Optical Coatings for Gravitational Wave Detection

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- On Behalf of the LIGO Science Collaboration -

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Gravitational Wave Detection

- Gravitational waves predicted by Einstein
- Accelerating masses create ripples in space-time
- Need astronomical sized masses moving near speed of light to get detectable effect

- Two 4 km and one 2 km long interferometers
- Two sites in the US, Louisiana and Washington
- Michelson interferometers with Fabry-Perot arms
- Whole optical path enclosed in vacuum
- Sensitive to strains around $10^{-21}$
Interferometer Sensitivity

- Measured sensitivity of initial LIGO 1/2004
- Nearing design goal
- Hanford 4 km within a factor of 2 near 100 Hz

- Design sensitivity of proposed Advanced LIGO
- Factor of 15 in strain improvement over initial LIGO
- Thermal noise from mirror substrates and coatings sets sensitivity limit
Coating Thermal Noise

Fluctuation-Dissipation Theorem

\[ S_F(f) = 4 \, k_B \, T \, \text{Re}[Z] \]

- Fluctuation-Dissipation Theorem predicts noise from mechanical loss
- Proximity of coating to readout laser means thermal noise from coatings is directly measured
- Initial LIGO has 40 layer silica/tantala dielectric coatings optimized for low optical absorption

\[ S_x(f) = 2 \, k_B \, T \, (\pi^{3/2} \, f \, w \, Y) \left( \phi + d/(\pi^{1/2} \, w) \right) (Y/Y_{\text{perp}} \, \phi_{\text{perp}} + Y_{\text{para}}/Y \, \phi_{\text{para}}) \]
Coating Mechanical Loss Experiments

Modal Q Measurements

- Test coatings deposited on silica substrates
- Normal modes (2 kHz to 50 kHz) decay monitored by interferometer/birefringence sensor.
- Coating loss inferred from modal Q and finite element analysis modelling of energy distribution
- Can examine many different coatings fairly quickly
## Results of Q Measurements

### Coating Mechanical Loss

<table>
<thead>
<tr>
<th>Layers</th>
<th>Materials</th>
<th>Loss Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>$\lambda/4$ SiO$_2$ - $\lambda/4$ Ta$_2$O$_5$</td>
<td>$2.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>60</td>
<td>$\lambda/8$ SiO$_2$ - $\lambda/8$ Ta$_2$O$_5$</td>
<td>$2.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>2</td>
<td>$\lambda/4$ SiO$_2$ – $\lambda/4$ Ta$_2$O$_5$</td>
<td>$2.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>30</td>
<td>$\lambda/8$ SiO$_2$ – $3\lambda/8$ Ta$_2$O$_5$</td>
<td>$3.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>30</td>
<td>$3\lambda/8$ SiO$_2$ – $\lambda/8$ Ta$_2$O$_5$</td>
<td>$1.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>30</td>
<td>$\lambda/4$ SiO$_2$ – $\lambda/4$ Nb$_2$O$_5$</td>
<td>$3.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>30</td>
<td>$\lambda/4$ SiO$_2$ – $\lambda/4$ Ta$_2$O$_5$</td>
<td>$4.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>30</td>
<td>$\lambda/4$ SiO$_2$ – $\lambda/4$ Ta$_2$O$_5$</td>
<td>$5.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>30</td>
<td>$\lambda/4$ SiO$_2$ – $\lambda/4$ Nb$_2$O$_5$</td>
<td>$2.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>43</td>
<td>$\lambda/4$ Al$_2$O$_3$ – $\lambda/4$ Ta$_2$O$_5$</td>
<td>$2.9 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

- Loss is caused by internal friction in materials, not by interface effects.
- Differing layer thickness allow individual material loss angles to be determined.

\[
\begin{align*}
\phi_{\text{Ta}_2\text{O}_5} &= 4.6 \times 10^{-4} \\
\phi_{\text{SiO}_2} &= 0.2 \times 10^{-4} \\
\phi_{\text{Al}_2\text{O}_3} &= 0.1 \times 10^{-4} \\
\phi_{\text{Nb}_2\text{O}_5} &= 6.6 \times 10^{-4}
\end{align*}
\]

Goal: $\phi_{\text{coat}} = 5 \times 10^{-5}$

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$a$ LMA/Virgo, Lyon, France  
$b$ MLD Technologies, Mountain View, CA  
$c$ CSIRO Telecommunications and Industrial Physics, Sydney, Australia  
$d$ Research-Electro Optics, Boulder, CO  
$e$ General Optics (now WavePrecision, Inc) Moorpark, CA
Evidence of frequency dependence of coating mechanical loss. Coating loss lower at lower frequencies, so in LIGO’s favor. Primarily in SiO$_2$. Frequency dependence known in bulk silica. Results rely on small number of thin sample modes.

\[
\phi_{Ta_2O_5} = (4.9 \pm 0.4) \times 10^{-5} - (1.8 \pm 2.5) \times 10^{-10}
\]
\[
\phi_{SiO_2} = (2.7 \pm 5.7) \times 10^{-5} + (2.5 \pm 0.3) \times 10^{-9}
\]
Direct Measurement of Coating Thermal Noise

- LIGO/Caltech’s Thermal Noise Interferometer
- 1 cm long arm cavities, 0.15 mm laser spot size
- Consistent with ~ 4 \(10^{-4}\) coating loss angle
### Advanced LIGO Coating Requirements

**Need to develop low thermal noise coating without sacrificing optical performance.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Current Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss Angle $\phi$</td>
<td>$5 \times 10^{-5}$</td>
<td>$1.5 \times 10^{-4}$&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Optical Absorption</td>
<td>0.5 ppm</td>
<td>1 ppm&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Scatter</td>
<td>2 ppm</td>
<td>20 ppm&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Thickness Uniformity</td>
<td>$10^{-3}$</td>
<td>$8 \times 10^{-3}$&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Transmission</td>
<td>5 ppm</td>
<td>5.5 ppm&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Transmission Matching</td>
<td>$5 \times 10^{-3}$</td>
<td>$5 \times 10^{-3}$&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Current values are from

- <sup>a</sup> small laboratory samples
- <sup>b</sup> installed optics in initial LIGO interferometers

No single sample has demonstrated all values.
Titania Dopant in Tantala

Work done in collaboration with LMA/Virgo in Lyon, France as part of advanced LIGO coating research

$\lambda/4$ SiO$_2$ – $\lambda/4$ Ta$_2$O$_5$ Coatings with TiO$_2$ dopant

<table>
<thead>
<tr>
<th>Dopant Conc.</th>
<th>Loss Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>$2.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>Low</td>
<td>$1.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>Medium</td>
<td>$1.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>High</td>
<td>?</td>
</tr>
</tbody>
</table>

Increasing dopant concentration reduces mechanical loss

- How far can this effect be pushed?
- Is there a better dopant?
- Will this compromise optical performance?
Secondary Ion-beam Bombardment

Work done in collaboration with CSIRO in Sydney, Australia as part of advanced LIGO coating research

$\lambda/4 \text{ SiO}_2 - \lambda/4 \text{ Ta}_2\text{O}_5$ Coatings

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\phi_{coat}$ (Grid 1)</th>
<th>$\phi_{coat}$ (Grid 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>4.1 $10^{-4}$</td>
<td>3.2 $10^{-4}$</td>
</tr>
<tr>
<td>8</td>
<td>4.2 $10^{-4}$</td>
<td>3.1 $10^{-4}$</td>
</tr>
<tr>
<td>9</td>
<td>5.0 $10^{-4}$</td>
<td>4.0 $10^{-4}$</td>
</tr>
<tr>
<td>10</td>
<td>4.1 $10^{-4}$</td>
<td>3.5 $10^{-4}$</td>
</tr>
<tr>
<td>12</td>
<td>4.4 $10^{-4}$</td>
<td>2.3 $10^{-4}$</td>
</tr>
</tbody>
</table>

Grid was adjusted from 1 to 2 to increase uniformity

- How far can this effect be pushed?
- Will this compromise optical performance?
Future Plans

- Continue with TiO$_2$ doped Ta$_2$O$_5$ up to stability limit of TiO$_2$ films
- Examine other dopants in Ta$_2$O$_5$
- Examine other high index materials
- Improve stoichiometry of Ta$_2$O$_5$, correlate with optical absorption
- Examine relationship between annealing and mechanical loss

- Need more input and collaboration with material scientists and optical engineers