Coating Absorption and its implications on Suspension Thermal Noise

Overview

• Ongoing research in multi-material coating designs
  • Room temp mechanical Loss with heat treatment
  • 2um absorption with heat treatment

• Coating absorption and suspension thermal noise
  • Finite element modelling of End Test Mirrors
  • Implications of coating absorption on operation temperature
  • Coating absorptions effect of suspension thermal noise
• aSi has very low loss, but too high absorption

• despite progress in reducing aSi absorption still > ET design requirement

• multi-material design tries to exploit low loss while minimising impact on coating absorption

Recent Publications:


R Birney et al, PRL 121 (2018) 191101
Thermal noise reduction with aSi-based coatings

<table>
<thead>
<tr>
<th></th>
<th>Loss $\phi \times 10^{-4}$</th>
<th>Brownian th. noise (100 Hz) $\times 10^{-21}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO₂</td>
<td>aSi</td>
</tr>
<tr>
<td>290 K</td>
<td>0.4 [15]</td>
<td>4.0 [16]</td>
</tr>
<tr>
<td>120 K</td>
<td>1.7 [6]</td>
<td>0.5 [16]</td>
</tr>
<tr>
<td>20 K</td>
<td>7.8 [6]</td>
<td>0.4 [16]</td>
</tr>
<tr>
<td>10 K</td>
<td>7 [6]</td>
<td>0.3 [16]</td>
</tr>
</tbody>
</table>

Illustrative Case

8 bilayers of SiO₂/Ta₂O₅ + bilayers of aSi/SiO₂

$\Rightarrow R > 99.999\%$

$= 5.7$ppm

$R \approx 99.6\%$

$1.7$ppm

$R \approx 99.75$

$(1 - 0.996) \times 1000$ppm
To minimise coating thermal noise:

- Alternating layer design reflects laser light at every boundary.
- Highly reduced field reaches high absorbing aSi
- Less number of coating layers with high refractive index contrast layers \( \approx \) less coating thermal noise

\[
s_x(f) = \frac{4k_B T}{\pi^2 f} \frac{(1 + \sigma_S)(1 - 2\sigma_S)}{E_S} \frac{d}{w_m} \phi_C
\]
Absorption at 2um

Absorption Measured with Photo-thermal Common Path Interferometry (PCI)

Absorption Map of Full Stack Coating

Histogram of Absorption

Absorption 24 ppm (As Deposited)

High absorption section exposed to too much laser power (damaged)
Absorption with Heat Treatment

absorption at 2um

heat treatment temperature [°C]

absorption [ppm]

- Multimaterial
- calculated
- SiO2/Ta2O5
- aSi/SiO2
Absorption with Heat Treatment

Minimum in absorption trend for both stacks

absorption at 2um

heat treatment temperature [°C]
Absorption with Heat Treatment

- Absorption at 2um
- Minimum in absorption trend for both stacks

Heat treatment temperature [°C]

Absorption [ppm]
Prototype multi material coating performs as expected
Mechanical loss measurements after progressive heat treatments underway
For more details on cryogenic coating loss on silicon substrates and predictions please see the poster by Peter Murray:

“Multimaterial Coatings for 3rd Generation Gravitational Wave Detectors”
Maximum Tolerable Absorption - a comparison

Comparison of current and cryogenic detector operation in relation to optical absorption.
Interferometer Laser power passing through test masses causes temperature gradient (dn/dT dominated)

Power buildup inside Fabery-Pèrot Cavity causes change in Test mass radius of curvature $\Delta S$ (coating absorption dominated)
If the incident gaussian laser beam is matched to the RoC of the mirror, the change in the heated area can be assumed as a hemispherical distortion on the mirror's surface.

The relative change in curvature can be simplistically calculated if the thermal expansion, absorbed power and wavelength are known using:

\[
\frac{\delta s}{s} \approx \frac{\alpha}{2\kappa\lambda} P_a
\]

W. Winkler, et al. (1991)
Using methods described by R.C. Lawrence (1997) and building on the work of A. Brooks, the test mass is modelled as a 2D approximation of a cylindrical mass: vastly decreases computation time.
To zeroth order due the thermoelastic expansion of silicon under these conditions can be considered relatively small (~ 0.0001% for R=10 km).

For ETMs - Heat absorption from incident laser becomes dominating.

Assuming a thermally isolated test mass the thermal effects on a cryogenic optic can be modelled to predict heat distribution through test mass.

How much conductive cooling can the suspension fibres provide?

What effect does this have on suspension thermal noise?
Under cryogenic conditions test mass cooling becomes more difficult.

<120K cooling power dominated by conduction through suspension fibres.

<40K conductive cooling limited by fibre cross section (phonon scattering).

We need fibres which are strong enough to support the 200 kg masses (3x with safety factor).

- Requires thicker suspension fibres.
- Increases suspension thermal noise.
Operating at ~40K would require a minimum 500um thick fibre.

How much heat extraction can this provide?

A V Cumming et al 2014 Class. Quantum Grav. 31 025017
40 K Operation

Test Mass Heating with coating absorption 40.0 K

Test Mass Heating With no Suspensions - i.e. No Conductive Cooling

Coating Absorption

- 1 ppm
- 1.1 ppm
- 1.5 ppm
- 2 ppm
- 2.5 ppm
$\Delta T$ with No Fibres

Test Mass Heating with coating absorption 40.0 K

1.5 ppm induces $\Delta T = 16$ K
Thicker Fibre does not meet ET Thermal noise
Thermal Noise with Coating Absorption

- 2mm thick fibre
- x3 safety factor
- 1mm fibre
- 500um fibre (improved Si)
Thermal Noise with Fibre Radius

- **2mm thick fibre**: x3 safety factor
- **1mm fibre**
- **500um fibre (improved Si)**
• The tolerable level of coating absorption is dominated by heat conduction through the fibres.

• Based on initial strength studies we need thick (~2mm) fibres to support 200kg mass.
  
  • Does not meet ET requirements
  
  • Can extract 55ppm of absorbed laser power
  
  • Higher absorption allows for more layers of aSi inside a multilayer stack. - reducing overall coating loss
  
  • 500um fibres would be below ET-LF total noise budget (@10 Hz)
  
  • Si fibre strength must be improved over initial measurements
  
  • Thinner fibre tightens requirements on tolerable absorption (1ppm)
A. Cumming et al. “Silicon mirror suspensions for gravitational wave detectors” 2014 Class. Quantum Grav. 31 025017


Multimaterial coatings with reduced thermal noise, W. Yam, S. Gras, and M. Evans PHYSICAL REVIEW D 91, 042002 (2015)