Update on Ternary coating : application to Ti:GeO2

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In collaboration with

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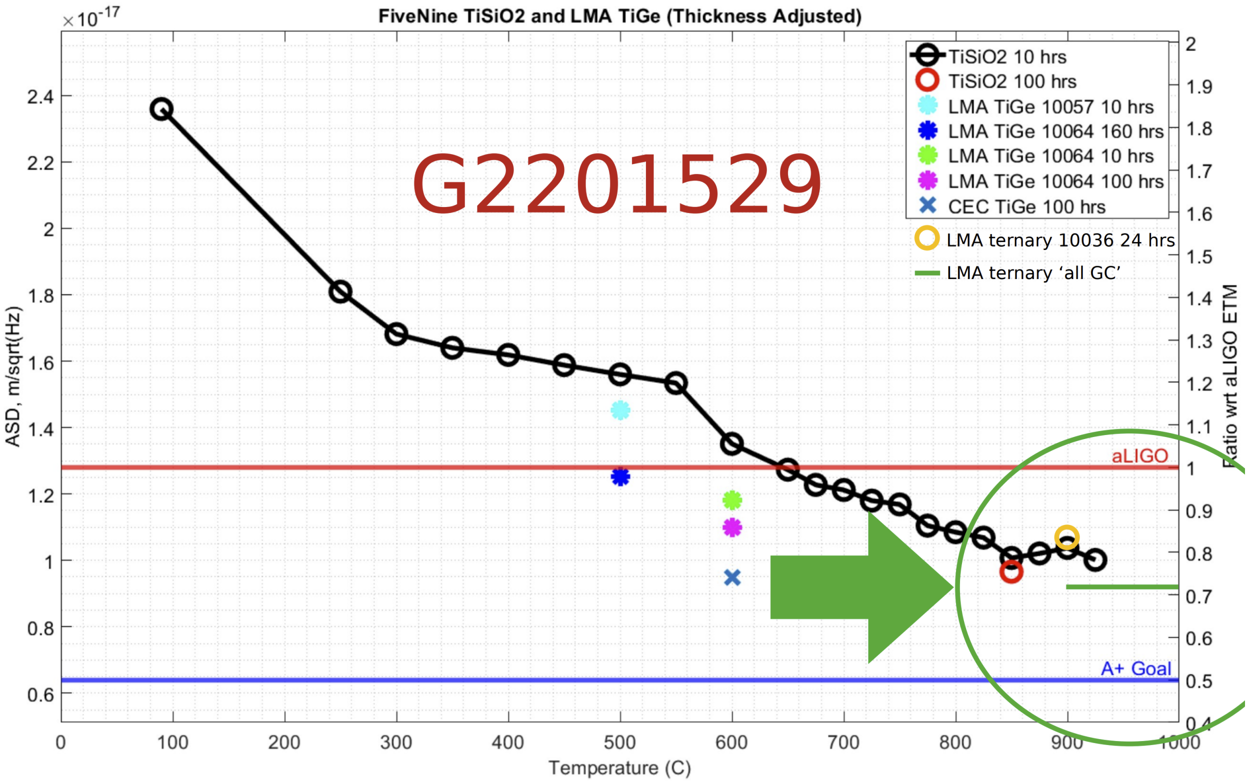
on behalf of LMA team

Presentation done @ VCR&D Meeting 21 March 2024

Previous work : application of ternary design to Silica/Ti:Ta2O5/SiNx
less stringent absorption constraint, validation of the method

Work done in collaboration with M. Granata,
Ch. Michel, D. Forest, B. Sassolas (LMA);
CTN measurements @ MIT by N. Demos, S. Gras



Binary Coating Optimization

10.1117/12.678977

10.1103PhysRevD.91.022005

10.1016/j.optmat.2019.109269

10.3390/app112411669pp112411669

Ternary Coating Optimization

10.1103/PhysRevResearch.3.023172

G2400526
G2300048
G2101842
G2101479
G2101040
G2100429
G2100124

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Compendium of thermal noises in optical mirrors

V. B. BRAGINSKY, M. L. GORODETSKY, AND S. P. VYATCHANIN

In the model of independent thin layers on an infinite half space substrate, each layer behaves the same as if it was the only layer. This model has been heavily studied and the solution is known (Harry *et al.*, 2002; Gurkovsky and Vyatchanin, 2010):

$$S_{\mathrm{CB,j}} = \frac{2k_{\mathrm{B}}T\phi'_j d_j}{\pi^2 w_m^2 f}\left[\frac{(1+\sigma'_j)(1-2\sigma'_j)}{Y_j(1-\sigma'_j)} + \frac{Y'_j(1+\sigma)^2(1-2\sigma)^2}{Y^2(1-\sigma'^2_j)}\right], \qquad (3.9)$$

where Y'_j, σ'_j, and ϕ'_j are, correspondingly, the Poisson's ratio, Young's modulus, and mechanical loss angle of a coating layer j, while unprimed values correspond to the substrate.

OPTICAL COATINGS AND THERMAL NOISE IN PRECISION MEASUREMENT

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Cambridge University Press 2012

The above statement lead to the definition:

$$\eta_j = \phi'_j Y\left[\frac{(1+\sigma'_j)(1-2\sigma'_j)}{Y_j(1-\sigma'_j)} + \frac{Y'_j(1+\sigma)^2(1-2\sigma)^2}{Y^2(1-\sigma'^2_j)}\right]$$

$$S_{CB,j} = \frac{2k_BT}{\pi^2 w_m^2 f}\frac{\eta_j}{Y}d_j$$

$$S_{CB,j} = \frac{2k_B T}{\pi^2 w_m^2 f} \frac{\eta_j}{Y} d_j$$

Temperature & Laser Beam

Coating & Substrate

Thickness

Linear model for the noise (PSD) of a multilayer coating (N_L layers):

$$S_{CB} = \sum_{j=1}^{N_L} S_{CB,j} = \frac{2k_B T}{\pi^2 w_m^2 f Y} \sum_{j=1}^{N_L} \eta_j d_j$$

Normalized Braginsky coefficients from direct measurements $\eta_j \longrightarrow \eta_j/\eta_{SiO_2}$

(Silica is the reference)

LMA last sample $\eta_{Ti::GeO_2} = 4.06$ ASD RF 0.73 ← This is considered in the simulations (low absorption)

Sample 230627a $\eta_{Ti::GeO_2} = 3.5052$ ASD RF 0.67

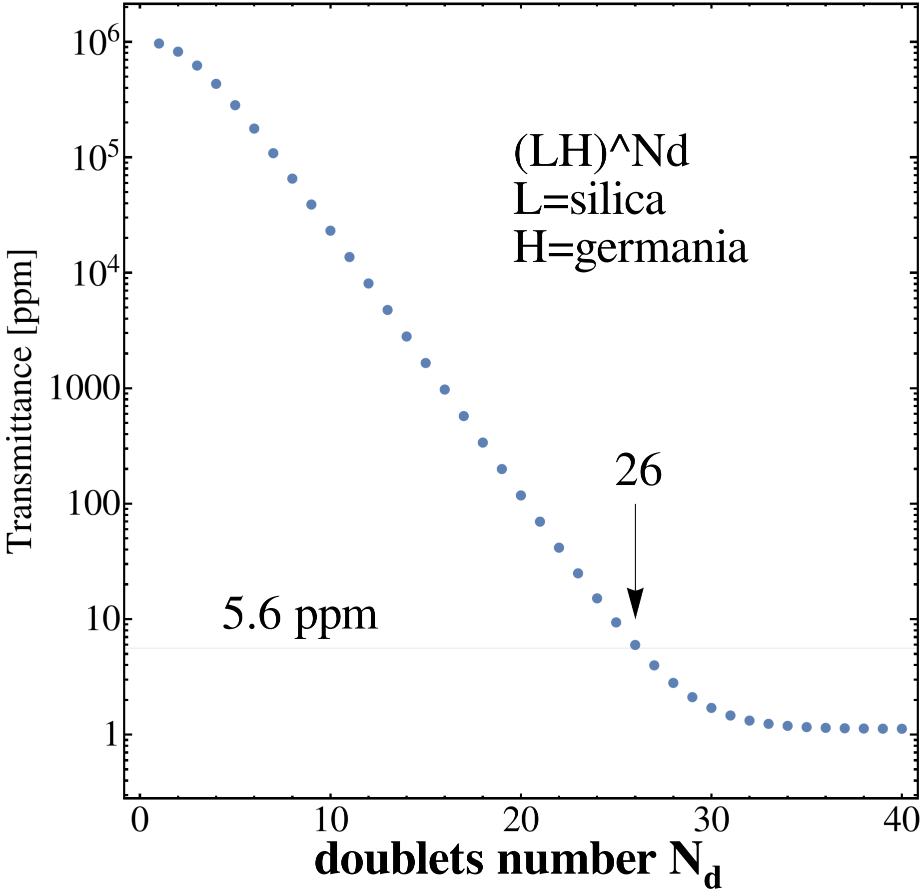
Sample 230125a $\eta_{Ti::GeO_2} = 4.229$ ASD RF 0.72

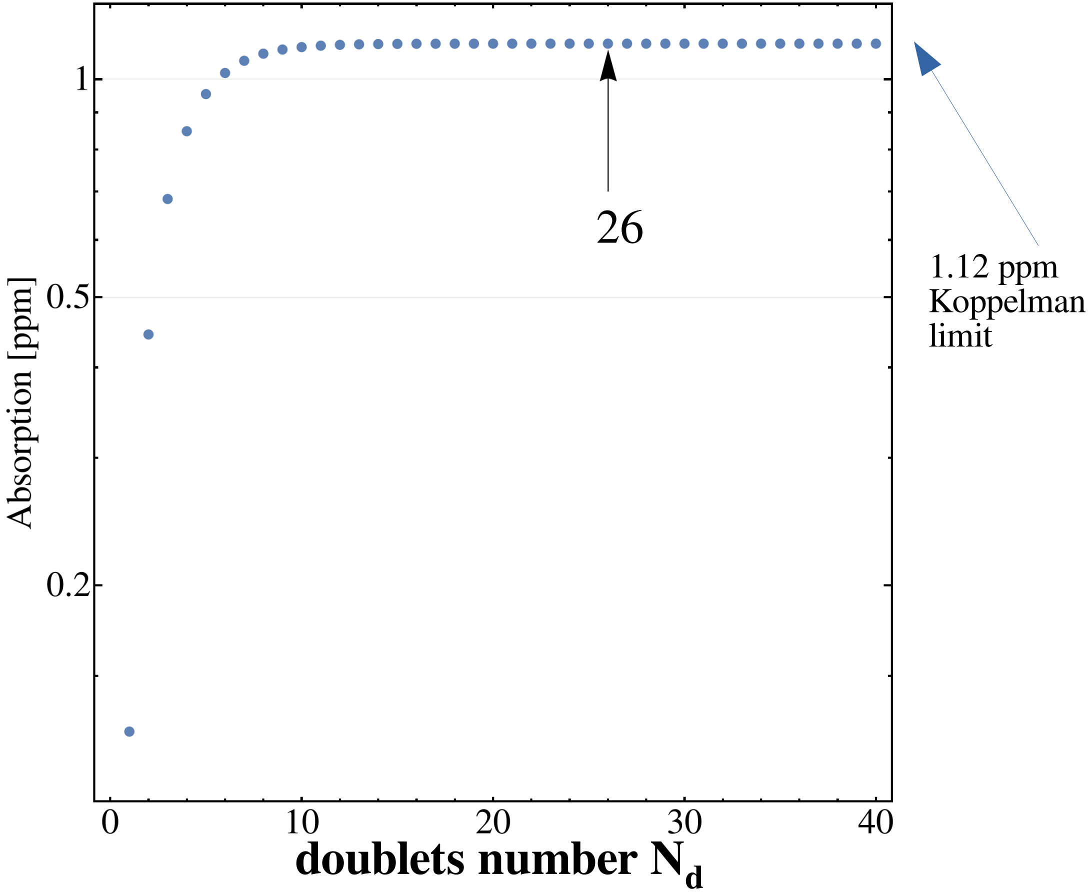
LIGO Document G2301806

$$\eta_{Ti::Ta_2O_5} = 15.824$$

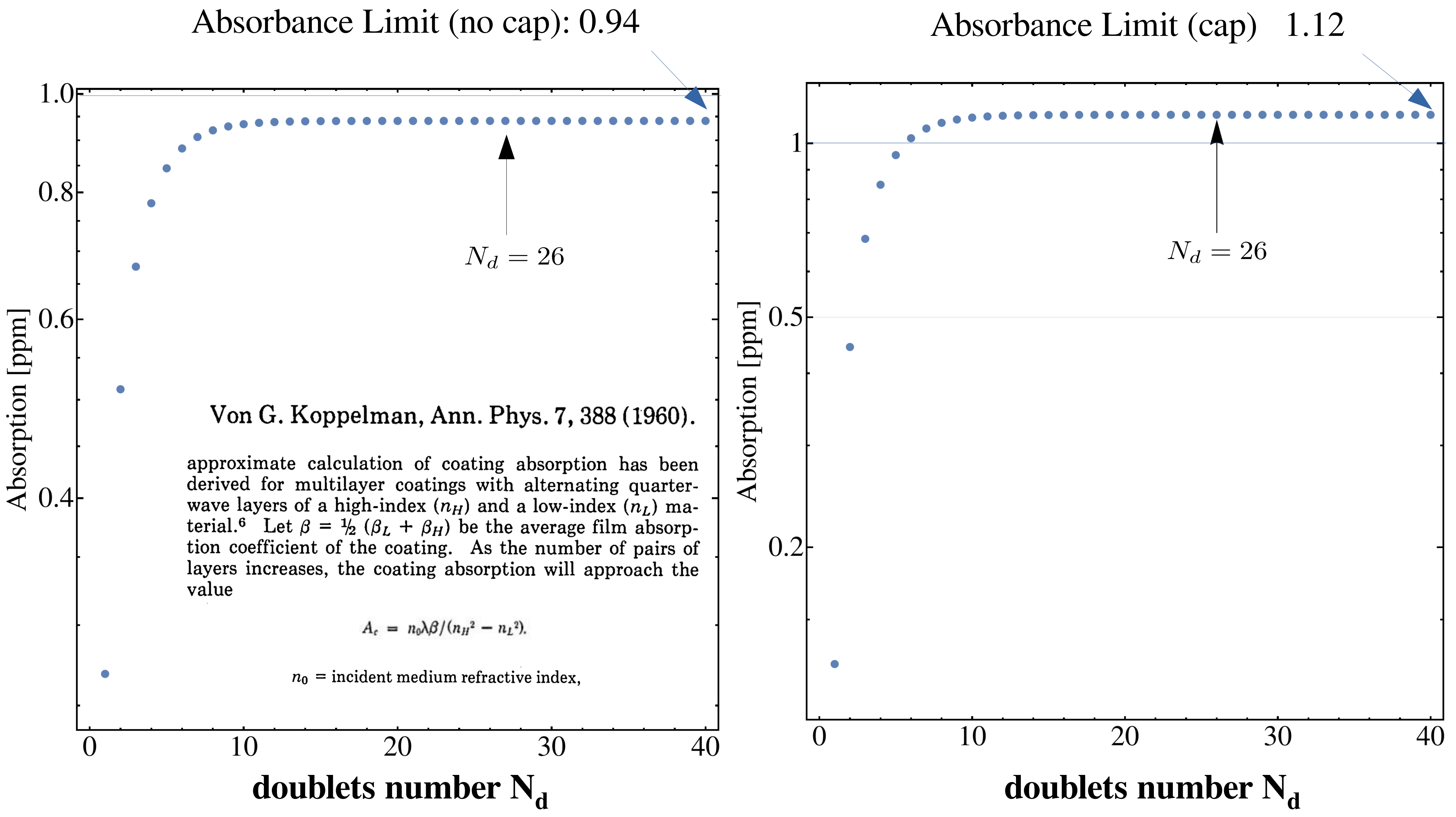
	n_1064	k_1064	Y [Gpa]	nu	phi_c [rad] @ 100 Hz
substrate	1.4499	< 1E-8	73	0.17	< 1E-8
SiO2 Grand Coater 500C	1.45	3E-08	70	0.19	2.3E-05
Ta2O5-TiO2 Grand Coater 500C	2.09	5E-08	120	0.29	3.6E-04
GeO2-TiO2 Grand Coater 600C	1.89	2E-07	92	0.25	1E-04

Transmittance & Absorbance as function of doublets number N_d



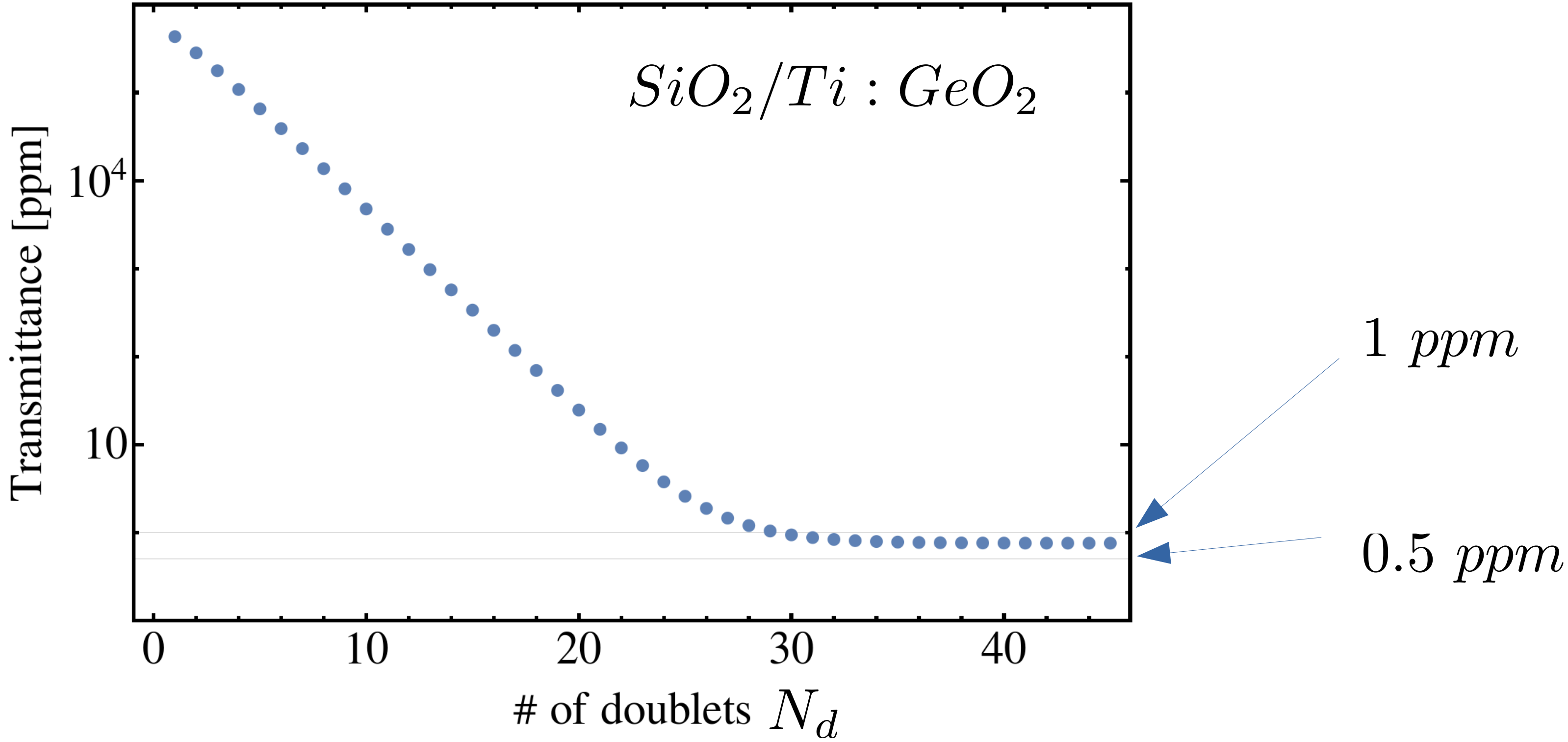


Rem: the first layer (near vacuum) is a cap (half wavelength). Other layers are quarter wavelength.


Absorbance Limit (no cap): 0.94
1.0
0.8
0.6
0.4
Absorption [ppm]
$N_d = 26$
Von G. Koppelman, Ann. Phys. 7, 388 (1960).
approximate calculation of coating absorption has been derived for multilayer coatings with alternating quarter-wave layers of a high-index (n_H) and a low-index (n_L) material.[6] Let $\beta = ½ (\beta_L + \beta_H)$ be the average film absorption coefficient of the coating. As the number of pairs of layers increases, the coating absorption will approach the value
$A_c = n_0\lambda\beta/(n_H^2 - n_L^2)$.
n_0 = incident medium refractive index,
0
10
20
30
40
doublets number N_d
Absorbance Limit (cap) 1.12
1
0.5
0.2
Absorption [ppm]
$N_d = 26$
0
10
20
30
40
doublets number N_d

Transmittance v.s. Number of doublets in binary coating tapering with Carniglia method

J. Opt. Soc. Am., Vol. 70, No. 5, May 1980

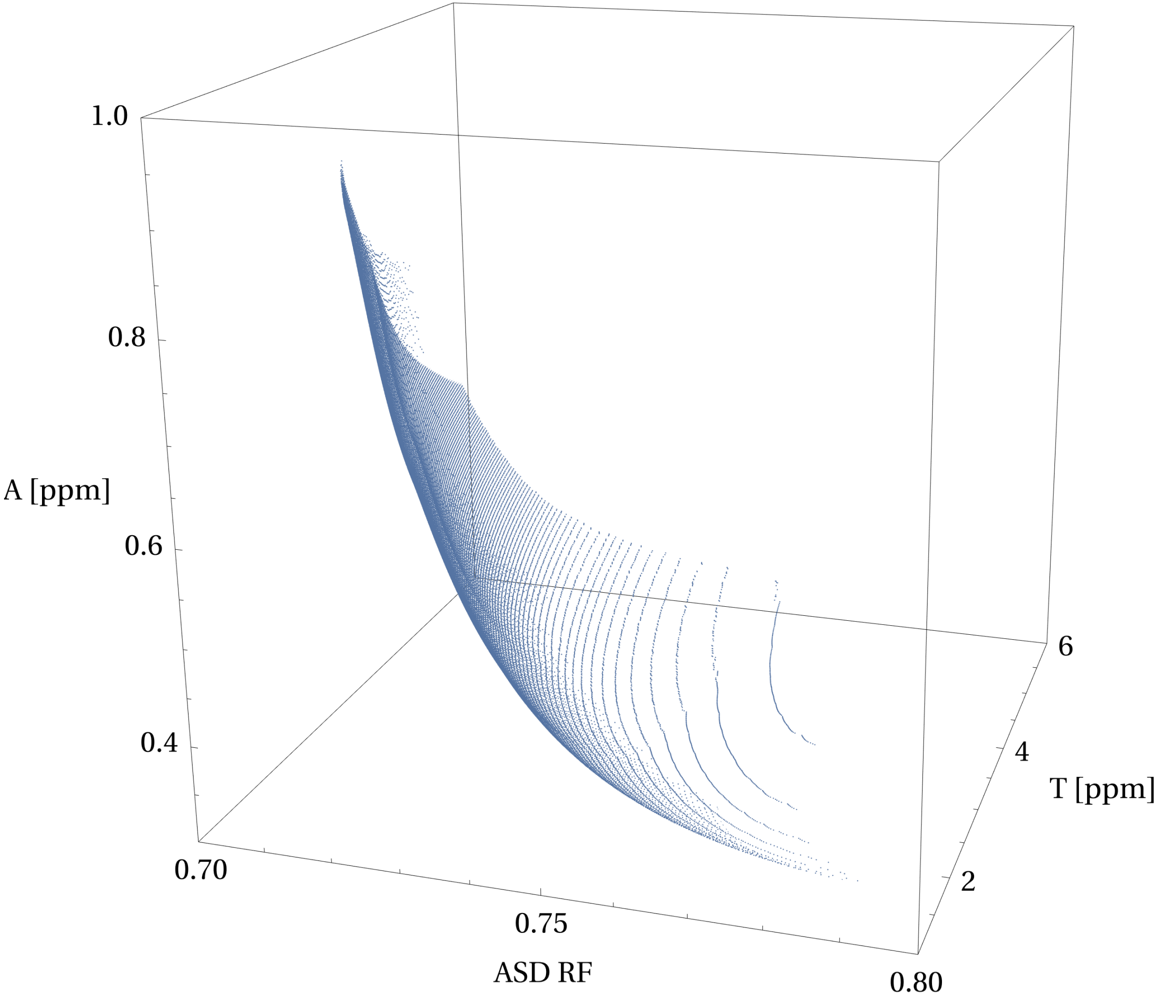


By using binary coating Silica/Ti:GeO_2 the minimum transmittance is 0.759453 [ppm]

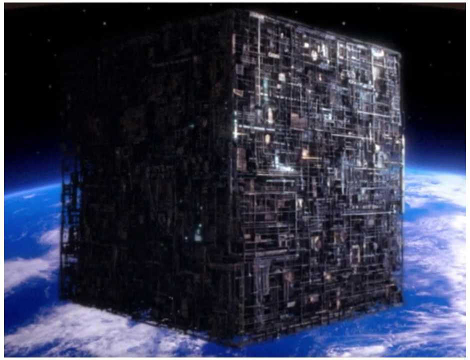
This is also the minimum absorbance.

The limit is above he prescribed value for advanced detectors (0.5 ppm)

Pareto Front 3D   Silica/Ti:Ta2O5/Ti:GeO2



AI based on evolutionary algorithm (borgMOEA)



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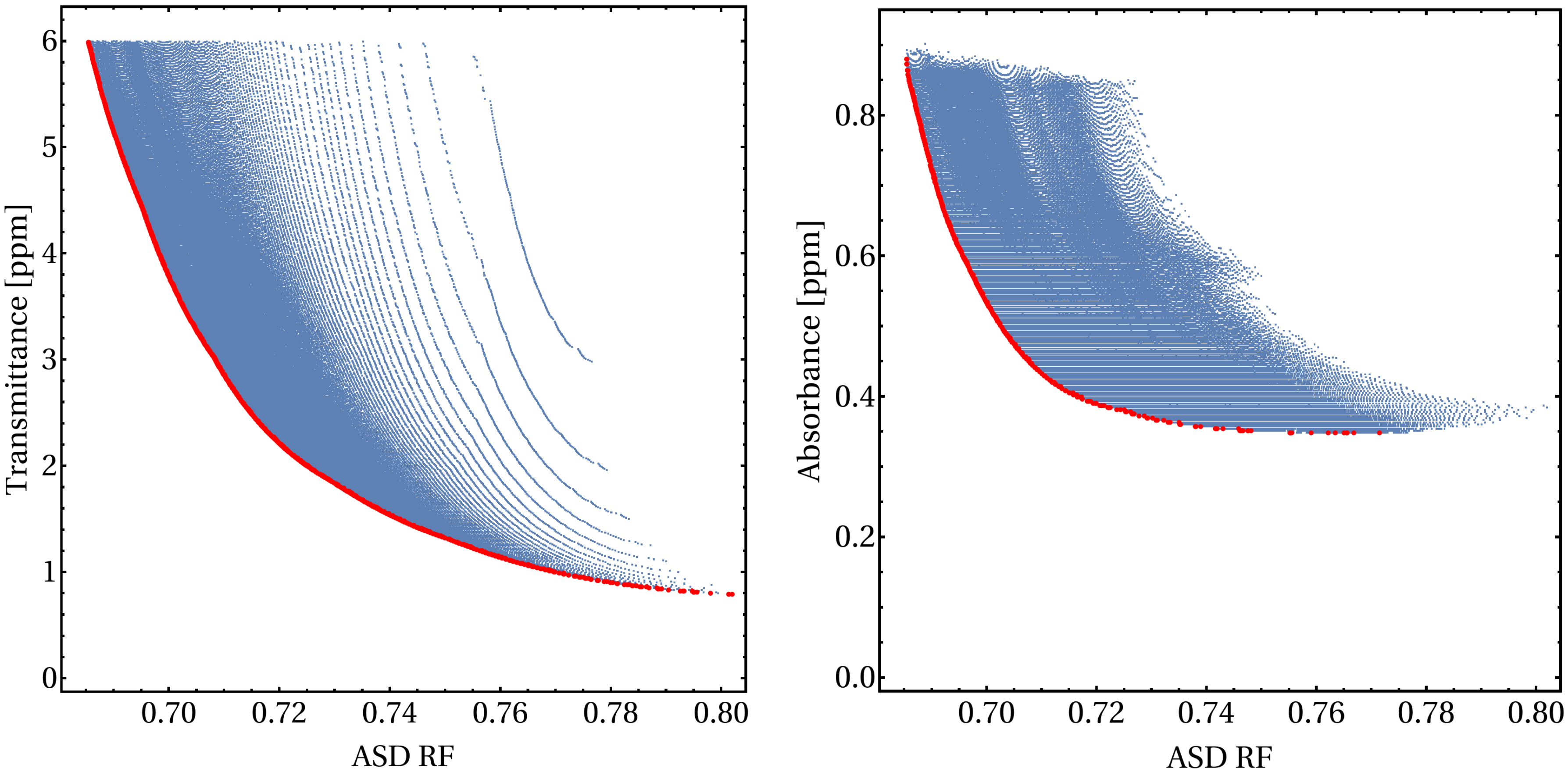
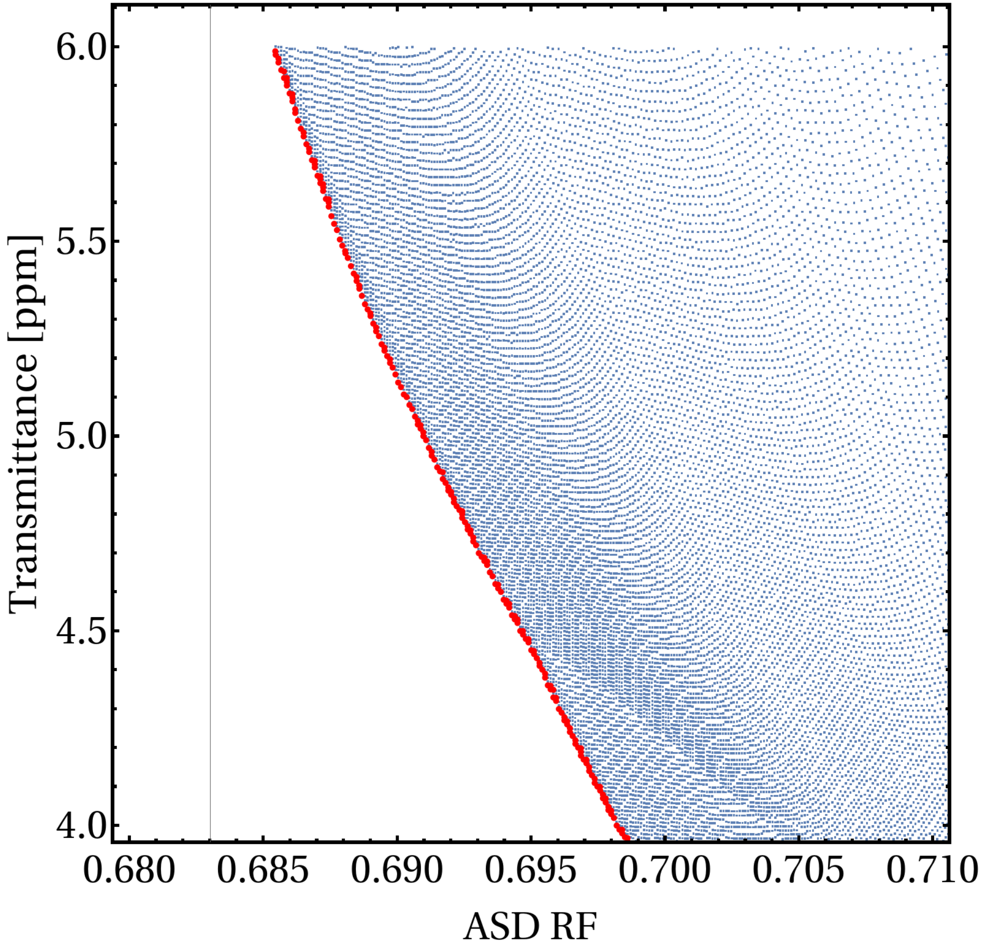
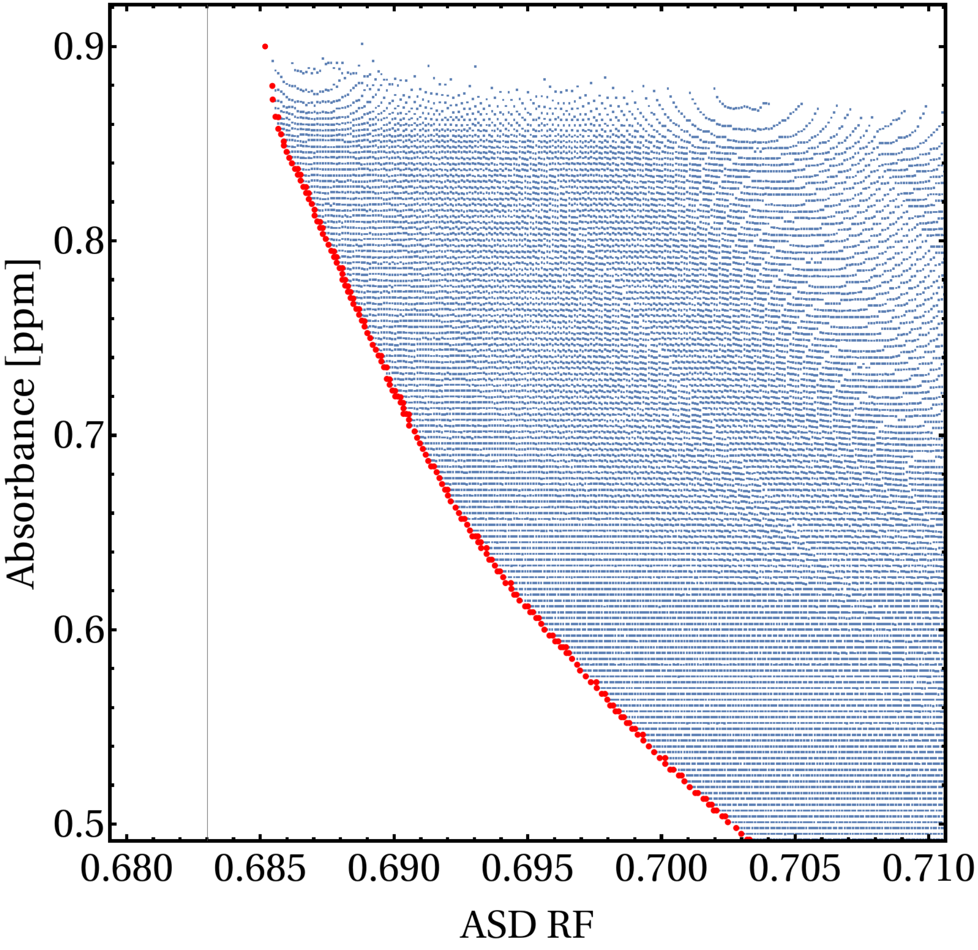
Pareto Front 2D projections



Pareto Front 2D closeup projections



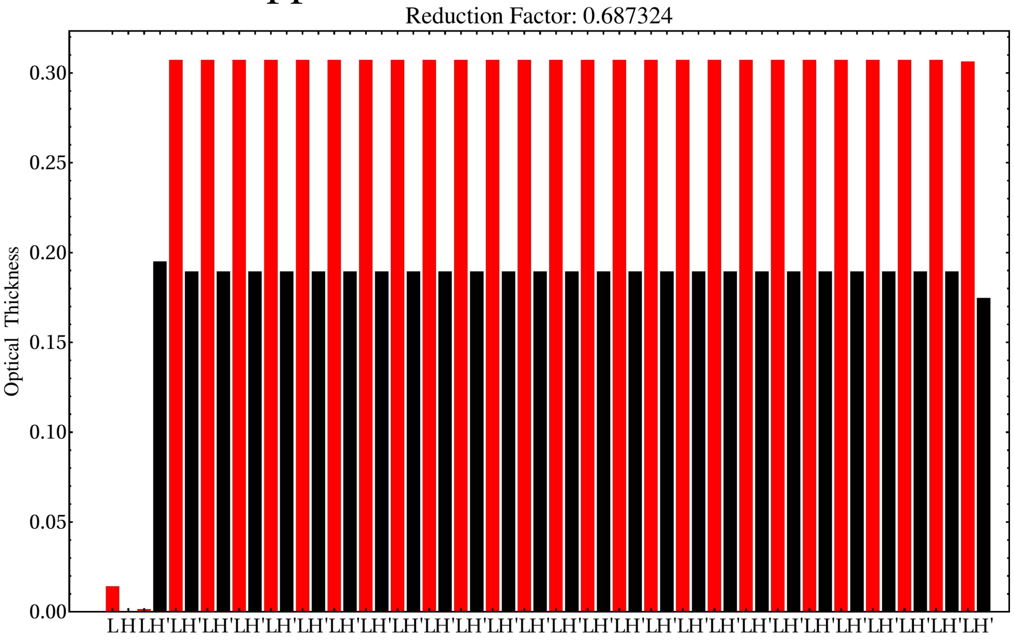


Solutions constraint: A<1 ppm

Colors code:
Red : silica
Blue : Ti::Ta2O5
Black: Ti::GeO2

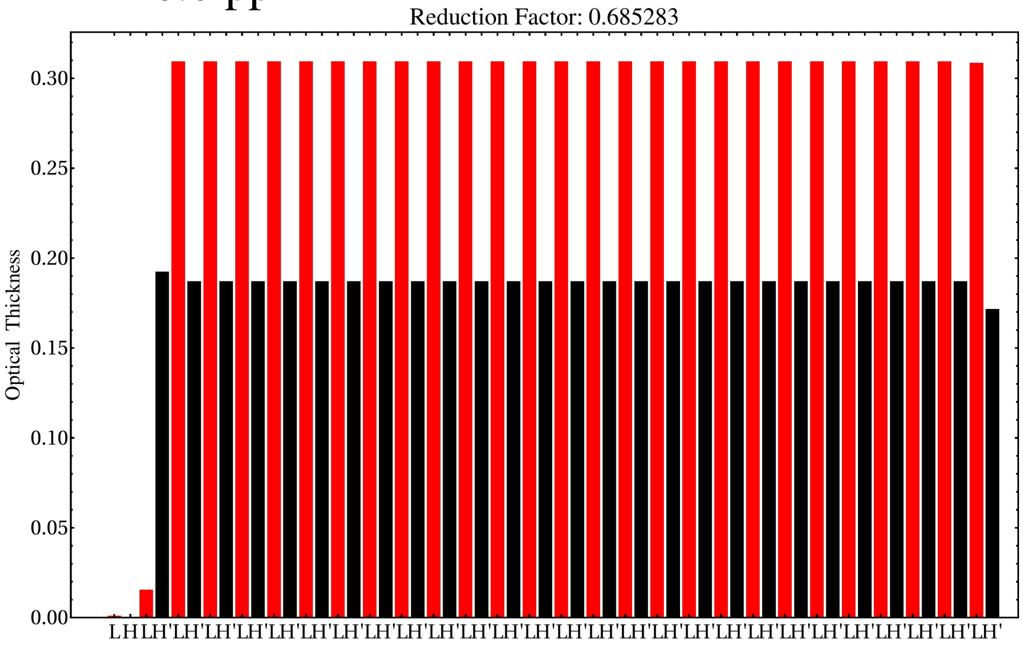
A=0.9046 ppm

T=5.6 ppm



A=0.9065 ppm

T=6.0 ppm

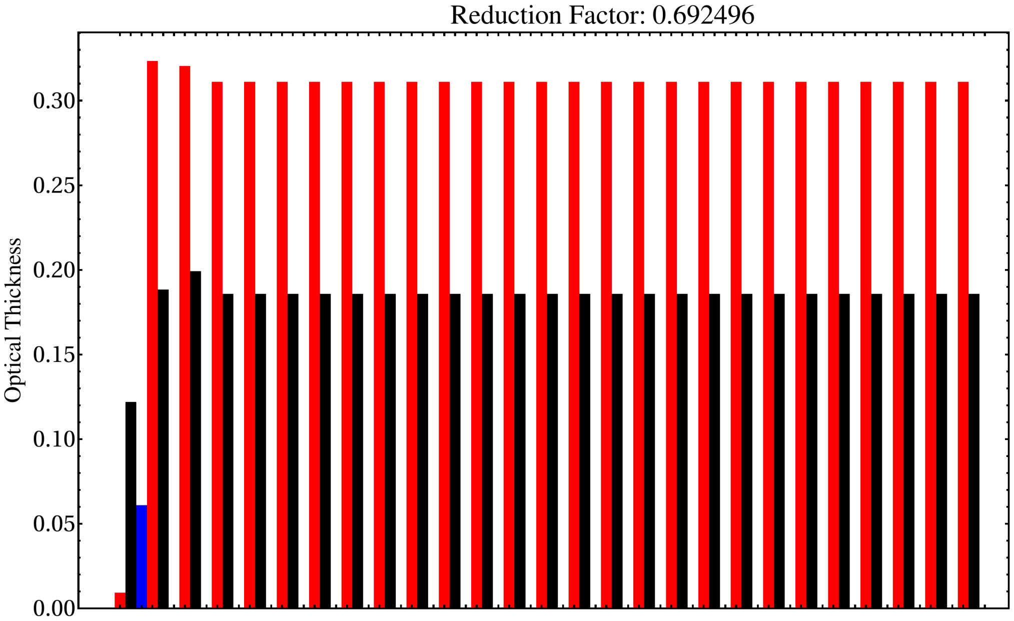


Substrate on the right; radiation on the left

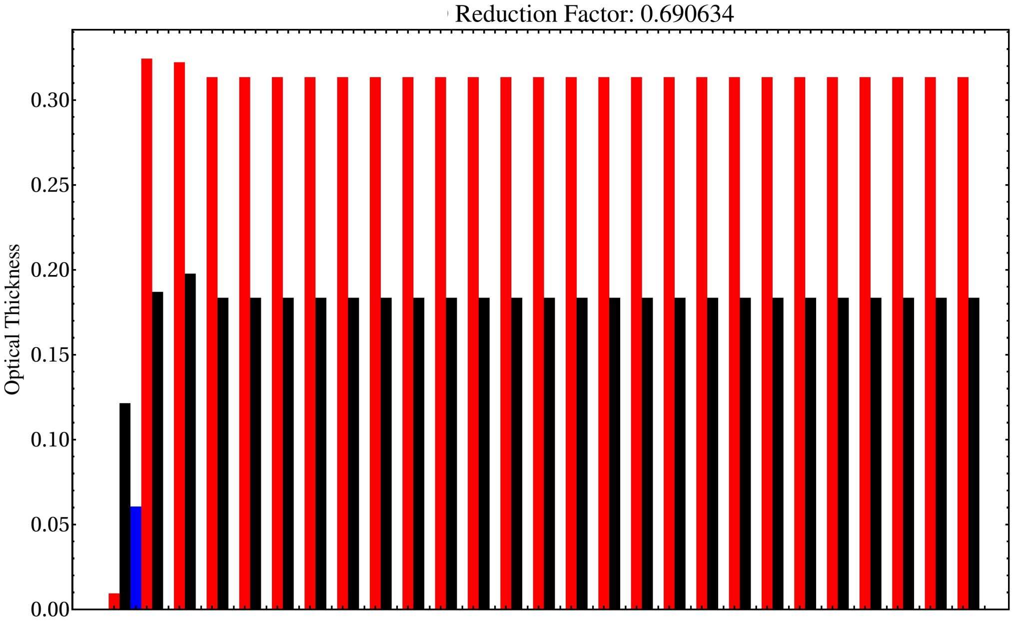
Solutions constraint: A=0.7 ppm

Colors code:
Red : silica
Blue : Ti::Ta2O5
Black: Ti::GeO2

T=5.6 ppm



T=6.0 ppm



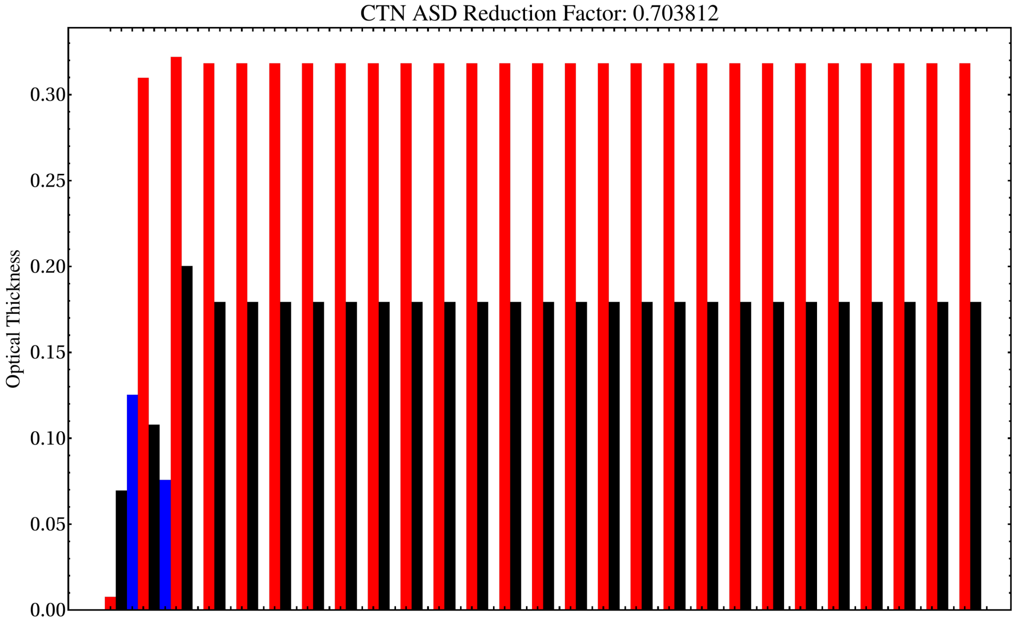
Substrate on the right; radiation on the left

Solutions constraint: A=0.5 ppm

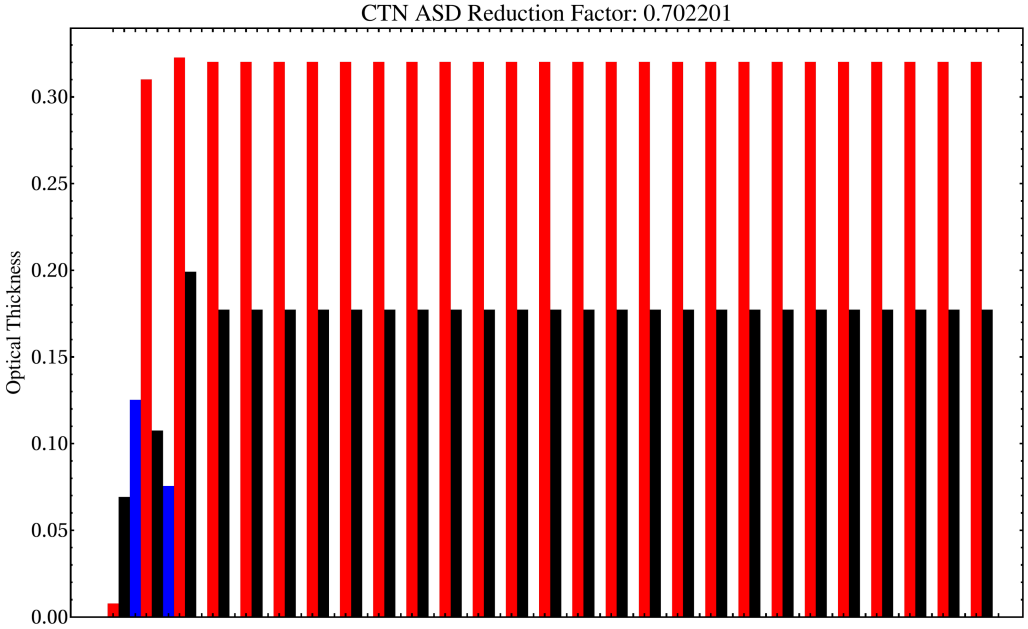
Colors code:
Red : silica
Blue : Ti::Ta2O5
Black: Ti::GeO2

UNDER FABRICATION @LMA

T=5.6 ppm



T=6.0 ppm



Substrate on the right; radiation on the left

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What does the future hold in store for us?

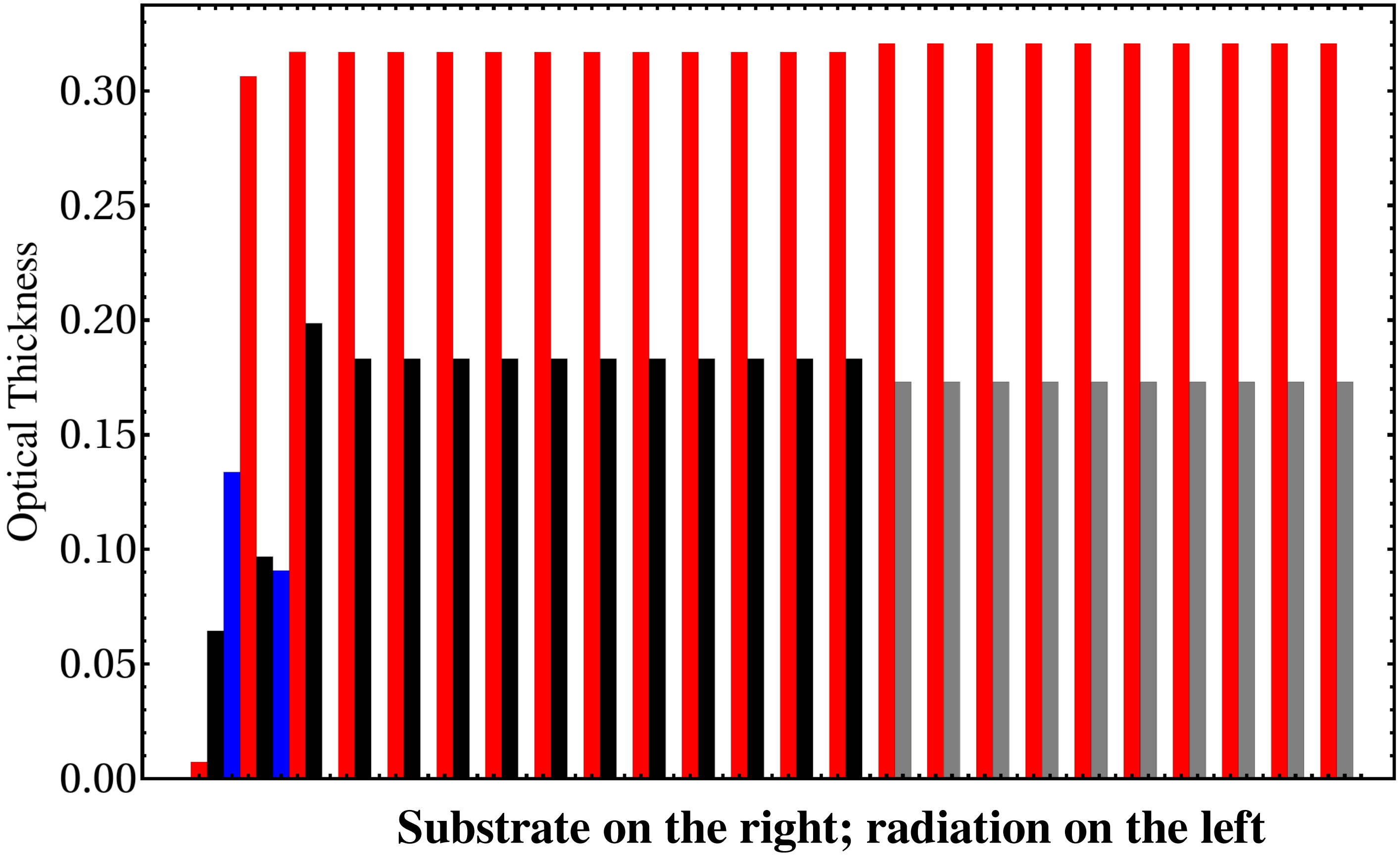
SiNx n=2.05 k=1.2E-4 $\eta_{SiN_x} = 5.44$ Coater B

Solutions constraint: A=0.5 ppm T=5.6 ppm

What if? → Reducing Braginsky Coeff.
ASD RF = 0.654
$\eta_{SiN_x} = 3.5$

2 12 10

CTN ASD Reduction Factor: 0.686372



Colors code:
Red : silica
Blue : Ti::Ta2O5
Black: Ti::GeO2
Gray: SiNx

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SiNx n=2.15 k=1.5E-4 $\eta_{SiN_x} = 5.44$ Coater B

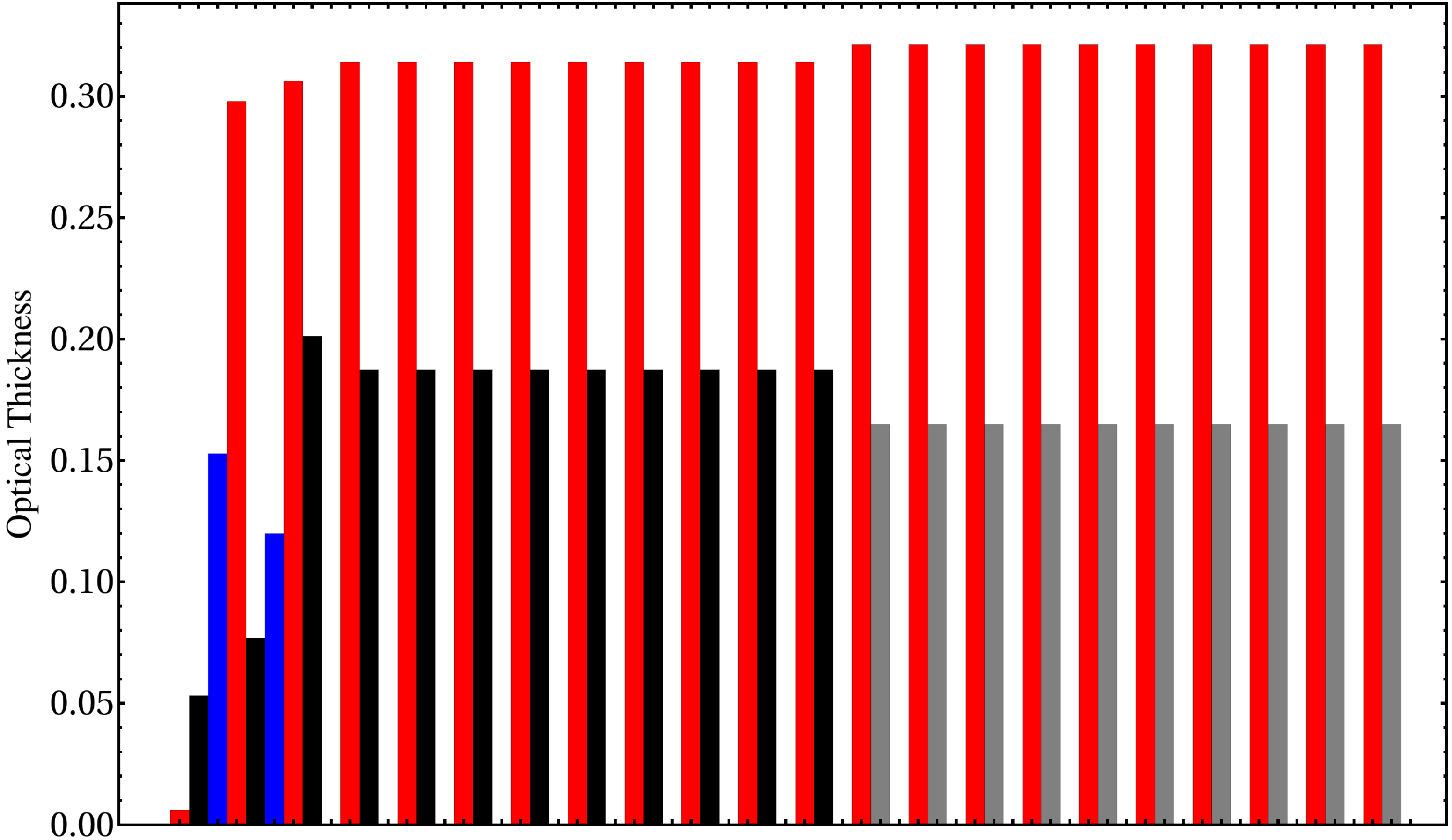
Solutions constraint: A=0.5 ppm T=5.6 ppm

What if?

Reducing Braginsky Coeff.
ASD RF = 0.628
$\eta_{SiN_x} = \mathbf{3.5}$

2 10 10

CTN ASD Reduction Factor: 0.663359



Colors code:
Red : silica
Blue : Ti::Ta2O5
Black: Ti::GeO2
Gray: SiNx

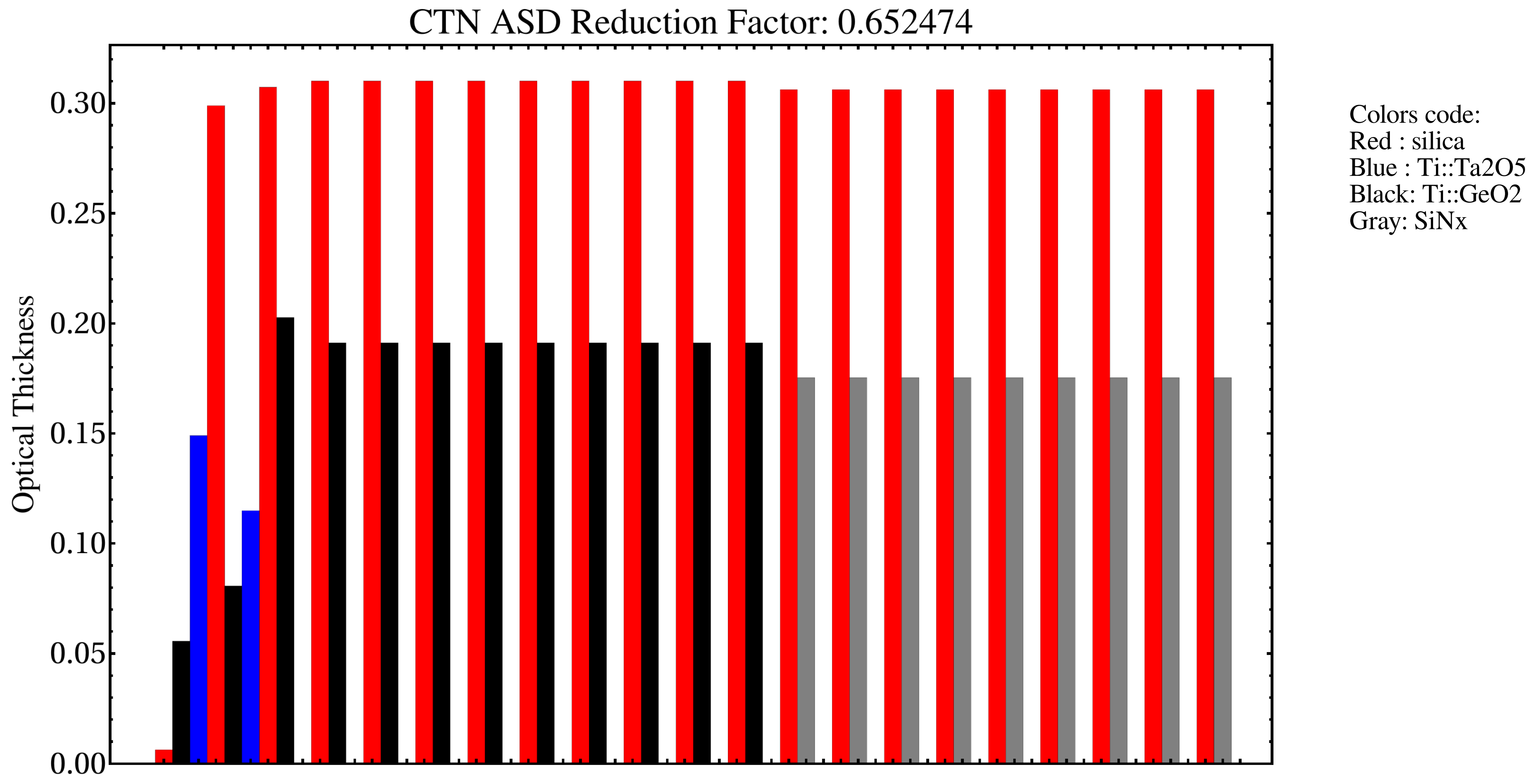
SiNx n=2.2 k=1.5E-4 $\eta_{SiN_x} = 5.44$ Coater B

Solutions constraint: A=0.5 ppm T=5.6 ppm

What if?

Reducing Braginsky Coeff.
ASD RF = 0.62
$\eta_{SiN_x} = 3.5$

2 10 9



Conclusion ?

Thanks for your attention

I think that the ternary optimization method, together with other technologies,
are an opportunity to broaden the set of materials that can be used in mirror production.

In some sense the problem becomes "two-dimensional" , on one axis are the materials
and on another axis the method for using them in mirrors.

Some conclusion.

With the current level of Ti:GeO2 extinction, it is not possible to go below 0.76 ppm absorbance (Koppelman for QWL design, Carniglia Limit).

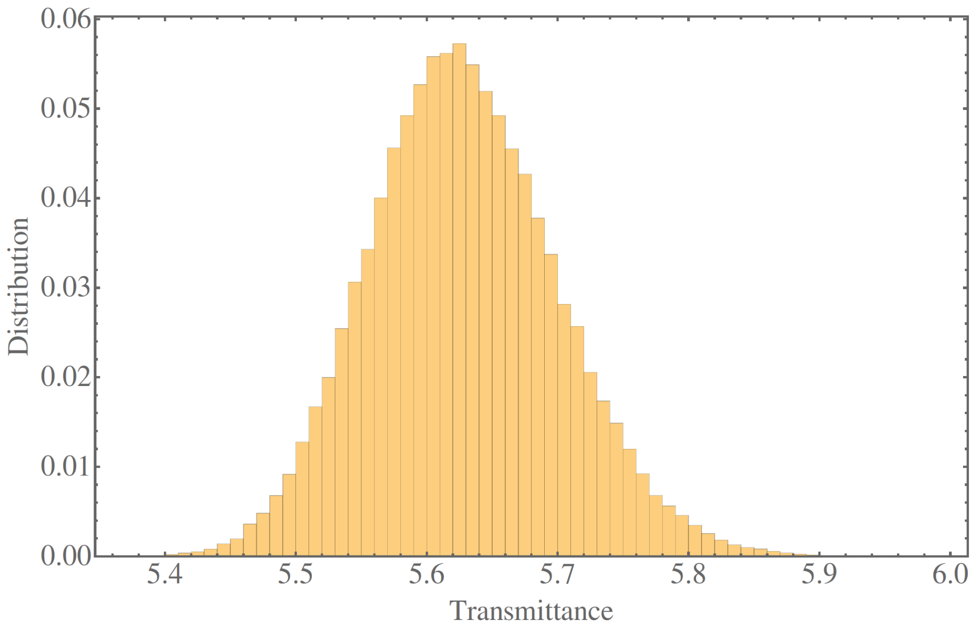
The ternary optimization method is applicable to mirrors made of Silica/Ti:Tantala/Ti:GeO2 the method succeeds in meeting the stringent absorbance specifications of future detectors (A=0.5 ppm)

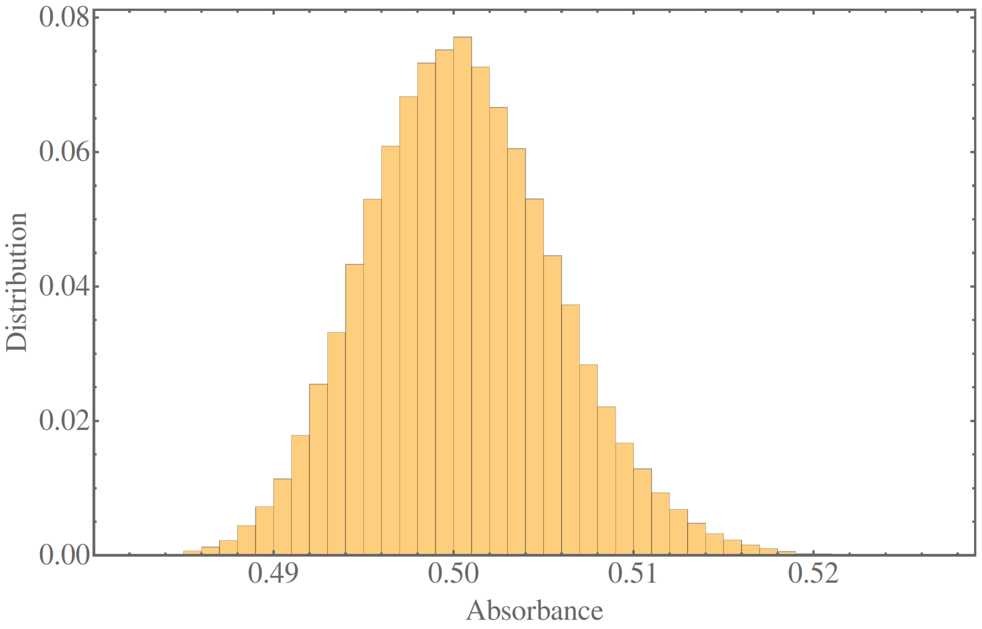
Quaternary coatings, based on silicon nitride (or something similar) can further reduce thermal noise

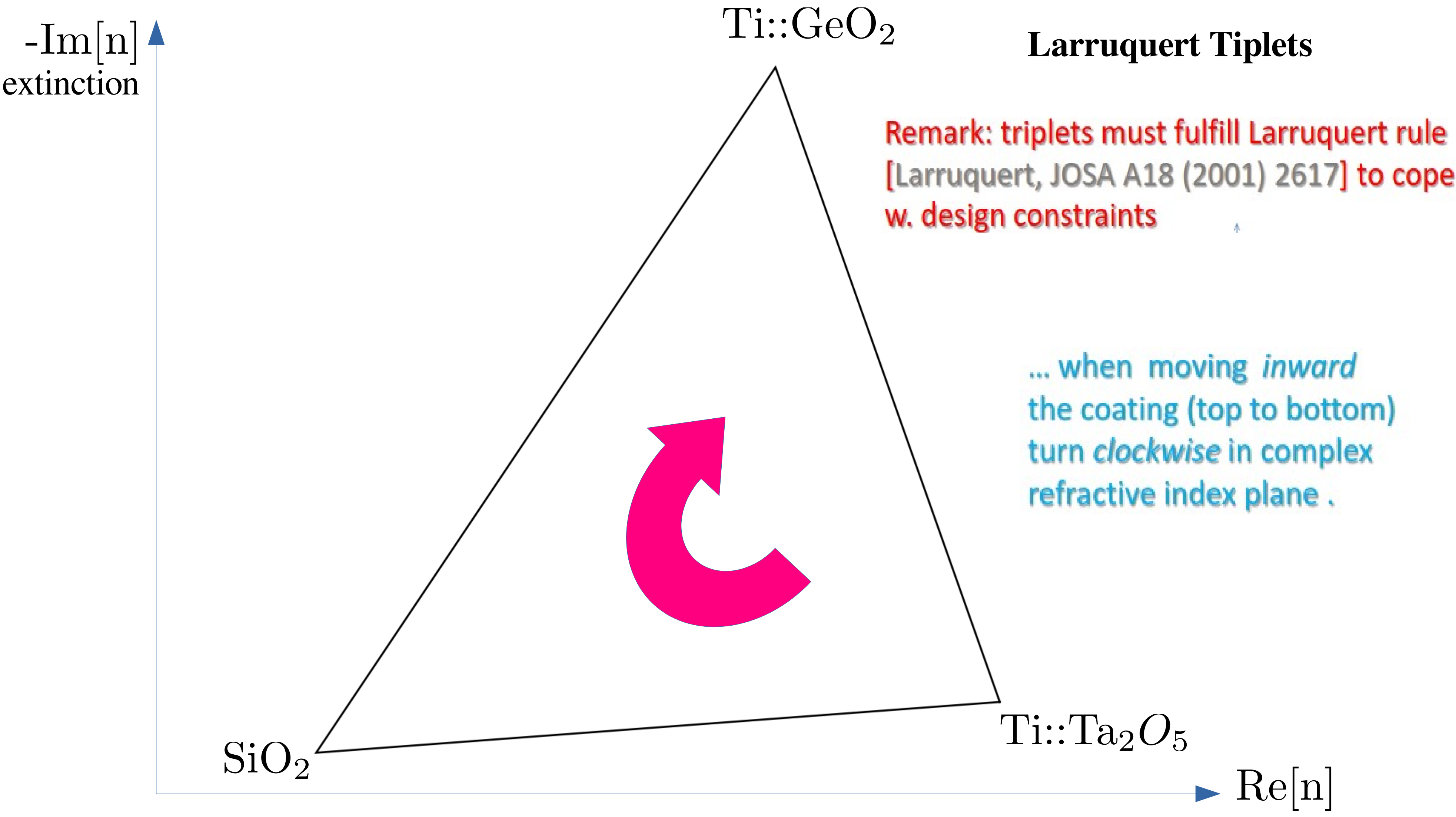
Design robustness analysis

The simulation was done assuming 1 nm standard deviation (Gaussianly distributed) on all layer thicknesses (trial = 10^5).

All the refractive indexes are not random.






Larruquert Tiplets
Remark: triplets must fulfill Larruquert rule [Larruquert, JOSA A18 (2001) 2617] to cope w. design constraints
... when moving *inward* the coating (top to bottom) turn *clockwise* in complex refractive index plane .
-Im[n]
extinction
Re[n]
$Ti::GeO_2$
SiO_2
$Ti::Ta_2O_5$