OPTIMIZED COATINGS

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The Waves Group

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Rationale

- Current mirror design: *quarter-wavelength* (QWL) alternating SiO_2 and Ta_2O_5 layers.
- Yields *largest reflectance* among all stacked-doublet designs for any *fixed* no. of layers (or equivalently, *smallest* no. of layers at any *fixed reflectance*).
- Coating (structural) noise *dominates thermal-noise budget* in key spectral range.
- QWL coating does *not* yield mimimum noise for a prescribed reflectivity, hence *not optimal.*

Coating Design Optimization: Status & Work Plan (2005-2006)

- **Status/Directions**
  - Genetic optimization (running)
    - ***The*** choice, for highest design flexibility and insight;
  - Stacked-doublet (completed)
    - Most obvious generalization of stacked quarter wavelength;
  - Regular non-periodic (just started)
    - getting closer to the "perfect mirror";

- On top of this: *new materials* (e.g., JMM TiO_2-doped Tantala)

Funding Proposal

INFN – COAT (2006 - PI Innocenzo M. Pinto)

Goal: prototyping four GA-optimized mirrors
to be tested at CALTECH TNI.

Time-span: 1 year (2006).

Participants: TWG (algorithm and code),
CALTECH LIGO-Lab (substrates & TNI),
LMA Lyon, FR (prototyping; bare costs).

Partnerships: ILIAS-Strega (S. Rowan/J. Hough),
TAMA (Tsubono K.), VIRGO (F. Vetrano).

Requested budget: 50 KEU (60 K$).

Genetic Optimization

- **Nice Features**
  - Multiple, *heterogeneous* mixed continuous/discrete constraints;
  - Multi-objective and/or best tradeoff optimization;
  - Robust.

Available options include:
-structural/rheology-related constraints;
-multiple-wavelength operation;
-several (> 2) materials, etc.…

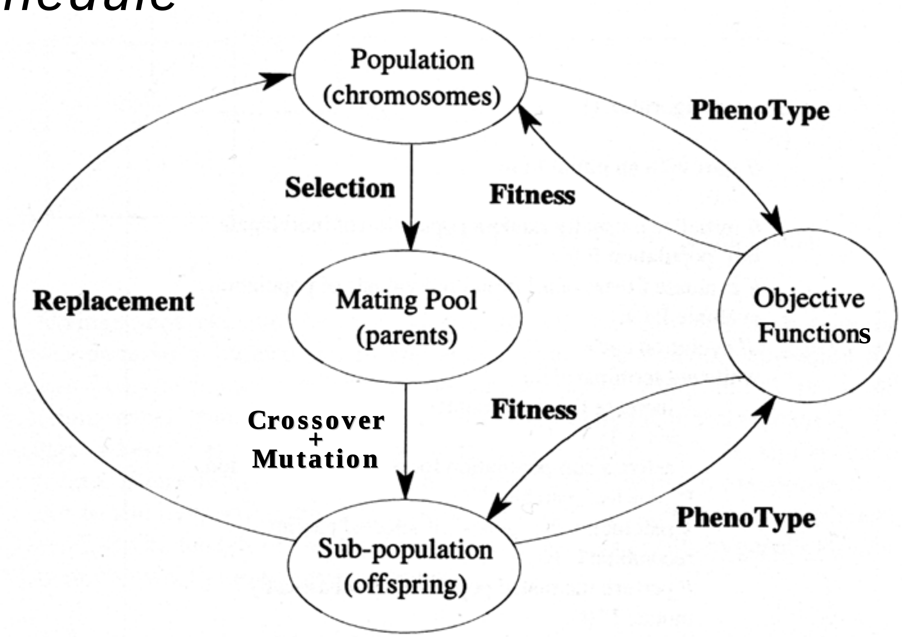
Educated ignorance attitude (almost *no a-priori assumption* on structure of sought solution - will shed light on it !);

Effective & well established (e.g. microwave antenna and filter design)…

Status: PIKAIA-based Code-kernel developed.

Genetic Algos in a Nutshell

-Problem unknowns ≡ *genes*;
-Point in search space ≡ *chromosome*;
-Set of points in search space ≡ *population*;
-Evolve *random* initial population according to an *evolutionary schedule*



Stacked Doublet Optimization

Most obvious generalization of current stacked-$\lambda/4$-design.

- Coating reflectivity is a monotonic (increasing) function of Bloch characteristic exponent (BCE) of transmission matrix of basic doublet (true for any *truncated-periodic*);
- Coating noise is closely modeled by a simple (linear) law:

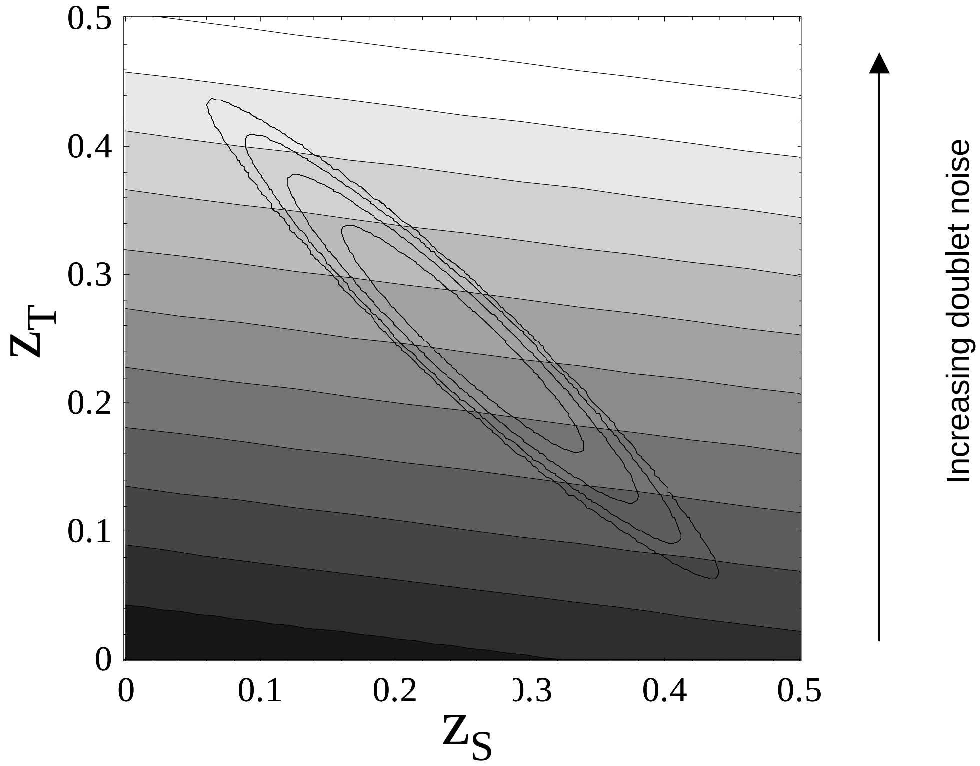
total (physical) thicknesses

$$\nu = C(\Delta_{Tantala} + \gamma^{-1}\, \Delta_{Silica})$$

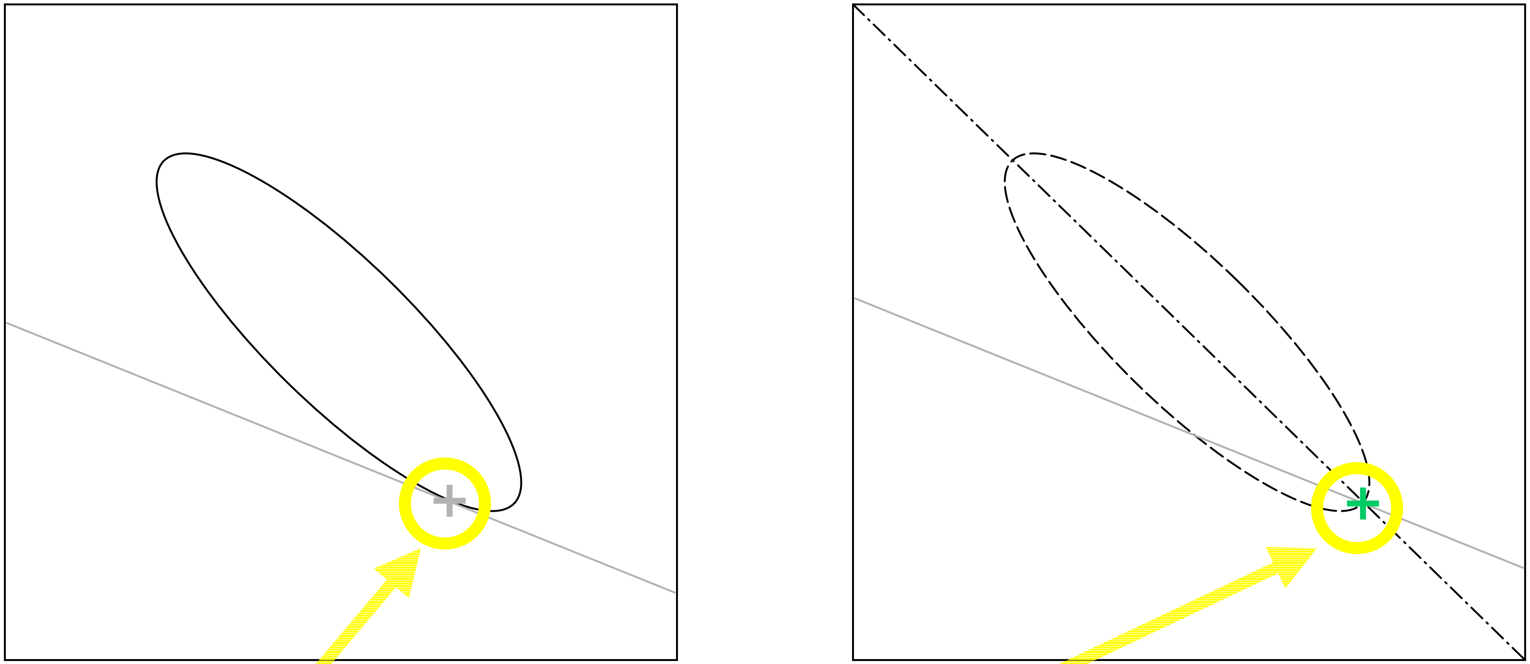
γ related to Young moduli, Poisson ratios & loss angles of both substrate & coating materials. In view of present measurement uncertainties γ can be anything between 10 and 30.

Stacked Doublet Optimization

z_S = optical length SiO_2 layer
z_T = optical length Ta_2O_5 layer
} In units of λ_0

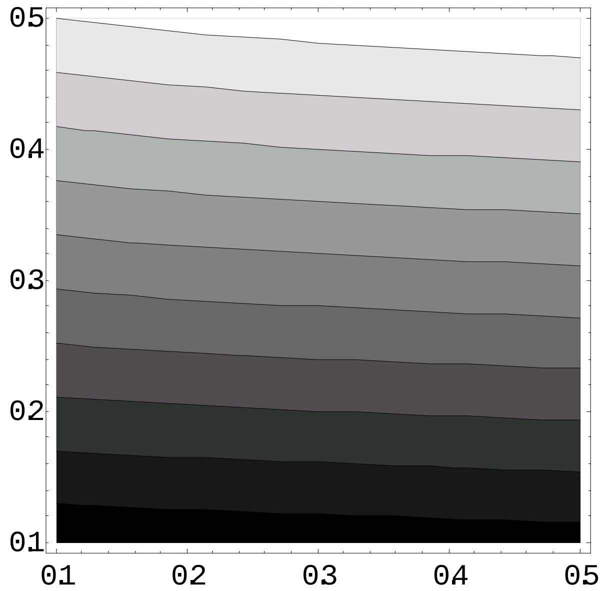


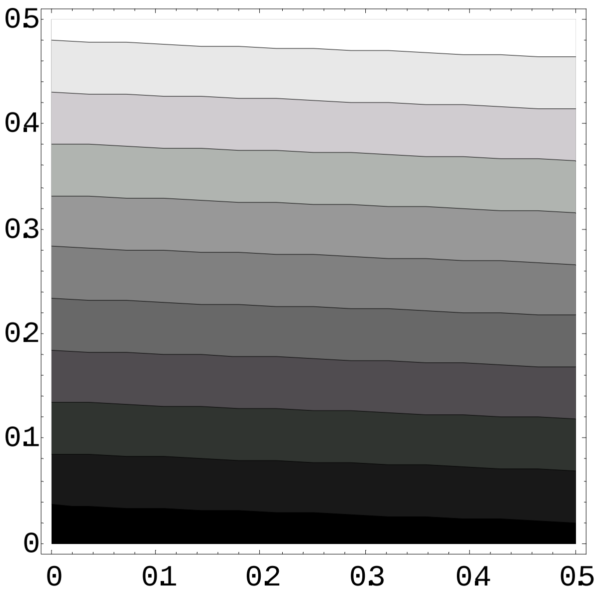
Stacked Doublet Optimization: Approximation # 1



BCE contour lines *very thin*: no sensible difference between exact and approximate ($z_T+z_S=1/2$) optimization

Stacked Doublet Optimization: Approximation # 2





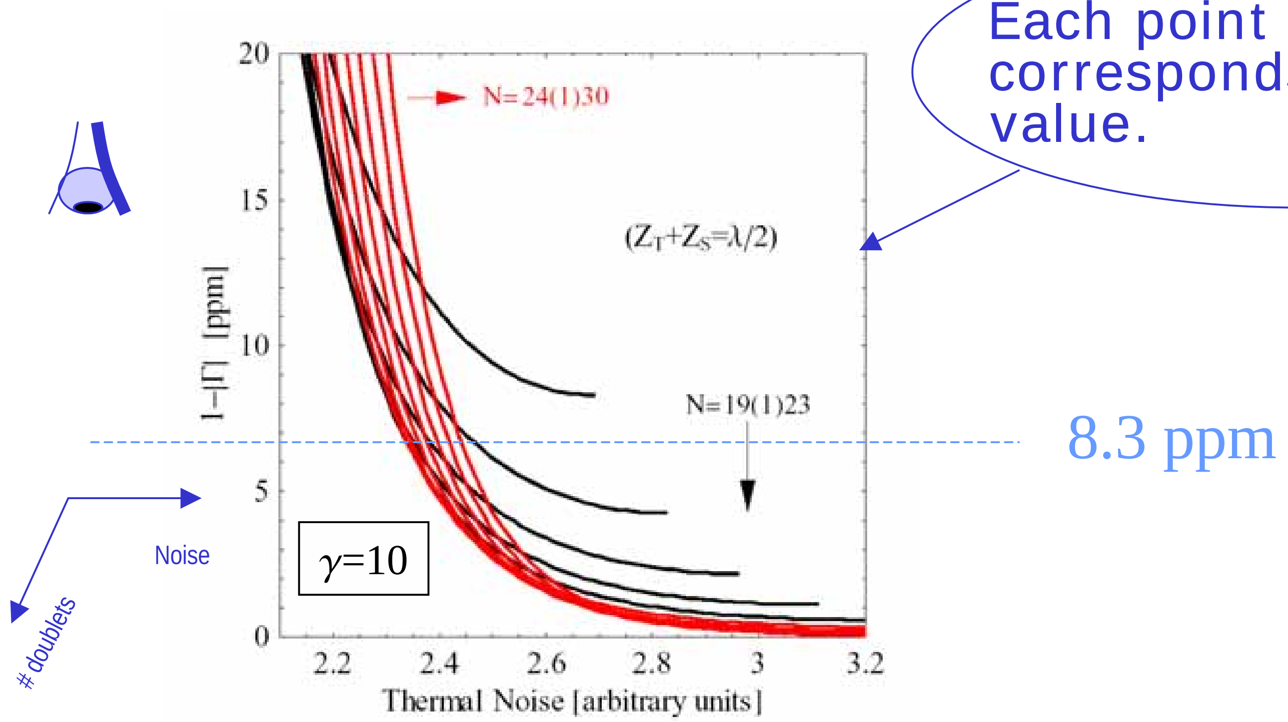
...both absorbed by large by uncertainty in γ

Constructing Tradeoff Curves

-Assign number N of doublets;
-Assign noise upper-bound noise for *whole* coating;
-Compute corresponding upper-bound for single doublet;
-Determine z_S and z_T so as to maximize BCE;
under tha above noise constraint;
-Compute terminated N-doublet reflection coefficient.

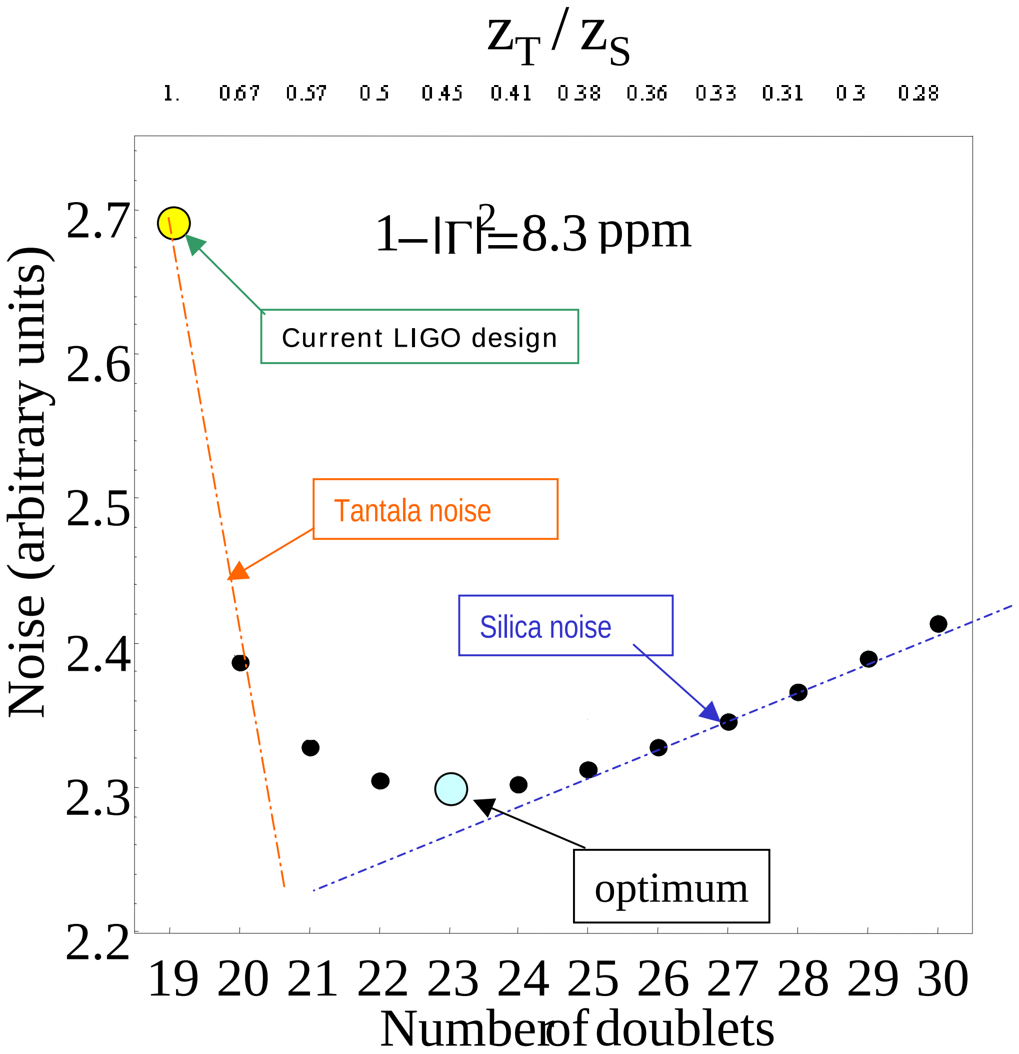
Stacked Doublet Optimization

Each point on any curve corresponds to a z_T/z_S value.



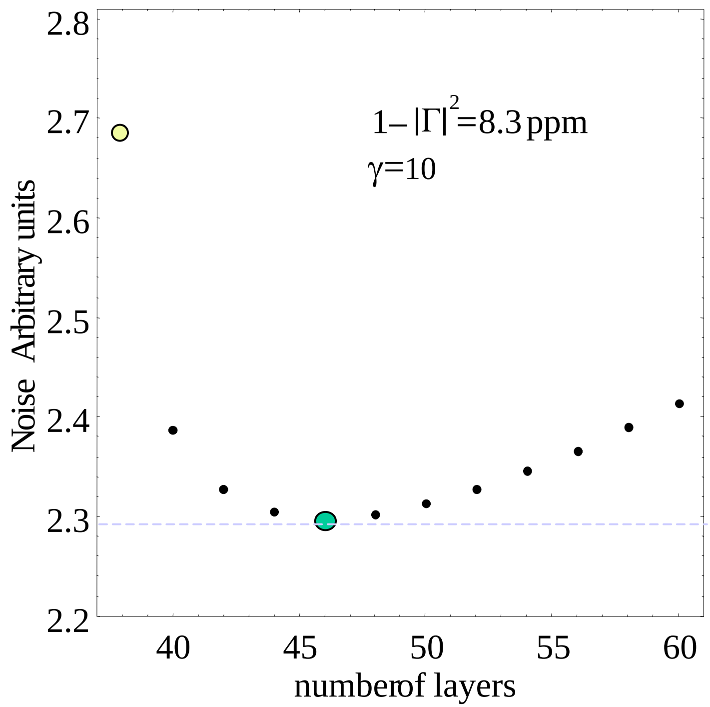
Status: Transmissivity vs. Noise Tradeoff Curves Drawn

Stacked Doublet Optimization

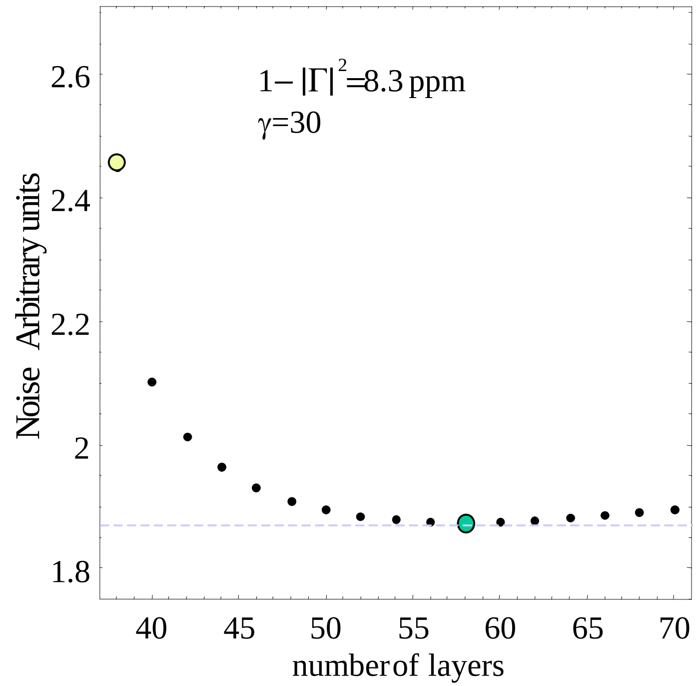


Quarter Wavelength (yellow bullets) vs. Optimized (grey bullets) Stacked Doublet Design. Transmissivity 8.3 ppm. Different SiO_2/Ta_2O_5 loss ratios.

LIGO G-050363-00-R



~14% noise reduction.
N_d raised from 19 to 22-24
(absolute optimum at 23)
$\Delta[SiO_2]$= 249.583 nm
$\Delta[Ta_2O_5]$= 80.8843 nm



~24% noise reduction.
N_d raised from 19 to $\geq$ 25
(absolute optimum at 29)
$\Delta[SiO_2]$= 280.216 nm
$\Delta[Ta_2O_5]$= 59.3664 nm

Quarter Wavelength (yellow bullets) vs. Optimized (grey bullets) Stacked Doublet Design. Transmissivity 1.12 ppm. Different SiO_2/Ta_2O_5 loss ratios.

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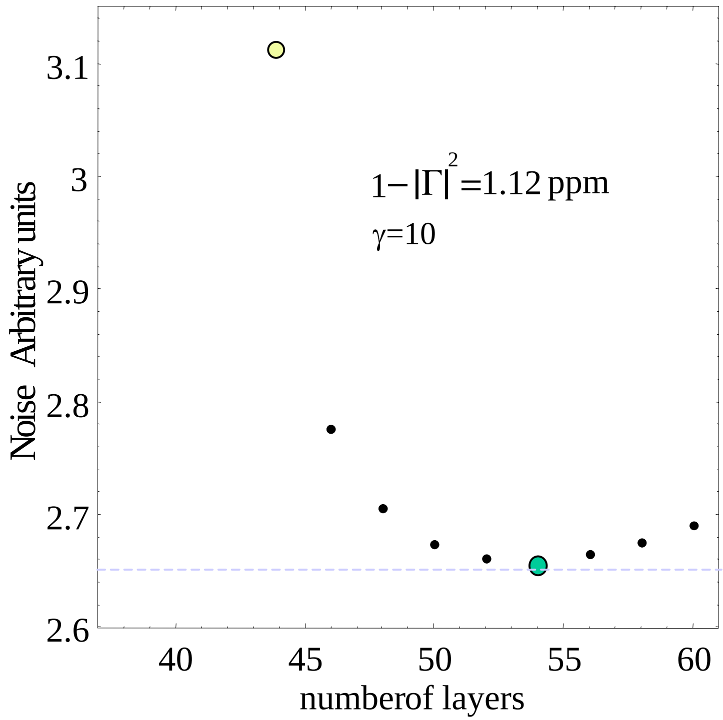
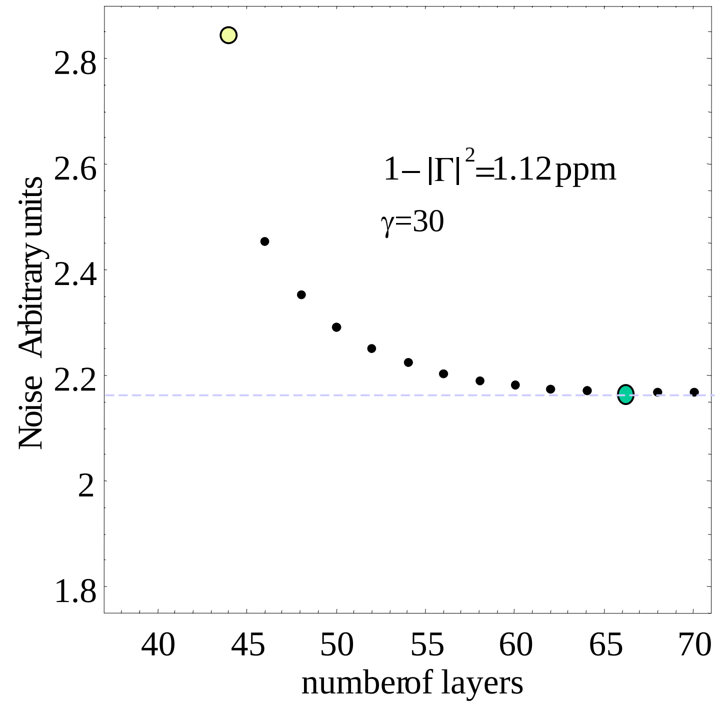


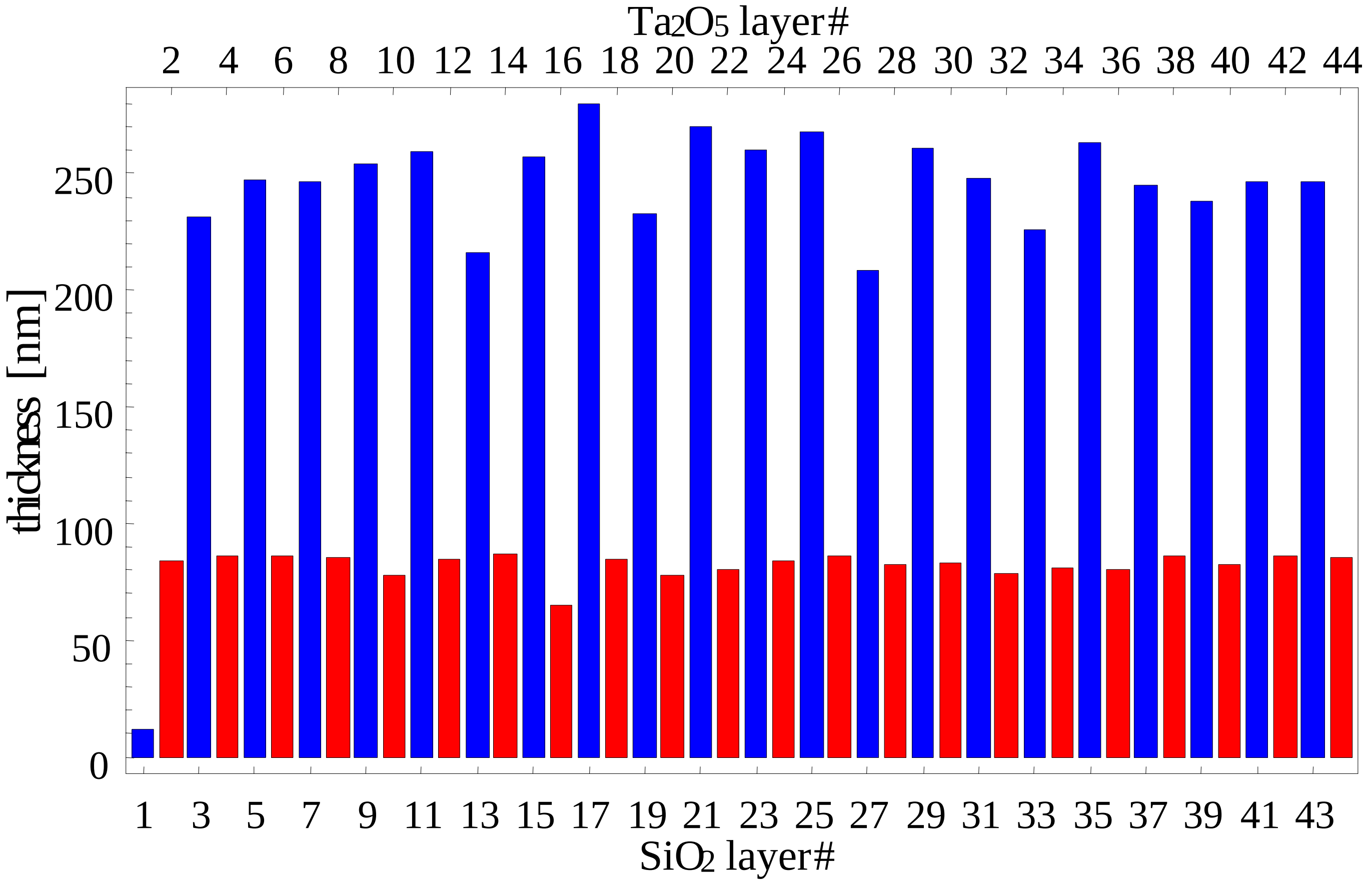
~14% noise reduction.
N_d raised from 22 to 25-28
(absolute optimum at 27)
Δ[SiO_2]= 251.871 nm
Δ[Ta_2O_5]= 60.5726 nm



~24% noise reduction.
N_d raised from 22 to ≥28
(absolute optimum at 33)
Δ[SiO_2]= 278.465 nm
Δ[Ta_2O_5]= 60.5726 nm

GA Engineered Prototype
(after 10^5 generations)

Goal: $1-|\Gamma|^2 < 15$ ppm. $L[Ta_2O_5] < 2000$ nm, $\gamma = \infty$.

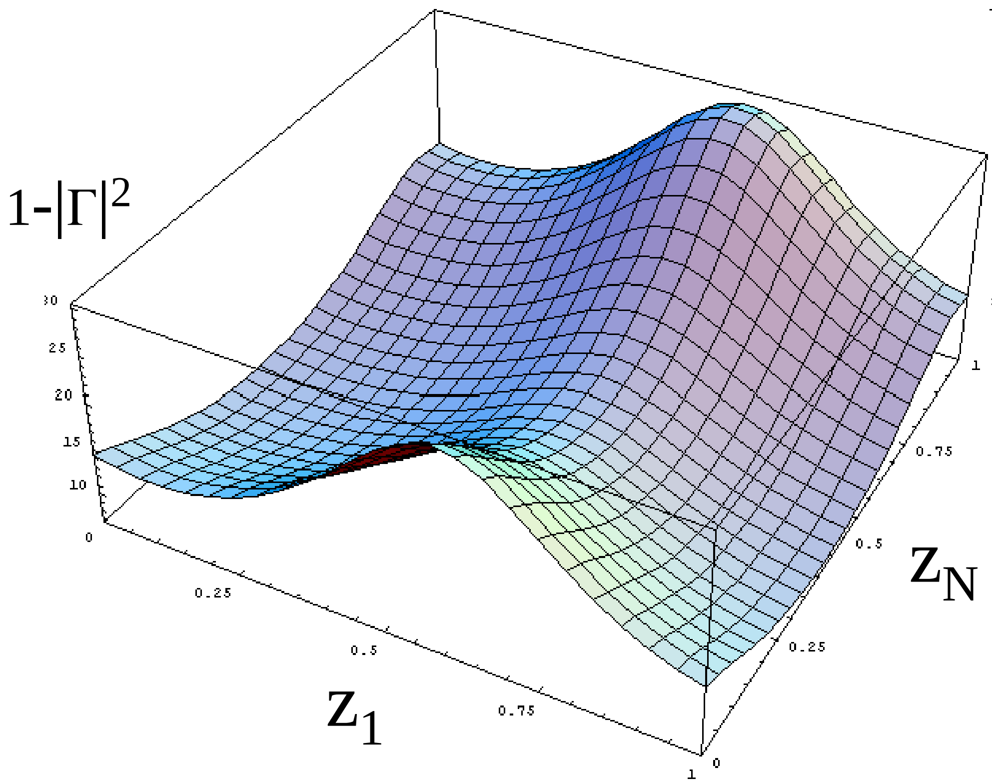


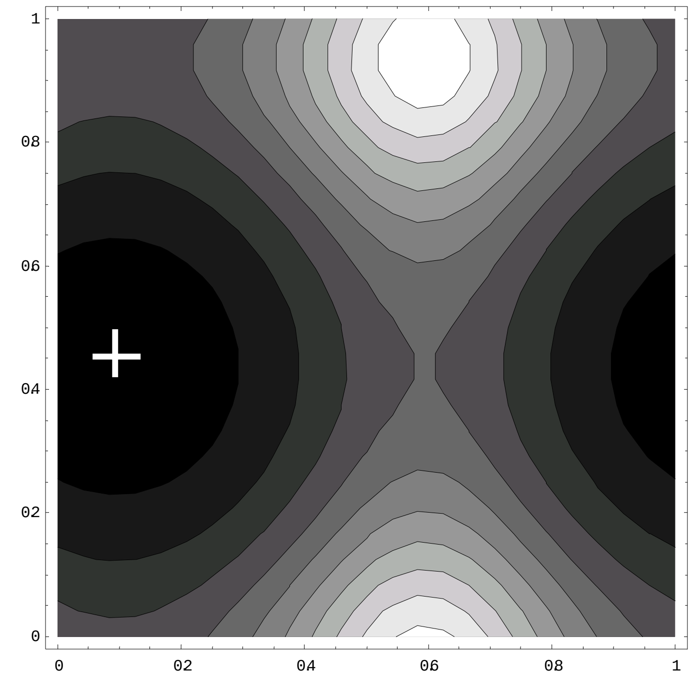
GA Prototype, contd.

vs. nearest-neighbour quarter-wavelengths (QWL)

	QWL-1	**Genetic**	QWL-2
N (cap included)	36	**44**	28
$1-\|\Gamma\|^2$ ppm	16.20	**14.91**	**235.46**
$L(Ta_2O_5)$ nm	**2359.43**	**1815.61**	1835.11
$L(SiO_2)$ nm	3479.98	**5217.4**	2747.35
L_{tot} nm	5839.41	**7033.01**	4582.46

Stacked Doublets: Lesson from GA: Tweak End Layers to Improve Reflectivity !

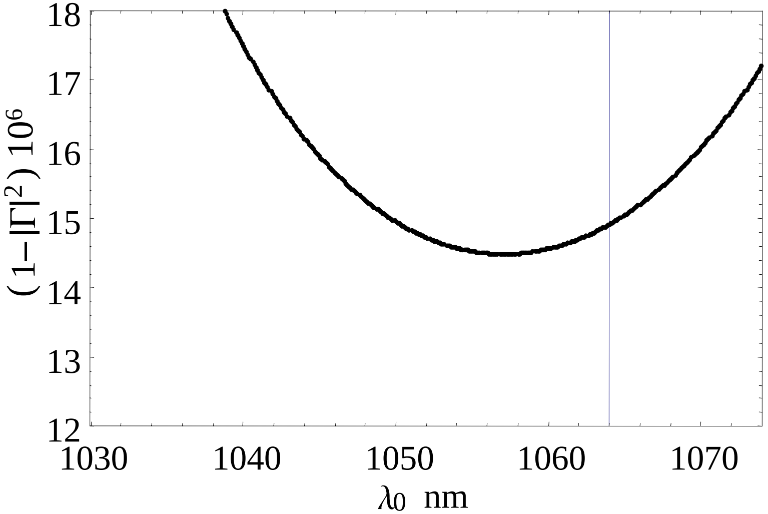




(z_1 = 0.0943, z_N =0.0437, in units of $\lambda/2$)

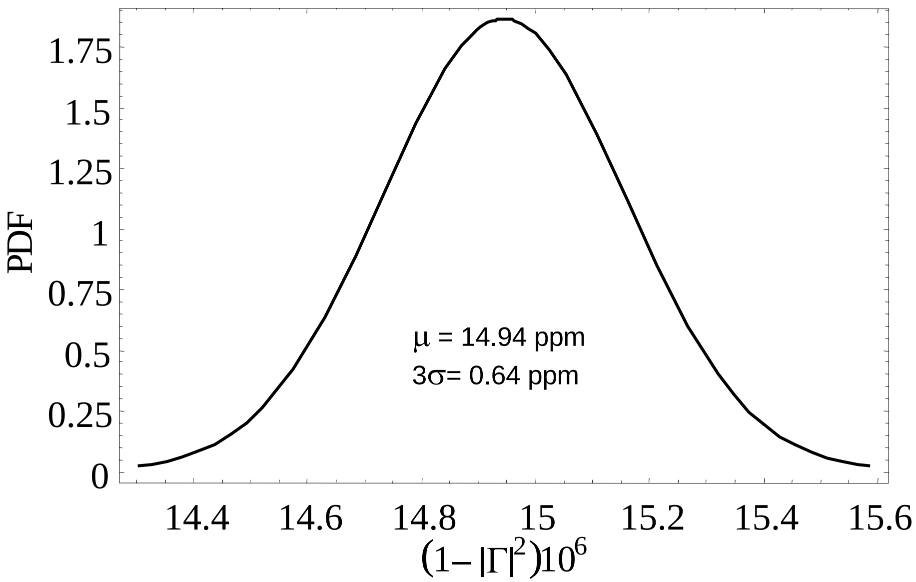
reflectance increased by ~ 10%, noise increased by ~ 1%

GA Prototype Characterization



Distribution of 1-$|\Gamma|^2$.
Random uniform errors, $|\delta\ell| \leq 1\text{nm}$ 10^4 trials.

Mirror frequency response (normal incidence).



Regular Non-Periodic Coatings

Two main sub-classes:
- Fractal (e.g., Cantor);
- Substitutional (e.g. Fibonacci);

Goal: large bandwidths (in frequency *and* wavenumber) [e.g., Optics Lett. 23 (1998) 1573];

Background: applications in antenna array synthesis [e.g., IEEE Trans. AP-53 (2005) 635]

Status: just started