Substrate mechanical loss studies

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LIGO Laboratory (Caltech, MIT, LLO, LHO)

LSC Partners (University of Glasgow, Syracuse University, Stanford University, Moscow State University, Iowa State University)

(also relevant work from TAMA project)

LSC Meeting, Hanford, August 2002
Plenary Instrument Science Session

LIGO-G020420-00-R

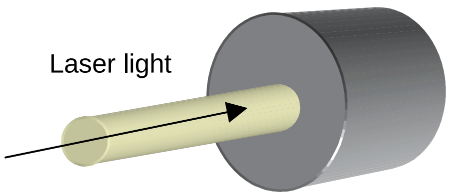
Introduction

- Core optics
  - **Sapphire/silica downselect** **Nov/Dec 2002**
- R & D areas
  - **Thermal noise performance**
    - Specifications for mirror substrate mechanical loss
    - Specifications for mirror coating mechanical loss - **see presentation by Gregg Harry**

Thermal noise

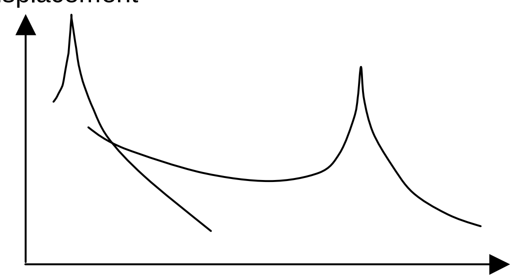
(a) Thermo-elastic noise

– **Fluctuations in temperature couple to displacements of front face of test mass through thermal expansion of substrate. Dependent on material properties of substrate (α, C, K etc)**



(b) 'Intrinsic' thermal noise

– **Thermal noise in an interferometer may be calculated using the energy dissipated by work done by a Gaussian pressure on front of test mass**



$$x^2(f) = \frac{2k_b T}{\pi^2 f^2}\frac{W_{diss}}{F_o^2} \qquad W_{diss} = \phi\omega U$$

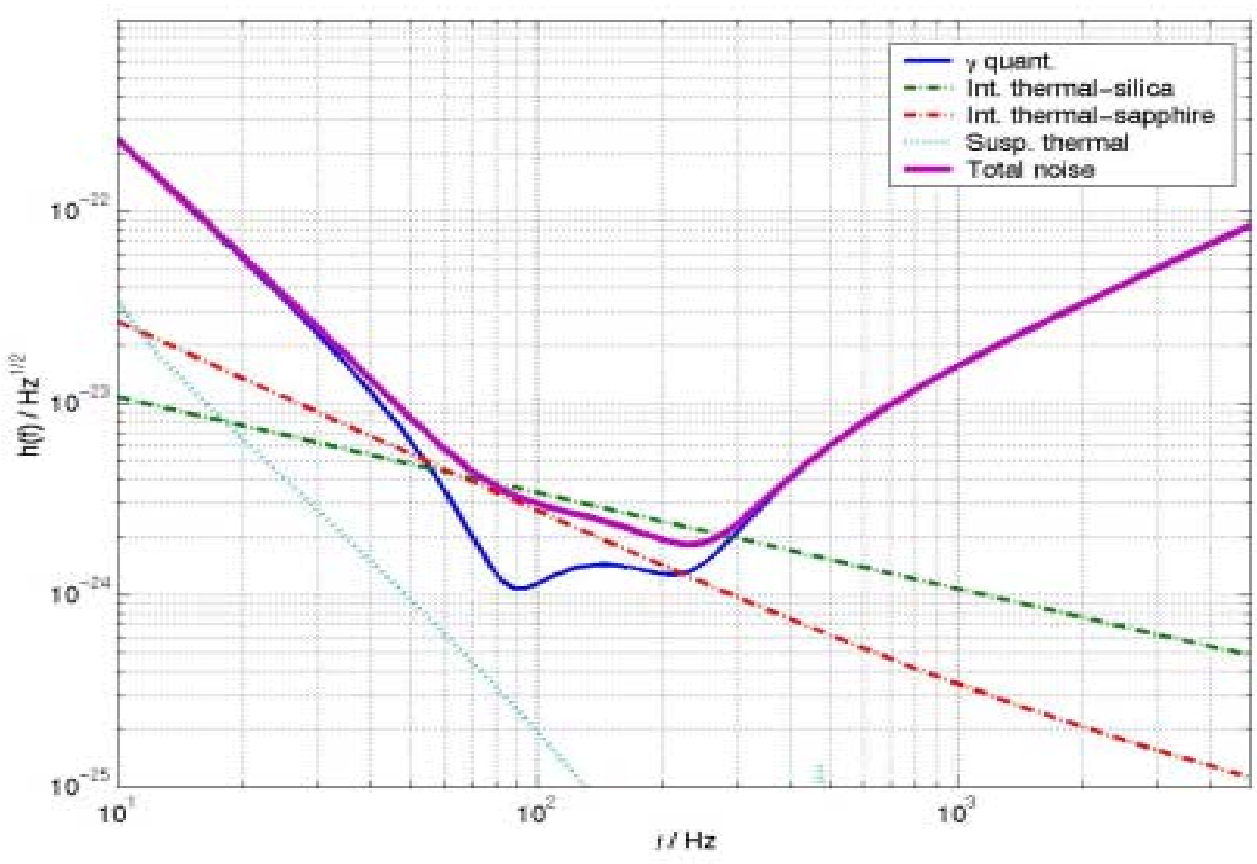
– **however x^2 and W_{diss} are very difficult to measure directly**

– **In the case of spatially homogeneous loss, the mechanical loss factor ϕ is equal to the inverse of the Q factor at the resonant frequencies of the modes of the test mass/suspension**

– **Thus, provided the frequency dependence of the loss is known, the thermal noise can be predicted from measurements of Q factor**

– **In the (real) case where loss is inhomogeneous (eg: mirror coatings, attachments etc) and where the spatial distribution of the energy stored is known, measurements of Q factor can provide us with information about the spatial distribution of ϕ and thus still be useful in allowing the thermal noise to be calculated. (Levin, Nakagawa, Yamamoto et al)**

Adv. LIGO sensitivity with sapphire or silica



Top level noise curves for Advanced LIGO showing internal thermal noise for silica and thermo-elastic noise for sapphire

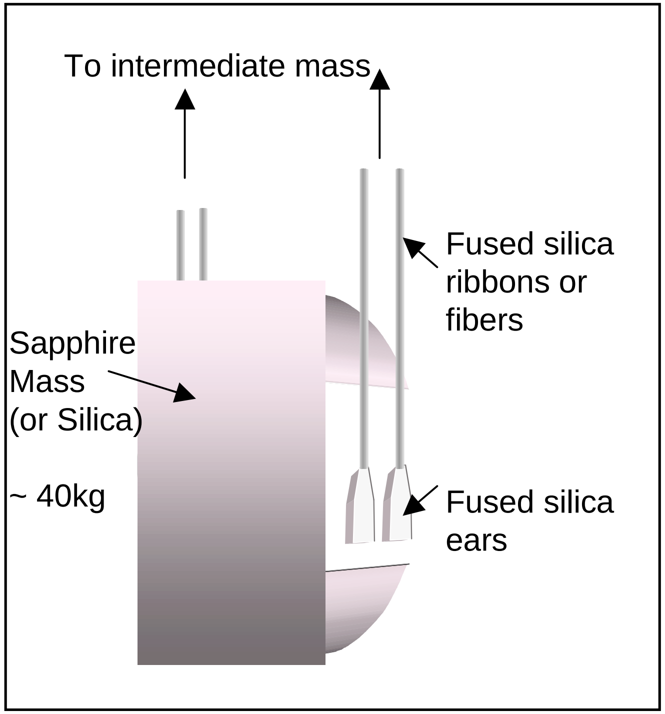
Thermal noise performance

In frequency band of interest:

– “Intrinsic” thermal noise

- Intrinsic dissipation
- Attachments
- Mirror coatings
- Surface effects

- Other related issues



– Thermo-elastic thermal noise

- How accurate is our knowledge of relevant material properties?
  – (J. Camp et al - Caltech)
  – (R. Lawrence et al - MIT)
- Scaling with beam size as expected?
  – (E. Black et al - Caltech)

(Expect thermo-elastic to be dominant provided intrinsic thermal noise is low enough)

Intrinsic thermal noise - specifications

Specification:

- Sapphire intrinsic mechanical loss factor: (see Adv. LIGO Systems Design)

  5×10^{-9} ($Q = 2 \times 10^{8}$)

Basis:

- **Measurements of Q/loss factors of samples of sapphire made at high frequencies - assume damping is frequency independent**
- **Original measurements (Moscow State)**
  - **Qs > 4×10^{8} samples ~ few cm diam. X 10cm long.**
  - **Various cuts measured.**
  - **Russian sapphire - variable optical quality**
- **Recent measurements**
  - **Q ~ 2.7×10^{8} samples ~ few cm diam. X 10cm long**
  - **"C-axis" (c-axis = cylindrical axis of sample)**
  - **Sapphire from Crystal Systems Inc - commercial polish**

Spec. for Adv. LIGO: $Q = 2 \times 10^{8}$ in "a-axis", 40kg sapphire substrate, ~31.4cm by 13cm

(Provided this is met - thermo-elastic noise is dominant)

Intrinsic dissipation - studies in progress

Work in progress:

Q measurements being extended - working towards sapphire samples of Adv. LIGO size/spec.

Cylindrical substrates under study of increasing size:

(a) 7.6cm by 2.5cm m-axis/ a-axis samples (underway)

(b) 12.7cm by 5.4cm c-axis / m-axis pieces (underway)

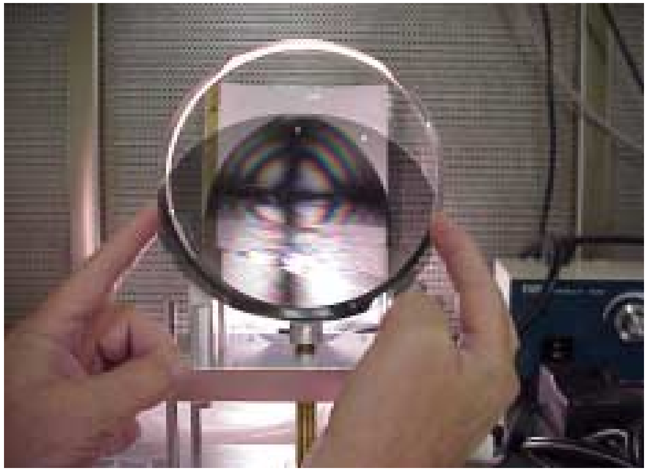
(c) 25cm by 12cm a-axis piece (delivery - Sept. 02)

- *Outer 2cm of sample shows a patch of scattering centers*

(d) 31.4cm by 13cm two a-axis pieces (delivery - Oct. 02)

(~ Adv LIGO size)

- *One sample "optically good"*
- *Second has scattering throughout*



C - axis sapphire from Crystal Systems Inc, with visible flaw Q >1.7 x 10^8 (Willems et al)

Characterization of this set of samples should provide info to allow assessment of specification for acceptability in terms of scattering centers etc

Intrinsic thermal noise comparison with fused silica

Specification

- **Fused silica intrinsic mechanical loss factor (see Adv. LIGO Systems Design Doc.) :**

  3×10^{-8} ($Q = 3 \times 10^{7}$)

Basis

- **Qs > 10^{7} measured for modes of LIGO I fused silica optics**
- **Qs ~ 3.4×10^{7} seen in Suprasil 311 and 312 samples ~ 6cm by 7cm (Numata et al)**
- **Q ~ 8.4×10^{7} seen in Suprasil 312 in small rods (8mm diameter)**

Nb: Q varies significantly between different commercially available of fused silica - source of dissipation in bulk fused silica is not known

Adv. LIGO requires:

- **Suprasil 311 SV grade (low optical absorption) for Beamsplitter**
- **Suprasil 312 SV grade (low optical absorption) for the Input Test Masses**

Intrinsic thermal noise comparison with fused silica

Work in progress

- **Q measurements of substrates**
  - **7.6cm by 2.5cm samples of Suprasil 312 SV (underway)**
- **311 SV material used in GEO (BS), VIRGO (BS)**
- **312 SV material used in VIRGO (ITM, RM))**

- **Ongoing studies of effects of polishing, annealing on fused silica throughout collaboration**
- **Interesting results from Numata et al suggest Q improving towards lower frequencies**

No measurement yet of Q of sample of Adv. LIGO type/size/polish which meets specifications

NB: could cooling induced stress in large samples be a problem in terms of associated mechanical dissipation?

Interpretation of results

- **Typical thermal noise estimates use measured Q (or $\phi(\omega_o)$), assume structural damping**

- **Following Levin and others:**
  - **Estimation of thermal noise requires knowledge of response of test mass to Gaussian force on front face - energy dissipation through imaginary part of elastic moduli of test mass**

- **Sapphire has 5 independent elastic constants - each elastic constant can have imaginary (dissipative) part**

- **Each mode of a test mass samples a subset of the elastic constants**
- **In principle by**
  - **(a) measuring the Q of a number of modes/number of cuts (c,a,m) of sapphire samples and**
  - **(b) calculating for each mode how much energy was stored in different types of deformation**

One could then back out loss factors associated with each elastic constant, calculate response of test mass to Gaussian pressure and use to calculate expected thermal noise.

NB: for this type of analysis to have any validity, measured Qs have to be a genuine measure of the internal dissipation of the material - i.e. not limited by suspension losses or any extrinsic mechanism

Interpretation of results

However in practice

- If all Qs measured are > 2 x 10^8 - as indicated by earlier experiments (see Braginsky/Mitrofanov measurements) then we probably do not need to carry out detailed reverse engineering of elastic loss coefficients.
- Q values need checked for sapphire from Crystal Systems- expts underway - see earlier in presentation

(Nb: requirement is to be less than thermo-elastic noise)

Surface effects - subset of intrinsic Q measurements

Sapphire

- **Q measurements on small samples with commercial available polish meet Adv. LIGO specifications.**

Silica

- **Q measurements on small samples of Suprasil 311/312 with commercial polish meet LIGO spec.**

However for both materials - evidence in small samples that dissipative surface layer can dominate damping

Thus assessment required of effect of damaged surface layer - carry out analysis similar to that of lossy mirror coatings on thermal noise

ie: treat as spatially localized loss in a thin film on mass, under pressure from Gaussian beam.

Attachments - sapphire test mass

Specifications:

- Addition of attachments should not add significant excess loss to intrinsic loss of sapphire **(5 x 10^{-9})**

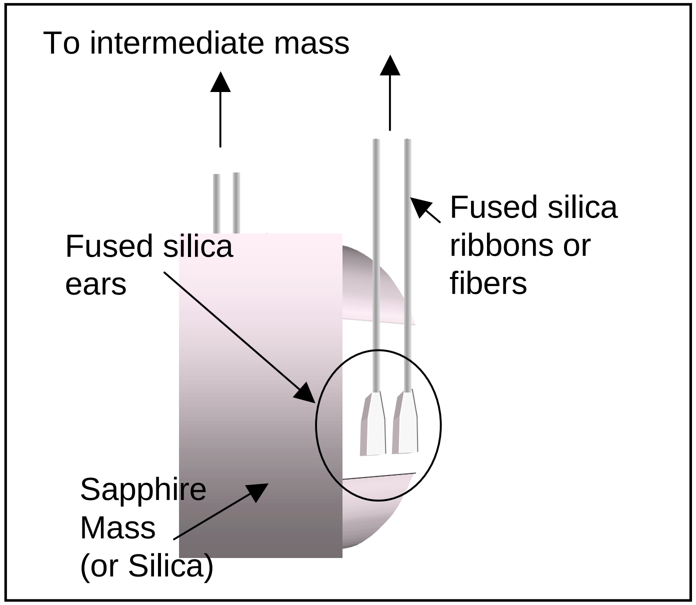
Basis:

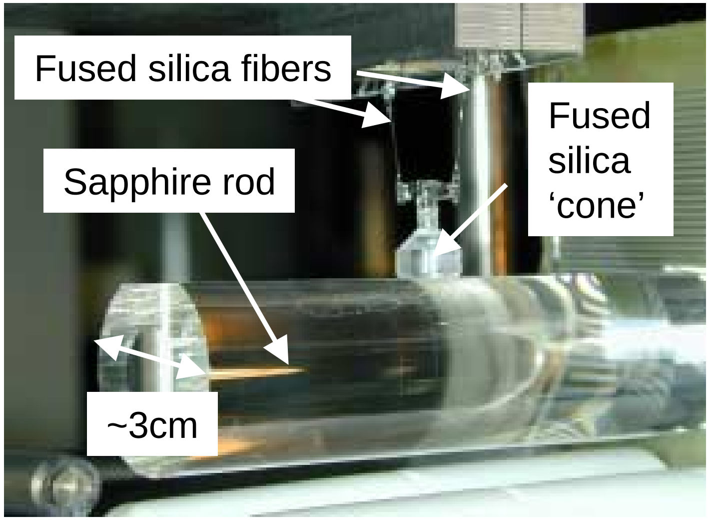
- Adaptation of GEO suspension design now installed in GEO interferometer
- Experiments carried out to assess the extra loss associated with adding bonded attachments to sapphire samples

Scale results to Adv. LIGO sized mass

- **Expected extra loss ~ 2.5 x 10^{-9}**
- **Less than spec of : 5 x 10^{-9}**

Suggests loss associated with adding attachments will not be significant





Attachments - comparison with fused silica

Specifications:

- **Addition of attachments should not add significant excess loss to that of intrinsic loss of silica (3 x 10^{-8})**

Basis:

- **Direct extension of GEO suspension design now installed in GEO interferometer**
- **Experiments carried out to assess the extra loss associated with adding bonded attachments to silica samples - similar to previous slide**
- **Scale results to Adv. LIGO sized mass**
- **Expected extra loss ~ 1.3 x 10^{-9}**
- **Less than spec of : 3 x 10^{-8}**

Suggests excess mechanical loss associated with adding attachments will not be significant

Attachments - work in progress

Work in progress: **(Both sapphire and silica)**

- **Above analyses are based on effect of bonds on Q**
- **Loss from bonds is spatially localized**

- **Several groups using techniques similar to those discussed in coating talk to**

  (a) obtain intrinsic loss factors of bonding material

  (b) use finite element or analytical techniques to calculate directly thermal noise from the inhomogeneous loss from attachments

Preliminary results agree with scaling arguments - suggests excess mechanical loss not significant. Work is ongoing.

Dissipation from coatings

- - see talk from Gregg Harry

Related issues

- Attachments
  - Bond breaking strengths
    - silica/silica and silica/sapphire measured - look adequate
  - Creep in bonds
    - silica/silica - suspensions installed in GEO will provide information
    - silica/sapphire - work in progress

- Excess loss from charging/patch fields/interaction with electrostatic actuator
  - **Charging of pendulum can damp Q**
  - **Discrete charging events seen in silica test pendulums monitored over periods of months (Moscow)**
  - **Damping of pendulums seen in presence of electrostatic drive plates (with or without field applied) - possibly due to charge patch effects on pendulums**
  - **Studies ongoing**

- Problems with high Q factors for test mass modes
  - "parametric instabilities" - Braginsky et al - is this a problem for Adv. LIGO?
- Others????

Summary

- Q measurements and modeling studies underway allowing estimation of thermal noise levels expected from:
  - Intrinsic mechanical loss
  - Surface related mechanical loss
  - Excess mechanical loss from attachments
  - Coating mechanical loss
  - Loss form actuator/charging issues
- We make assumptions about frequency dependence of damping
- To confirm expected noise levels, experiments underway to measure directly thermal/thermoelastic noise in suspended mirror substrates (E. Black et al)