Excess Mechanical Loss From Dielectric Mirror Coatings on Interferometer Test Masses

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Mirror substrate materials

- From measurements of intrinsic loss factor (and other considerations – suitability for polishing etc) two most likely choices for advanced interferometer test masses
  - Sapphire
  - Fused silica

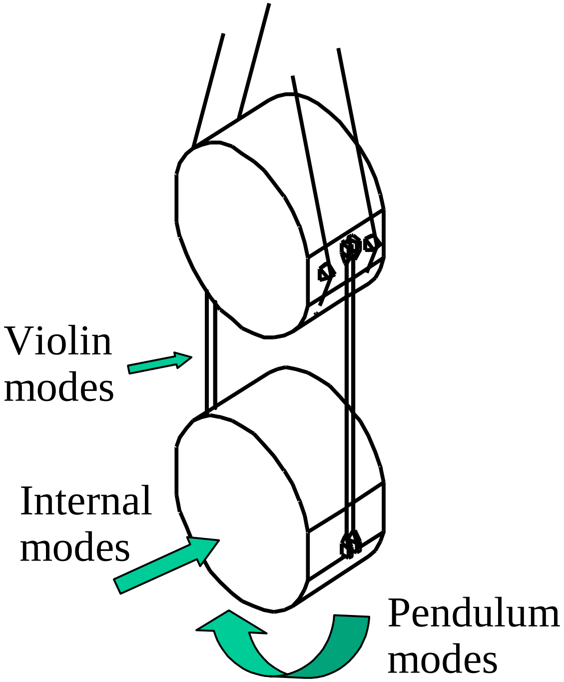
- Possible areas of excess loss are being addressed
  - Bonding silica to sapphire to allow suspension of test masses on silica fibers
  - Dielectric mirror coatings

Reminders

Consider thermal noise in g.w. interferometers

- Thermal motion of test masses well below their resonances sets sensitivity between few 10s and few 100 Hz - want loss factor of test mass materials as low as possible over this range
- Very difficult to measure directly – hence measure Q or $\phi(\omega_0)$ at resonant frequencies - assume can deduce off resonance thermal noise from this

(n.b. This method requires care..)



Schematic final stage of mirror suspension

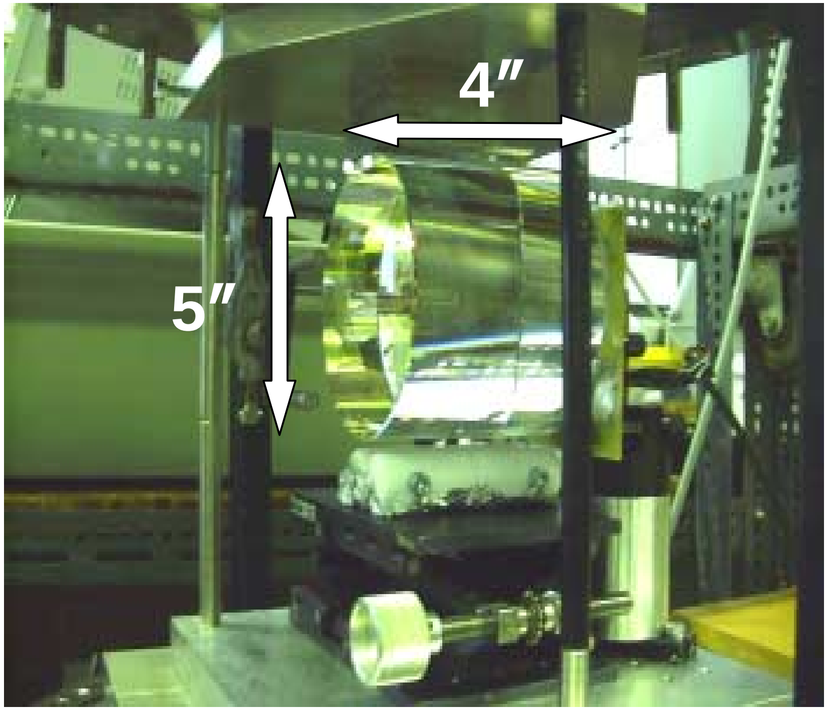
Excess loss introduced by coatings

- Aim
  - Measure Q (loss) of samples before and after application of a dielectric mirror coating to estimate level of any excess mechanical loss associated with coating
- Interpretation
  - how does this affect thermal noise in an interferometer

Fused silica substrates

- Corning 7940 (3G)
- 2 samples (nominally identical*)
- Dimensions 5 in. dia x 4 in. thick

  (size of mirrors in Glasgow 10m prototype)
- 1 sample uncoated
- 1 sample coated by General Optics
  - HR @1064nm
  - AR @ 1064nm



Test mass in Q measurement apparatus

- Qs measured for 6 modes of each mass

Excess loss introduced by coatings

- Ideally measure Q (loss, $\phi(\omega_0)$) on coated and uncoated mass

$$\phi(\omega_0)_{\text{coated}} = \phi(\omega_0)_{\text{uncoated}} + \phi(\omega_0)_{\substack{\text{associated}\\ \text{with coating}}} \qquad (1)$$

$$\phi(\omega_0)_{\text{coated}} = \phi(\omega_0)_{\text{uncoated}} + \frac{E_{\substack{\text{coating}\\ \text{face}}}}{E_{\text{bulk}}}\,\phi(\omega_0)_{\substack{\text{coating}\\ \text{face}}} + \frac{E_{\substack{\text{barrel}\\ \text{coating}}}}{E_{\text{bulk}}}\,\phi(\omega_0)_{\substack{\text{barrel}\\ \text{coating}}} \qquad (2)$$

- use FE program to evaluate ratios of energy stored in coatings on barrel and faces to energy stored in bulk of samples (D. Crooks, G. Cagnoli)
- in principle allows values for the loss of the coating on the faces and on the barrel to be calculated

Interpretation of results for coating loss

- **Assume structural (frequency independent) damping for measured loss of coating material**
- (Compare magnitudes of calculated thermo-elastic loss for coating with Brownian thermal noise at frequency range of interest for GW detectors - show it is not significant)
- **Calculate effect on predicted performance of advanced LIGO detector using methods of Nakagawa et al**

Results for silica sample

Mode	Frequency (Hz)	Coated mass	Uncoated mass
Bending	22361	1.6×10^{-7}	0.95×10^{-7}
Asy. Dr.	23004	1.2×10^{-7}	1×10^{-7}
Fund	25404	0.5×10^{-7}	0.88×10^{-7}
Clover (4)	26193	1.9×10^{-7}	0.95×10^{-7}
Sym. dr.	28395	3.6×10^{-7}	0.95×10^{-7}
2nd Asy. dr.	36072	0.9×10^{-7}	0.87×10^{-7}

Note relatively constant loss for uncoated mass at a level significantly greater than best measurement of coated mass

P. Sneddon

Results for silica

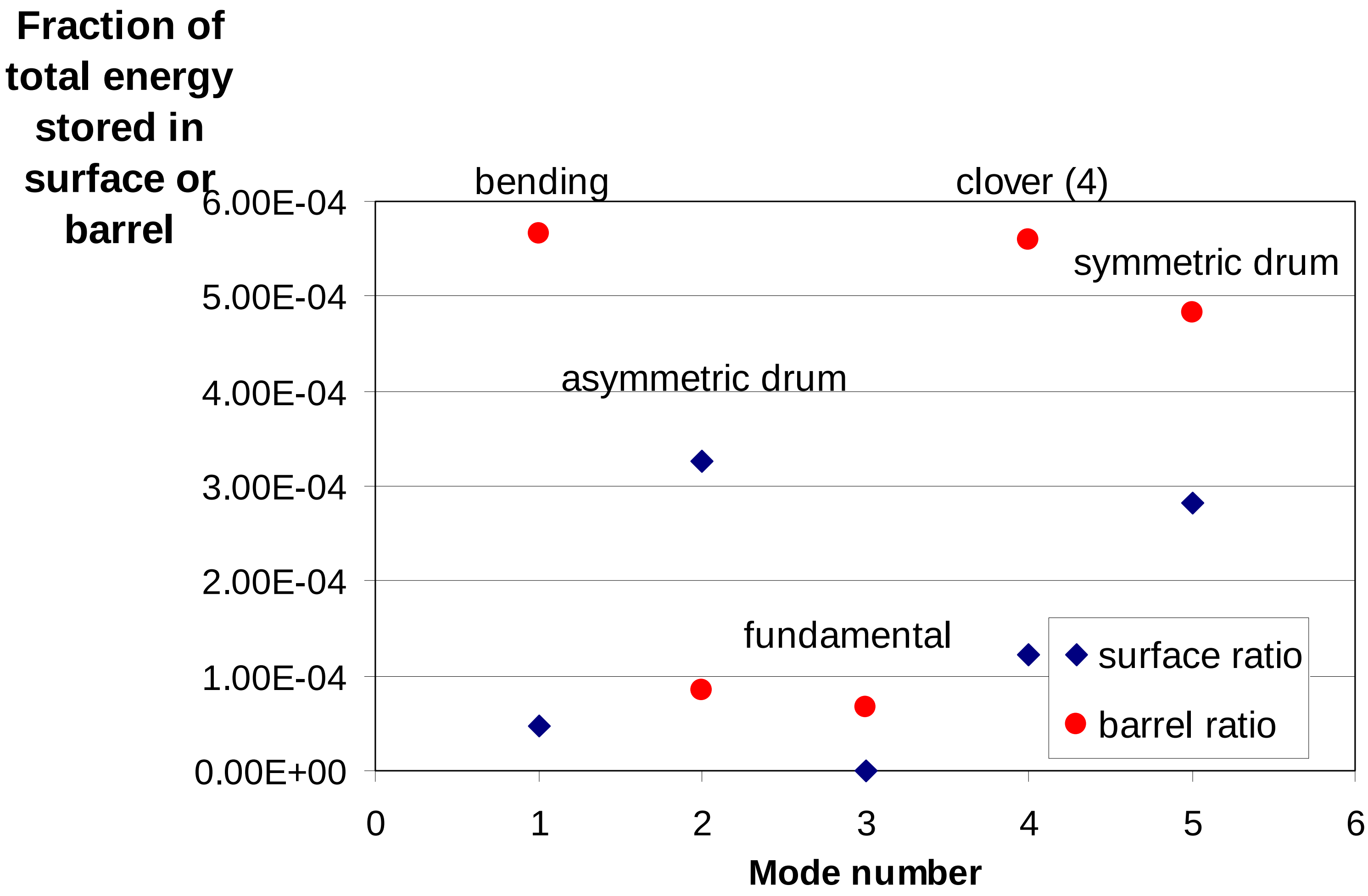
- Thus cannot use uncoated mass as a reference.
- Suggests the coated and uncoated substrates have different intrinsic losses (perhaps due to damage from mechanical polish?) **Now known to be of different materials**
- Instead use results only from coated mass -

$$\phi_{coated} = \phi_{bulk} + \frac{Y_{coating}}{Y_{bulk}} \frac{E_{surface}}{E_{bulk}} \phi_{\substack{coating\\face}} + \frac{E_{barrel}}{E_{bulk}} \phi_{eff}$$

Where ϕ_{eff} absorbs variations in coating thickness and elastic modulus, Y, on the barrel

- Take five modes of coated mass, in groups of three, and use to solve above eqn for ϕ_{bulk}, $\phi_{coating}$ and $\phi_{effective}$
- 7 of the 10 combinations give relatively consistent results
- nb suspension losses assumed negligible

Fraction of energy in a 10 micron thick surface layer of silica sample (assuming isotropic material properties)



Silica coating losses

Taking the averages of the 7 sets of results gives,
for coated 7940 fused silica:

$\phi_{intrinsic}$	$\phi_{coating}$	ϕ_{eff} (barrel)
$(4.4 \pm 0.5) \times 10^{-8}$	$(1.7 \pm 0.3) \times 10^{-4}$	$(9 \pm 1) \times 10^{-5}$

Repeating this experiment on a sample of coated 7980
fused silica:

$\phi_{intrinsic}$	$\phi_{coating}$	ϕ_{eff} (barrel)
$(5.8 \pm 0.3) \times 10^{-8}$	$(1.5 \pm 0.5) \times 10^{-4}$	$(1.4 \pm 0.2) \times 10^{-5}$

Interpretation for advanced LIGO (1)

- From Nakagawa et al (submitted to LSC for rev.) the spectral density of thermal noise from a coated mass is related to the spectral density of an uncoated mass by

$$S_\phi^{\mathrm{total}}(\mathrm{f}) = S_\phi^{\mathrm{single}}(\mathrm{f}, \phi_{\mathrm{bulk}}) \underbrace{\left\{ 1 + \frac{2}{\sqrt{\pi}} \frac{(1-2\sigma)}{(1-\sigma)} \frac{\phi_{\mathrm{coating}}}{\phi_{\mathrm{bulk}}} \left(\frac{\mathrm{d}}{\mathrm{w}} \right) \right\}}_{\textbf{Excess factor}}$$

- where σ is the Poisson ratio of the bulk material, d is the coating thickness and w is the beam spot radius
- The above formula holds for the assumption that the coating and substrate have the same mechanical properties (Young’s modulus and Poisson ratio)

Interpretation for advanced LIGO (2)

- Modifying this “excess factor” for the case where the coating and substrate materials have differing Young’s modulii and Poisson’s ratio gives:

(N. Nakagawa , Private communication)

- Excess factor =

$$\left\{1+\frac{1}{\sqrt{\pi}}\frac{\left(1+\sigma_{\mathrm{coating}}\right)}{\left(1-\sigma_{\mathrm{bulk}}^{2}\right)\left(1-\sigma_{\mathrm{coating}}\right)}\frac{\phi_{\mathrm{coating}}}{\phi_{\mathrm{bulk}}}\frac{Y_{\mathrm{bulk}}}{Y_{\mathrm{coating}}}\left[\left(1-2\sigma_{coating}\right)+\left(1-2\sigma_{bulk}\right)^{2}\frac{\left(1+\sigma_{bulk}\right)^{2}}{\left(1+\sigma_{coating}\right)^{2}}\left(\frac{Y_{coating}}{Y_{bulk}}\right)^{2}\right]\left(\frac{\mathrm{d}}{\mathrm{w}}\right)\right\}$$

Evaluation of excess noise due to coating

- Let:

  $d = 10\mu m$ and $w = 6 \times 10^{-2} m$

  ϕ_{bulk} = 3.3×10^{-8} for fused silica

  Y_{bulk} = 7.2×10^{10} Pa

  σ_{bulk} = 0.17

  $Y_{coating}$ = 10.5×10^{10} (taking average of Y's for SiO_2 and Ta_2O_5)

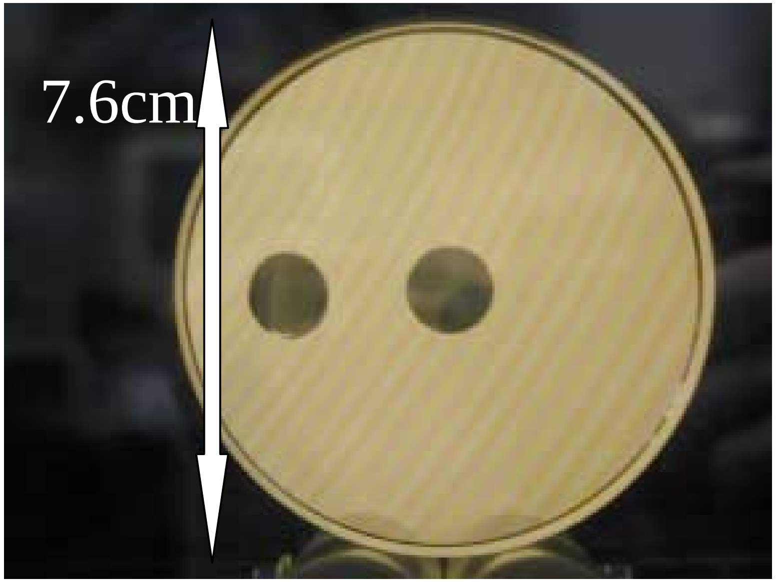
  $\sigma_{coating}$ = 0.21 (taking average of σ's SiO_2 and Ta_2O_5)

- Our measurements give $\phi_{coating} \sim 1.7 \times 10^{-4}$

- Suggests power spectral density of noise is increased by 1 + 0.62 = X1.62
- so amplitude spectral density of noise increased by X1.27

Sapphire substrate

- Crystal Systems
- m-axis sample
- Dimensions 7.6cm dia x 3cm thick
- Q's of 5 modes measured with sample uncoated
- Sample then coated by REO
  - HR @1064nm
  - AR @ 1064nm
- Q's re-measured for each mode
- **nb: Complication - coatings have run over on to large portion of barrel surface**



View of m-axis sapphire sample, on loan from LIGO project, through crossed polarizers. Dark spots are small amounts of Al, used as mirrors

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Results for sapphire sample

Mode	Frequency (Hz)		Loss before coating	Loss after coating
	measured	modelled		
'Clover (4) leaf'	35674	35085	3.5×10^{-8}	9.4×10^{-8}
Asymmetric drum	54850	53074	4.5×10^{-8}	15×10^{-8}
Bending	68633	66657	11×10^{-8}	14×10^{-8}
Fundamental	82980	82296	1.9×10^{-8}	6.4×10^{-8}
'Clover (6) leaf'	87267	88292	3.7×10^{-8}	9.4×10^{-8}

Note: loss before coating is different for different modes - suggests suspension losses non-zero - possibly due to visibly poor barrel polish.

Calculation of coating loss

- From previously:

$$\phi_{\substack{\text{after}\\\text{coating}}} = \phi_{\substack{\text{before}\\\text{coating}}} + \frac{E_{\substack{\text{coating}\\\text{face}}}}{E_{\text{bulk}}} \phi_{\substack{\text{coating}\\\text{face}}} + \frac{E_{\substack{\text{barrel}\\\text{coating}}}}{E_{\text{bulk}}} \phi_{\substack{\text{barrel}\\\text{coating}}}$$

Becomes:

$$\phi_{\substack{\text{after}\\\text{coating}}} = \phi_{\substack{\text{before}\\\text{coating}}} + \frac{Y_{\text{coating}}}{Y_{\text{bulk}}} \frac{E_{\text{surface}}}{E_{\text{bulk}}} \phi_{\substack{\text{coating}\\\text{face}}} + \frac{E_{\text{barrel}}}{E_{\text{bulk}}} \phi_{\text{eff}}$$

- Apply to the modes in pairs and solve for ϕ_{coating} and ϕ_{eff}

Coating losses

- This time, of the 10 mode pair combinations, results for ϕ of the coating were very scattered - possibly due to variable suspension losses?
- So, concentrate on the two simplest modes - the fundamental and the asymmetric drum
- These give:

$\phi_{coating} = 3.7 \times 10^{-4}$ and $\phi_{effl} = 1.5 \times 10^{-4}$

Interpretation for advanced LIGO

- Evaluation of excess noise due to coating
- Consider f = 250Hz, close to maximum interferometer sensitivity

– ϕ_{bulk}(due to thermo-elastic damping) ~ 3×10^{-8}

Let:

$Y_{bulk} = 3.6 \times 10^{11}$Pa

$\sigma_{bulk} = 0.23$

-Then excess factor = 1 + 3.16 = 4.16

-ie noise power is increased by x 4.2 at 250Hz

-so amplitude spectral density increased by X 2.04

Conclusions

- Experiments suggest coating losses are of a level which may be significant for advanced LIGO
- Coating losses in sapphire seem greater in sapphire than silica - substrate effect or supplier effect?
- Topics to be addressed:
  - What is source of loss - homogenous throughout layers of coating; coating/substrate interface; interface between individual layer…….
  - Does loss differ for coatings from different vendors
  - Is loss observed greater for sapphire substrates