Progress on Thermal Noise From Optical Coatings

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Context

Previously measured coating loss:

- SiO_2/Ta_2O_5 on silica substrate $\phi = 1.0 \pm 0.3 \; 10^{-4}$
- AL_2O_3/Ta_2O_5 on silica substrate $\phi = 6.4 \pm 0.6 \; 10^{-5}$

Theory to predict thermal noise from ϕ_{coat}

FEA code to compute energy in coating

Implications for advanced LIGO

- silica mirrors BNS range 115 Mpc → 100 Mpc
- sapphire mirrors BNS range 195 Mpc → 170 Mpc

See DRM Crooks et al, <u>CQG</u> 19, 5(2002) 883; GM Harry et al, CQG 19, 5(2002) 897.

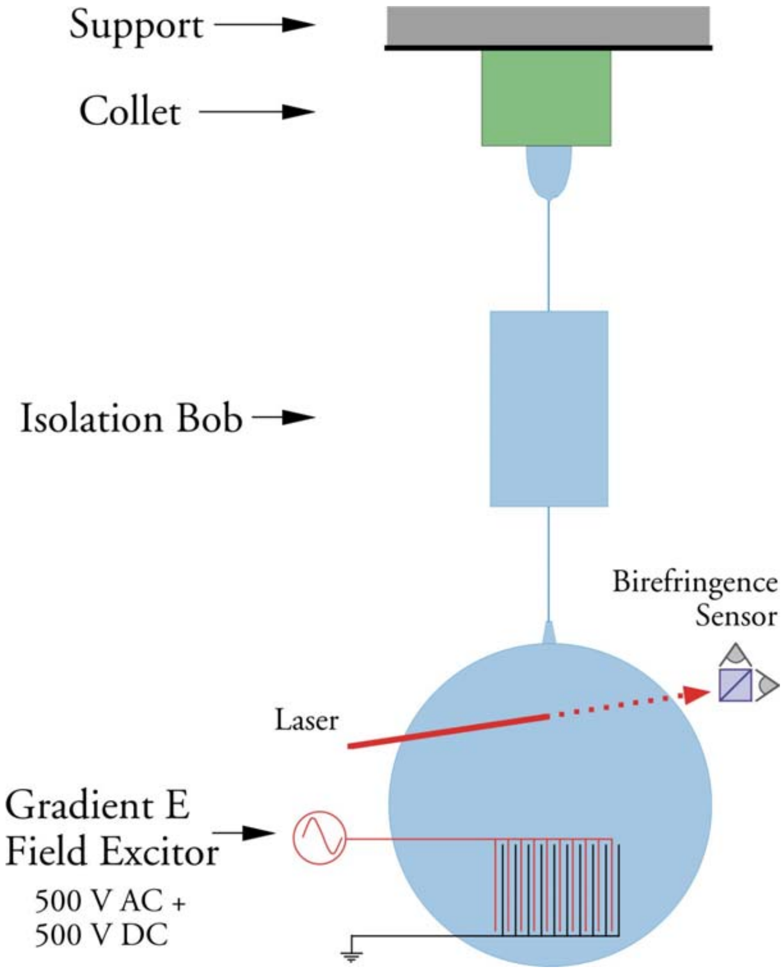
Measurement

Thin fused silica samples (3 inch diameter by 0.1 inch thick)

Samples suspended from monolithic, double-bob suspensions (*see Steve Penn's presentation*)

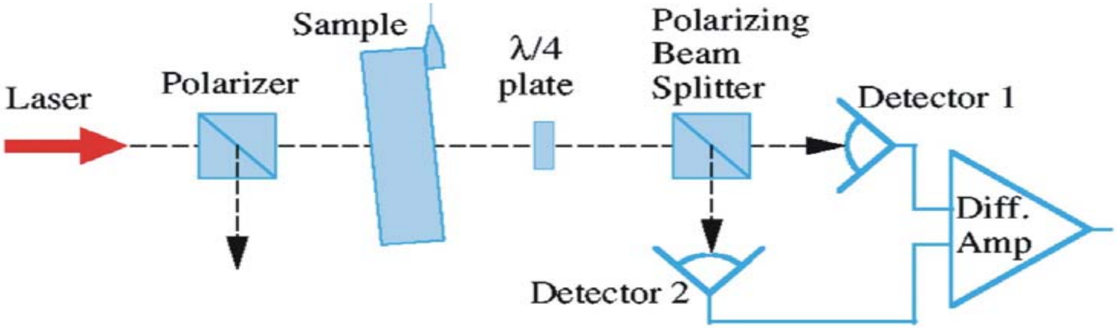
Q of normal modes measured before and after coating

- two butterfly modes (n=0, l=2)
- single drumhead (n=1, l=0)



Measurement, *cont d*

- Birefringence sensor used to readout oscillating strain in normal mode



- Data fit to full damped sinusoid to get Q

- FEA results used to determine energy in coating for each mode

- $?_{coat}$ deducted from Q s and FEA

Finite Element Analysis (FEA)

Make Algor model of samples

- $f_{butterfly}$ = 2659 Hz
- $f_{drumhead}$ = 4038 Hz

Use Ocean to get energy ratio in coating

(for 8 ?m coating)

- butterfly 1.19×10^{-2}
- drumhead 1.26×10^{-2}

Analyses

Determine if loss due to factor other than coating

- uncoated sample

annealed

Determine if loss scales with coating thickness or with number of layers

- 2 layers, $\lambda/4$ SiO_2 and $\lambda/4$ Ta_2O_5
- 30 layers, $\lambda/4$ SiO_2 and $\lambda/4$ Ta_2O_5
- 60 layers, $\lambda/8$ SiO_2 and $\lambda/8$ Ta_2O_5

Determine if SiO_2 or Ta_2O_5 is lossier

- 30 layers, $\lambda/8$ SiO_2 and $3\lambda/8$ Ta_2O_5

Annealing Results

Sample annealed at 900° C

Mode	Annealing	Frequency	Q
Butterfly 1	Unannealed	2720	11 million
	Annealed	2717	42 million
Butterfly 2	Unannealed	2720	14 million
	Annealed	2718	54 million

Sample annealed at 600° C

Mode	Annealing	Frequency	Q
Butterfly 1	Unannealed	2779	15 million
	Annealed	----	----
Butterfly 2	Unannealed	2781	12 million
	Annealed	2781	44 million

Coating Results
2 layers

Samples coated with 2 layers of $\lambda/4$ SiO_2 and $\lambda/4$ Ta_2O_5

Mode	Frequency	Q
Butterfly +	2679	5.4 million
Butterfly x	2681	6.5 million

Mode	Frequency	Q
Butterfly 1	2711	8 million
Butterfly 2	2722	9 million

Coating Results
30 layers even

Samples coated with 30 layers of $\lambda/4$ SiO_2 and $\lambda/4$ Ta_2O_5

Mode	Frequency	Q
Butterfly +	2708	528,000
Butterfly x	2840	

Mode	Frequency	Q
Butterfly 1	2732	536,000
Butterfly 2	2735	549,000
Drumhead	4130	433,000

Coating Results
30 layers uneven

Samples coated with 30 layers of $\lambda/8$ SiO_2 and $3\lambda/8$ Ta_2O_5

Mode	Frequency	Q
Butterfly 1	2721	400,000
Butterfly 2	2723	403,000
Drumhead	4107	285,000

Mode	Frequency	Q
Butterfly 1	2700	409,000
Butterfly 2	2694	404,000

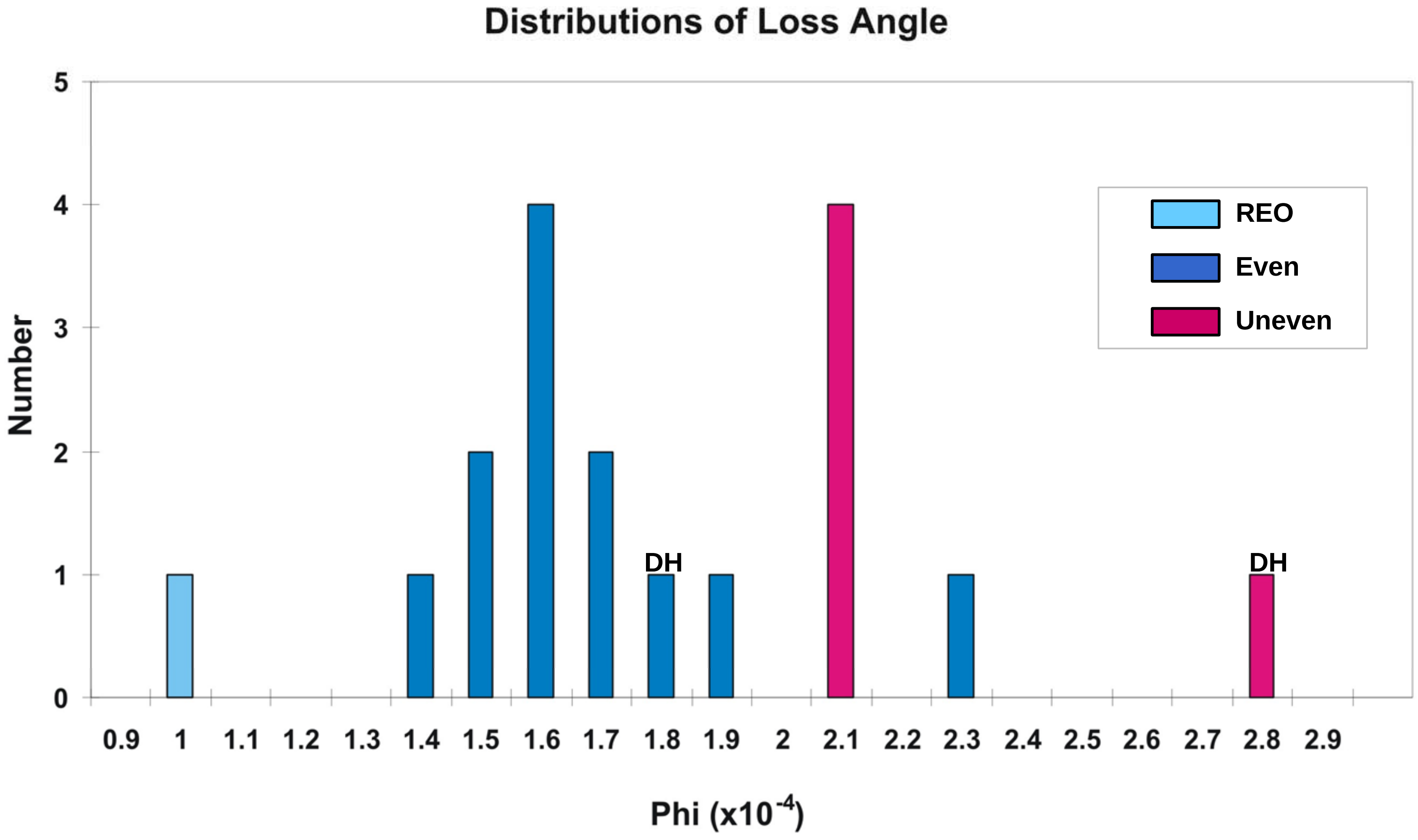
Coating Results
60 layers

Samples coated with 60 layers of $\lambda/8$ SiO_2 and $\lambda/8$ Ta_2O_5

Mode	Frequency	Q
Butterfly +	2712	548,000
Butterfly x	2690	487,000
Drumhead	4057	439,000

Mode	Frequency	Q
Butterfly +	2786	502,000
Butterfly x	2782	520,000

Coating ϕ s


Distributions of Loss Angle
Number
Phi (x10^-4)
0
1
2
3
4
5
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
DH
DH
REO
Even
Uneven

Interpretation

Annealing can reduce silica loss, even for thin samples

$\phi_{coat} = 1.7 \pm 0.2 \times 10^{-4}$

Loss scales with coating thickness

No significant effect from first or subsequent layers

Ta_2O_5 is lossier than SiO_2

$\phi_{Ta_2O_5} = 2.7 \pm 0.7 \times 10^{-4}$

$\phi_{SiO_2} = 0.7 \pm 0.9 \times 10^{-4}$

Next Steps

Anneal current coated samples

- limited maximum temperature due to Ta_2O_5
- adjust cooling rate

Try other materials and combinations

- SiO_2 /Al_2O_3 (need ~80 layers to get HR)
- Nb_2O_5 , HfO_2 , ZrO_2 (optically lossy)

Changes to coating process

- adjust purity of target materials
- change substrate temperature
- change ion beam energy

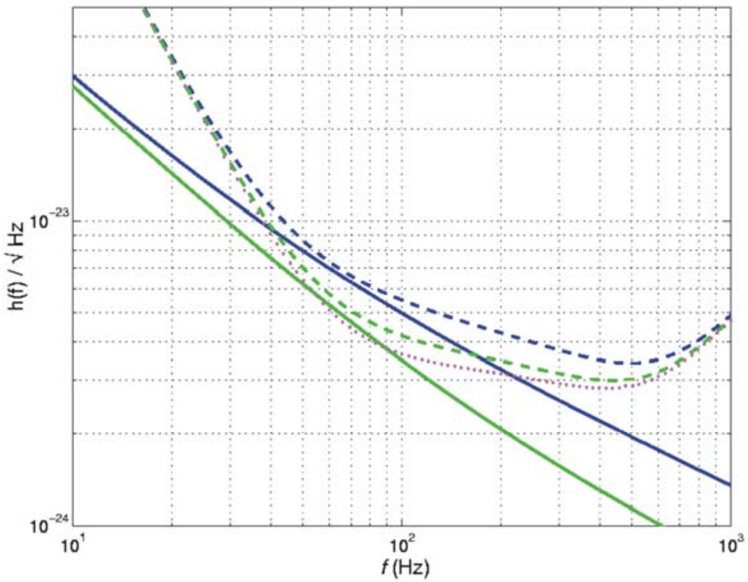
Predicting Thermal Noise from Coating ?

$$\phi_{\text{readout}} = \phi_{\text{bulk}} + \frac{1}{\sqrt{\pi}} \frac{(1-\sigma_{\text{sub}})}{(1-2\sigma_{\text{sub}})} \frac{d}{w} \left(\frac{Y_{\text{coat}}}{Y_{\text{sub}}} \phi_{\text{coat}\,\parallel} + \frac{Y_{\text{ub}}}{Y_{\text{coat}}} \phi_{\text{coat}\,+}\right)$$

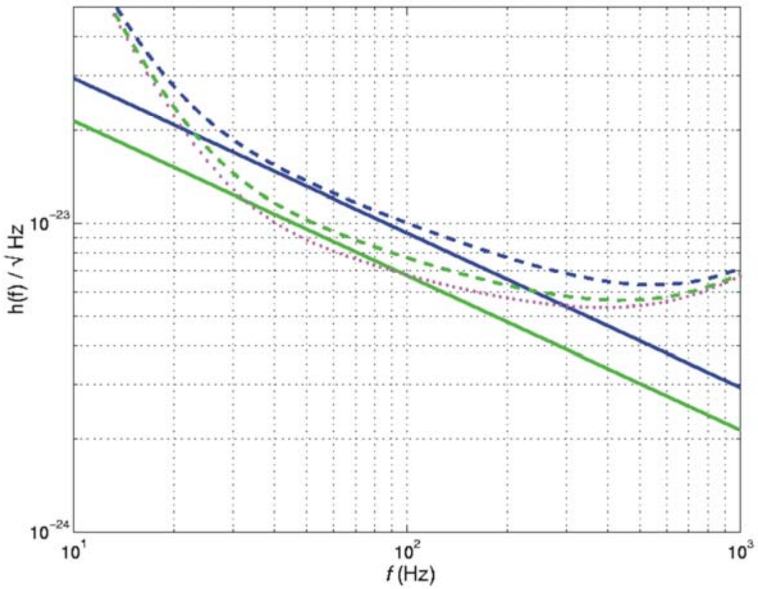
Still needed

- **value for ?$_{\text{coat+}}$**
- **more complete accounting for coating anisotropy** ***(could have similar problem/solution in sapphire)***
- **accounting for finite size of mirrors**

Implications for Advanced LIGO



sapphire mirrors



fused silica mirrors

Comparison of $?_{coat}$ = 1 x 10^{-4} and $?_{coat}$ = 4 x 10^{-4}

5.5 cm beam spot, 30 kg masses

Goals

How large can $?_{coat}$ be without affecting the astronomical reach of advanced LIGO?

Choose reduction of 5 Mpc for BNS as limit

Fused silica mirrors	$?_{coat} < 3 \times 10^{-5}$
Sapphire mirrors	$?_{coat} < 1 \times 10^{-5}$

How realistic is this? (*while maintaining low optical loss*)