Collaboration on Development of Sapphire for Test Masses

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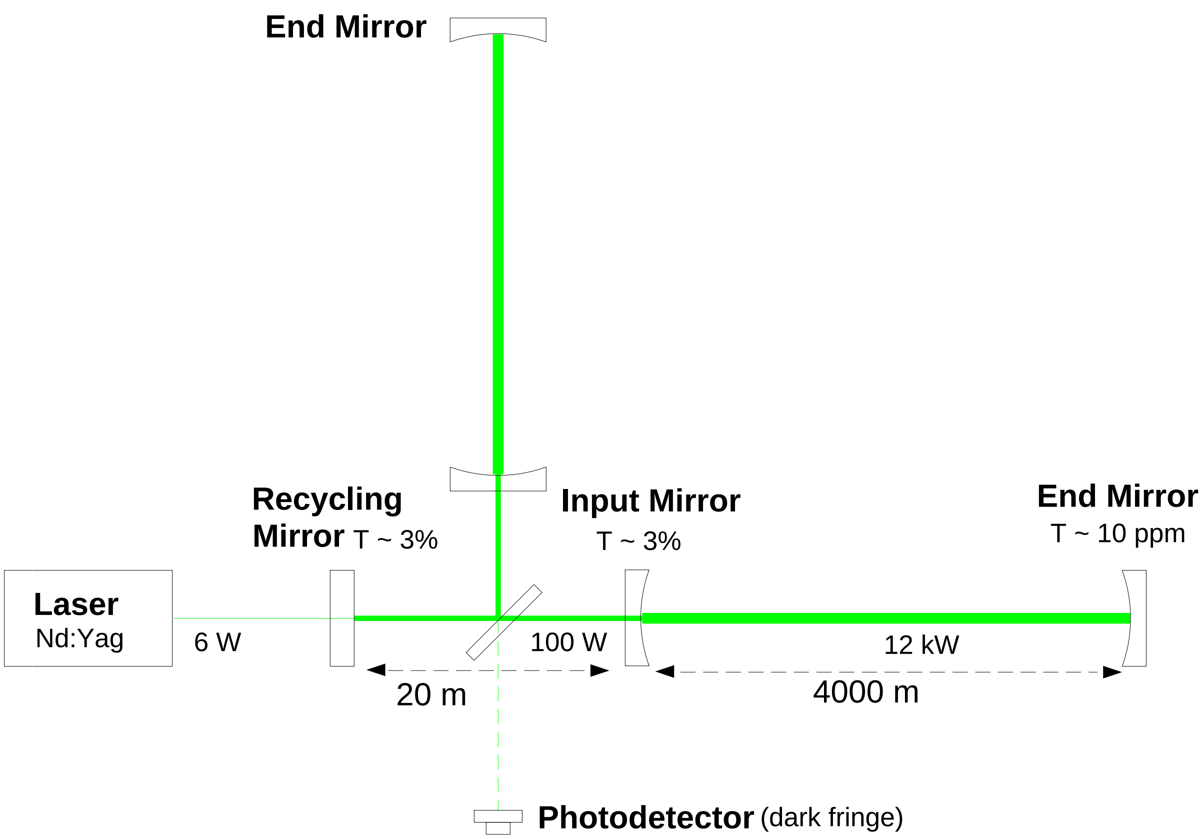
Large Optical Components ("Core Optics")

- Test Masses
  - End Mirror
  - Input Mirror
- Beamsplitter
- Recycling Mirror
- Initial LIGO substrates will all be fused silica
- Future LIGO substrates????



Issues for Choosing a Test Mass Material

- Optical surface quality (LIGO, ACIGA, Industry)
  - Low spatial frequency surface figure errors, leading to small angle scattering
  - Microroughness
- Optical homogeneity and birefringence (ACIGA, Virgo, LIGO)
  - For transmissive applications
- Thermal distortion and lensing (Virgo, Stanford, LIGO)
  - Bulk Absorption
  - Thermal Conductivity
- Thermal noise (ACIGA, Virgo, LIGO)
  - High mechanical Q to minimize thermal noise (Q ~ 10^6-10^8)
  - Size, density, speed of sound,...
- Producibility and cost (LIGO, Crystal Systems, SIOM)

Thermal Noise

- The primary motivation for sapphire test masses is thermal noise
- Thermal noise

$$\Delta x^2 = \frac{4kT}{\omega} \cdot \frac{\Phi(\omega)}{M\omega_0^2}$$

  - » Loss factor Φ for sapphire ~0.1 that for fused silica
  - » Sapphire is denser than fused silica (~ x2) and has higher speed of sound so $M\omega_0^2$ is larger by x6
- Net gain is nearly x10 in internal thermal noise
- (Provided suspension does not compromise internal Q)
- Near-term tests of Q's at UWA(ACIGA), eventually at Virgo/ LIGO

Polishing: Low Spatial Frequency Surface Errors

- What we know about industry capability over 25 cm diameter:

- Polishing samples currently being done for LIGO by CSIRO(ACIGA) and General Optics

Microroughness

- Largest source of lost optical power in initial detectors
- Sapphire is an exceptionally hard material
  - Moh hardness 9 (vs. ~6 for fused silica); harder than most polishing powders
- Microroughness < 1 Å demonstrated 10 years ago
  - But never on the scale of LIGO optics
- For simple “smooth” surfaces,

$$\text{Scatter Loss} = \left(4\pi\frac{\sigma}{\lambda}\right)^2$$

  - For $\lambda = 1.063\mu\mathrm{m}$, $\sigma = 0.2\mathrm{nm}$, scatter loss ~ 6 ppm
- Point defects likely to be an issue due to use of diamond dust
  - Point defects will cause few ppb loss each
- CSIRO and GO pieces to be tested by LIGO

Coating Issues

- Main coating issue: Stress
  - Thermal expansion coefficient of sapphire ~15 x that of fused silica
  - Expansion coefficient has different values parallel and perpendicular to crystal axis
- Anisotropy in expansion will lead to birefringence in mirror, i.e., cavity will have different resonance point for different polarizations
  - Observed in cryogenic (?) cavity at UWA at 0.1 milliradian level
  - Leads to requirement that even ETM's should have crystal axis normal to mirror surface
- Discussions with REO indicate willingness to work with LIGO on development and no particular concerns about coating sapphire

Optical Homogeneity

- Higher index of refraction for Sapphire means that equal $\delta n/n$ gives factor of 2 larger OPD
- Limited number of measurements have given as good as $\delta n = 3 \times 10^{-6}$
  - May be measurement limited....
  - Compare fused silica 2.5×10^{-7}
- Technology for control of optical homogeneity not yet well developed
- Working with Crystal Systems and Shanghai Institute of Optics and Fine Mechanics (SIOM) to evaluate current capabilities

Heating Effects

- Surface distortion
  - Important for reflective and transmissive optics
  - Typically not most important in SiO_2 due to low expansion coefficient
- Thermal lensing
  - Important for transmissive optics only
  - Important in SiO_2 due to low thermal conductivity and high dn/dT
- Heat deposition matches beam profile; temperature gradient from heat flow to optic surfaces (radiatively coupled to vacuum chamber)
  - First order distortion is a simple change in radius (or simple lens)
  - Gaussian beam profile leads to higher order distortions

Absorption in Sapphire

- Source of absorption unknown; some speculation due to Ti^{3+} (Stanford data show some correlation with fluorescence)

Sample	*Blair et al. Published Measurements*	*Absorption-Stanford Measurement*	*Absorption-Virgo Measurement*
Union Carbide (1996)	**16 - 22 ppm/cm**	**--**	**--**
CSI Hemex Ultra	**55 +- 4**	**140**	**--**
RISC, China	**200 +- 20**	**--**	**--**
Melles-Griot	**11 - 16**	**--**	**--**
CSI White	**3.1 - 3.5**	**120**	**--**
CSI White #0 (1998)	**--**	**41 (recal underway)**	**--**
CSI White #1 (1998)	**--**	**68 (recal underway)**	**142 +- 15**
CSI White #2 (1998)	**--**	**58 (recal underway)**	**90 +- 10**

- Typical SiO_2 values 2-20 ppm/cm at 1.064 μm
  - » IR absorption due to OH (usually?)

Surface Distortion

- Reflective optics
  - Proportional to absorption (of coating)
  - Inversely proportional to thermal conductivity of substrate
  - Proportional to coefficient of thermal expansion
- Compare sapphire with fused silica

Property	*Fused Silica*	*Sapphire*
Thermal Conductivity	**1.4 W m^{-1} K^{-1}**	**30 W m^{-1} K^{-1}**
Coefficient of Thermal Expansion	**5 x 10^{-7} K^{-1}**	**8 x 10^{-6} K^{-1}**
Relative Surface Distortion	**1**	**~0.7**

Thermal Lensing

- Important for transmissive optics only
  - » Proportional to absorption
  - » Inversely proportional to thermal conductivity of substrate
  - » Proportional to dn/dT
- Compare sapphire with fused silica

Property	*Fused Silica*	*Sapphire*
Absorption	**4 ppm/cm**	**10 ppm/cm (????)**
Thermal Conductivity	**1.4 W m^{-1} K^{-1}**	**30 W m^{-1} K^{-1}**
dn/dT	**9 x 10^{-6} K^{-1}**	**13 x 10^{-6} K^{-1}**
Relative Thermal Lensing	**1**	**~ 0.15 (????)**

Production Capacity

- Sapphire boules up to 65 kg have been produced in test runs
- Standard production sizes up to 32 cm dia x 15 cm (~30 kg)
  - But not (yet?) with C axis parallel to cylinder axis
- Largest C-axis pieces currently 15 cm dia x 15 cm
- Growth cycle for large boules is 1-2 months
  - Production of substrates for ETM's alone would take ~1 year of a dedicated furnace once process is finalized
- Polishing cycle is also slow (example: single 15 cm piece at GO quoted at 6-8 month delivery time)
- Good news: Production costs approximately comparable with Heraeus fused silica
- LIGO working with Crystal Systems and SIOM

Future Directions

- Production Issues
  - » Size is biggest challenge, but ability to produce sufficient number is still iffy
- Polishing
  - » Need to determine ability to achieve adequate surface figure
- Understand limits to Q (fundamental limit or technical limit)
  - » Including how to suspend and control without degrading intrinsic Q
- Issues specific to ITM's
  - » Source of absorption and its control
  - » Birefringence, homogeneity,