LIGO-G1902307

Nanolayers Re-Thought

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Outlook

- Coating Materials – the Titania Paradigm
- Goal and Background
- A QWL HR-Coating
- Modeling
- Questions
- Selecting Nanocomposite Materials
- Simulation Algorithm
- Selecting Nanocomposite Designs
- Selection Winners
- Deposition Accuracy and Robustness
- Conclusions

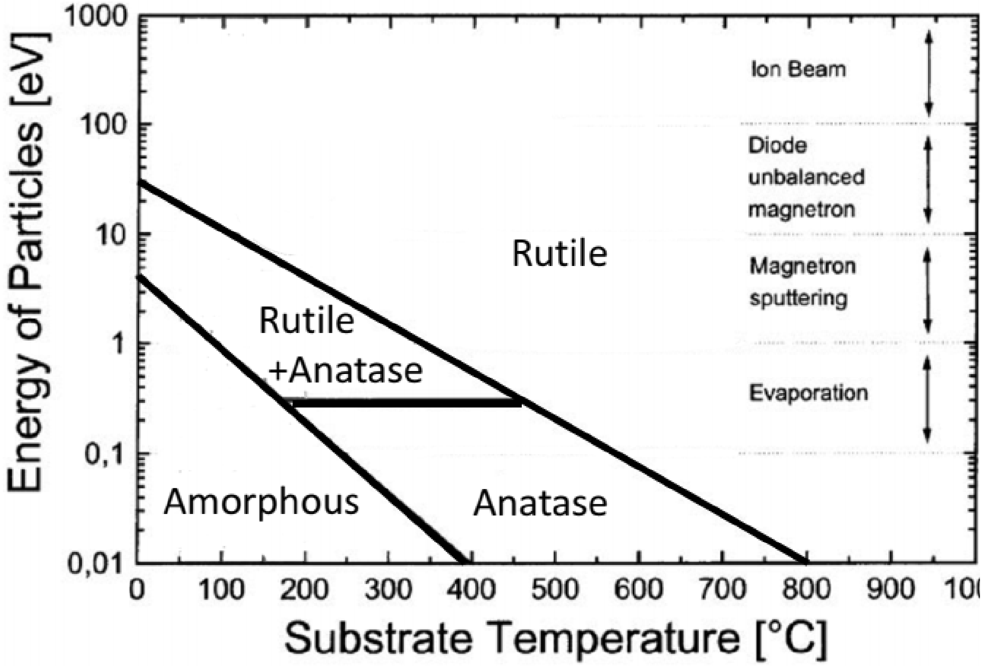
Coating Materials (Amorphous)

	n @ 1064nm	k @ 1064nm	Y [Gpa]	ϕ	ν
SiO_2	1.4496 (1)	uncertain	72 (2)	$5.0 \cdot 10^{-5}$ (2,3)	0.17 (2)
Al_2O_3	1.7545 (1)	uncertain	210 (2)	$2.4 \cdot 10^{-4}$ (2)	0.22 (2)
Ta_2O_5	2.0760 (1)	uncertain	140 (2)	$4.72 \cdot 10^{-4}$ (3)	0.23 (2)
HfO_2	2.0813 (1)	uncertain	380 (2)	$5.9 \cdot 10^{-4}$ (2)	0.2 (2)
ZrO_2	2.1224 (1)	uncertain	200 (2)	$2.3 \cdot 10^{-4}$ (2)	0.27 (2)
Nb_2O_5	2.2537 (1)	uncertain	68 (2)	$4.6 \cdot 10^{-4}$ (2)	0.20 (2)
TiO_2	2.4789 (1)	uncertain	165 (3)	$1.4 \cdot 10^{-4}$ (3)	0.28 (2)

(1) https://refractiveindex.info/
(2) Franc et al., ET-021-09 (2009), arxiv/papers/0912/0912.0107.pdf;
    Flaminio et al., CQG 27 (2010) 083030
(3) Principe et al., Phys. Rev. D81 (2015) 022005
    (consistent with Scott and MacKrone, Rev. Sci. Instr. 39 (1968) 821)

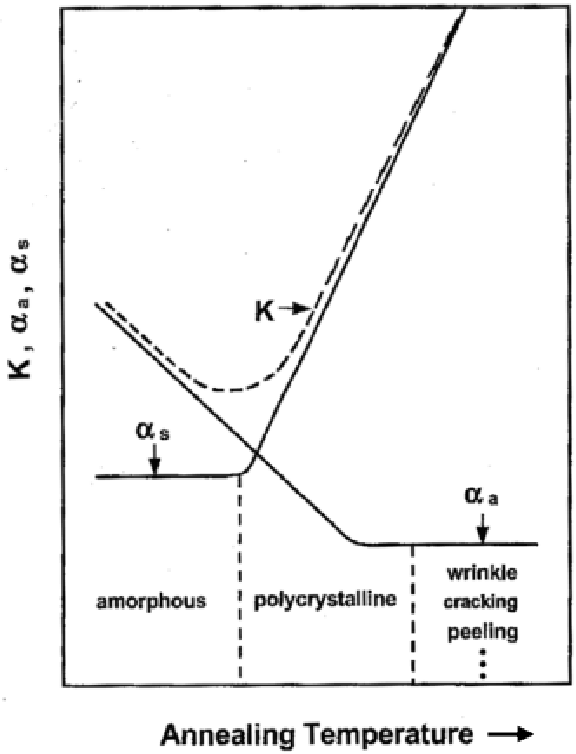
See also:
    Granata et al., Phys. Rev. D93 (2016) 012007
    Vajente, LIGO-G1900400

Crystalization – the Titania Paradigm



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

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

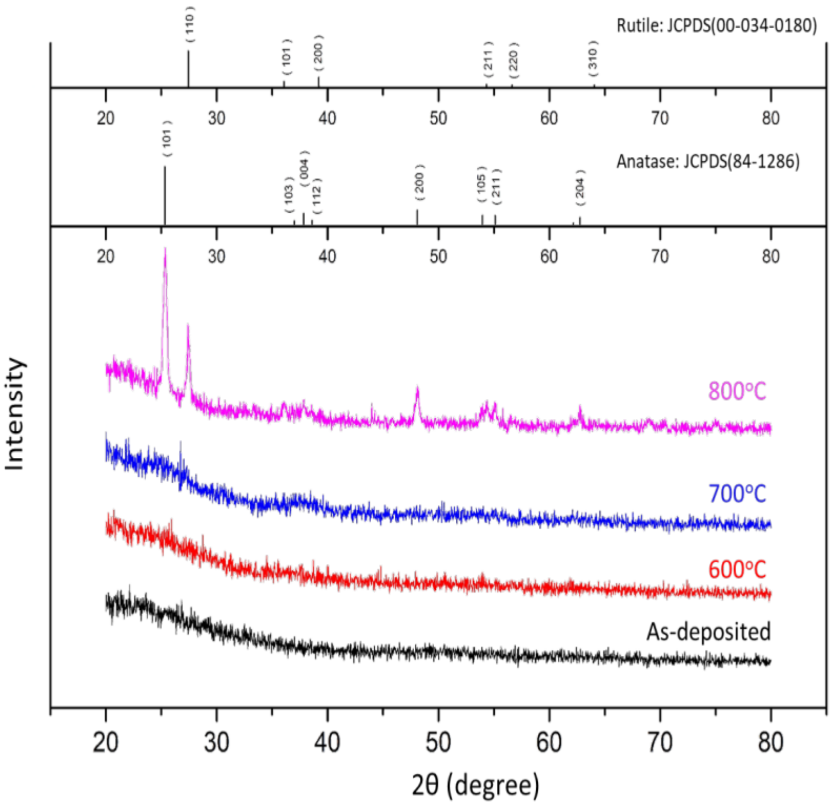


W.H. Wang & S. Chao, Opt. Lett., 23 (1998) 1417

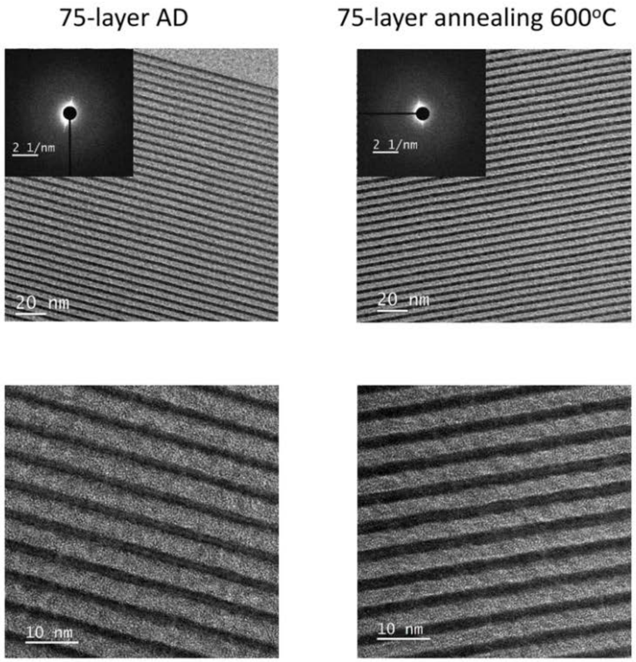
Nanolayers: Background

Silica/Titania Nanocomposite – Nanolayering hinders crystalization

[Chao et al., LIGO-G1900356]



→ 1.8nm TiO_2 sustained to 700°C~800°C without crystallization. 75-layer (TiO_2=1.8nmx38, SiO_2=3.6nmx37)

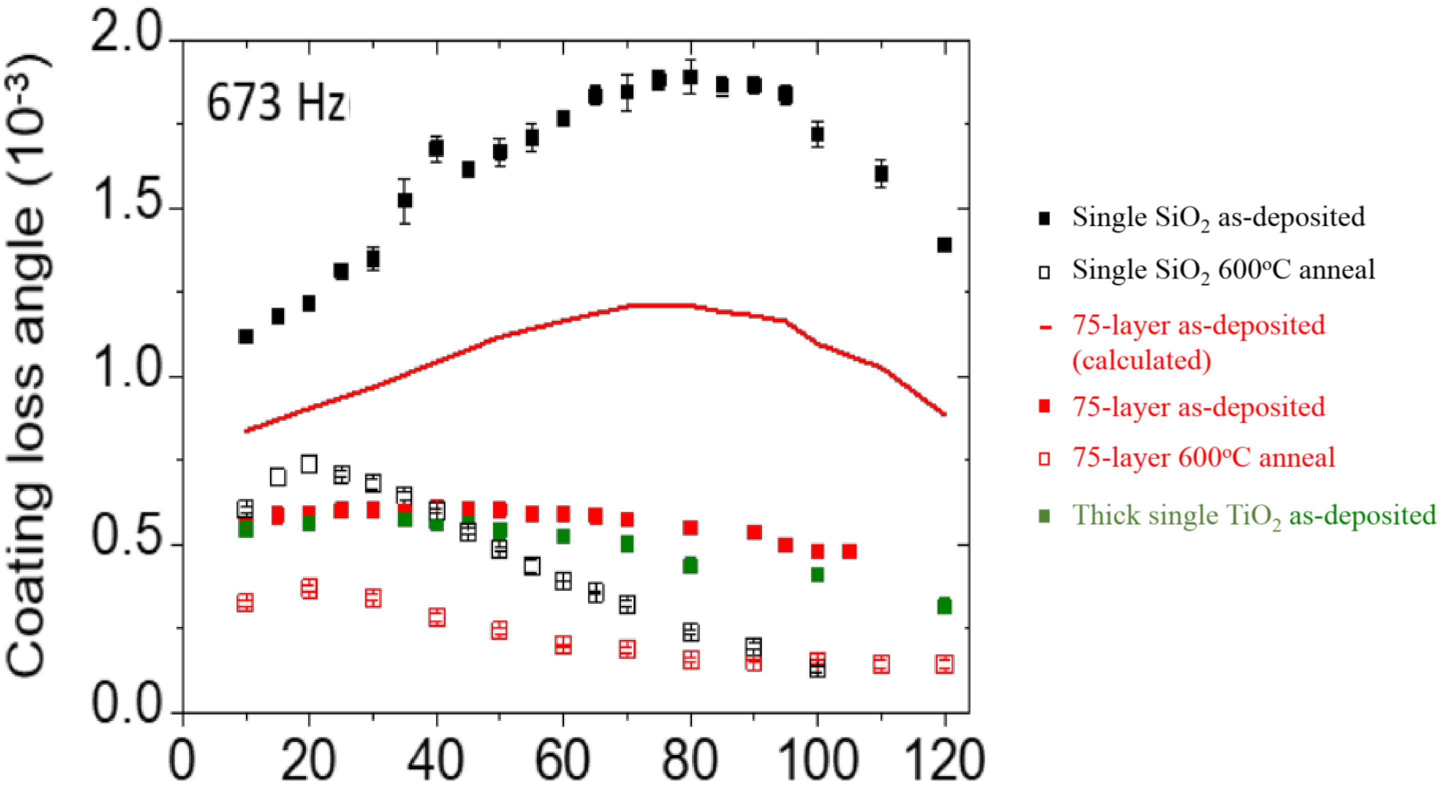


75-layer (TiO_2=1.8nmx38, SiO_2=3.6nmx37)

The film remain amorphous and the morphology is intact

Nanolayers : Background, contd.

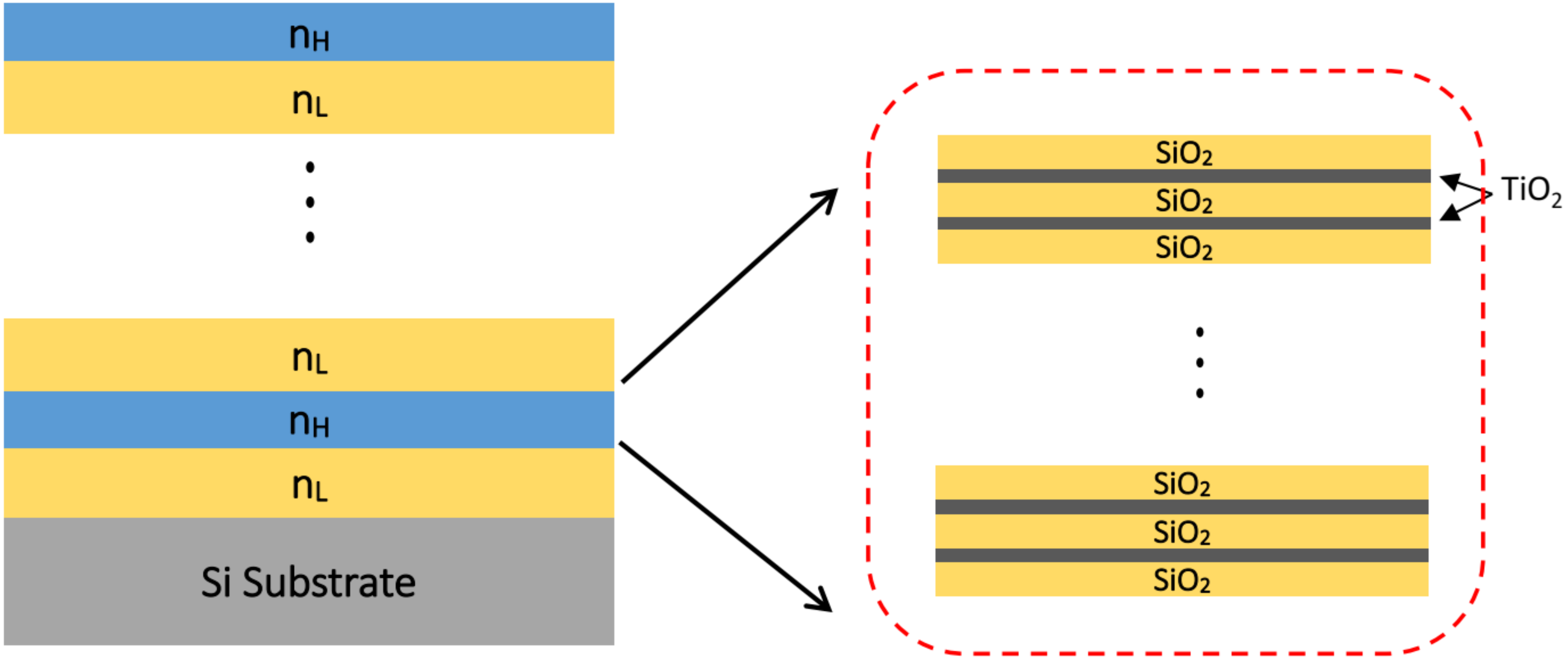
[Chao et al., LIGO-G1900356]



- The cryogenic loss of the 75-layer nano-layer (TiO_2=1.8nm x 38, SiO_2=3.6 nm x 37) was reduced after 600°C anneal to below that of the single SiO_2 annealed at 600°C and the as-deposited single TiO_2.

- The room temperature loss of the 75-layer nano-layer was reduced after 600°C anneal from 9x10^{-4} down to 1X10^{-4} at ~100Hz.

Goal : a Nanolayer Based HR Coating



Rationale: nice properties of nanolayered materials :

- Suppression of Silica cryopeak in mechanical loss [Kuo et al. Opt. Lett. 44 (2019) 247]
- Inhibition of crystallization at increasing annealing-T [Pan et al. Opt. Exp. 22 (2014) 29847]

In the following we stick to the case where the coating low-index material is Silica.
For cryogenic operation Silica/Alumina nanocomposites could be a nice alternative …

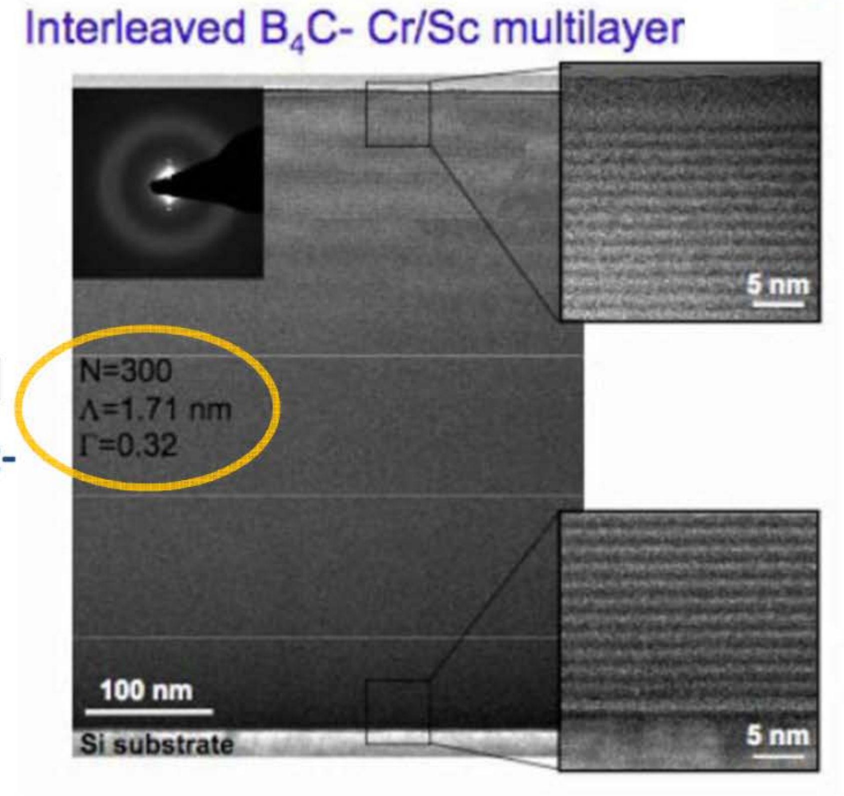
… Is it *Feasible* ?

Nanolayers are *routinely deposited* to make X-Ray Mirrors

Interference mirrors consisting of hundreds/thousands of nm scale layers, with sub - nm precision [see, e.g., Proc . 10th PXRMS Conf. (2008)] , using

- Interleaved nm-scale “buffering” layers to prevent crystallization & maintain flatness [E. Gullikson, Proc. 8th PXRMS (2006)]
- Ion assisted (modulated) magnetron sputtering [N. Ghafoor et al., Thin Sol. Films 516 (2008) 982]

Control of stress, crystallite size, and roughness [D.L. Windt, Proc. SPIE (2007) vol 6688]



See also [R. DeSalvo, LIGO-G080106] for a survey.

Modeling : HR Multilayers

Simplest Option: QWL :

- Requires *minimum number* of LH doublets for a given transmittance.
- QWL is conservative (can be improved) in terms of noise.

Transmittance

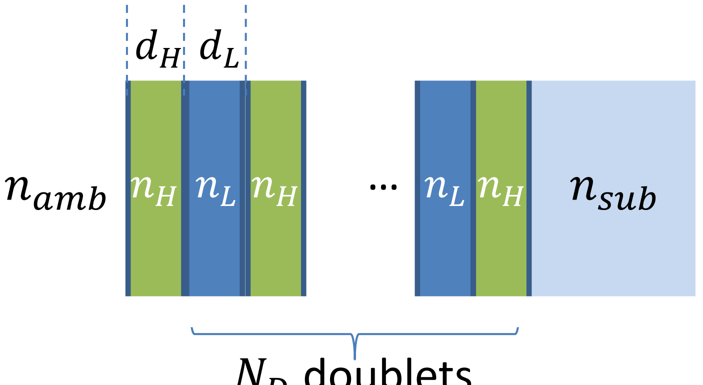
number of doublets

$$\Gamma = \frac{1-\left(\frac{n_H}{n_L}\right)^{2N_D+2}\frac{n_L{}^2}{n_{amb}n_{sub}}}{1+\left(\frac{n_H}{n_L}\right)^{2N_D+2}\frac{n_L{}^2}{n_{amb}n_{sub}}}, \qquad \tau_P = 1-|\Gamma|^2$$

index ratio (*contrast*)

$\cong n_L$, typically

$(A)H(LH)^{N_D}(S)$



N_D doublets

(a further HWL low-index protective-cap may be added)

yields N_D from prescribed τ_P and given contrast

Coating Loss Angle (Thermal (Brownian) Noise PSD) can be written

$$\phi_c = \boxed{\frac{1}{4\pi^{1/2}}\frac{\lambda_0}{w}\frac{\phi_L}{n_L}\left(\frac{Y_L}{Y_s}+\frac{Y_s}{Y_L}\right)}\left[\boxed{N_d+\boxed{\frac{n_L}{n_H}\frac{\phi_H\left(\frac{Y_H}{Y_s}+\frac{Y_s}{Y_H}\right)}{\phi_L\left(\frac{Y_L}{Y_s}+\frac{Y_s}{Y_L}\right)}}(1+N_d)}\right]$$

blows up linearly with N_d

depends on choice of L-material only

key quantity, depends on choice of H-material

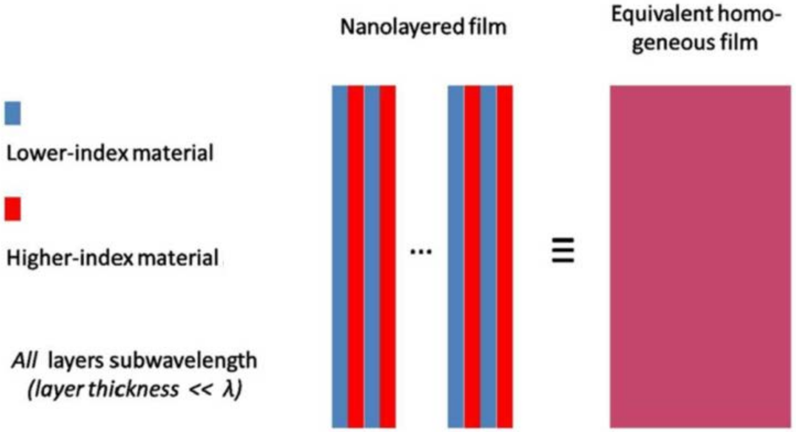
Modeling : Nanolayered Composites

- For simplicity, restrict to *binary* nanolayered composites using two materials with parameters $\{\tilde{n}_{L,H}, \tilde{Y}_{L,H}, \tilde{\phi}_{L,H}\}$.

$$n_{eff} = \left[r_H \widetilde{n}_H{}^2 + (1 - r_H)\widetilde{n}_L{}^2\right]^{1/2}$$

Drude's formula

(normal incidence, $\delta_{L,H} \ll \lambda$)



$$Y_{eff}^{\perp} = [r_H/\widetilde{Y}_H + (1 - r_H)/\widetilde{Y}_L]^{-1}$$

Reuss formula

$$Y_{eff}^{\parallel} = r_H \widetilde{Y}_H + (1 - r_H)\widetilde{Y}_L$$

Voigt formula

Let : $r_H = \dfrac{\delta_H}{\delta_L + \delta_H}$

thickness fraction

total metric thicknesses of high (δ_H) and low (δ_L) index nanocomposite contituents

$$\boxed{\phi_{eff}\left(\frac{Y_{eff}}{Y_s} + \frac{Y_s}{Y_{eff}}\right)} = \left(\frac{\widetilde{Y}_H}{Y_s} + \frac{Y_s}{\widetilde{Y}_H}\right) r_H \widetilde{\phi}_H + \left(\frac{\widetilde{Y}_L}{Y_s} + \frac{Y_s}{\widetilde{Y}_L}\right)(1 - r_H)\widetilde{\phi}_L$$

(mere consequence of (simple) coating noise formula)

Questions – Nanolayers Rethought

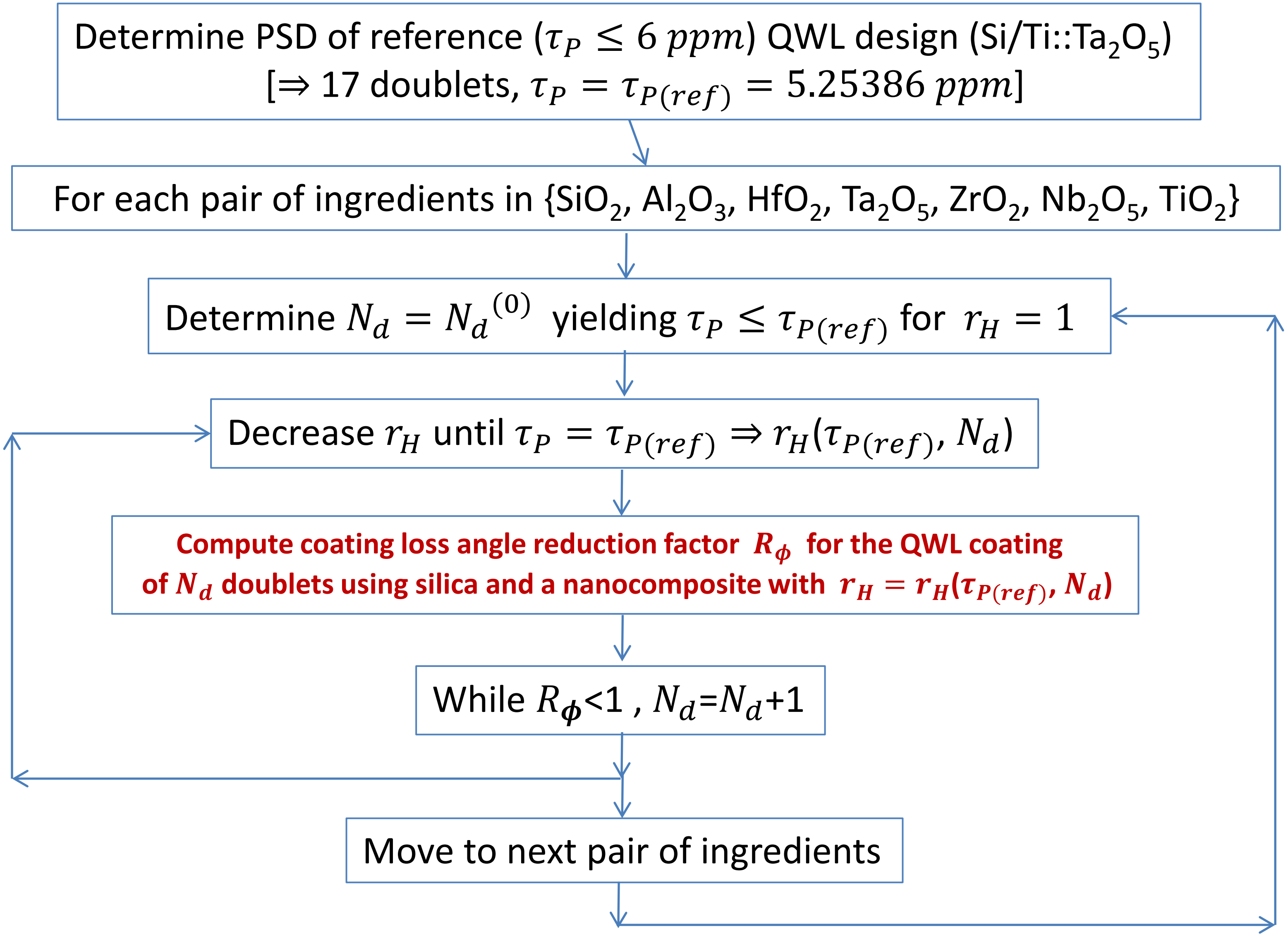
- Which materials are *more promising* in terms of noise reduction when used to produce (binary) high-index nanolayered films ?

- Which nanolayer *designs* are *more feasible* for a given material pair ?

- Blind trial-and-error would be *impractically time (and money) consuming.* Preliminary simulations may/should be used to provide guidelines and priorities.

Selecting Nanocomposite Materials

Simulation Algorithm



Determine PSD of reference ($\tau_P \leq 6\ ppm$) QWL design (Si/Ti::Ta_2O_5)
[$\Rightarrow$ 17 doublets, $\tau_P = \tau_{P(ref)} = 5.25386\ ppm$]

For each pair of ingredients in {SiO_2, Al_2O_3, HfO_2, Ta_2O_5, ZrO_2, Nb_2O_5, TiO_2}

Determine $N_d = {N_d}^{(0)}$ yielding $\tau_P \leq \tau_{P(ref)}$ for $r_H = 1$

Decrease r_H until $\tau_P = \tau_{P(ref)} \Rightarrow r_H(\tau_{P(ref)}, N_d)$

Compute coating loss angle reduction factor R_ϕ for the QWL coating of N_d doublets using silica and a nanocomposite with $r_H = r_H(\tau_{P(ref)}, N_d)$

While R_ϕ<1 , N_d=N_d+1

Move to next pair of ingredients

Selecting Nanocomposite Materials

Simulation Results

Noise PSD (and Coating Loss Angle) Reduction Factor compared to Reference (Si/Ti::Ta, 5.32ppm@1064nm)

	SiO_2	Al_2O_3	HfO_2	Ta_2O_5	ZrO_2	Nb_2O_5	TiO_2
SiO_2	x	>1	>1	>1	>0.794	>0792	>0.309
Al_2O_3		x	>1	>1	>0.833	>0.796	>0.352
HfO_2			x	>1	>1	>0.849	>0.663
Ta_2O_5				x	>1	>0.802	>0.415
ZrO_2					x	>0.791	>0.369
Nb_2O_5						x	>0.433
TiO_2							X

Note: Changing the noise PSD by a factor ρ yields an event rate boost by $\rho^{-3/2}$

Simulation Results

a Closer Look

using glass formers

QWL HR Coating – Silica (L) / Silica-Titania nanolayered composite (H)

#of doublets in Coating	Silica Fraction in nanocomposite	Effective index of nanocomposite	Coating power transmittance	Noise PSD Reduction
12	0.0882959	2.40581	5.25386	0.308983
13	0.188226	2.32031	5.25386	0.322875
14	0.269172	2.24867	5.25386	0.337020
15	0.335952	2.1878	5.25386	0.351363
16	0.391907	2.13547	5.25386	0.365862
17	0.439421	2.09	5.25386	0.380487

QWL HR Coating – Silica (L) / Alumina-Titania nanolayered composite (H)

#of doublets in Coating	Alumina Fraction in nanocomposite	Effective index of nanocomposite	Coating power transmittance	Noise PSD Reduction
12	0.116424	2.40581	5.25386	0.352285
13	0.248188	2.32031	5.25386	0.425948
14	0.35492	2.24867	5.25386	0.499978
15	0.442974	2.1878	5.25386	0.574344
16	0.516755	2.13547	5.25386	0.649013
17	0.579404	2.09	5.25386	0.723955

Arrows point to nanocomposites with noise $PSD \leq 0.5\, PSD_{REF}$

Simulation Results
a Closer Look, contd.

not using glass formers

QWL HR Coating – Silica (L) / Zirconia-Titania nanolayered composite (H)

#of doublets in Coating	Zirconia Fraction in nanocomposite	Effective index of nanocomposite	Coating power transmittance	Noise PSD Reduction
12	0.217655	2.40581	5.25386	0.368841
13	0.463991	2.32031	5.25386	0.465358
14	0.663526	2.24867	5.25386	0.562285
15	0.828143	2.1878	5.25386	0.659601
16	0.966077	2.13547	5.25386	0.757277

QWL HR Coating – Silica (L) / Tantala-Titania nanolayered composite (H)

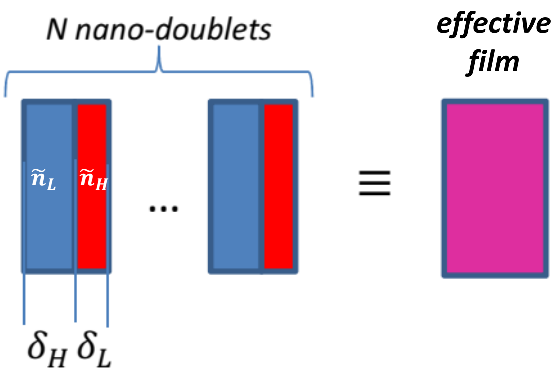
#of doublets in Coating	Tantala Fraction in nanocomposite	Effective index of nanocomposite	Coating power transmittance	Noise PSD Reduction
12	0.194551	2.40581	5.25386	0.415789
13	0.414737	2.32031	5.25386	0.577109
14	0.593092	2.24867	5.25386	0.738964
15	0.740235	2.1878	5.25386	0.901357

QWL HR Coating – Silica (L) / Niobia-Titania nanolayered composite (H)

#of doublets in Coating	Niobia Fraction in nanocomposite	Effective index of nanocomposite	Coating power transmittance	Noise PSD Reduction
12	0.334997	2.40581	5.25386	0.433520
13	0.714136	2.32031	5.25386	0.619317

Arrows point to nanocomposites with noise $PSD \leq 0.5\, PSD_{REF}$

Selecting Nanocomposite Design



- For simplicity, restrict to composites made of identical nanoscale-doublets. These are entirely specified by a triplet (δ_L, δ_H, N).

- To any given value of the effective index $n_{eff} \in (\tilde{n}_L, \tilde{n}_H)$ corresponds the ratio

$$\frac{\delta_L}{\delta_H} = \left(\frac{\tilde{n}_H{}^2 - n_{eff}{}^2}{n_{eff}{}^2 - \tilde{n}_L{}^2}\right) \quad (1)$$

- Prescribing the optical thickness z of the nanolayered film (in units of the local wavelength) enforces the further condition

$$N(\delta_H + \delta_L) = z\frac{\lambda_0}{n_{eff}} \quad (2)$$

Equations (1) and (2) determine *an infinite set* of nanolayer designs (δ_L, δ_H, N) yielding *the same* effective index n_{eff} and optical thickness z. *Larger* N correspond to *thinner* nano layers. The set of feasible designs is determined by the machine-dependent minimum deposition thickness and the maximum thickness of the material(s) prone to crystallization.

Note: inaccuracies in the individual nanolayer thicknesses *have no effect*, insofar as the total thickness fraction is preserved, and all individual nanolayers are much thinner than the (local) wavelength.

Selecting a Nanodesign: Silica/Titania

- **Select annealing-tolerant design featuring smallest R_{PSD} and minimum N, subject to $\delta_L \geq 0.9nm$, $\delta_H \leq 2nm$ (highlighted in yellow); select *easiest* one (circled in red)**

$r_L = 0.0882959$
$(R_{PSD} = 0.30983)$

N	$\delta_L[nm]$	$\delta_H[nm]$
7	1.39464	14.4005
8	1.22031	12.6004
9	1.08472	11.2004
10	0.97625	10.0803

$r_L = 0.188226$
$(R_{PSD} = 0.322875)$

N	$\delta_L[nm]$	$\delta_H[nm]$
18	1.19879	5.17009
19	1.13570	4.89798
20	1.07891	4.65308
21	1.02754	4.43151
22	0.98083	4.23008

$r_L = 0.269172$
$(R_{PSD} = 0.33702)$

N	$\delta_L[nm]$	$\delta_H[nm]$
28	1.13717	3.08754
29	1.09796	2.98108
30	1.06136	2.88171
31	1.02713	2.78875
32	0.99503	2.70160

Expected to crystallize before reaching $T_{ann} = 650C$

$r_L = 0.335952$
$(R_{PSD} = 0.351363)$

N	$\delta_L[nm]$	$\delta_H[nm]$
27	1.51282	2.99026
28	1.45879	2.88347
29	1.40848	2.78404
30	1.36153	2.69123
31	1.31761	2.60442
32	1.27644	2.52303
33	1.23776	2.44658
34	1.20135	2.37462
35	1.16703	2.30677
36	1.13461	2.24270
37	1.10395	2.18208
38	1.07490	2.12466
39	1.04733	2.07018
40	1.02115	2.01843
41	0.996245	1.96920

$r_L = 0.391907$
$(R_{PSD} = 0.365862)$

N	$\delta_L[nm]$	$\delta_H[nm]$
25	1.95268	3.02983
26	1.87758	2.91330
27	1.80804	2.80540
28	1.74347	2.70521
29	1.68335	2.61192
30	1.62724	2.52486
31	1.57474	2.44341
32	1.52553	2.36705
33	1.47930	2.29533
34	1.43580	2.22782
35	1.39477	2.16416
36	1.35603	2.10405
37	1.31938	2.04718
38	1.28466	1.99331
39	1.25172	1.94220
40	1.22043	1.89364
41	1.19066	1.84746
42	1.16231	1.80347
43	1.13528	1.76153
44	1.10948	1.72149
45	1.08482	1.68324
46	1.06124	1.64665
47	1.03866	1.61161
48	1.01702	1.57804
49	0.996267	1.54583

$r_L = 0.439421$
$(R_{PSD} = 0.3808437)$

N	$\delta_L[nm]$	$\delta_H[nm]$
23	2.43158	3.10202
24	2.33026	2.97277
25	2.23705	2.85386
26	2.15101	2.74409
27	2.07135	2.64246
28	1.99737	2.54809
29	1.92849	2.46022
30	1.86421	2.37821
31	1.80407	2.30150
32	1.74770	2.22958
33	1.69474	2.16201
34	1.64489	2.09842
35	1.59789	2.03847
36	1.55351	1.98184
37	1.51152	1.92828
38	1.47175	1.87754
39	1.43401	1.82940
40	1.39816	1.78366
41	1.36406	1.74016
42	1.33158	1.69872
43	1.30061	1.65922
44	1.27105	1.62151
45	1.24281	1.58548
46	1.21579	1.55101
47	1.18992	1.51801
48	1.16513	1.48638
49	1.14135	1.45605
50	1.11853	1.42693
51	1.09659	1.39895
52	1.07551	1.37205
53	1.05521	1.34616
54	1.03567	1.32123
55	1.01684	1.29721
56	0.99868	1.27404

Expected to remain amorphous at $T_{ann} = 650C$

QWL HR Coating – Silica (L) / Silica-Titania nanolayered composite (H)				
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Selecting a Nanodesign : Alumina/Titania

$r_L = 0.116424 \ (R_{PSD} = 0.35492)$

N	$\delta_L[nm]$	$\delta_H[nm]$
9	1.43028	10.8548
10	1.28725	9.76933
11	1.17023	8.88121
12	1.07271	8.14111
13	0.99019	7.51487

$r_L = 0.248188 \ (R_{PSD} = 0425948)$

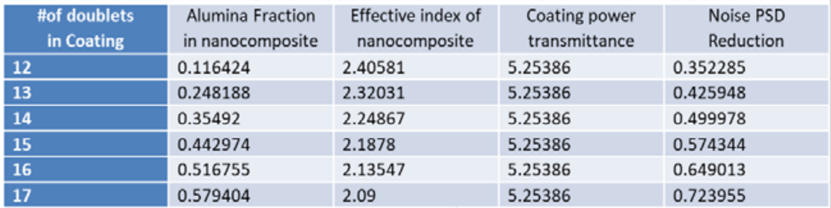
N	$\delta_L[nm]$	$\delta_H[nm]$
25	1.13809	3.44750
26	1.09432	3.31491
27	1.05379	3.19213
28	1.01615	3.07813
29	0.98111	2.97199

Expected to crystallize before reaching $T_{ann} = 650$C

Expected to remain amorphous at $T_{ann} = 650C$

$r_L = 0.354920 \ (R_{PSD} = 0.499978)$

N	$\delta_L[nm]$	$\delta_H[nm]$
25	1.67937	3.05231
26	1.61478	2.93492
27	1.55497	2.82622
28	1.49944	2.72528
29	1.44773	2.63131
30	1.39947	2.54360
31	1.35433	2.46154
32	1.31201	2.38462
33	1.27225	2.31236
34	1.23483	2.24435
35	1.19955	2.18022
36	1.16623	2.11966
37	1.13471	2.06237
38	1.10485	2.00810
39	1.07652	1.95661
40	1.04961	1.90770
41	1.02401	1.86117
42	0.99962	1.81685



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➡ **Select annealing-tolerant design featuring smallest R_{PSD} and minimum N, subject to $\delta_L \geq 0.9nm$, $\delta_H \leq 2nm$ (highlighted in yellow); select *easiest* one (circled in red)**

Selecting a Nanodesign : Zirconia/Titania

$r_L = 0.217655$ $(R_{PSD} = 0.368841)$

N	$\delta_L[nm]$	$\delta_H[nm]$
21	1.14596	4.11907
22	1.09387	3.93184
23	1.04631	3.76089
24	1.00272	3.60419
25	0.96261	3.46002

Expected to crystallize before reaching $T_{ann} = 650\text{C}$

$r_L = 0.463991$ $(R_{PSD} = 0.464358)$

N	$\delta_L[nm]$	$\delta_H[nm]$
24	2.21633	2.56034
25	2.12767	2.45792
26	2.04584	2.36339
27	1.97007	2.27585
28	1.89971	2.19457
29	1.83420	2.11890
30	1.77306	2.04827
31	1.71587	1.98220
32	1.66225	1.92025
33	1.61187	1.86206
34	1.56447	1.80730
35	1.51977	1.75566
36	1.47755	1.70689
37	1.43762	1.66076
38	1.39979	1.61705
39	1.36389	1.57559
40	1.32980	1.53620
41	1.29736	1.49873
42	1.26647	1.46305
43	1.23702	1.42902
44	1.20891	1.39655
45	1.18204	1.36551
46	1.15634	1.33583
47	1.13174	1.30741
48	1.10816	1.28017
49	1.08555	1.25404
50	1.06384	1.22896
51	1.04298	1.20486
52	1.02292	1.18169
53	1.00362	1.15940
54	0.98503	1.13793

Expected to remain amorphous at $T_{ann} = 650C$

QWL HR Coating – Silica (L) / Zirconia-Titania nanolayered composite (H)

#of doublets in Coating	Zirconia Fraction in nanocomposite	Effective index of nanocomposite	Coating power transmittance	Noise PSD Reduction
12	0.217655	2.40581	5.25386	0.368841
13	0.463991	2.32031	5.25386	0.465358
14	0.663526	2.24867	5.25386	0.562285
15	0.828143	2.1878	5.25386	0.659601
16	0.966077	2.13547	5.25386	0.757277

Select annealing-tolerant design featuring smallest R_{PSD} and minimum N, subject to $\delta_L \geq 0.9nm$, $\delta_H \leq 2nm$ (highlighted in yellow); select *easiest* one (circled in red)

Selecting a Nanodesign : Tantala/Titania

$r_L = 0.194551$ ($R_{PSD} = 0.415788$)

N	$\delta_L[nm]$	$\delta_H[nm]$
18	1.19504	4.94751
19	1.13214	4.68711
20	1.07553	4.45276
21	1.02432	4.24072
22	0.97775	4.04796

Expected to crystallize before reaching $T_{ann} = 650$C

$r_L = 0.414737$ ($R_{PSD} = 0.577109$)

N	$\delta_L[nm]$	$\delta_H[nm]$
29	1.63950	2.3136
30	1.58485	2.23648
31	1.53372	2.16434
32	1.48580	2.09670
33	1.44077	2.03317
34	1.39840	1.97337
35	1.35844	1.91698
36	1.32071	1.86373
37	1.28501	1.81336
38	1.25120	1.76564
39	1.21911	1.72037
40	1.18864	1.67736
41	1.15965	1.63645
42	1.13203	1.59749
43	1.10571	1.56034
44	1.08058	1.52487
45	1.05657	1.49099
46	1.03360	1.45858
47	1.01161	1.42754
48	0.99053	1.39780

Expected to remain amorphous at $T_{ann} = 650C$

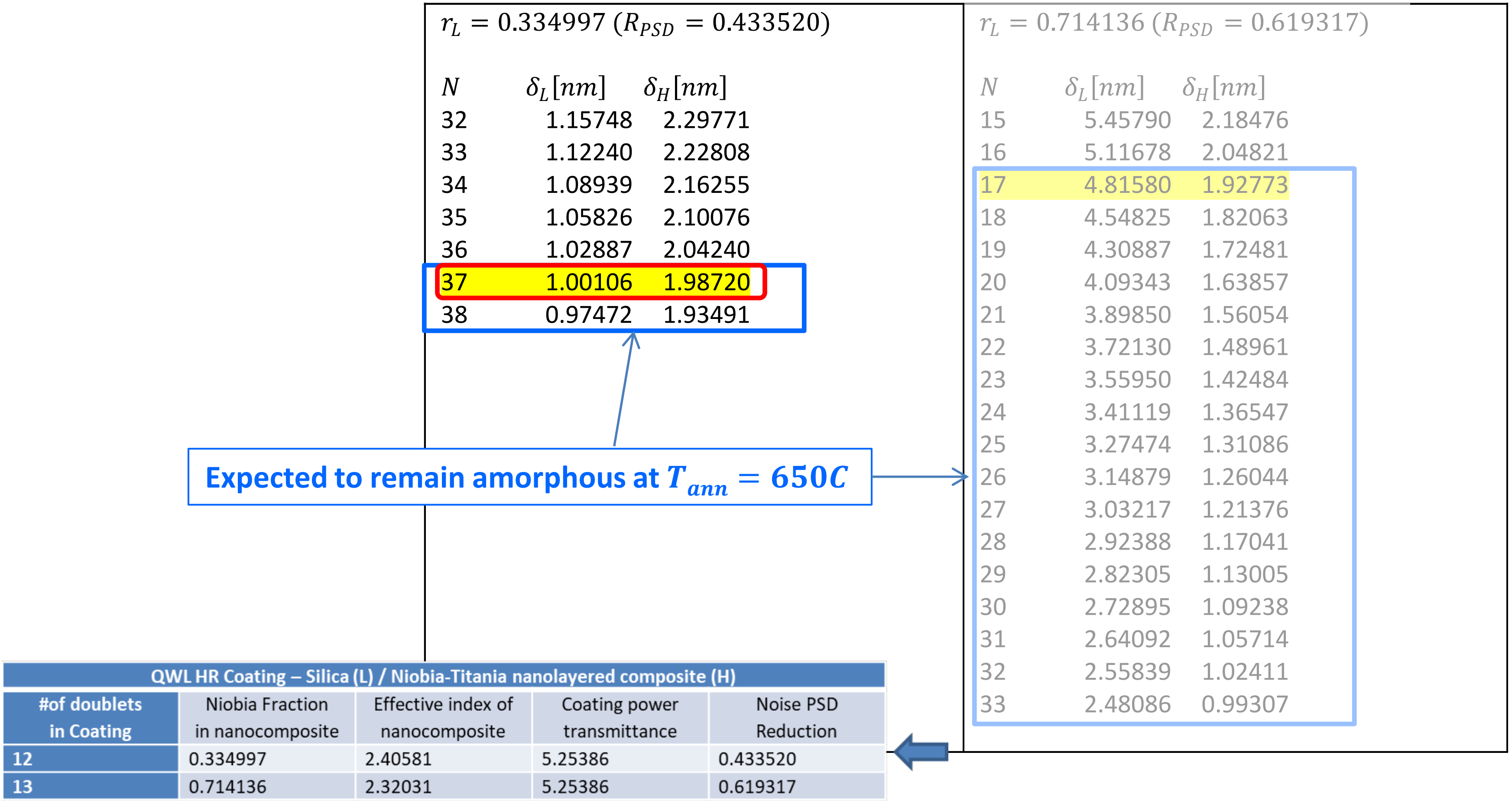
QWL HR Coating – Silica (L) / Tantala-Titania nanolayered composite (H)

#of doublets in Coating	Tantala Fraction in nanocomposite	Effective index of nanocomposite	Coating power transmittance	Noise PSD Reduction
12	0.194551	2.40581	5.25386	0.415789
13	0.414737	2.32031	5.25386	0.577109
14	0.593092	2.24867	5.25386	0.738964
15	0.740235	2.1878	5.25386	0.901357

➡ **Select annealing-tolerant design featuring smallest R_{PSD} and minimum N, subject to $\delta_L \geq 0.9nm$, $\delta_H \leq 2nm$ (highlighted in yellow); select *easiest* one (circled in red)**

Note: for Tantala /Titania $R_{PSD} \cong 0.58 > 0.5$.

Selecting a Nanodesign: Niobia/Titania



$r_L = 0.334997$ ($R_{PSD} = 0.433520$)

N	$\delta_L[nm]$	$\delta_H[nm]$
32	1.15748	2.29771
33	1.12240	2.22808
34	1.08939	2.16255
35	1.05826	2.10076
36	1.02887	2.04240
37	1.00106	1.98720
38	0.97472	1.93491

$r_L = 0.714136$ ($R_{PSD} = 0.619317$)

N	$\delta_L[nm]$	$\delta_H[nm]$
15	5.45790	2.18476
16	5.11678	2.04821
17	4.81580	1.92773
18	4.54825	1.82063
19	4.30887	1.72481
20	4.09343	1.63857
21	3.89850	1.56054
22	3.72130	1.48961
23	3.55950	1.42484
24	3.41119	1.36547
25	3.27474	1.31086
26	3.14879	1.26044
27	3.03217	1.21376
28	2.92388	1.17041
29	2.82305	1.13005
30	2.72895	1.09238
31	2.64092	1.05714
32	2.55839	1.02411
33	2.48086	0.99307

Expected to remain amorphous at $T_{ann} = 650C$

QWL HR Coating – Silica (L) / Niobia-Titania nanolayered composite (H)

#of doublets in Coating	Niobia Fraction in nanocomposite	Effective index of nanocomposite	Coating power transmittance	Noise PSD Reduction
12	0.334997	2.40581	5.25386	0.433520
13	0.714136	2.32031	5.25386	0.619317

- **Select annealing-tolerant design featuring smallest R_{PSD} and minimum N, subject to $\delta_L \geq 0.9nm$, $\delta_H \leq 2nm$ (highlighted in yellow); select *easiest* one (circled in red)**

Selection Winners

$$(\delta_L, \delta_H)^{N_N}[\delta_{SiO_2}, (\delta_L, \delta_H)^{N_N}]^{N_D}$$

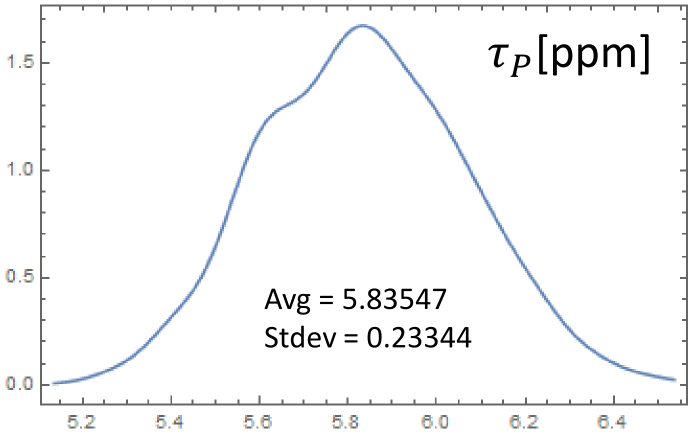
	Silica-Titania	Niobia-Titania	Zirconia-Titania	Alumina-Titania	Tantala-Titania
$\tau_P\ [ppm]$	5.25386	5.25386	5.25386	5.25386	5.25386
R_{PSD}	0.36586	0.43352	0.464358	0.49998	0.57711
N_D	16	12	13	14	13
N_N	38	37	31	39	34
δ_L [nm]	1.28466	1.00106	1.71587	1.07652	1.39840
δ_H [nm]	1.99331	1.98720	1.98220	1.95661	1.97337
δ_{SiO2} [nm]	183.499	183.499	183.499	183.499	183.499

Note: Changing the noise PSD by a factor ρ yields an event rate boost by $\rho^{-3/2}$

Deposition Accuracy and Robustness

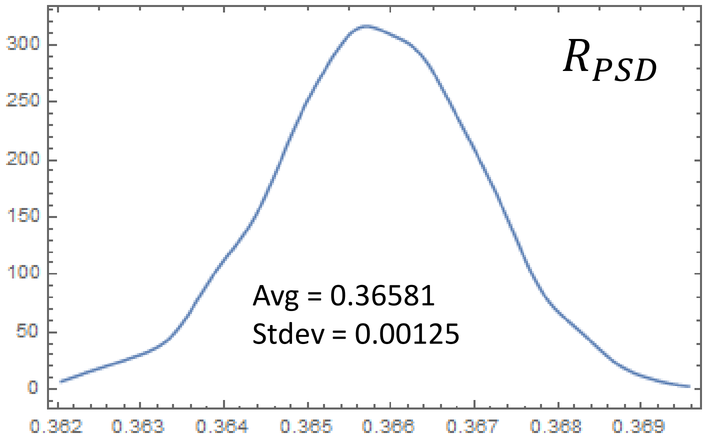
Assumption: i.i.d. Gaussian thickness errors with 0 avg. and .3nm std. deviation
on each layer. 1000 trial-depositions.

	Silica-Titania
τ_P [ppm]	5.25386
R_{PSD}	0.36586
N_D	16
N_N	38
δ_L [nm]	1.28466
δ_H [nm]	1.99331
δ_{SiO2} [nm]	183.499



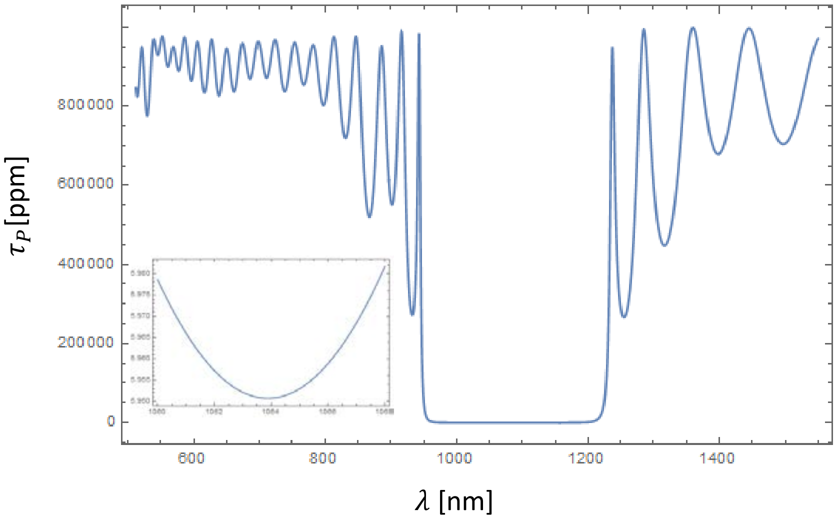
τ_P[ppm]

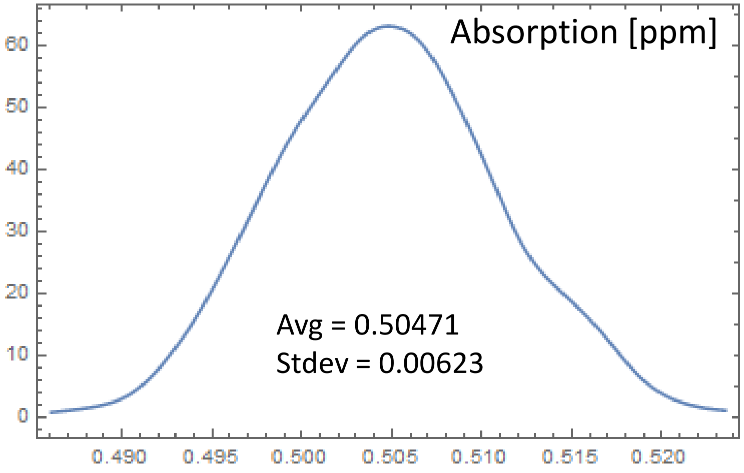
Avg = 5.83547
Stdev = 0.23344



R_{PSD}

Avg = 0.36581
Stdev = 0.00125





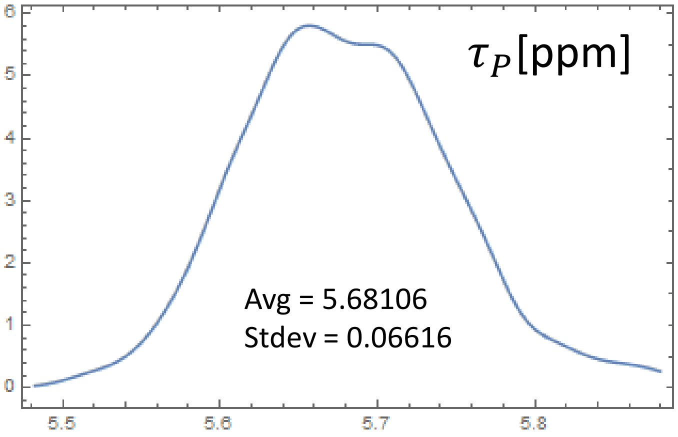
Absorption [ppm]

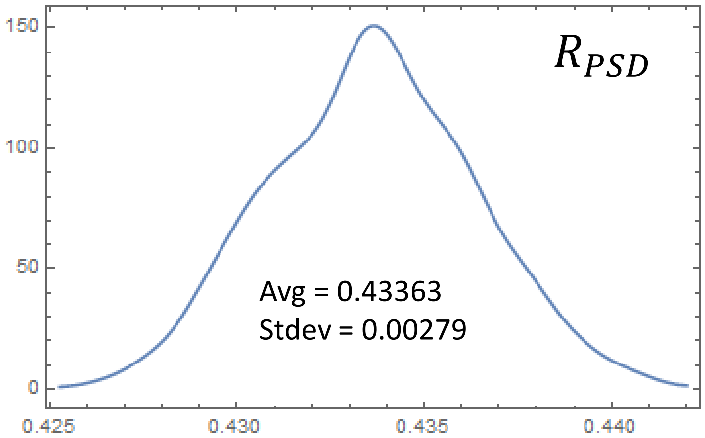
Avg = 0.50471
Stdev = 0.00623

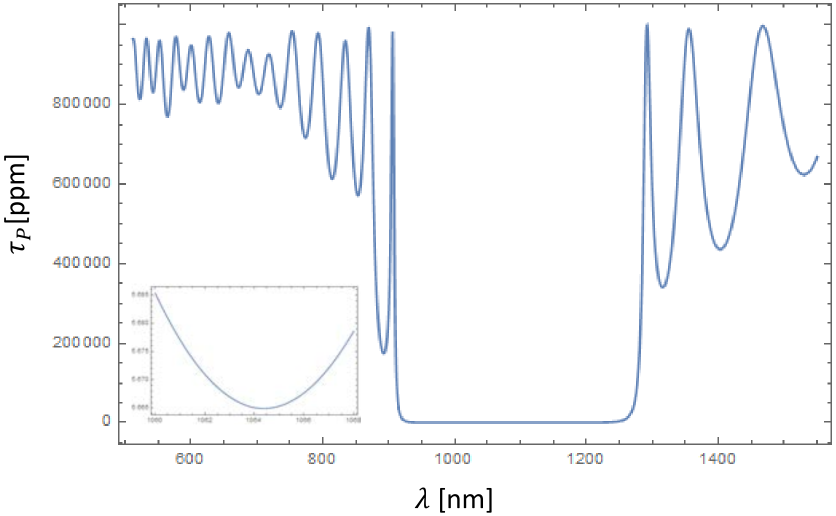
Deposition Accuracy and Robustness, contd.

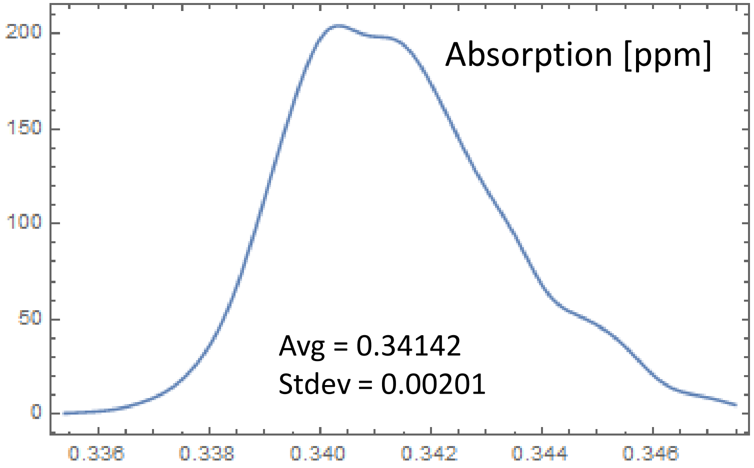
Assumption: i.i.d. Gaussian thickness errors with 0 avg. and .3nm std. deviation on each layer. 1000 trial-depositions

	Niobia-Titania
τ_P [ppm]	5.25386
R_{PSD}	0.43352
N_D	12
N_N	37
δ_L [nm]	1.00106
δ_L [nm]	1.98720
δ_{SiO2} [nm]	183.499









Conclusions

- The nanolayered (binary) composites that may be used in place of the high index material in a QWL coating with the same τ_P as the reference Si/Ti::Ta2O5 design, to obtain $PSD \leq 0.5\, PSD_{REF}$ are (best to worst)

  {SiO_2, TiO_2}, {Nb_2O_5,TiO_2}, {ZrO_2, TiO_2}, {Al_2O_3, TiO_2}, {Ta_2O_5, TiO_2}

- For each of these material-pairs there's at least one design that (fiducially) should be both free from crystallization upon annealing up to 650C, and feasible/easy to deposit (sufficiently thick nanolayers, including several atomic layers, reasonably small number of nanolayers)

- The number of *promising/easy* nanolayered prototypes (and QWL HR coatings) is basically 5 for the considered pool of material constituents.
  These 5 prototypes are scheduled for deposition in our Lab.

- Thickness optimization of the above coatings is expected to provide some extra noise reduction (to be calculated soon – stay tuned…)