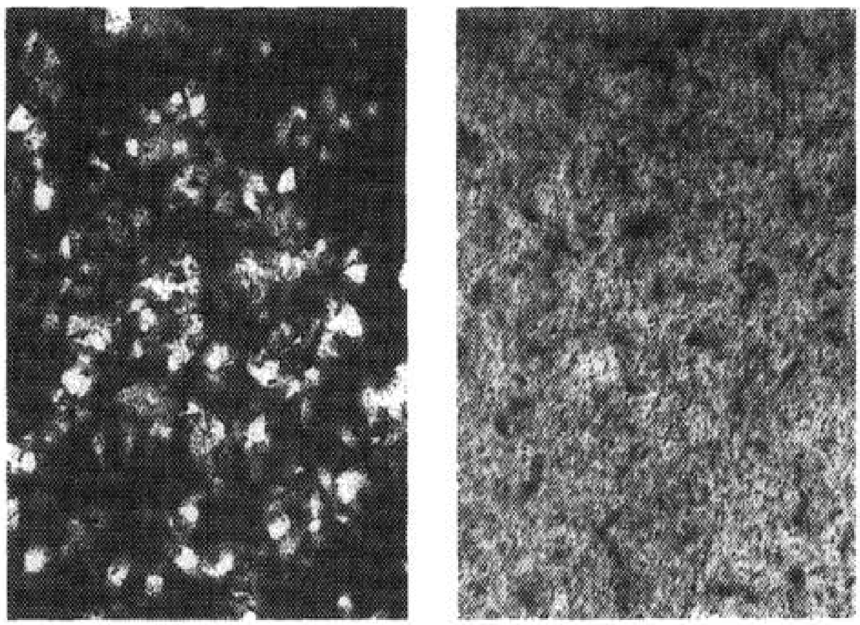
Extinction coefficient , K
Absorption coefficient , α_a
Scattering coefficient , α_s



Annealing Temp.

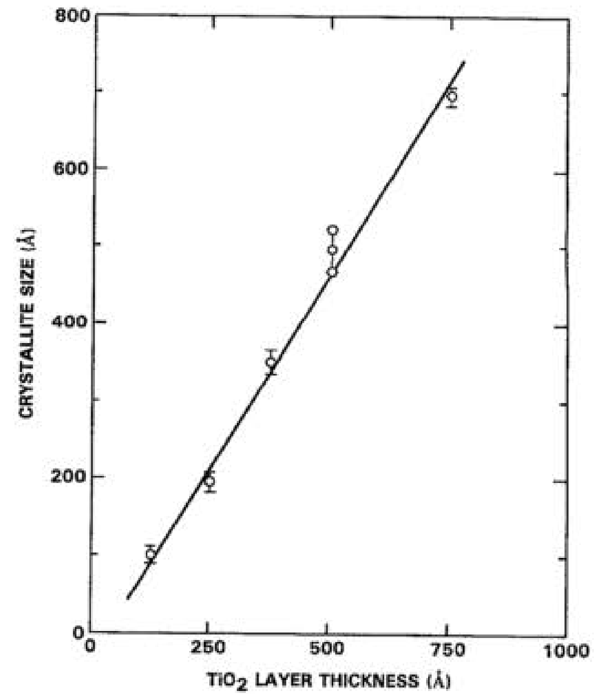
SiO_2::TiO_2 , contd.

The *maximum annealing temperature* above which TiO_2 crystallizes *increases* by *increasing SiO_2 content* (co-sputtered SiO_2::TiO_2 mixtures) and/or *decreasing TiO_2 thickness* (layered SiO2::TiO2 mixtures).



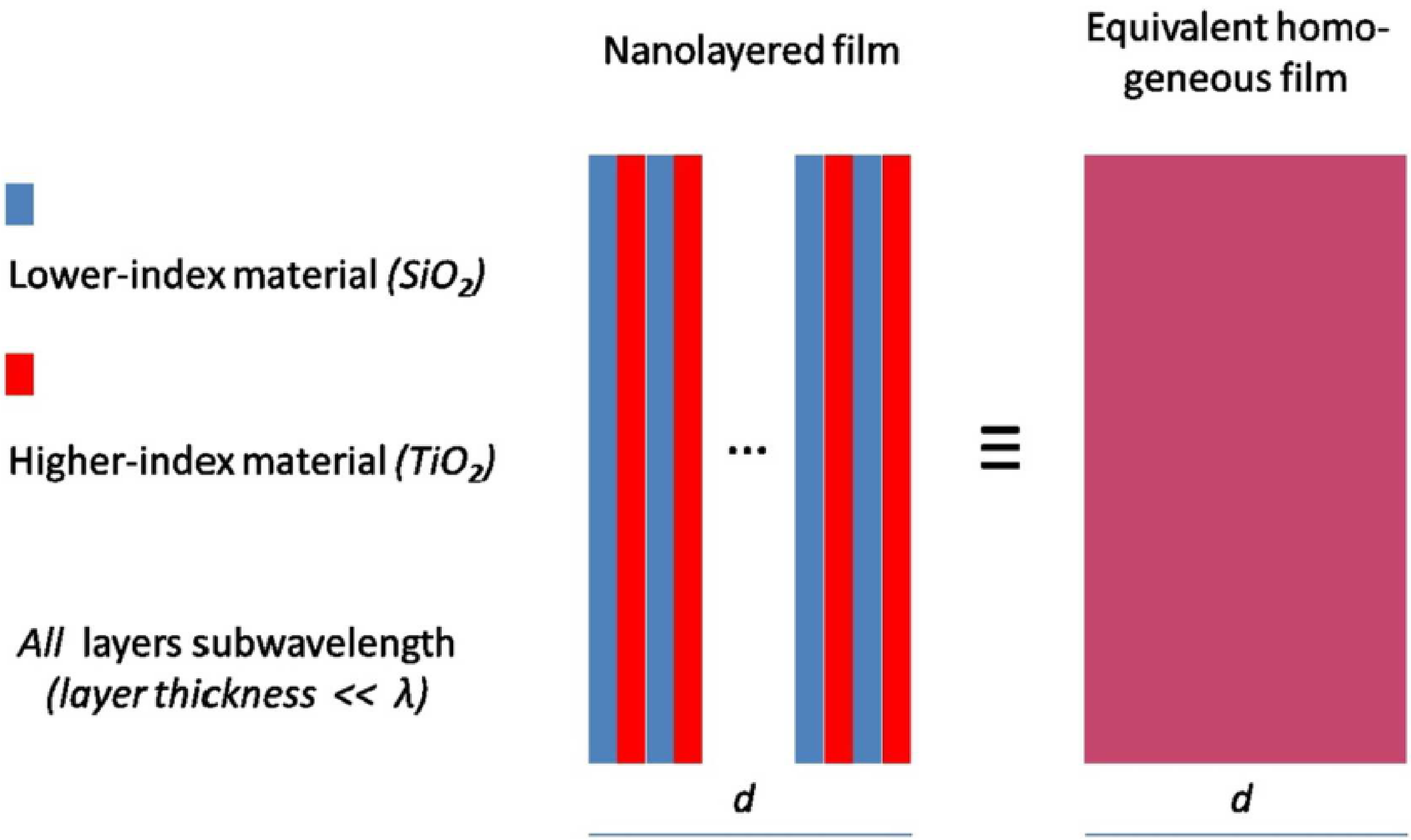
(a) 1 μm (b) 1 μm

[H. Sankur and G. Gunning, J. Appl. Phys. 66 (1989) 4747]



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

nm - Layered Mixture Modeling



All layers subwavelength
(layer thickness << λ)

nm - Layered Mixture Modeling

nanometer ➡ subwavelengh thick

$$n_f = \left[r_H n_H^2 + (1 - r_H) n_L^2\right]^{1/2}$$

$$Y_f^{\perp} = \left[r_H / Y_H + (1 - r_H)/Y_L\right]^{-1} \quad , \qquad r_H = \frac{z_H}{z_L + z_H}$$

$$Y_f^{||} = r_H Y_H + (1 - r_H) Y_L$$

$z_{L,H}$ = physical thickness of L/H index material

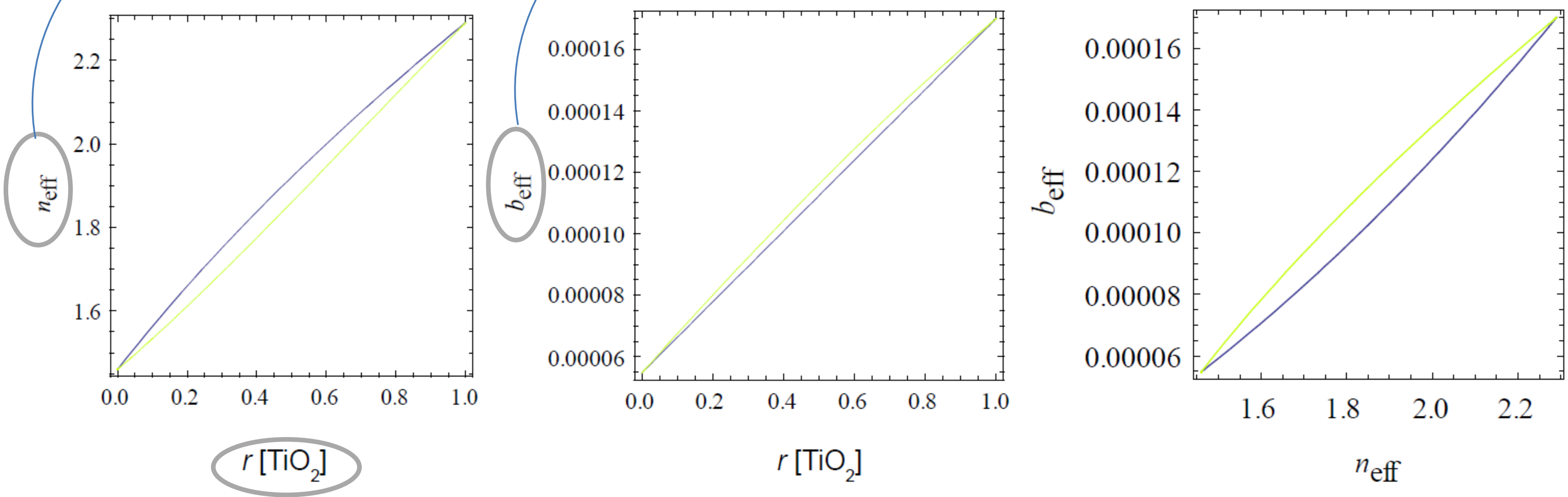
$$\phi_f = \frac{\left(\frac{Y_s}{Y_H} + \frac{Y_H}{Y_s}\right) r_H \phi_H + \left(\frac{Y_s}{Y_L} + \frac{Y_L}{Y_s}\right)(1 - r_H)\phi_L}{Y_s\left[r_H/Y_H + (1 - r_H)/Y_L\right] + Y_s^{-1}\left[r_H/Y_H + (1 - r_H)/Y_L\right]^{-1}}$$

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

Cosputtered vs nm-Layered SiO_2::TiO_2

refractive index

measures "noisyness" per unit thickness

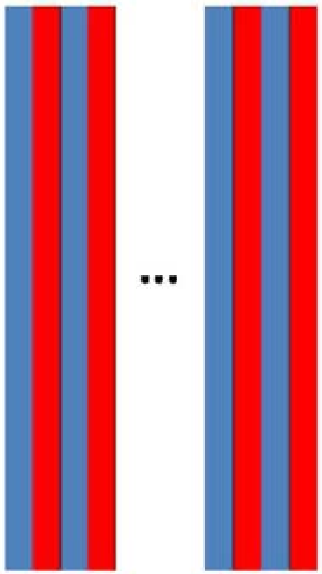


volume fraction of Titania

cosputtered

nm-layered

Isorefractive nm-Layered Designs



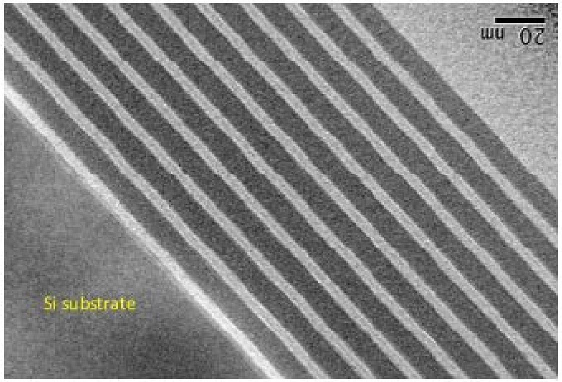
Number of nanolayers

N TiO2	Thickness TiO2 [nm]	N SiO2	Thickness SiO2[nm]
2	42.56	1	42.15
3	28.37	2	21.07
4	21.28	3	14.05
5	17.02	4	10.54
6	14.19	5	8.43
7	12.16	6	7.02
8	10.64	7	6.02
9	9.46	8	5.27
10	8.51	9	4.68

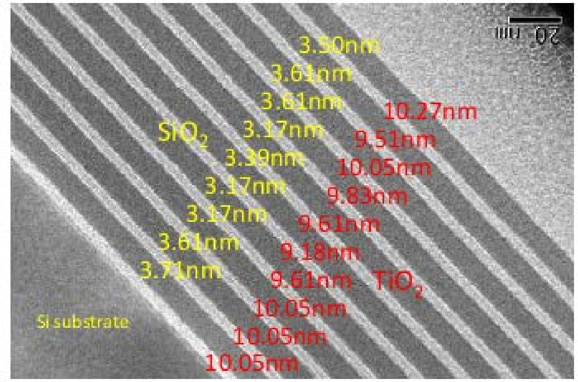
All designs share the same refractive index, and optical (QWL@1064nm) thickness, but expectedly *different* loss angles, due to different crystallite concentration.
Accuracy in *single* layer thicknesses nor critical, provided thickness *fractions* are OK…

Prototypes (NTHU)

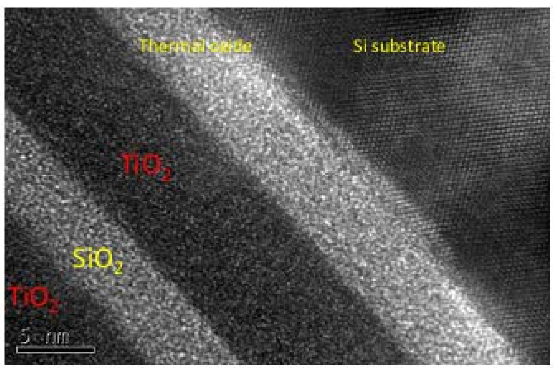
Nano-layer sample #2 TEM pictures



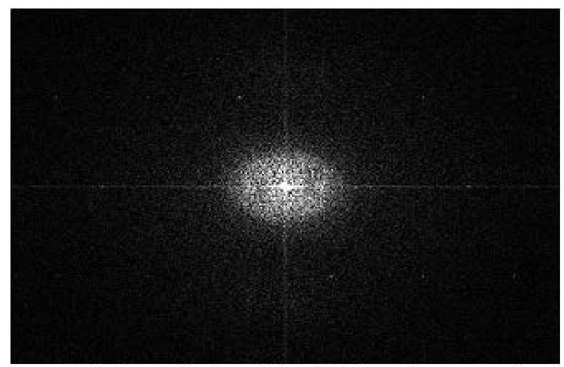
Sample #2



Sample #2 with thickness



close-up view of the layer interfaces

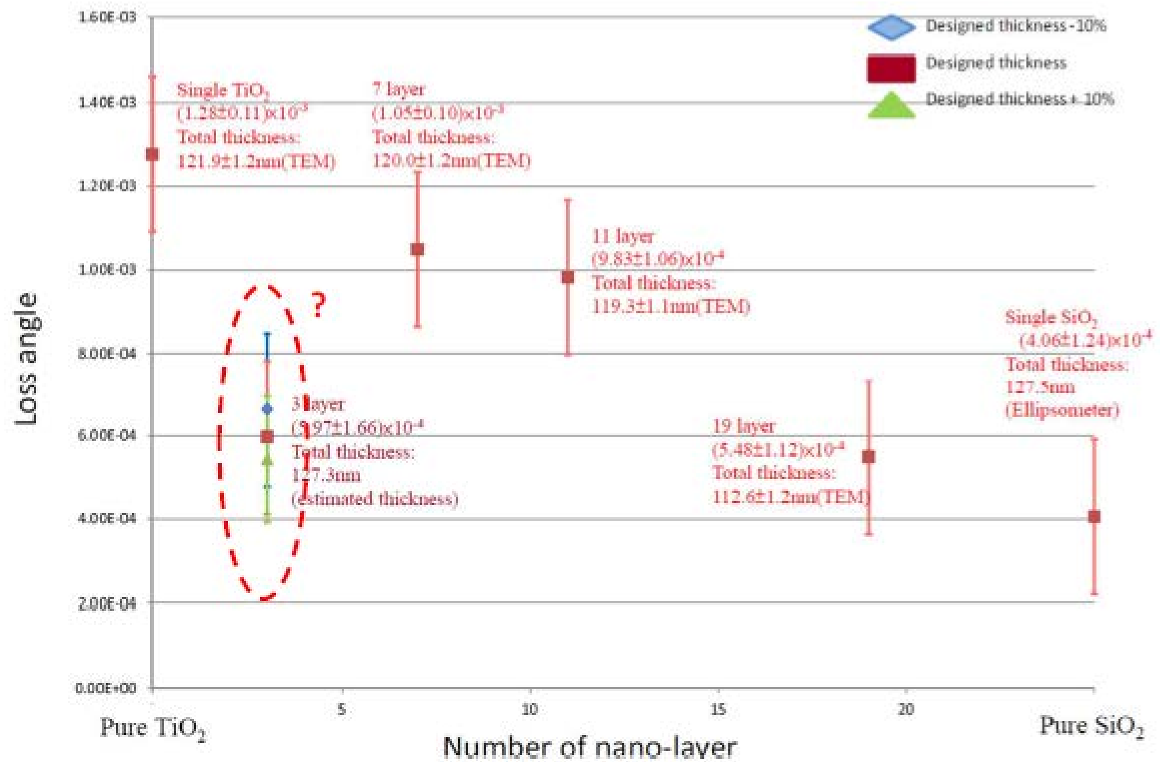


Electron diffraction pattern of the layers (amorphous)

[S. Chao et al., LIGO-G1200849]

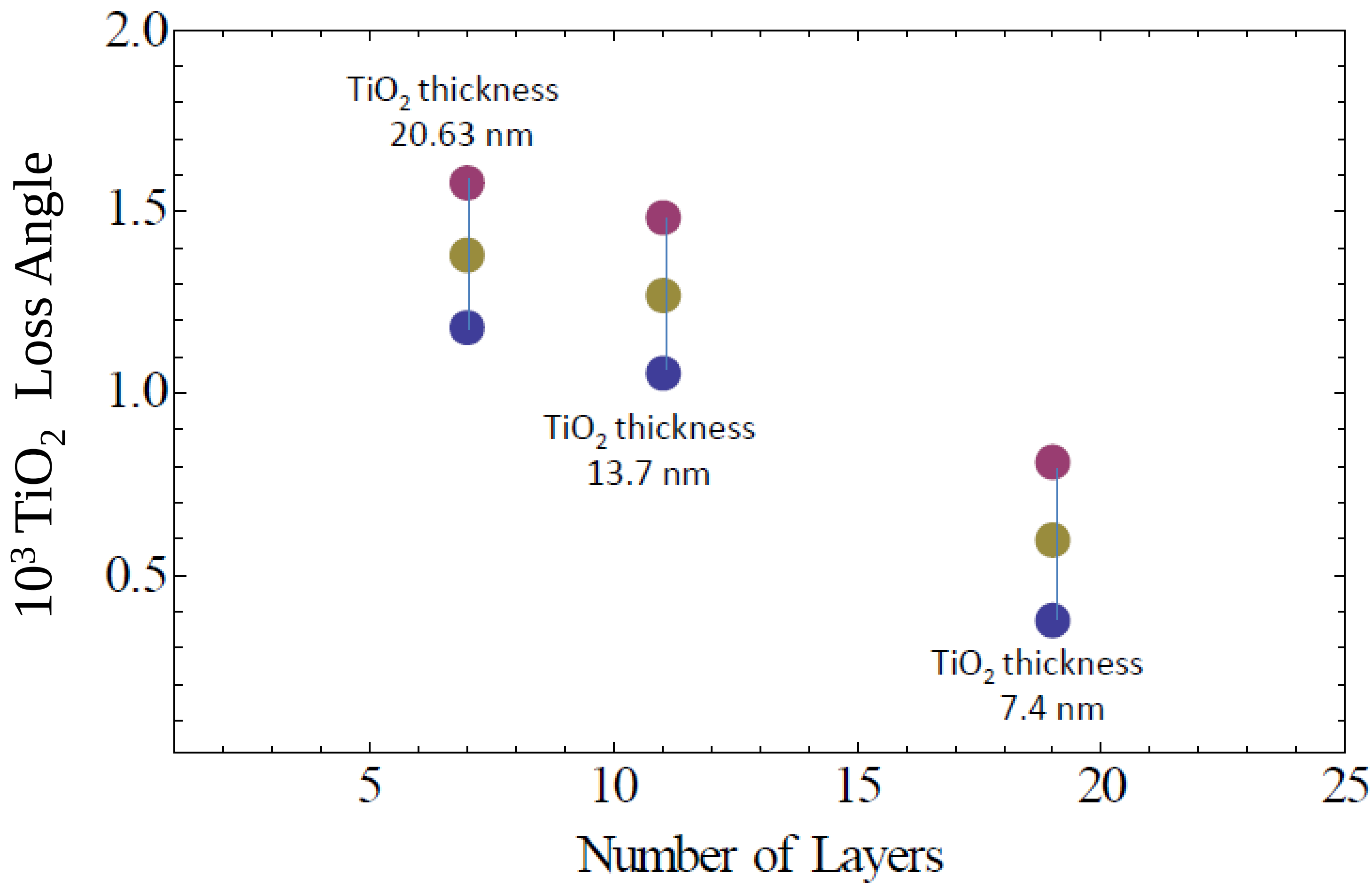
Deposition quality better than expected
No evidence of crystallite formation from XRD

Prototype Characterization (NTHU)



[S. Chao et al., LIGO-G1200849]

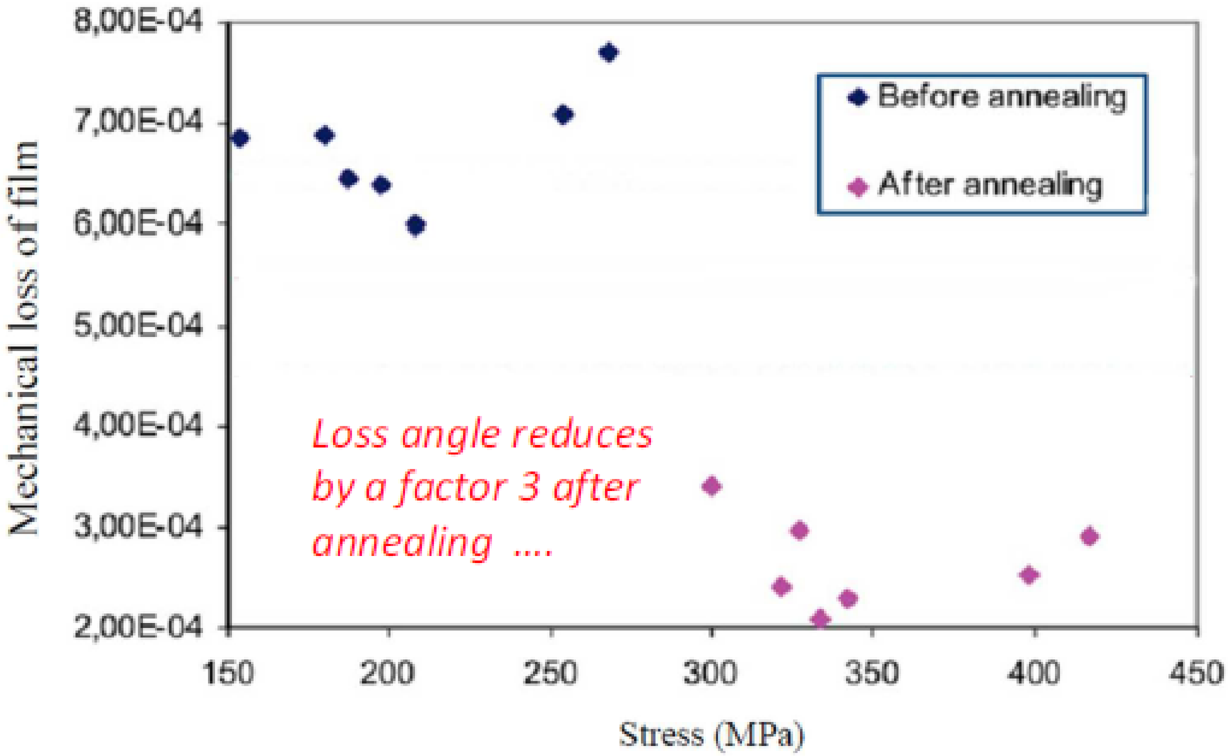
Prototype Characterization (NTHU)



[I. Pinto et al., LIGO-G1300321]

Prototype Characterization (NTHU)

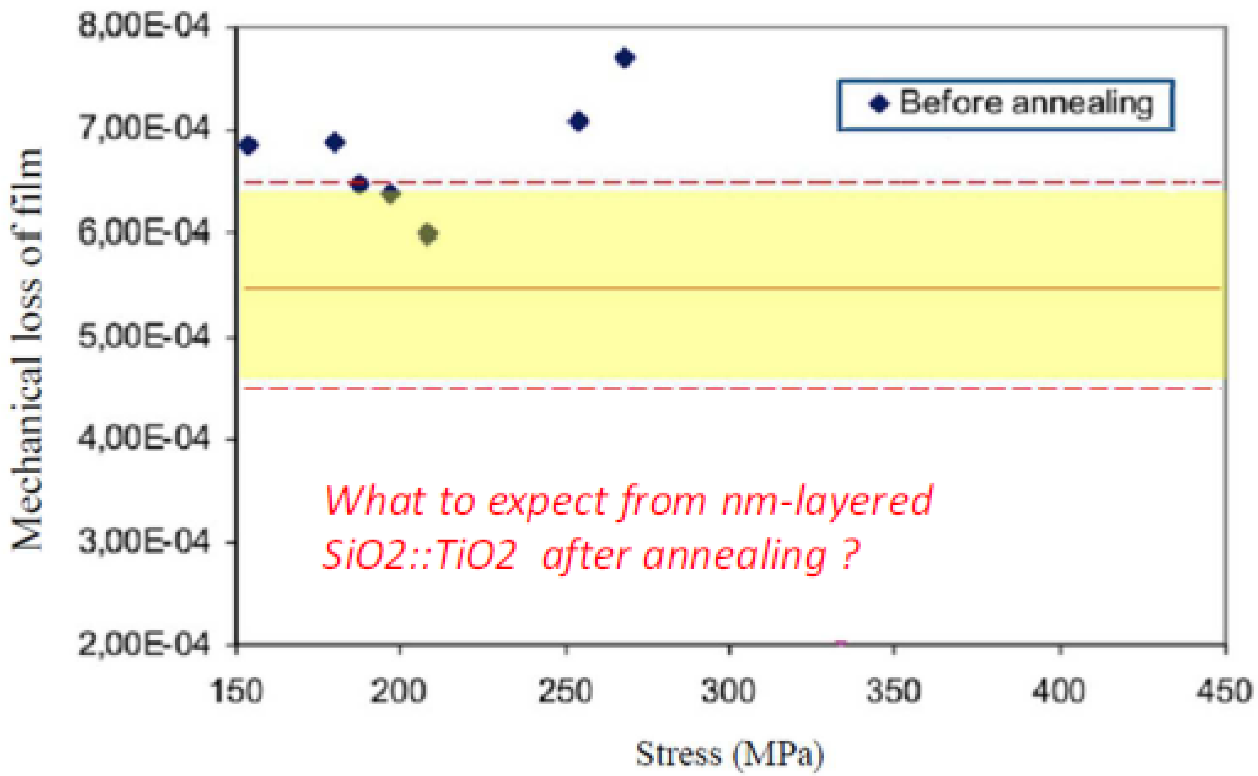
TiO_2::Ta_2O_5 film prototypes (LMA "formula 5") and related stresses



Prototype Characterization (NTHU)

Un-annealed $TiO_2::Ta_2O_5$ film prototypes (LMA “formula 5”) and related stresses

... uncertainty strip of 19-nanolayers isorefractive TiO2::SiO2 film prototype



16 layer (nm) $SiO_2::TiO_2$ film w. same index as $TiO_2::Ta_2O_5$

Further Coating Material Research

Silicon/Silica Coatings

Silicon is candidate for the ET substrate. Operation at 1550 nm.
Silicon has large(r) contrast against SiO_2 compared to TiO_2::Ta_2O_5
(6 x Si/SiO_2 doublets same reflectivity as 15 x SiO_2 / TiO_2::Ta_2O_5
Silicon better than TiO_2::Ta_2O_5 at cryo temperatures than TiO_2::Ta_2O_5

[K. Craig, Elites Meeting October 2012]

Crystalline Coatings

AlGaAs/GaAs bonded to Silicon
AlGaAs/GaAs epitaxially integrated via graded GaP buffer layer
AlGaP/GaP epitaxially integrated into Si
study of loss relationship to lattice defects

[A.C. Lin, et al., LIGO-G1300268]

… and more

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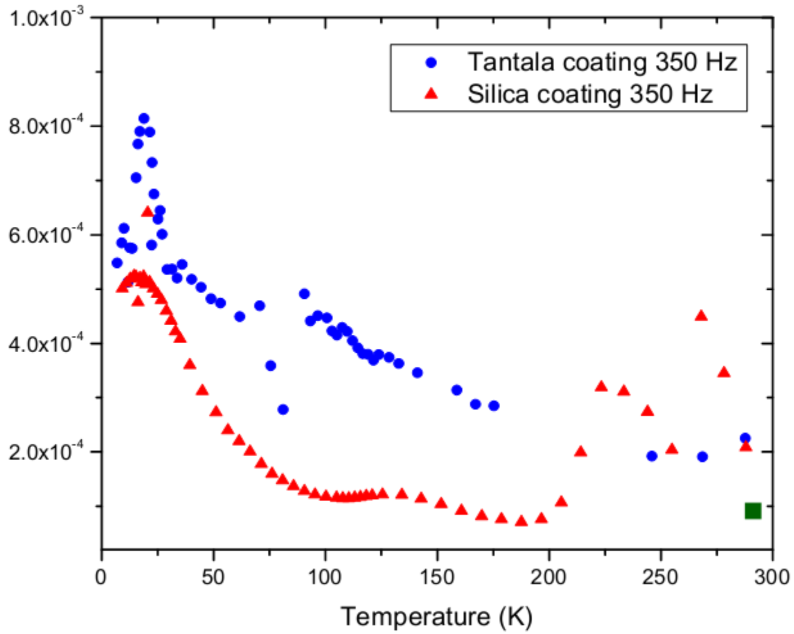
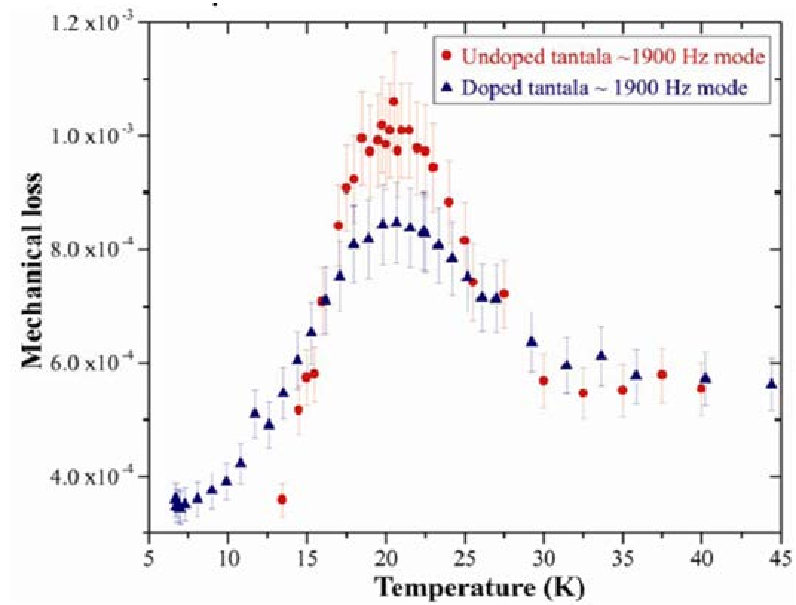
The Cryogenic Loss Peak



Cryogenic peak in the range 10-20 K observ-ed in many glassy oxides, including Silica and Tantala (plain as well as TiO_2 doped).

Ti-doped Tantala slightly better compared to plain Tantala.

[I. Martin et al., LIGO-G080313]

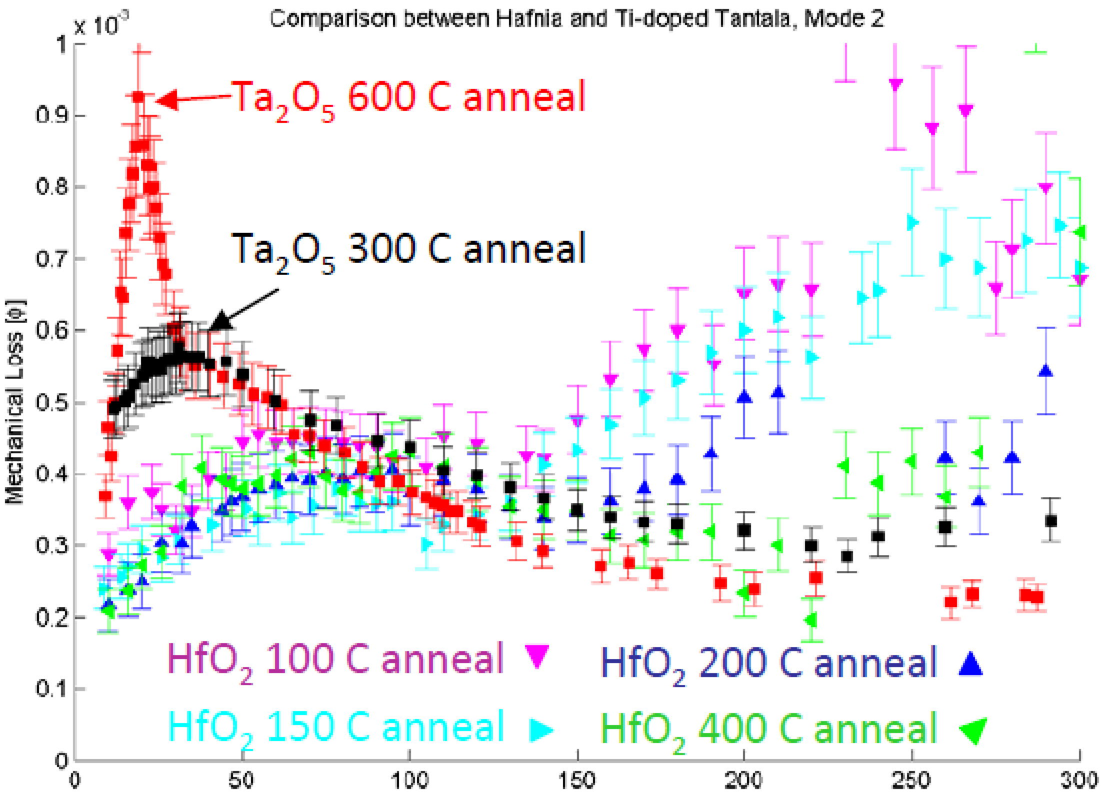


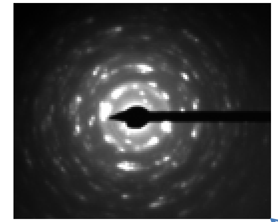
Consistent with a (spectrum of) therm-ally activated relaxation processes, with

$$\phi(\omega) \propto \frac{\omega\tau}{1+(\omega\tau)^2}\ , \ \tau^{-1} = \tau_0^{-1}\, e^{-\frac{E_a}{k_B T}}$$

[I. Martin et al., CQG 25 (2008) 055005]

Hafnia





Even if prone to crystallization Hafnia has a *lower* loss angle compared to Titania doped Tantala at cryo - temperatures and has been indicated as a possible substitute, for cryo-genic operation …

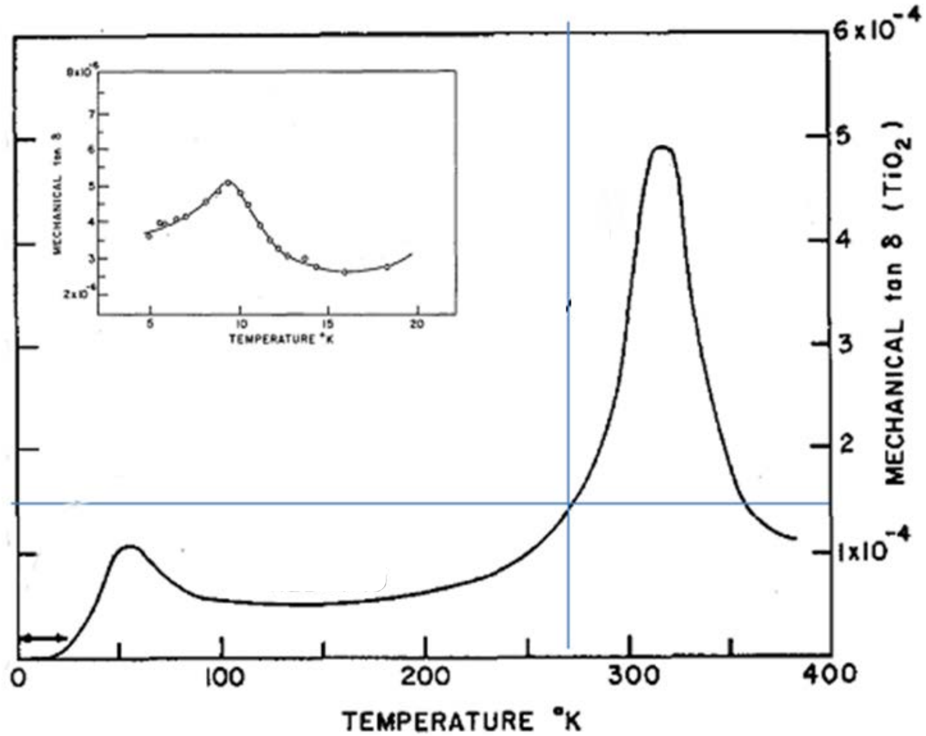
[M. Abernathy et al., CQG 28 (2011) 195017]

Titania

Results in [Scott and MacCrone, Rev. Sci. Instr. 39 (1968) 821] suggest that Titania may be similarly exempt from a cryogenic loss angle peak…

(warning: *no* recent loss angle meas-urements available for TiO_2 in the cryogenic regime is available, to the best of our knowledge)….

Titania has the *largest refractive index* (n ≈ 2.3) among all candidate glassy oxides for optical coatings



Back to Hafnia

Similar to Titania,

Silica doping *stabilizes* Hafnia against *crystallization* [Z. Ushakov et al., Phys. Stat. Sol. B241 (2004) 2268].

Silica doped Hafnia mixtures (at fixed thickness) allow for *higher annealing temperatures* before crystallization sets in [K. Craig, LIGO-G1300256].

Silica has long since been credited to acts as a stabilizing (buffering) dopant against crystallization for a variety of glassy oxides [S. Pond, Appl. Optics, 28 (1989) 2800)].

Nanometer-layered Hafnia (12nm)/Alumina (3nm) composites do not crystallize upon annealing up to temperatures of 800 ^{o}C [M. Liu et al., Appl. Surf. Sci. 252 (2006) 6206].

Silica Doped Hafnia/Titania for ET & KAGRA ?

The above suggests that Silica doped Hafnia and Silica doped Titania could be possible low/high index materials for cryogenic coatings.

By changing the dopant fractions, the dielectric contrast between the doped materials can be tuned (e.g., made equal to Tantala/Silica).

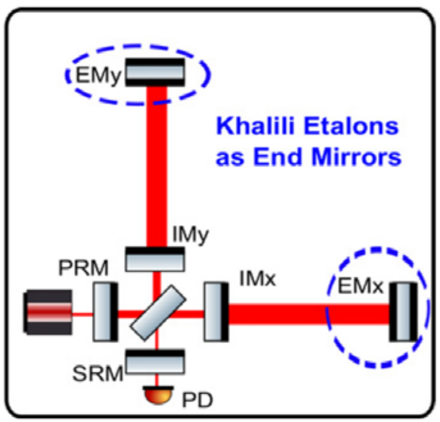
Effective medium theory suggests that nanometer layered mixtures would have smaller loss angles compared to co-sputtered mixtures having the same refractive index.

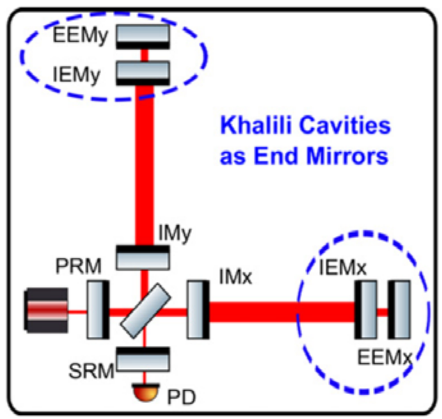
Plan for funding application to test nm-layered material properties in the cryogenic regime [University of Sannio & NTHU].

Resonator Mirrors

Khalili *etalon* [A.G. Gurkovski et al., Phys. Lett. A375 (2011) 4147]. Test mass mirrors are replaced by short solid FP resonators, with coating layers on both faces; bottom-face coating contributes negligibly to thermal noise. No working prototype yet.

Improved version of Khalili *resonator* with *suspended* terminal mirrors. [F. Khalili, Phys. Lett. A334 (2004) 67], featuring severe suspension & alignment/control issues [K. Somiya, Phys. Rev. Lett. 102 (2009) 230801].





[AEI, Glasgow, Jena Moscow, Tokyo]

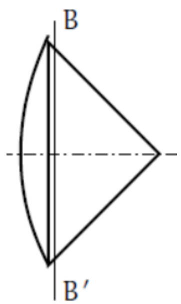
Khalili etalons could be designed so as to act also as h.o. (LG) *mode selectors* [G. Castaldi and V. Galdi (2012) yet unpublished, USannio]

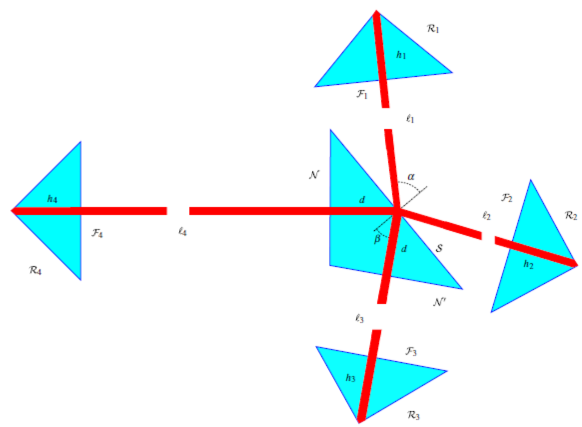
Coating Free Mirrors

Earliest suggestion by Braginsky and Vyatchanin [Phys Lett A324 (2004) 345] , corner reflectors + lens, thin AR coating (a). Edge diffraction issues; thermo elastic noise.

Broader/deeper discussion by Giazotto and Cella [PRD 74 (2006) 042001] , multi-prism based configurations (b). Strict geometric and bulk homogeneity tolerances. Non-monolithic design.

First experimental results in Goβler et al. [PRD 76 (2007) 053810]. Small scale working prototype w. R≈0.99. Monolithic design, total internal reflection + Brewster angle coupling (c). Polarization sensitivity issues.





[ANU, Moscow, Pisa]

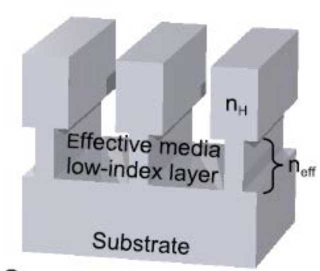
Diffractive Mirrors

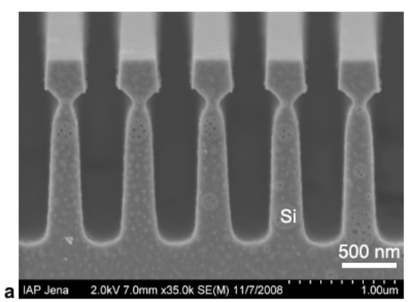
Monolithic (possibly monocristalline) T-ridge based grating reflector prototype built [F. Bruckner et al., Opt. Lett. 33 (2008) 264]. Operation demonstrated w. R ≈ 99.8 @1550nm (normal incidence) [F. Bruckner et al., Phys. Rev. Lett. 104 (2010) 163903]. 2D grating; polarization dependent response; edge scatter.

Earliest suggestion in [G.A. Gunkovski et al., CQG 23 (2006) 7297] based on plain ray-optical analysis from [A. Sharon et al., JOSA A14 (1997) 2245].

Full wave (modal) math modeling available [M.Moharam et al., JOSA A5 (995) 1068];

Thermal noise model implemented [D. Heinert et al., LIGO P-1300034 (2013)]; possible noise reduction by a factor of ≈ 10 compared to coatings ?





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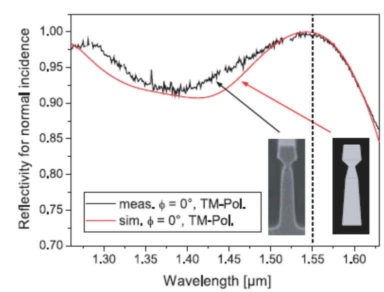

[AEI, Hannover, Jena, Glasgow]

Conclusions

- Many R&D directions for coating noise reduction;
- Thickness optimization well understood and tested;
- Beam and material optimization ongoing along several lines; time will tell;
- Crystalline coatings could be a breakthrough;
- The cryogenic peak issue is fundamental for 3rd generation detectors. Si-doped or nm-layered Si-buffered Hafnia and Titania look promising, as well as Si/SiO_2 ;
- Coating-free and diffractive mirrors may be an option for the future.

ありがとうございました

Grazie per l'attenzione

Thanks for your attention