Thermal Corrective Devices for Advanced Gravitational Wave Interferometers

Marie Kasprzack,
Louisiana State University

6th October 2016

COMSOL Conference 2016 Boston
1. Advanced Gravitational Wave Detectors

- Based on resonant optical cavities with suspended optics under vacuum: **dual recycling Michelson interferometer**

- On the way to the 2\textsuperscript{nd} Observing run:
  - 2 \textbf{LIGO} detectors in operation, \textbf{Virgo} detector will join in 2017

- First observations started recently at LIGO: \textbf{GW150914, GW151226}

- Facilities use \textbf{high power laser} (\text{CW 1064 nm})
1. Advanced Gravitational Wave Detectors

High laser power brings thermal effects:

• Thermal load on a Test Mass: **Heating of the substrate**
  - Coating and substrate absorb the beam power
  - Index of refraction of the mirror changes
    - produces a **thermal lens**
    - and potentially **high order modes**
  - Thermal expansion
    - changes the **curvature** of the mirror

• In the main cavities, thermal lensing ~ 0.8 μm (focal length 5 km)

• Thermal load changes over time

→ We need adaptive optics devices to correct for in-situ aberrations and input mode matching
2. Thermal devices for aberration mitigation

- **Ring heater**: *installed*
  - Around the main mirrors of the cavities
  - Target: correction of the Radius of Curvature
  - Two semispherical heating segments

- **Thermally deformable mirror**: *prototype*
  - Outside the cavity
  - Target: correction of higher mode aberrations for mode matching
  - Set of 61 resistors in the back of a 2” Ø mirror
3. Ring Heater

- **Simple analytical model:**
  - From the heat equation
  - Both in steady state and time dependent model
  - One circular segment
  - Useful to predict the general behavior of the system

- **Limitations:**
  - Design very limited
  - Axis-symmetry

- **COMSOL® Model**
  Double purpose of validate our analytical model and lay the foundations for a more complex model
3. Ring Heater

- **Main time constant:**
  - 27 hours to reach steady state

- **Very good agreement between our analytical model and COMSOL**
  - at $t = 1000 \text{ s}$, relative difference below 5%
  - At $t = 100000 \text{ s}$, relative difference below 1%
4. Thermally Deformable Mirror

- Actuation:
  Control of the **optical path length** via the **substrate temperature**

\[ \text{OPD} = \left( \frac{\partial n}{\partial T} + (1+u)(n-1) \right) \cdot \int_{z=0}^{d} T(x,y,z) \, dz \]

**Opto-mechanical parameters**

**Temperature field**

*Incident aberrated wavefront*  
*Reflected corrected wavefront*

[Diagram of a thermally deformable mirror with AR and HR coatings, resistor array, and substrate with non-homogeneous temperature distribution]
4. Thermally Deformable Mirror

- COMSOL® Model
  - Finite dimensions
    - 24.5 mm radius
    - 10 mm thick
  - No axis-symmetric assumption
  - Square actuator
  - 100 mW coupled

- Effect of the actuator size?

- What is the best substrate for our application?
  - Moderate temperature increase
  - Large amplitude of the optical response
4. Thermally Deformable Mirror

- Global shape of temperature integral dominated by the heat radiation

![Response of the FS](image)

- Shape characterized by:
  - The width at half maximum (HWHM)
    - depends on actuator size
    - mostly independent from the thermal properties of the substrate
    - independent from the thickness
  - the amplitude
4. Thermally Deformable Mirror

- Amplitude of actuation:
  - Thermal conductivity $K$ is the most important parameter
  - Material study:
    - Choice of the substrate with the lowest thermal conductivity

<table>
<thead>
<tr>
<th>Substrate</th>
<th>$K$ [W.m$^{-1}$.K$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK7</td>
<td>1.11</td>
</tr>
<tr>
<td>FS</td>
<td>1.38</td>
</tr>
<tr>
<td>SF57</td>
<td>0.62</td>
</tr>
<tr>
<td>Zerodur</td>
<td>1.46</td>
</tr>
<tr>
<td>CaF$_2$</td>
<td>9.71</td>
</tr>
<tr>
<td>Sapphire</td>
<td>40</td>
</tr>
</tbody>
</table>
4. Thermally Deformable Mirror

- Figure of merit: trade-off between the amplitude response and the temperature of the substrate

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Delta T$ (K)</th>
<th>OPD Amplitude (nm)</th>
<th>OPD HWHM (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK7</td>
<td>52.5</td>
<td>368</td>
<td>2.39</td>
</tr>
<tr>
<td>FS</td>
<td>43.1</td>
<td>400</td>
<td>2.41</td>
</tr>
<tr>
<td>SF57</td>
<td>91.2</td>
<td>1543</td>
<td>2.32</td>
</tr>
<tr>
<td>Zerodur</td>
<td>40.9</td>
<td>603</td>
<td>2.41</td>
</tr>
<tr>
<td>CaF$_2$</td>
<td>9.0</td>
<td>130</td>
<td>2.48</td>
</tr>
<tr>
<td>Sapphire</td>
<td>4.6</td>
<td>31</td>
<td>2.49</td>
</tr>
</tbody>
</table>

- Best solutions: Zerodur, Fused Silica, BK7

→ Current prototype: **Fused silica with 61 actuators of 1 mm$^2$**
5. Conclusion

Ring heater
• Geometric improvement of the model (shape, fibers, …)
• High order mode estimation
• Kalman filter implementation for the live prediction of aberrations

Thermally Deformable Mirror:
• Choice of material
• Design study from influence functions
• Tests and validations of proof of principle
• Still under development
6. References

• Overview of Advanced LIGO Adaptive Optics
  A.F. Brooks et al.

• Analytical model for ring heater thermal compensation in the Advanced Laser Interferometer Gravitational-wave Observatory,
  J. Ramette, M. Kasprzack, et al.

• Thermal Live Estimator for Advanced LIGO,
  J. Ramette, LIGO Document T1500390

• Performance of a thermally deformable mirror for correction of low-order aberrations in laser beams,
  M. Kasprzack et al.

• Thermally Deformable Mirrors: a new Adaptive Optics scheme for Advanced Gravitational Wave Interferometers
  M Kasprzack