Investigations of mechanical loss from mirror coatings in gravitational wave interferometers

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Introduction - Thermal Noise From Mirror Coatings

- Optics for Adv LIGO will be of either fused silica or sapphire
  - Chosen for a variety of reasons - one of these is LOW THERMAL NOISE

- Addition of dielectric mirror coatings can increase the thermal noise [Levin, Nakagawa, Yamamoto, Crooks, Harry et al]

- A set of experiments were carried out to
  - determine level of mechanical loss associated with typical coatings (which allows the effect on thermal noise to be investigated)
  - investigate the source of the mechanical loss in coatings
  - study different types of dielectric coating

- Experiments carried out by LSC collaboration
  - Glasgow, Stanford, MIT, Syracuse, Hobart and William Smith

- This talk will summarise the current state of this work.

Experimental Technique

- All GW interferometers so far use coatings consisting of alternating layers of SiO_2/Ta_2O_5

- The power spectral density of thermally induced displacement of a coated mirror can be determined by [Harry, Nakagawa]

$$x^2(f) \approx \frac{2k_bT}{\pi^{3/2} f} \frac{1}{wY_s} \left[\phi_s + \frac{1}{\sqrt{\pi}} \frac{d}{w} \phi_c \left(\frac{Y_c}{Y_s} + \frac{Y_s}{Y_c} \right) \right]$$

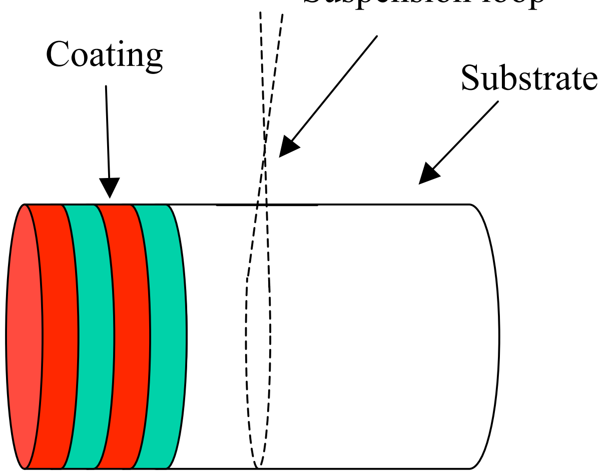
d = coating thickness
w = radius of incident laser beam where intensity is $1/e^2$ of max
f = frequency
k_b = Boltzmann's constant
T = temperature
Y_c = coating Young's modulus
Y_s = substrate Young's modulus
ϕ_s = substrate mechanical loss

- So, need to know the loss of the coating, ϕ_c

- This can be determined from:

$$\phi_{coated}(\omega_0) \approx \phi_s(\omega_0) + \frac{E_{coating}}{E_{substrate}} \phi_c(\omega_0)$$

Measured — Measured — Calculated by FEA



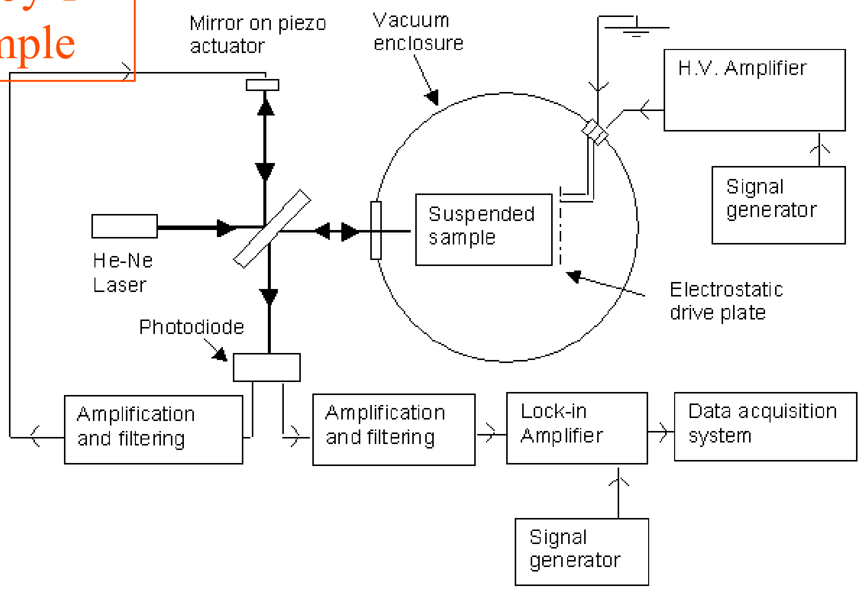
Experimental Set-Ups

- Loss factors were measured by exciting resonances in the samples (3” by 1” and 3” by 0.1”) and then recording the subsequent decay. ϕ was then obtained from:

$$A = A_0 \exp\left[\frac{-\omega_0 t \phi(\omega_0)}{2}\right]$$

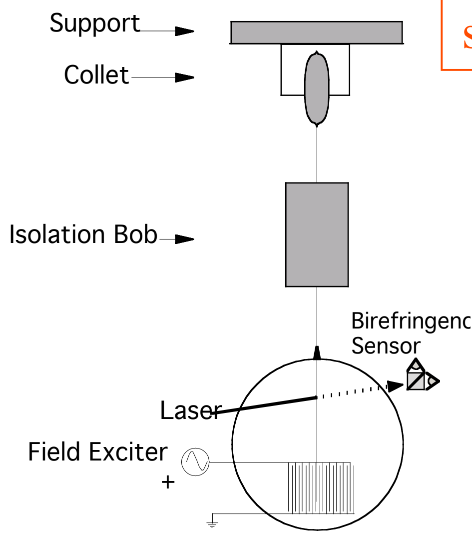
A_0 = initial amplitude
A = amplitude at time t
ω_0 = resonant frequency
$\phi(\omega_0)$ = loss of resonance with frequency ω_0

3” by 1” sample



- Advantage - non-invasive suspension
- Disadvantage - effect of coating loss lower
- Measurements made between ~20 kHz and ~73 kHz

3” by 0.1” sample



- Advantage - effect of coating loss greater
- Disadvantage - have to weld directly to sample
- Measurements made at a few kHz

- Advantage of the two geometries is that it allows coating loss to be investigated over a wider frequency range.

SiO_2/Ta_2O_5 Coatings (by SMA Lyon)

- Typical high reflectance coatings at 1 μm have alternating λ/4 layers of SiO_2 and Ta_2O_5
- To evaluate a coating loss for this use: $\phi_{coated}(\omega_0) \approx \phi_s(\omega_0) + \frac{E_{coating}}{E_{substrate}}\phi_c(\omega)$
- Consider a coating of 30 layers of SiO_2/Ta_2O_5
- After coating the samples are heated
  - Evidence [Numata, Penn et al] suggests heating affects the intrinsic loss of the substrate

(a) Thick samples

- A control sample was put through the same heating cycle as the coated sample. The loss values of the control were used for $\phi_s(\omega_0)$
- 4 modes were measured
  - Coating loss was assumed to be frequency independent (see the following talk by David Crooks)
  - $\phi_c = (2.8 \pm 0.7) \times 10^{-4}$

(b) Thin samples

- $E_{coating}/E_{substrate}$ dominates
  ⇒ $\phi_s(\omega_0)$ can be ignored
- 2 modes measured
  - $\phi_{clover4} = 2.7 \times 10^{-4}$
  - $\phi_{drum} = 3.1 \times 10^{-4}$

- For a coating loss of 2.8×10^{-4} the increase in the thermal noise power spectral density is 40 %. To limit any increase to 10 % for this coating requires a coating loss of $\sim 7 \times 10^{-5}$. The specification for Adv LIGO is 2×10^{-5}.

Source of Coating Loss

- By considering the losses of coatings with varying amounts of Ta_2O_5 and SiO_2 it was possible to

  (a) show that the measured loss of the coating was consistent being dominated by the intrinsic loss of the coating materials

  (b) determine the losses of the individual components:

  $\square_{silica} = (0.5 \pm 0.3) \times 10^{-4}$ and $\square_{tantala} = (4.4 \pm 0.2) \times 10^{-4}$

- The above suggests that other coating material combinations should be investigated

Other Coating Combinations

- The combinations chosen were also candidates for low optical loss - parallel study by Route et al (Stanford)

Coating: High index	Coating: Low index	Vendor	Coating Loss Thick samples ($\times 10^{-4}$)	Coating Loss Thin samples ($\times 10^{-4}$): Clover 4	Coating Loss Thin samples ($\times 10^{-4}$): Drum
Nb_2O_5	SiO_2	MLD	3.8 ± 0.3 4.5 ± 0.4	2.86 ± 0.01 -	3.21 ± 0.02 -
Ta_2O_5	Al_2O_3	WavePrecision	2.9 ± 0.4 3.1 ± 0.3	5.90 ± 0.08 -	- -
Ta_2O_5	Al_2O_3	MLD	3.56 ± 0.02 3.66 ± 0.07	10.2 ± 0.1 11.5 ± 0.1	12.4 ± 0.1 14.0 ± 0.1
Al_2O_3	SiO_2	MLD	?? ± ??	?? ± ??	?? ± ??

Ta_2O_5	SiO_2	SMA	2.8 ± 0.7	2.7	3.1

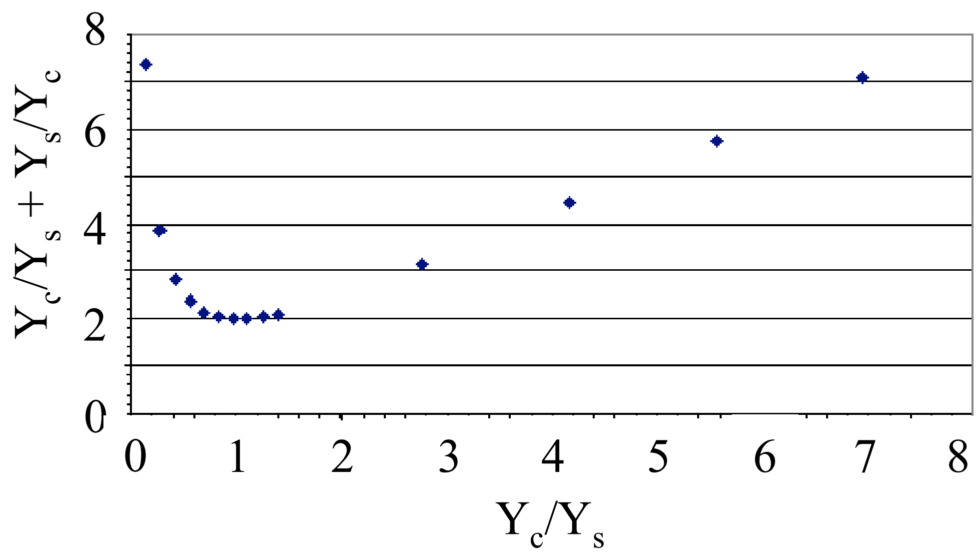
Implications of coating properties

- Recall from earlier that, for a given substrate material the thermal noise for a coating, $x_c^{\,2}$ is

$$x_c^2(f) \propto \phi_c d \left(\frac{Y_c}{Y_s} + \frac{Y_s}{Y_c} \right)$$

where ϕ_c = coating loss, d = coating thickness, and Y_c, Y_s are the Young's moduli of the coating and substrate respectively.

- This is minimised when $Y_c = Y_s$. Clearly there may be a different optimum coating for silica and sapphire substrates.

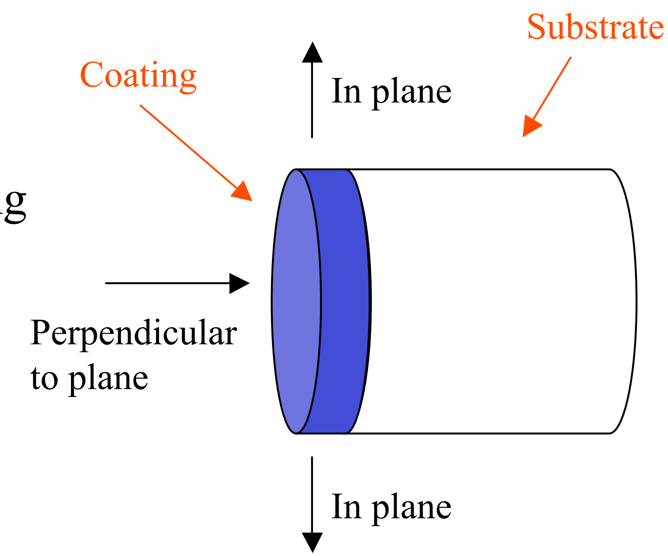


Implications (contd.)

- A more realistic situation allows that the Y_c and ϕ_c are anisotropic in the multi-layer coating. So, [Harry et al]

$$x_c^2(f) \propto d\left[\frac{Y_{||}}{Y_s}\phi_{||} + \frac{Y_s}{Y_{\perp}}\phi_{\perp}\right]$$

where $Y_{||}$, $\phi_{||}$ = Y_c, ϕ_c for deformation in plane of coating
$Y_{\perp}$, $\phi_{\perp}$ = Y_c, ϕ_c for deformation perpendicular to plane of coating



- Nb. $Y_{||}$ and $Y_{\perp}$ are weighted combinations of the Young's moduli of the individual coating layers.

- Assume $\phi_{||} = \phi_{\perp} = \phi_c$. So,

$$x_c^2(f) \propto \phi_c d\left[\frac{Y_{||}}{Y_s} + \frac{Y_s}{Y_{\perp}}\right]$$

- We have measured ϕ_c for different coatings, but to compare coating performance, need to take into account the different d, $Y_{||}$ and $Y_{\perp}$ for the coatings.

Implications (contd)

- In a gravitational wave detector, the fixed parameter will be the mirror reflectivity. We choose to compare coatings with R ~ 99.997 %.
- So for any given substrate material, to minimise the coating contribution to the thermal noise, we want to minimise

$$\phi_c d \left[\frac{Y_{\parallel}}{Y_s} + \frac{Y_s}{Y_{\perp}} \right]$$

Silica substrate - $Y_S = 7.2 \times 10^{10}$ Pa

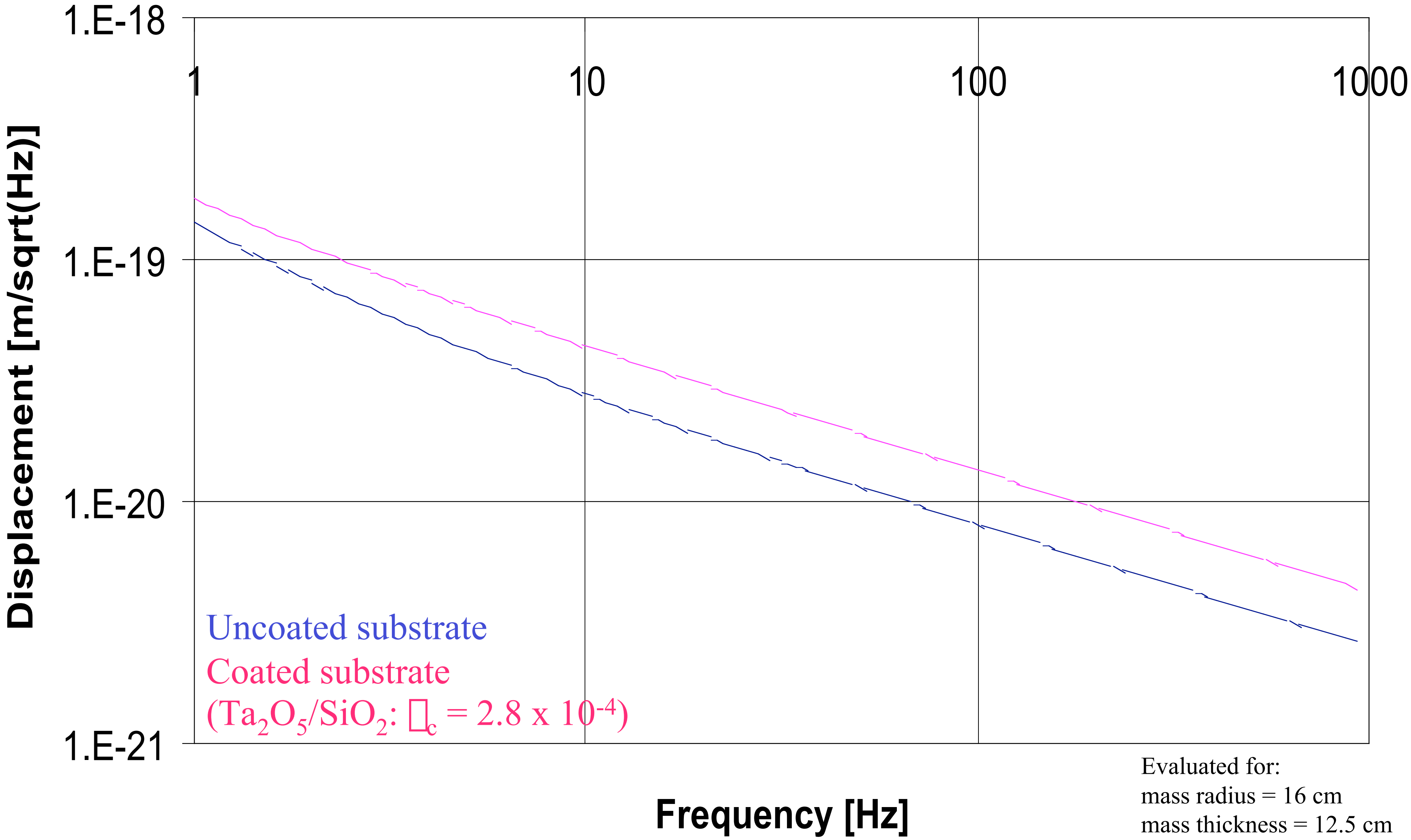
Sapphire substrate - $Y_S = 3.6 \times 10^{11}$ Pa

	d (μm)	$Y_{\parallel}$(Pa) (x 10^{10})	$Y_{\perp}$ (Pa) (x 10^{10})	ϕ_c (x 10^{-4})	Silica: $\phi_c d \left[\frac{Y_{\parallel}}{Y_s} + \frac{Y_s}{Y_{\perp}} \right]$	Sapphire: $\phi_c d \left[\frac{Y_{\parallel}}{Y_s} + \frac{Y_s}{Y_{\perp}} \right]$
a) SiO_2/Ta_2O_5	5.02	10	5.02	2.7	3.0×10^{-9}	5.8×10^{-9}
b) SiO_2/Nb_2O_5	4.28	7.72	4.28	3.8	3.3×10^{-9}	8.0×10^{-9}
c) SiO_2/Al_2O_3	13.8	20.7	13.8	-	$A \times 4.92 \times 10^{-5}$	$B \times 5.12 \times 10^{-5}$
d) Al_2O_3/Ta_2O_5	7.3	26.1	7.3	2.9	8.6×10^{-9}	5.1×10^{-9}

$A < 6.1 \times 10^{-5}$ $B < 1 \times 10^{-4}$

Nb. All measurements of coating loss presented here have used coatings on silica substrates. Level to be checked on sapphire substrates.

Thermal Noise - Silica Substrate



Evaluated for:
mass radius = 16 cm
mass thickness = 12.5 cm
r_0 = 5.5 cm

How to reduce coating loss?

- Measurements so far for $\square_c$ for Ta_2O_5/SiO_2 and Nb_2O_5/SiO_2 are consistent with being associated with the intrinsic loss of coating materials.

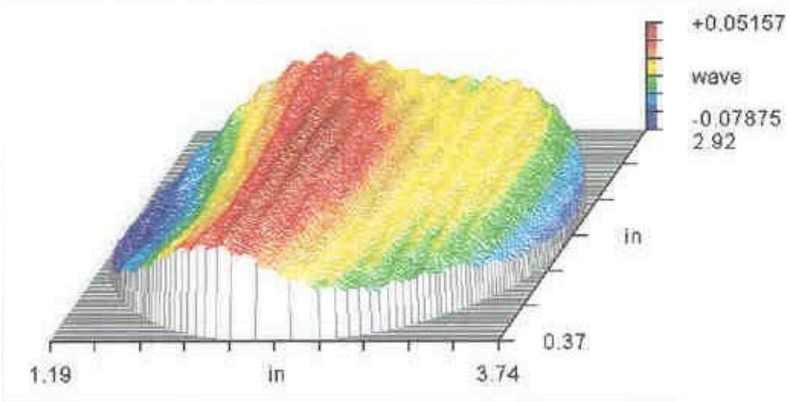
- How to reduce the coating loss?

  – We know that heating affects the intrinsic loss of the silica substrates
    - Could this also reduce the intrinsic loss of the coating?
    - What is the effect of residual stress in the coating?

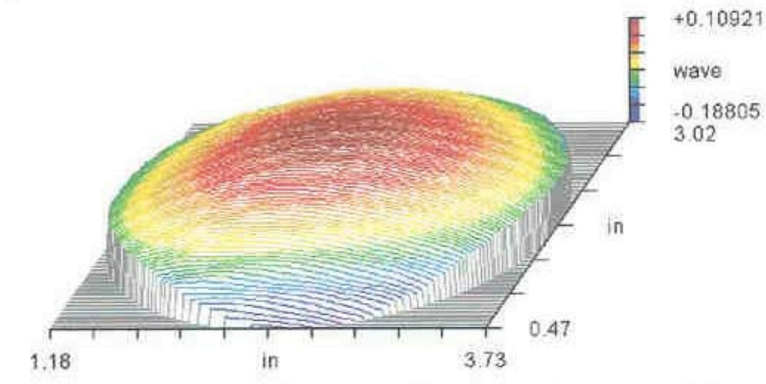
  – Engineer low loss coatings?

Stress in coating

- Distortions of test masses (before and after coating and/or annealing) can be detailed in interferograms.



Coated (Ta_2O_5/SiO_2), unannealed



Coated (Ta_2O_5/SiO_2), annealed

- From these, information regarding the stress in the coatings can be determined

- Look for correlations between the stress and the coating loss.

Collaboration with SMA/Virgo to lower coating loss

- Ta_2O_5/SiO_2 Coating - Ta_2O_5 doped with proprietary dopant
  - Dopant chosen to reduce stress
  - Young's modulus of coating unchanged by dopant
  - Thin sample tested (Gregg Harry, MIT)
    - $\phi_c \sim 1.8 \times 10^{-4}$ (cf. 2.8×10^{-4})
- SiO_2/New Material coating
  - New material is a mixture of two oxides
  - Young's modulus is similar to that for SiO_2
  - Index of refraction a little lower than Ta_2O_5
  - Work (at SMA) proceeding to lower optical loss

Conclusions

- Our measured values for the mechanical losses of currently available dielectric mirror coatings are of a level that suggests coating thermal noise will affect the sensitivity of future gravitational wave detectors
- Analysis shows that a combination of the material properties and intrinsic loss must be considered
- Various standard coating combinations have been investigated; none yet meet Adv LIGO requirements
- Investigations on ways to reduce the coating loss continue, including
  - heating coatings to reduce intrinsic loss
  - heating coatings to reduce residual stress
  - engineering the properties of the coating materials (SMA Lyon)
- Tests on coated sapphire samples are now beginning