Investigations of mechanical loss from mirror coatings in gravitational wave interferometers

Peter Sneddon, David Crooks, Geppo Cagnoli, Jim Hough
University of Glasgow

Sheila Rowan, Marty Fejer, Roger Route
Stanford University

Norio Nakagawa
Iowa State University

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Introduction

- Motivation:
  - Mechanical loss due to dielectric coatings may increase thermal noise in gravitational wave detectors. Therefore, need to understand the sources of this loss and determine how to reduce it
- Previous Experiments:
  - Work at Glasgow, Stanford and Syracuse have shown coating loss to be significant for Advanced LIGO.
    - ~ 6.4×10^{-5} for Al_2O_3/Ta_2O_5 Coatings
    - ~ $1 - 4 \times 10^{-4}$ for SiO_2/Ta_2O_5 coatings
  - The goal is a coating loss of ~3×10^{-5} for an SiO_2/Ta_2O_5 coating, giving a 10% increase in thermal noise power spectral density in Advanced LIGO
- Development plan:
  - Collaboration between Glasgow, Stanford, Syracuse, MIT and Caltech has developed a set of experiments designed to determine the source of the coating loss – the first step in reducing it.

Measurement technique

- Measure mechanical loss of several modes of suspended fused silica substrates before and after coating

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

- Mechanical loss is different for each mode of coated mass due to fraction of energy stored in coating for given modeshape
- For each mode, finite element analysis was used to calculate the relevant energy ratios,

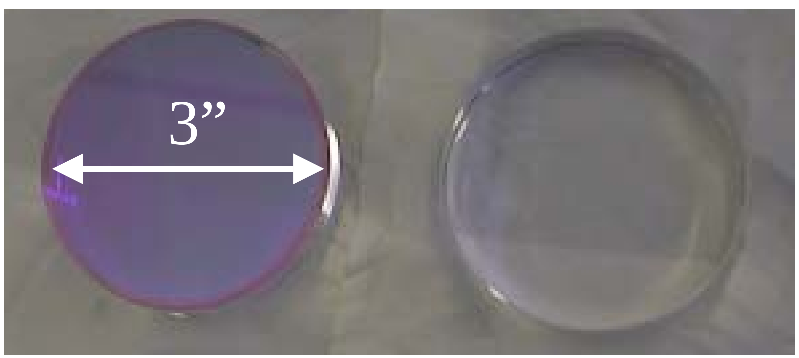
$$\phi(\omega_0)_{\text{coated}} \approx \phi(\omega_0)_{\text{substrate}} + \frac{E_{\substack{\text{coating on}\\\text{face}}}}{E_{\text{substrate}}} \phi(\omega_0)_{\substack{\text{coating}\\\text{on face}}}$$

- A linear regression algorithm can then be used to find $\phi(\omega_o)_{\text{coating}}$, assuming $\phi(\omega_0)_{\text{coating}}$ constant with ω_0.

Experimental Technique

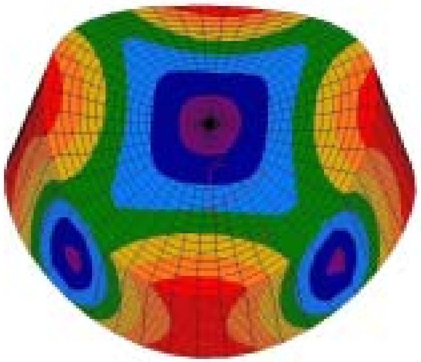
- 3” by 1” fused silica samples
- Set of internal resonances of suspended samples excited using electrostatic drive
- Measure decay of amplitude of excitation for each mode (interferometric sensing)
- Obtain quality factor, Q, for each mode before and after coating and hence the loss, ϕ, for each mode where $\phi(\omega_0) = Q^{-1}$

Suspended sample

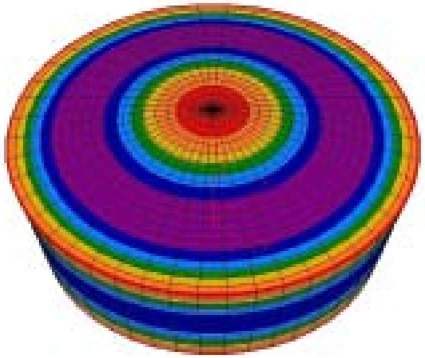


Coated and uncoated silica samples

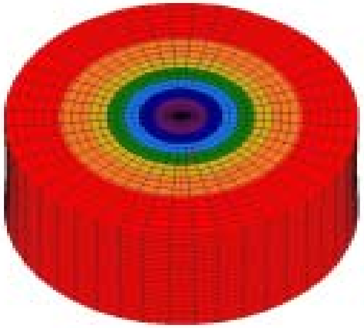
Mode shapes



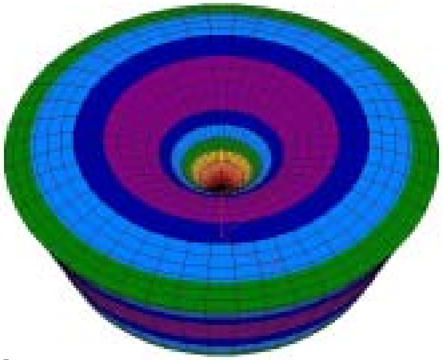
Clover 4 = C4



Asymmetric Drum = A



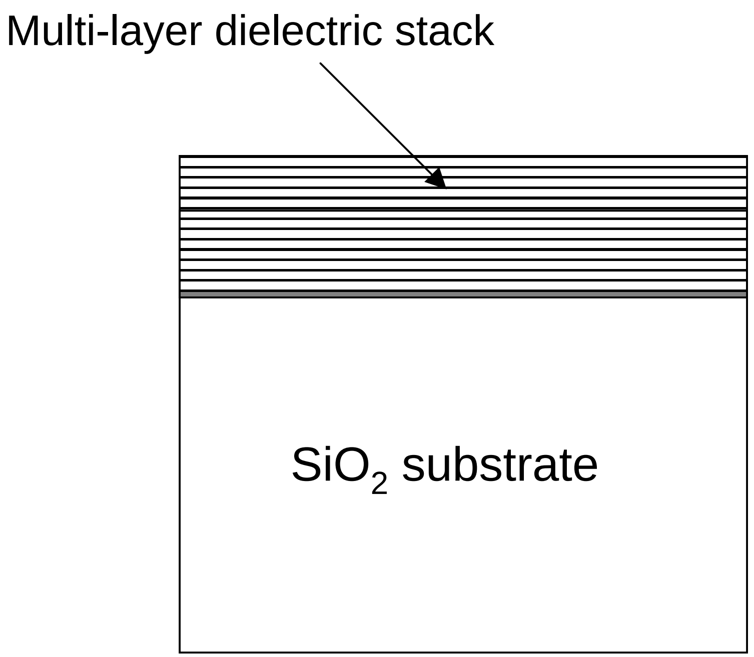
Fundamental Longitudinal = F



2nd Asymmetric Drum = 2A

Rationale of Current Studies

- First question:
  - Where is physical location of mechanical loss of the coatings?
    - 1st interface of coating and substrate?
    - Total volume of coating material?
      - Individual interfaces of coatings?
      - Bulk of the actual coating materials?
    - (or some combination of these?)



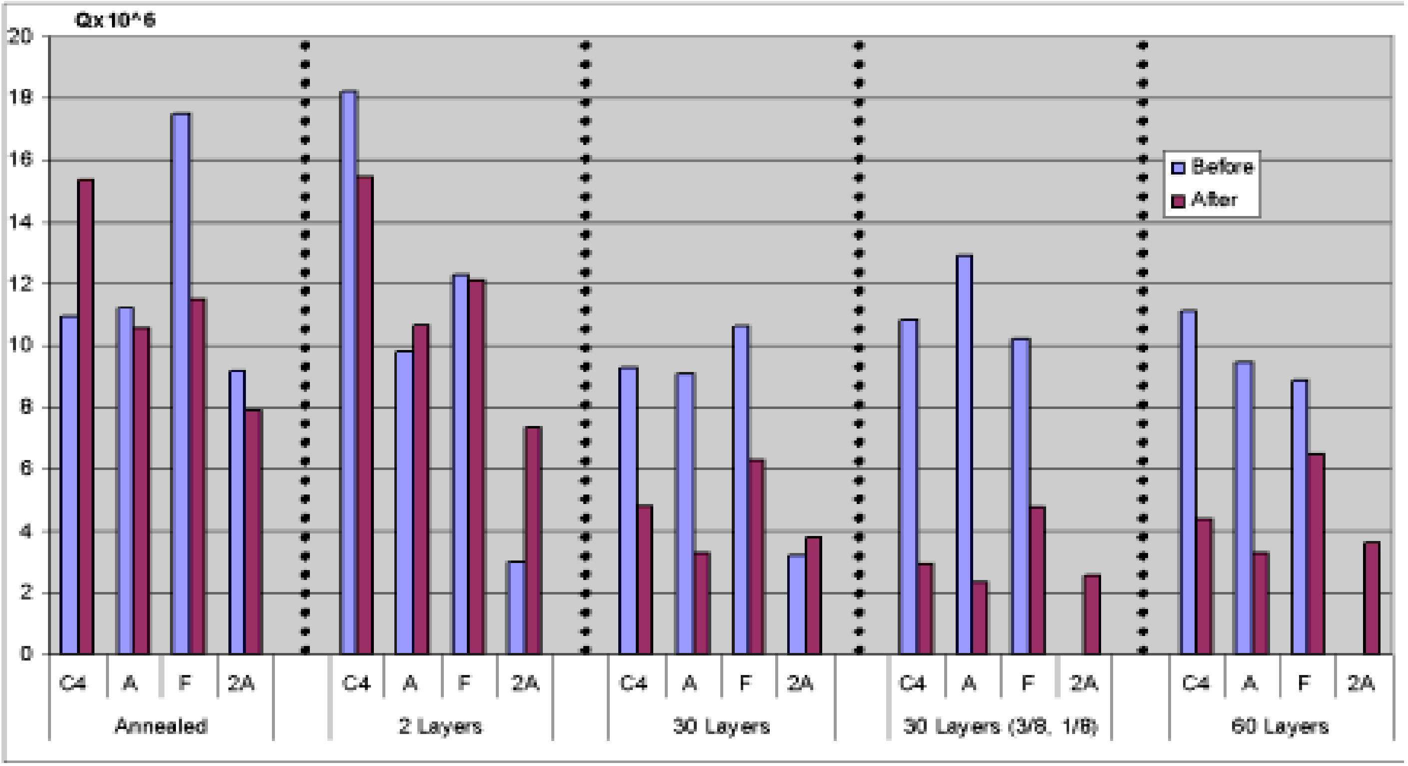
Coatings/Treatments Considered (So Far)

Run	Number of samples	Coating	Test	Comments
0	1	No coating	Effect of cleaning and annealing on loss	
1	2	SiO_2/Ta_2O_5 $\lambda/4$, $\lambda/4$ 30 layers	Effect of surface layer + 30 layer coating on loss	
2	1	SiO_2/Ta_2O_5 $\lambda/4$, $\lambda/4$ 2 layers	Effect of surface layer + 1st coating layer on loss	
3a	2	SiO_2/Ta_2O_5 $\lambda/8$, $3\lambda/8$ 30 layers	Which material has effect on loss	Assumes run 1 is dominant effect
3b	2	SiO_2/Ta_2O_5 $\lambda/8$, $\lambda/8$ 60 layers	Does material thickness or number of interfaces affect loss	Assumes run 1 is dominant effect

- The coating/annealing was carried out by SMA Lyon

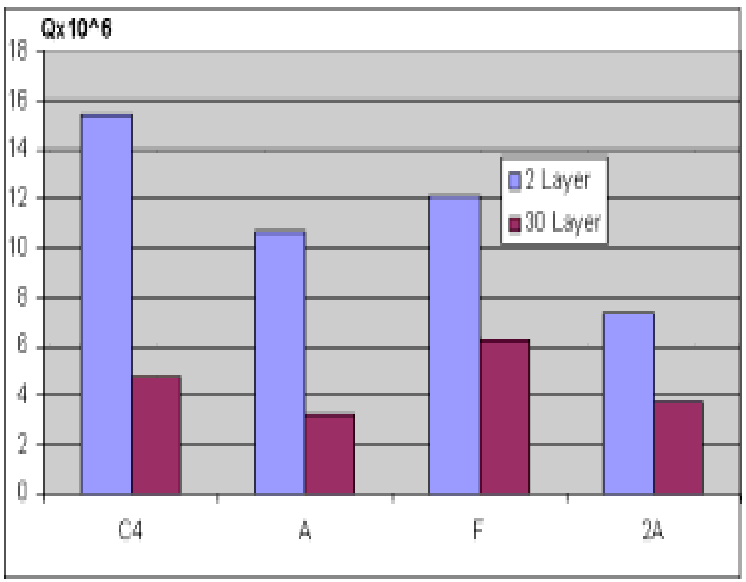
Q Results (I) - Overview

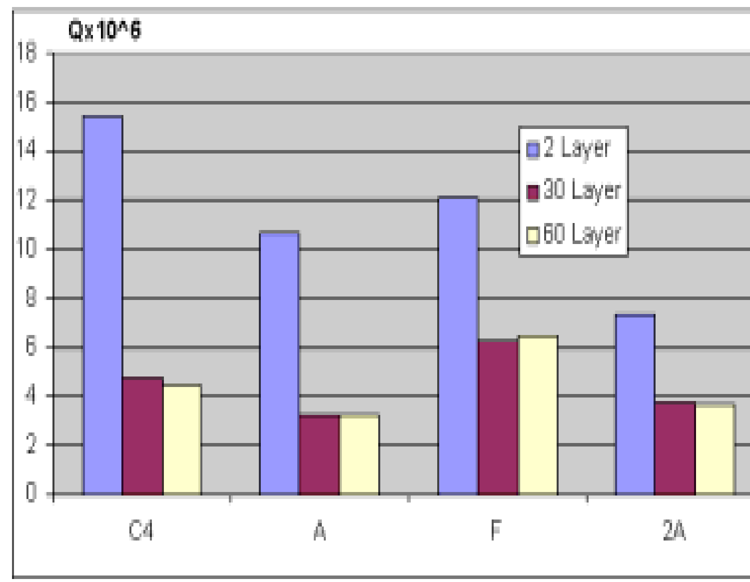
- Q measurements were made on a range of samples.
- The plot below shows the before and after results for one of each type of coating/treatment.



Q Results (II) – Initial Deductions

- Comparing 2 layer results with 30 suggest the first interface is not the dominant source of mechanical loss
- 60 layer results suggest that interfaces within the multi-layer dielectric coating are not the dominant source of mechanical loss





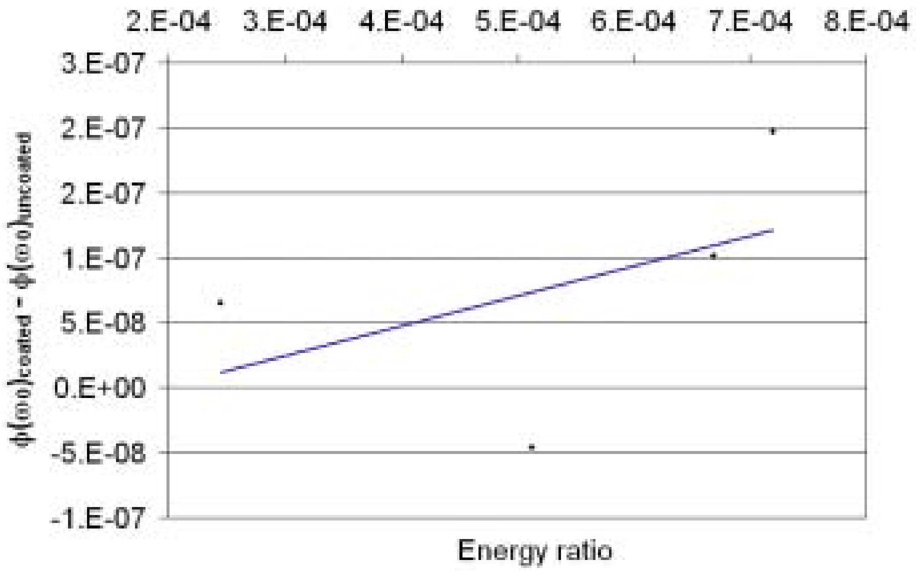
- Need more quantitative analysis of results

Consider 30 $\lambda/4$ – estimate coating loss

- Using our measurements of loss before and after coating and the following model for the loss, $\phi(\omega_o)$, of each mode:

$$\phi(\omega_0)_{\text{coated}} \approx \phi(\omega_0)_{\text{uncoated}} + \frac{E_{\text{coating on face}}}{E_{\text{substrate}}} \phi(\omega_0)_{\text{coating on face}}$$

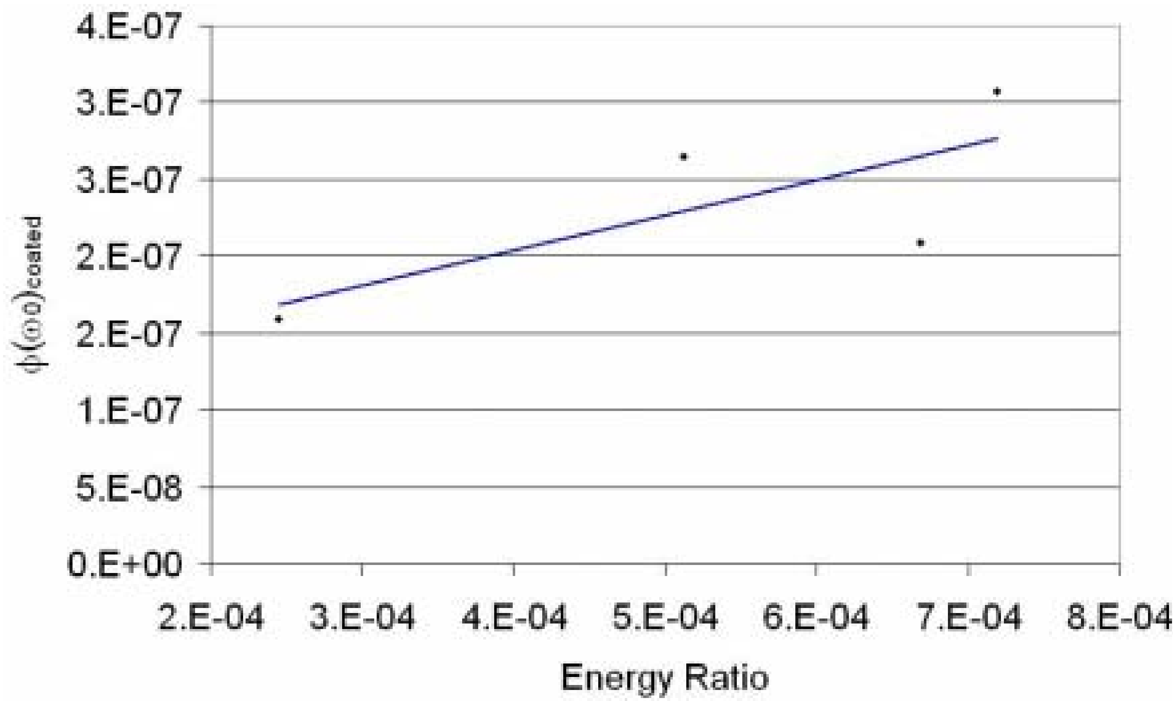
- We can plot $\phi(\omega_0)_{\text{coated}} - \phi(\omega_0)_{\text{uncoated}}$ against energy ratio for each mode.



However, data appears far from expected straight line $R^2 = 0.24$

30 λ/4 coating - continued

- Recall, samples are annealed as part of coating process
- Previous work by Numata et al (LIGO doc G010365-00-1), Penn et al (Rev Sci Inst 72 (9)) suggests annealing may affect intrinsic loss
- Using before and after measurements invalid?
- Instead use equation from previous slide and fit for intrinsic loss ($\phi_{uncoated}$)

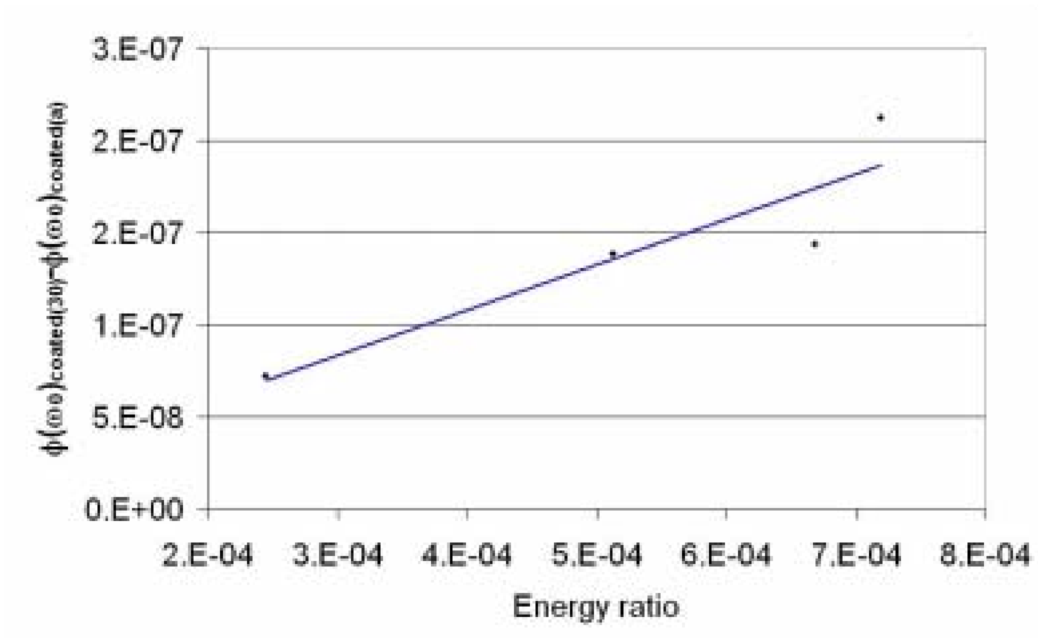


$R^2 = 0.57$

Significant improvement in fit

Analysis – subtraction of annealed mass losses

- We have an uncoated substrate annealed in the same way as coated samples
- Thus directly remove the effect of substrate



$R^2 = 0.84$

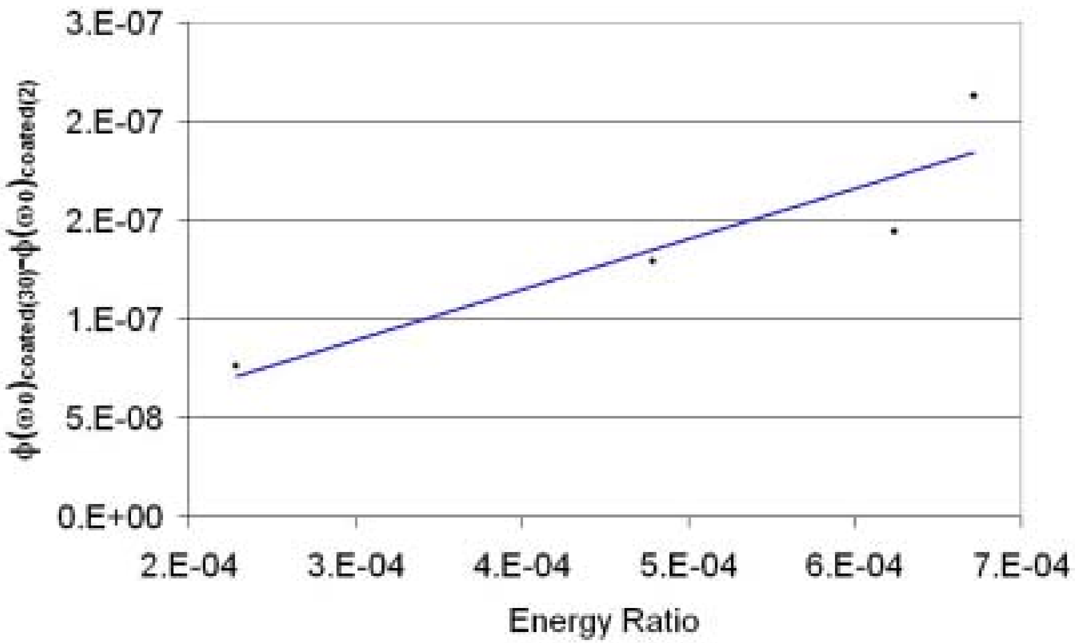
This model an improved fit to data

Use this model for subsequent analyses

- Nb: Consistent with annealing/ coating process resulting in **mode dependent** loss

Analysis - subtraction of 2 layer mass losses

- In a similar way the losses of the 2 layer mass can be subtracted to obtain an improved fit



$R^2 = 0.82$

This model also gives An improved fit to data

Use this model for subsequent analyses as well

Loss summary

- Results of analysis are summarised below
- c-a indicates fit using coated - annealed results
- c-2 indicates fit using coated - 2 layer results

	c-a fit	c-2 fit
30 (1/4,1/4)*	$(2.7 \pm 0.7) \times 10^{-4}$	$(2.8 \pm 0.7) \times 10^{-4}$
60 (1/8,1/8)†	$(2.7 \pm 0.5) \times 10^{-4}$	$(2.8 \pm 0.5) \times 10^{-4}$
30 (3/8,1/8)**	$(3.7 \pm 0.5) \times 10^{-4}$	$(3.7 \pm 0.5) \times 10^{-4}$
2 (1/4,1/4)††	$(0.9 \pm 2.8) \times 10^{-4}$	-

- Notes:
  - * - 30 layer results are mean from two masses
  - † - 60 layer results are from a single mass
  - ** - 30 3/8,1/8 results are mean from two masses
  - †† - 2 layer results are from a single mass

Deductions

1. Compare losses from 30 $\lambda/4$ to 2 $\lambda/4$ –

   $(2.8 \pm 0.7) \times 10^{-4}$ to $(0.9 \pm 2.8) \times 10^{-4}$

   – Difficult to compare because error in 2 layer result is high
   – Differences in Q values suggest 30 layer coating has greater effect
   – Substrate/coating interface not a significant source of loss

2. Compare losses from 30 $\lambda/4$ to 60 $\lambda/8$

   $(2.8 \pm 0.7) \times 10^{-4}$ to $(2.8 \pm 0.5) \times 10^{-4}$

   – These *are* the same
   – Intra-coating interfaces not a significant source of loss

3. Compare losses from 30 $\lambda/4$ to 30 $3\lambda/8$ (Ta_2O_5), $\lambda/8$ (SiO_2)

   $(2.8 \pm 0.7) \times 10^{-4}$ to $(3.7 \pm 0.5) \times 10^{-4}$

   – $\phi_{3\lambda/8,\ \lambda/8}$ is significantly higher than $\phi_{\lambda/4}$
   – Suggests Ta_2O_5 has a higher loss than SiO_2 in this case

Deductions (contd.)

- Partitioning the loss between the silica and tantalum we arrive at the following set of simultaneous equations:

$$\frac{Y_{\lambda/4,\lambda/4\ \text{coating}}t_{\lambda/4,\lambda/4\ \text{coating}}}{1-2\sigma_{\lambda/4,\lambda/4\,\text{coating}}}\phi_{\lambda/4,\lambda/4\ \text{coating}} = \frac{Y_{\text{silica}}t^{\lambda/4}_{\text{silica}}}{1-2\sigma_{\text{silica}}}\phi_{\text{silica}} + \frac{Y_{\text{tantala}}t^{\lambda/4}_{\text{tantala}}}{1-2\sigma_{\text{tantala}}}\phi_{\text{tantala}}$$

$$\frac{Y_{3\lambda/8,\lambda/8\ \text{coating}}t_{3\lambda/8,\lambda/8\ \text{coating}}}{1-2\sigma_{3\lambda/8,\lambda/8\,\text{coating}}}\phi_{3\lambda/8,\lambda/8\ \text{coating}} = \frac{Y_{\text{silica}}t^{\lambda/8}_{\text{silica}}}{1-2\sigma_{\text{silica}}}\phi_{\text{silica}} + \frac{Y_{\text{tantala}}t^{3\lambda/8}_{\text{tantala}}}{1-2\sigma_{\text{tantala}}}\phi_{\text{tantala}}$$

- Using results for the 30 layer $\lambda/4$ and 30 layer $3\lambda/8,\lambda/8$ coatings, a set of simultaneous equations can be solved for the individual losses of silica and tantala
- This gives:

$$\boldsymbol{\phi_{\text{silica}} = (-0.2 \pm 1.3) \times 10^{-4} \ \text{ and } \ \phi_{\text{tantala}} = (4.3 \pm 0.5) \times 10^{-4}}$$

- Using the previously obtained loss for an alumina/tantala coating $(6.3 \pm 1.6) \times 10^{-5}$ (Crooks *et al*, Clas Quant Grav **19** (2002)) we obtain for the loss of an alumina coating:

$$\boldsymbol{\phi_{\text{alumina}} = (-4 \pm 4) \times 10^{-5}}$$

- This implies that the loss of the alumina layer is very low and that the tantala loss (obtained from the SMA coatings) is higher than that in the alumina/ tantala coatings

Addendum - Recent findings

- Different analysis calculating $\phi_{coating}$ for each mode separately suggests $\phi_{coating}$ has a frequency dependence.
- For example, for the 30(4)-a
- Using this method we obtain the following results for the SiO_2/ Ta_2O_5 losses:

$$\boldsymbol{\phi_{silica}=(-0.7 \pm 0.7) \times 10^{-4} \text{ and } \phi_{tantala}=(4.7 \pm 0.7) \times 10^{-4}}$$

- And accordingly for alumina:

$$\boldsymbol{\phi_{alumina} = (-0.5 \pm 0.4) \times 10^{-4}}$$

The way forward

- In summary:
  - Mechanical loss appears to be connected to bulk material of coatings
  - Ta_2O_5 appears significantly lossier that either SiO_2 or Al_2O_3
- Options for investigation
  - Fabricate coatings from alternating layers of low index materials (SiO_2/Al_2O_3 - used for narrow bandwith mirrors in gas lasers)
  - Trade-offs - need many more layers, each of greater physical thickness to make a high reflector (~80 layers for 30ppm). Raises questions of practicability, optical performance and mechanical loss.
- Alternate high index materials
  - NbO_2, TiO_2, others
- Effects of annealing on mechanical loss - relation to coating stress?

The way forward

- Need to correlate with optical loss measurements - see talk by Roger Route

- Need to carry all parameters through to thermal noise calculation, not just to coating loss