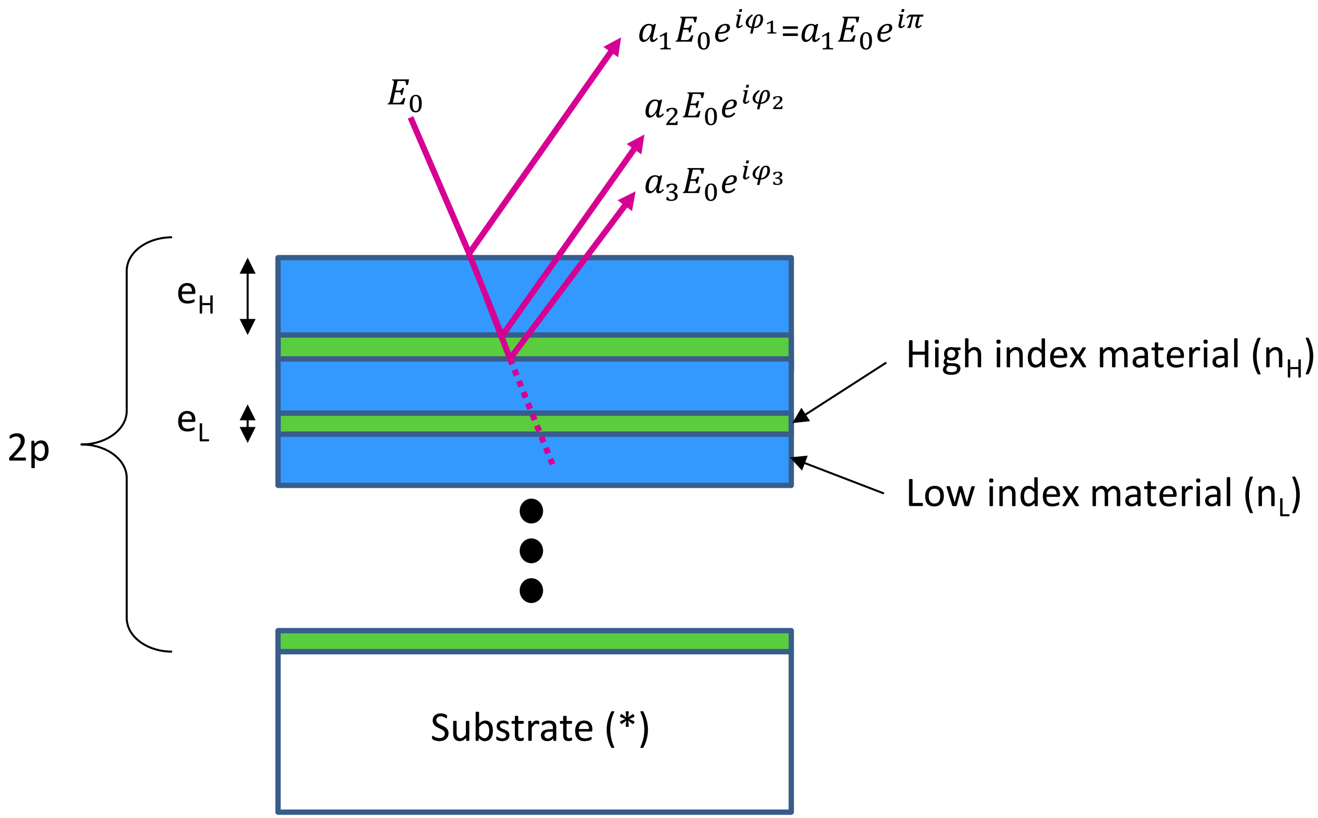
Mirror Coatings for ET

First ET-France workshop

4 février 2021

Benoît Sassolas

What is a mirror coating ? (1/2)

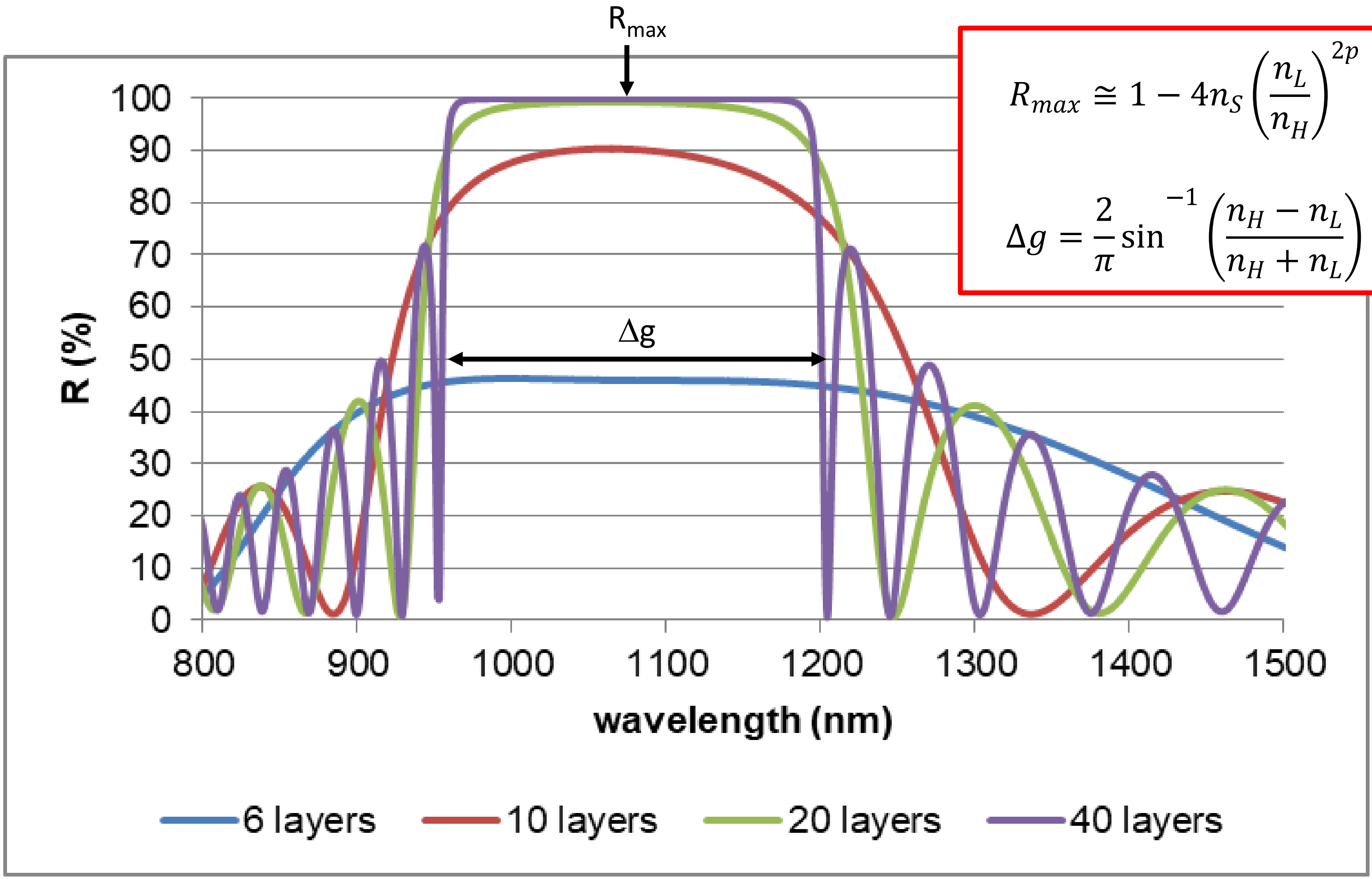


Stack of thin films :

- 2p layers
- Two materials with different index of refraction n_H and n_L
- Constructive interferences in reflection $\varphi_1 = \varphi_2 = \varphi_3 = \pi\ [2\pi]$
- Thicknesses of the layers $n_H e_H$= $n_H e_H$=λ/4 ; i.e. Quarter Wave Layer (QWL)

(*) see A. Amato's talk

What is a mirror coating ? (2/2)

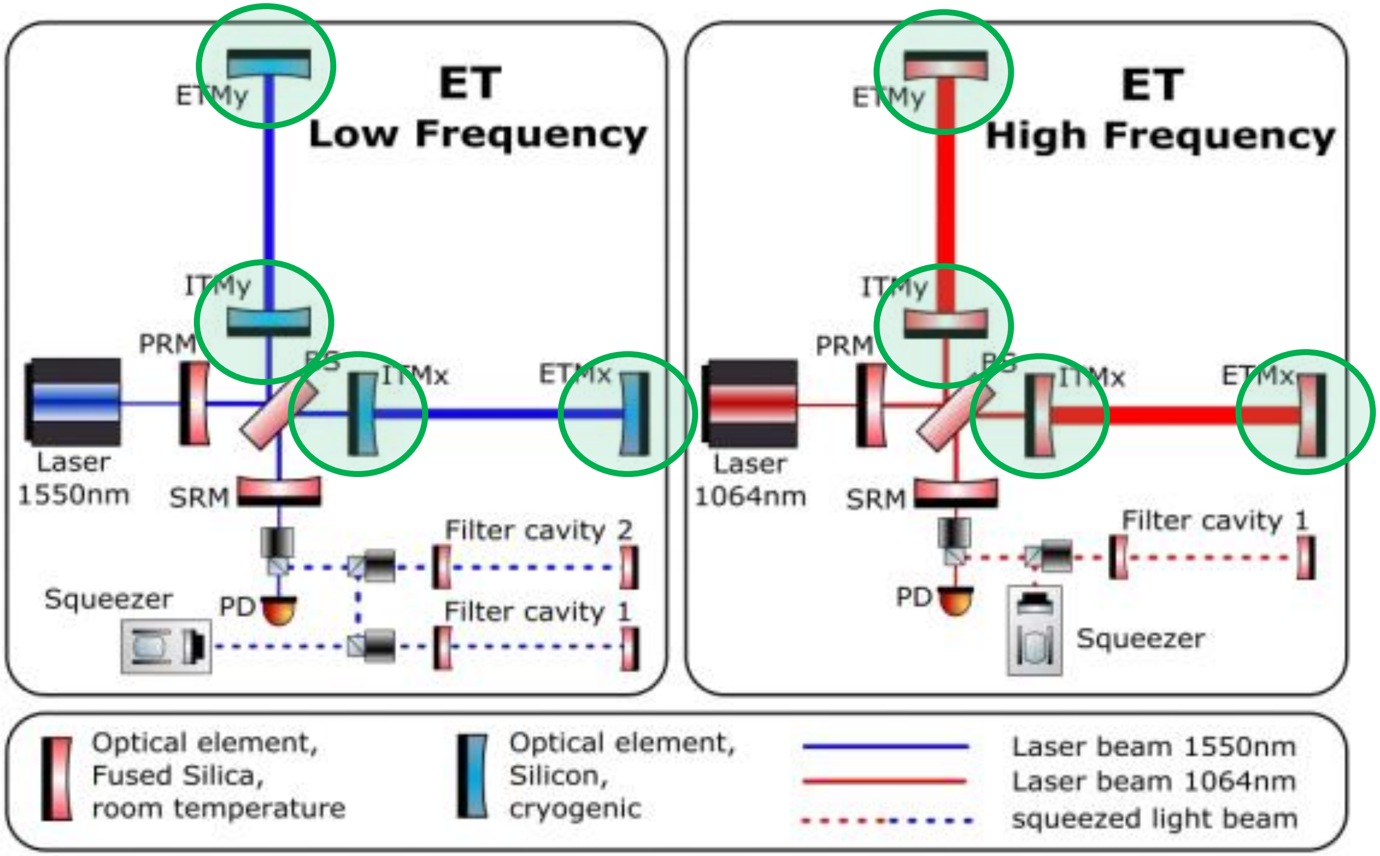


$$R_{max} \cong 1 - 4n_S\left(\frac{n_L}{n_H}\right)^{2p}$$

$$\Delta g = \frac{2}{\pi}\sin^{-1}\left(\frac{n_H - n_L}{n_H + n_L}\right)$$

The more the layers, the more the reflectivity
The more the refractive index contrast, the more the reflectivity

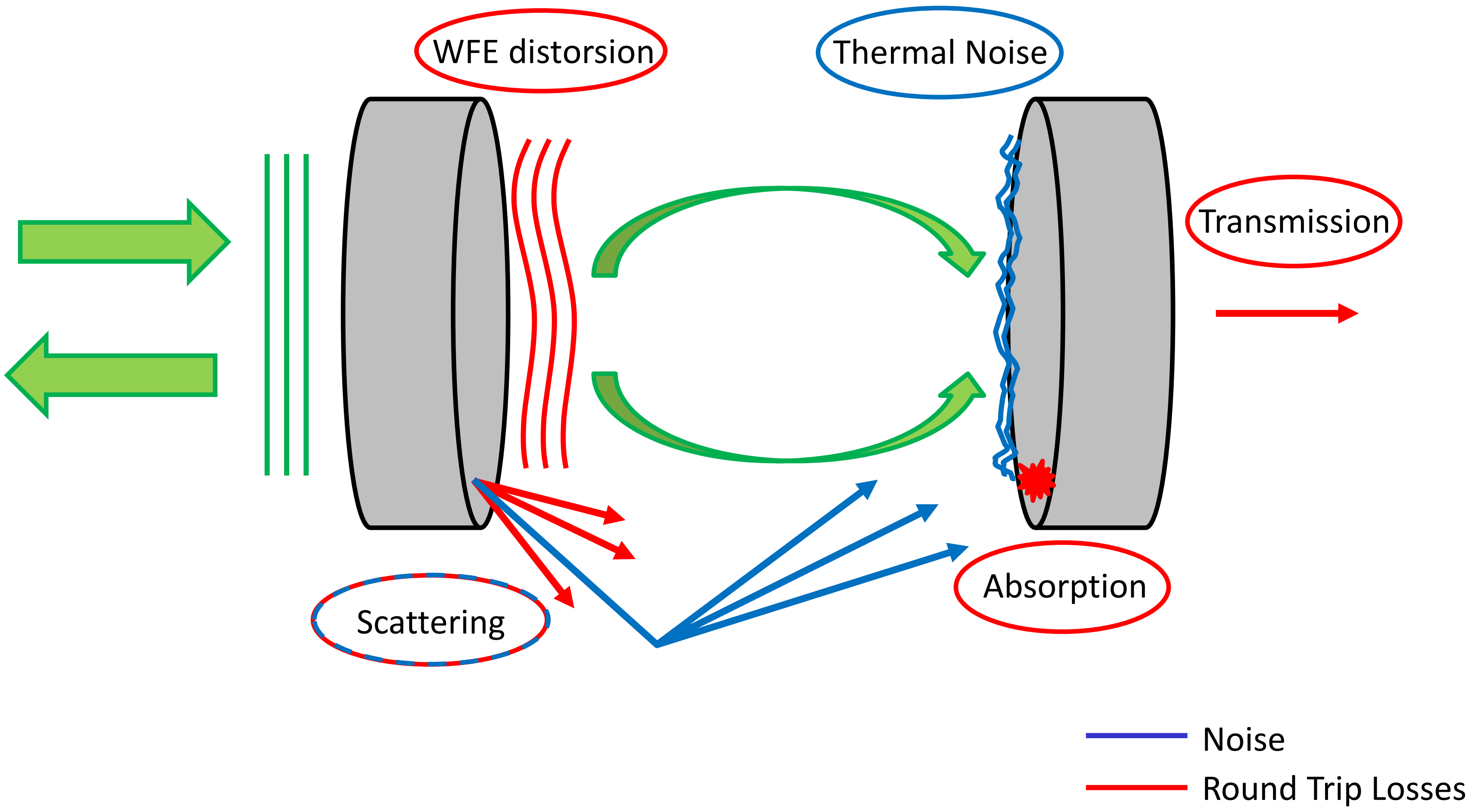
Where are the mirror coatings in ET ?



From Design Report Update 2020

Four high reflectance mirrors per interferometer

Major effects in mirror coating



Thermal Noise : the most critical issue

Amplitude spectral density of thermal noise

$$x(f) = \sqrt{\frac{2k_B T}{\pi^2 f}\frac{d}{w^2}\phi\left(\frac{Y_{\mathrm{coat}}}{Y_{\mathrm{sub}}^2} + \frac{1}{Y_{\mathrm{coat}}}\right)}$$

Temperature

Total thickness

Beam diameter

Mechanical loss

Several approaches to decrease the thermal noise :

- Reducing the temperature (ET-LF)
- Reducing the total thickness : increase the contrast in refractive index allows the same reflectivty with fewer layers
- Increasing the beam diameter (ET-LF & ET-HF)
- Reducing the loss of the coating materials
  - Factor of 3.8 for ET-LF
  - Factor of 7.1 for ET-HF

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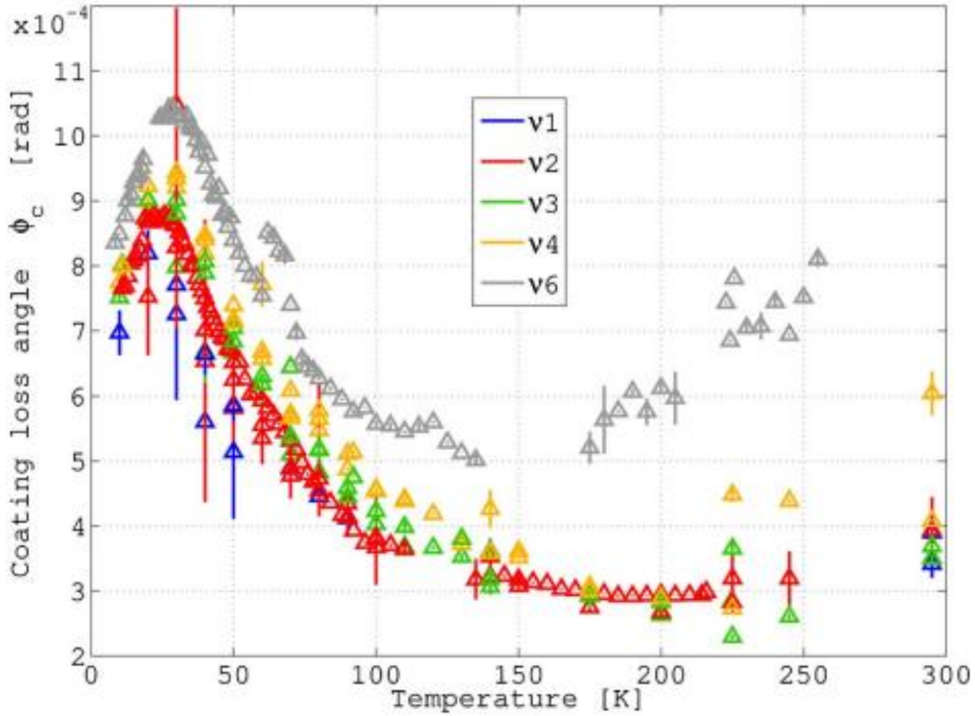
Challenging requirements !!!

Cryogenic temperature vs mechanical loss



Granata et al. OL-38-24-5268 2013

- High reflective coating (aLIGO and AdVirgo)
- SiO_2 and $Ti{:}Ta_2O_5$
- Lowest noise at room temperature so far
- Worse performances at low temperature
- Mainly due to a loss peak in the SiO_2 φ~8e-4 rad

New mirror's coating required !

Several research lines for reducing the mechanical losses

Coating design

Multimaterial

Nanolayering

Cristalline coatings

GaAs/AlGaAs

GaP/AlGeP

Materials

Amorphous silicon

Silicon Nitride

Silica doped Hafnia

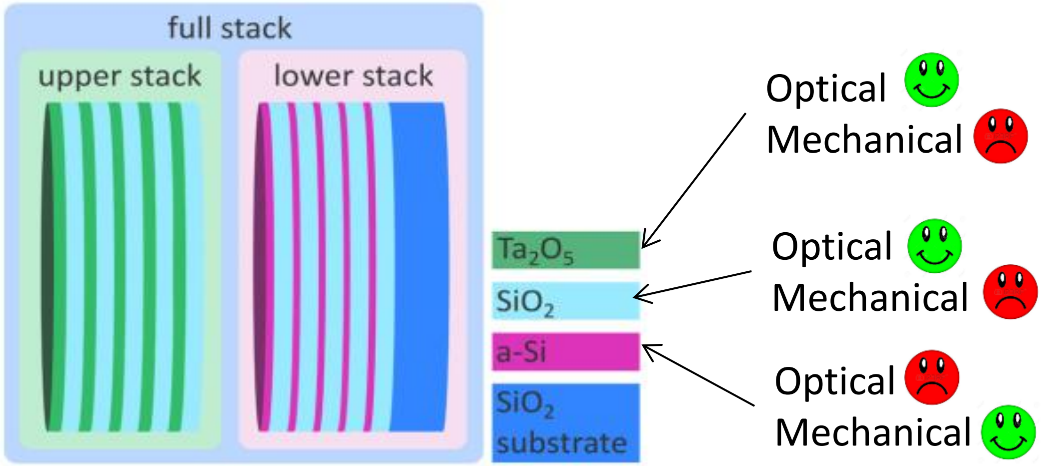
Alumina

Low index materials

Coating design

Multimaterial coatings:

- Use of a lower loss material deeper in the stack
- Decrease the thickness of the most dissipative material
- Limit the impact on the absorption



Room temperature, A=8 ppm @ 2000 nm - φ =2e-4 rad [1]

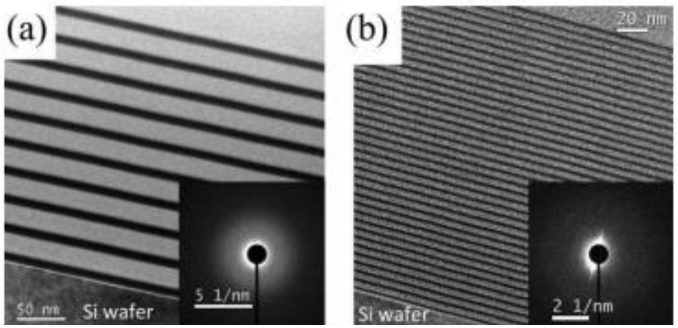
Several design studies and experimental results done so far.
Experimental coatings compliant to the optical and mechanical requirements still needed to be demonstrated.

[1] Tait et al. PRL 125-01102 (2020)
See also Craig et al. PRL 122-231102 (2019); Steinlechner et al. Phys. Rev. D 91-069904 (2015); Murray et al. LIGO-G1900549-v1

Coating design

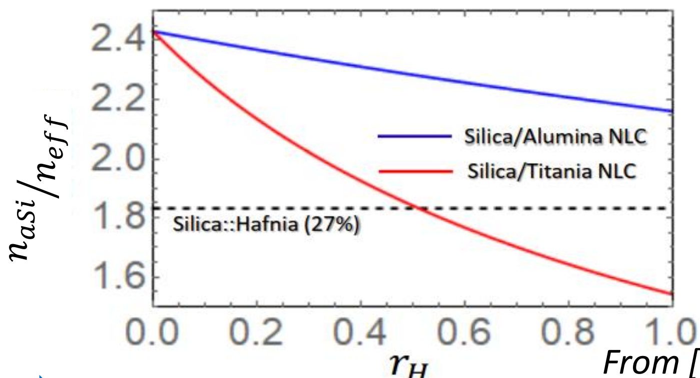
Nanolayering :

- Substructure of a QWL by thinner layers of two materials
- Drude's formula $n_{eff} = [r_H n_H^2 + (1 - r_H) n_L^2]$ with $r_H = \frac{e_{H,tot}}{e_{H,tot} + e_{L,tot}}$
- Inhibits crystallisation in the material => higher temperature annealing [1]
- Eliminates the cryogenic loss peak in silica coating [2]



From [2]

Nanolayered material made up of silica and titania [2]
n_{eff} = 1.76
Loss decreased by a factor of 2 @ 10K wrt SiO2
Absorption increased by a factor of 2 wrt SiO2



From [3]

Other developments are in progress with silica and alumina => higher optical contrast and lower absorption expected [3]
Low AFM roughness (<0.8nm rms)
Mechanical and structural analysis in progress.

Investigations are required to validate high-reflective coating and large area deposition feasibilty

[1] Pan et al. Opt. Exp. 22-24-29847 (2014); [2] Kuo et al. Opt. Lett. 44-2-247 (2019); [3] Pinto et al. LIGO-G2001499

Materials

Amorphous silicon (a-Si) :

ET-LF

- Low loss material @ cryo temperature : φ=2e-6 – 2e-5 rad [1]
- High refractive index : 3.5 @ 1550 nm
- Absorbing material : k~1.2e-5 @ 1550 nm [2] et k~3.4e-4 @ 2000 nm [3]
- Better suited to the multimaterial coatings approach

Silicon Nitride (Si_xN_y) :

ET-LF

- Intensive developments for the upcoming upgrade of Advanced Virgo
- Low loss at room temp. φ=1e-4 rad [4] and φ=1e-5 rad [5] @ 10K
- Slightly absorbing 1e−6 < k < 1e−5
- Good association with a-Si for high reflective coating @ 1550nm
- Multimaterial Coatings approach could provide multilayer coating with low absorption but slightly higher thermal noise than required [5]

[1] Liu et al. PRL 113-025503 (2014)
[2] Birney et al. PRL 121-1911101 (2018)
[3] Tait et al. PRL 125-01102 (2020)
[4] Granata et al. App. Opt. 59-5-A229 (2020)
[5] Liu et al. MRS Proceedings 989 0989–A22–01 (2007)

Materials

Silica doped hafnia (SiO_2:HfO_2) :

ET-LF

- Doping prevents crystallization during annealing
- No increase of the loss at cryogenic temperature unlike silica : φ =3.8e-4 rad @ 10K [1]
- Multimaterial coatings should comply with both optical and thermal noise requirements
- Experimental coating is required to demonstrate the the real performances

Alumina (Al_2O_3) :

ET-LF

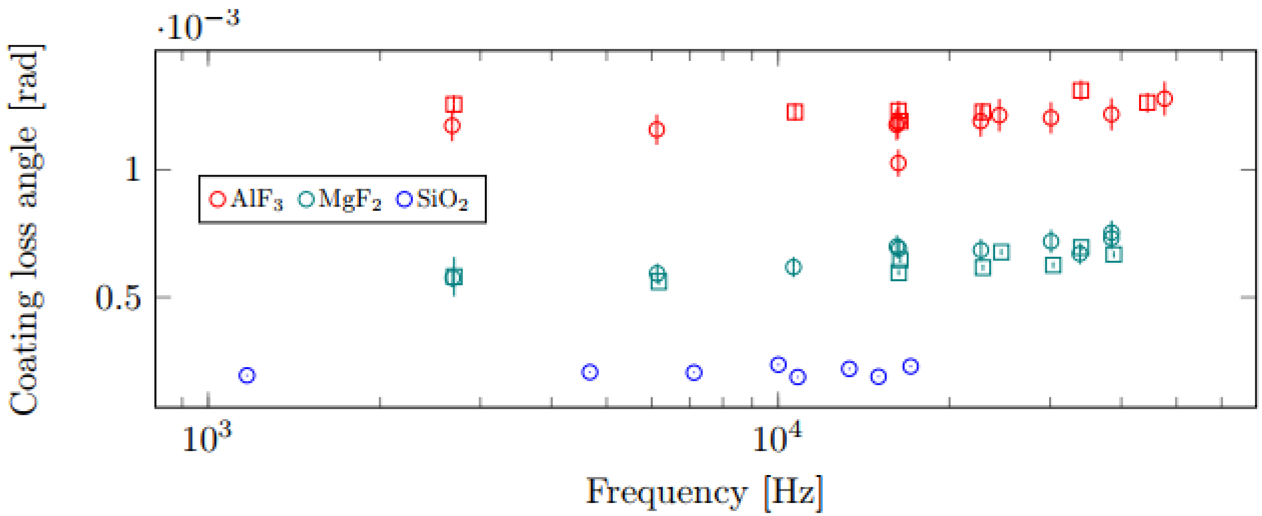
- Lower loss than silica @ 10K : φ < 4.1e-4 rad [2]
- Dual-material coating and multimaterial coatings
- Expected reduction of about 30-40% in thermal noise compared to aLIGO

[1] Craig et al. PRL 122-231102 (2019)
[2] R. R. Robie, PhD thesis, University of Glasgow, 2018.

Materials

Fluorides:

- Interesting to both ET-LF and ET-HF
- Lower refractive index than SiO_2
- Provide material with a lower refractive index than SiO_2 for increasing the reflectivity efficiency at room temperature
- Absorption and mechanical properties worse than SiO_2 at room temperature
- Further investigations at cryogenic temperature



Granata et al. App. Opt. 59-5-A229 (2020)

Crystalline coatings

Breakthrough in optical coating
Mirror is grown epitaxially

GaAs/AlGaAs :

- Already promising results [1]
  - φ=5e-6 rad @ 20K and φ=4e-5 rad @ room tempertature
  - Low optical losses scattering + absorption <5 ppm
- Growth on GaAs wafer and then transfer onto large silicon substrate
- Transfer onto fused silica and sapphire substrate with ∅2'' with good optical results [2]
  - Absorption <0.8 ppm
  - Scattering : 9.5 ppm for the fused silica substrate and 6 ppm for the sapphire substrate

GaP/AlGaP

- Growth directly onto silicon substrates
- Good mechanical properties φ=1.4e-5 rad @ 12K [3]
- Absorption still high ~2.3% [4]

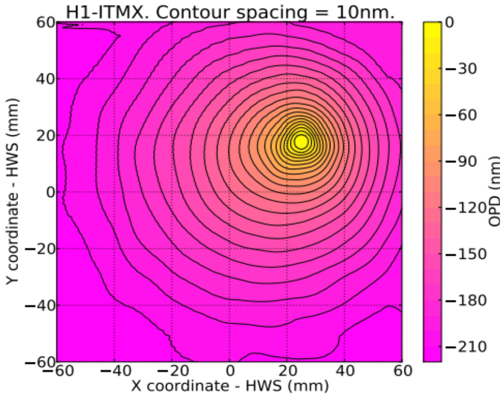
[1] Cole et al. Optica 3-6-647 (2016)
[2] Marchio et al. Opt. Exp. 26-5-6114 (2018)
[3] Cumming CQG 32-035002 (2015)
[4] Lin et al. Opt. Mat. Exp. 5-8-1890 (2015)

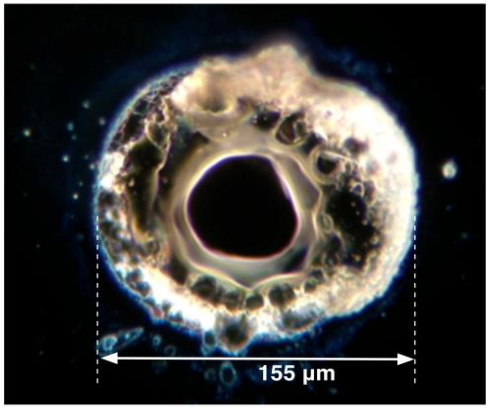
Point-like defects issue

Small defects (∅ 10-100µm) inside the high-reflective coating

Two major effects :

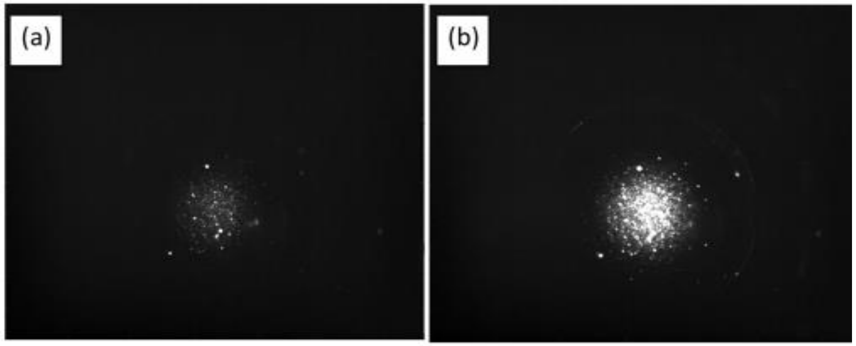
- Absorption
  - Optical path distortion
  - Limitation of the circulating power
  - Degradation of the coating





Brooks et al. LIGO-P1900287-v2

- Scattering
  - Reducing the circulating power
  - Phase noise after reflection on the vacuum tubes



Theses defects have to be strictly controlled

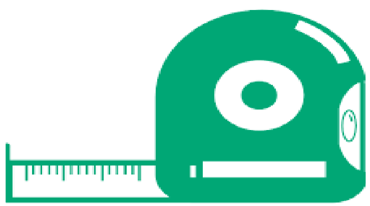
Manufacturability concerns

When the recipe will be found, we will need to go from small test samples to large Test Masses

- Thickness monitoring accuracy
- Thickness deposition uniformity
- Control of the point-like defects
- Cleaning
- Handling
- Annealing
- …

Once the Test Mass will be produced, we need to measure them carefully

- Scattering
- Absorption
- Reflectivity
- Wavefront
- …



Summary

Lot of work dedicated to :

- Decrease the optical absorption
- Reduce mechanical loss
- Several different/complimentary approaches

Several promising solutions that require experimental demonstration with relevant sample

Keep in mind that the recipe is only the first (but important) step
Lot of work will be required for large Test Mass

Any volunteer willing to contribute in the Core Optics effort,
please free to contact A. Amato and/or me