Optical Coatings for Gravitational Wave Detection

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- On Behalf of the LIGO Science Collaboration -

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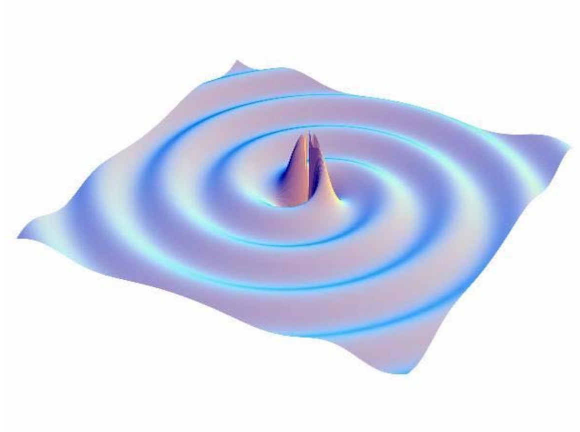
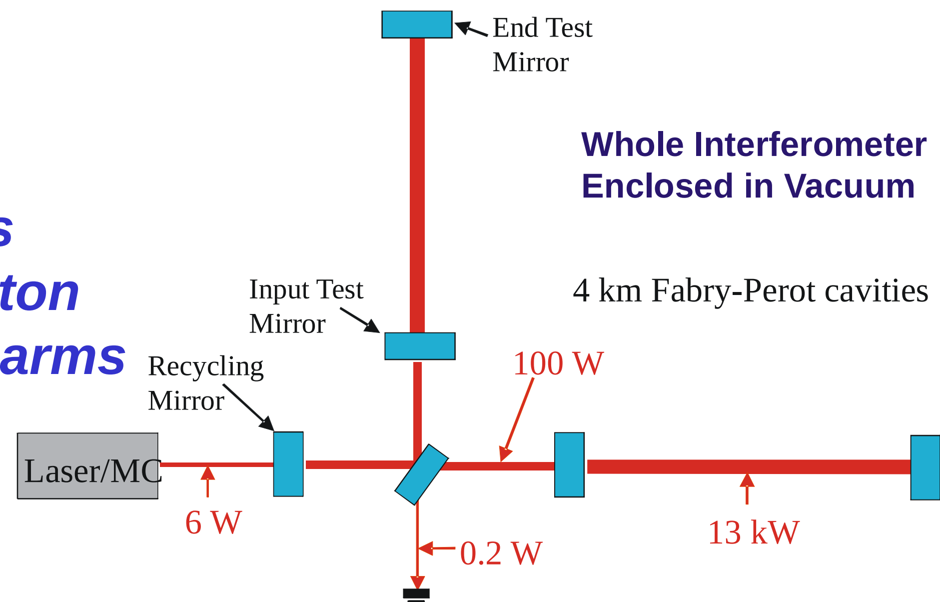
Gravitational Wave Detection



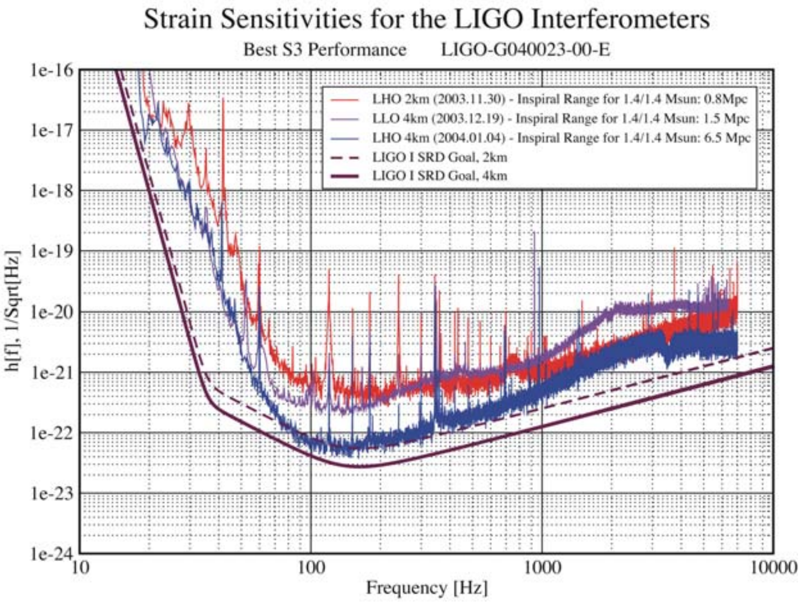
- *Gravitational waves predicted by Einstein*
- *Accelerating masses create ripples in space-time*
- *Need astronomical sized masses moving near speed of light to get detectable effect*

LIGO

- *Two 4 km and one 2 km long interferometers*
- *Two sites in the US, Louisiana and Washington*
- *Michelson interferometers with Fabry-Perot arms*
- *Whole optical path enclosed in vacuum*
- *Sensitive to strains around 10^{-21}*

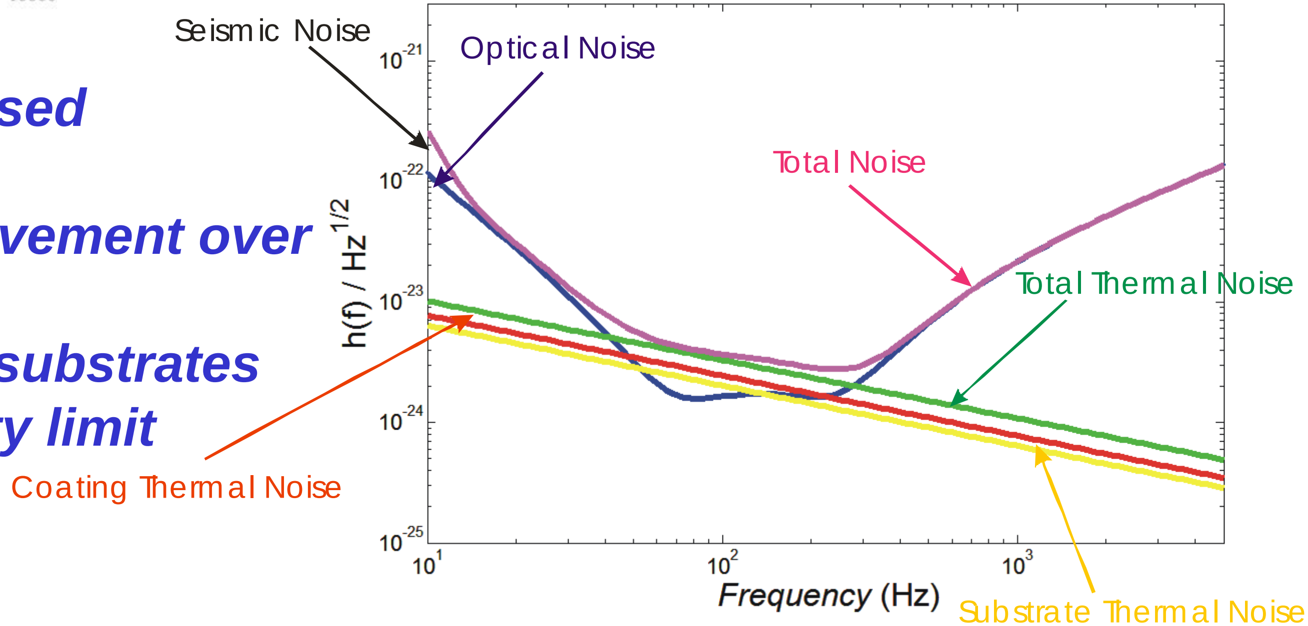


Interferometer Sensitivity



- *Measured sensitivity of initial LIGO 1/2004*
- *Nearing design goal*
- *Hanford 4 km within a factor of 2 near 100 Hz*

- *Design sensitivity of proposed Advanced LIGO*
- *Factor of 15 in strain improvement over initial LIGO*
- *Thermal noise from mirror substrates and coatings sets sensitivity limit*



Coating Thermal Noise

Fluctuation-Dissipation Theorem

$$S_F(f) = 4\ k_B\ T\ \ Re[Z]$$

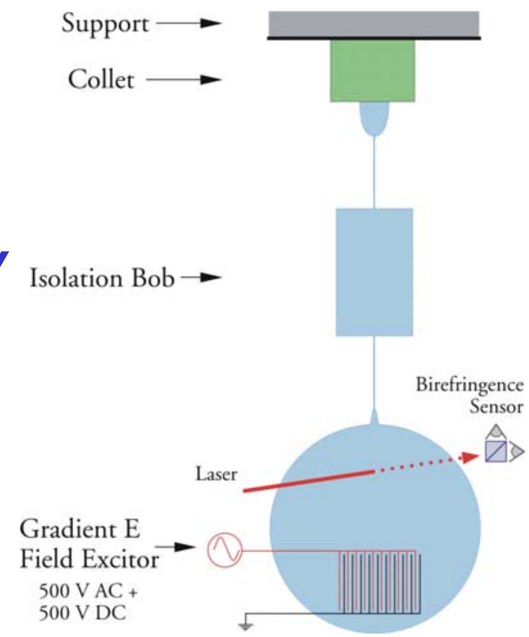
- *Fluctuation-Dissipation Theorem predicts noise from mechanical loss*
- *Proximity of coating to readout laser means thermal noise from coatings is directly measured*
- *Initial LIGO has 40 layer silica/tantala dielectric coatings optimized for low optical absorption*

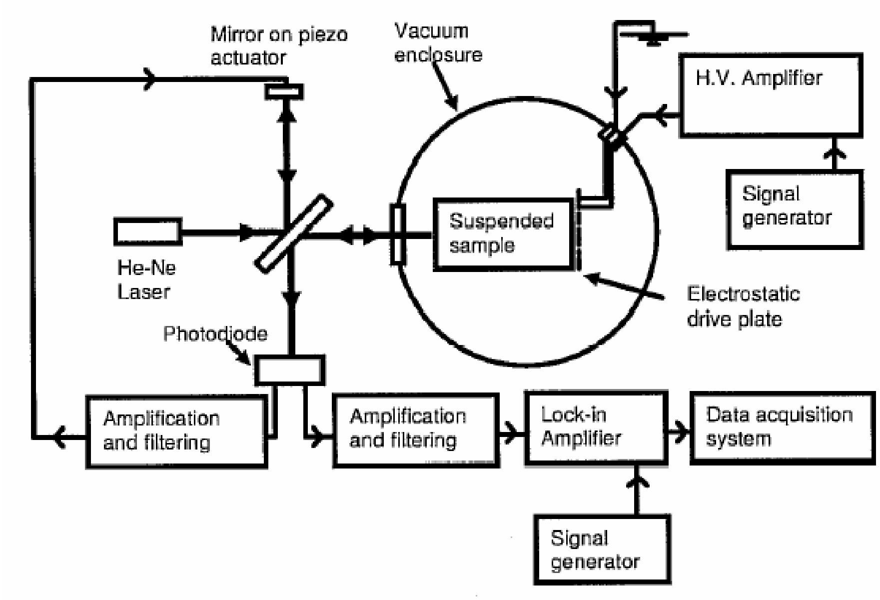
$$S_x(f) = 2\ k_B\ T\ /(\pi^{3/2}\ f\ w\ Y)\ (\ \phi + d/(\pi^{1/2}\ w)\ (Y/Y_{perp}\ \phi_{perp} + Y_{para}/Y\ \phi_{para})$$

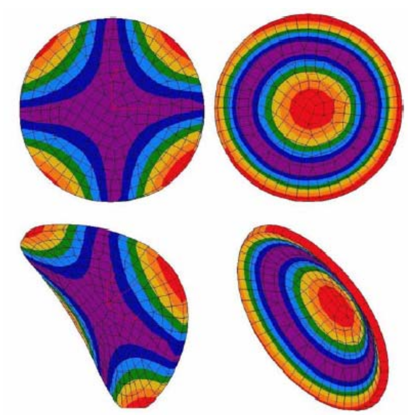
Coating Mechanical Loss Experiments

Modal Q Measurements

- ***Test coatings deposited on silica substrates***
- ***Normal modes (2 kHz to 50 kHz) decay monitored by interferometer/birefringence sensor.***
- ***Coating loss inferred from modal Q and finite element analysis modelling of energy distribution***
- ***Can examine many different coatings fairly quickly***







LIGO

Results of Q Measurements

Coating Mechanical Loss

Layers	Materials	Loss Angle
30	[a] $\lambda/4\ SiO_2 - \lambda/4\ Ta_2O_5$	$2.7\ 10^{-4}$
60	[a] $\lambda/8\ SiO_2 - \lambda/8\ Ta_2O_5$	$2.7\ 10^{-4}$
2	[a] $\lambda/4\ SiO_2 - \lambda/4\ Ta_2O_5$	$2.7\ 10^{-4}$
30	[a] $\lambda/8\ SiO_2 - 3\lambda/8\ Ta_2O_5$	$3.8\ 10^{-4}$
30	[a] $3\lambda/8\ SiO_2 - \lambda/8\ Ta_2O_5$	$1.7\ 10^{-4}$
30	[b] $\lambda/4\ SiO_2 - \lambda/4\ Ta_2O_5$	$3.1\ 10^{-4}$
30	[c] $\lambda/4\ SiO_2 - \lambda/4\ Ta_2O_5$	$4.1\ 10^{-4}$
30	[d] $\lambda/4\ SiO_2 - \lambda/4\ Ta_2O_5$	$5.3\ 10^{-4}$
30	[b] $\lambda/4\ SiO_2 - \lambda/4\ Nb_2O_5$	$2.8\ 10^{-4}$
43	[e] $\lambda/4\ Al_2O_3 - \lambda/4\ Ta_2O_5$	$2.9\ 10^{-4}$

[a] LMA/Virgo, Lyon, France
[b] MLD Technologies, Mountain View, CA
[c] CSIRO Telecommunications and Industrial Physics, Sydney, Australia
[d] Research-Electro Optics, Boulder, CO
[e] General Optics (now WavePrecision, Inc) Moorpark, CA

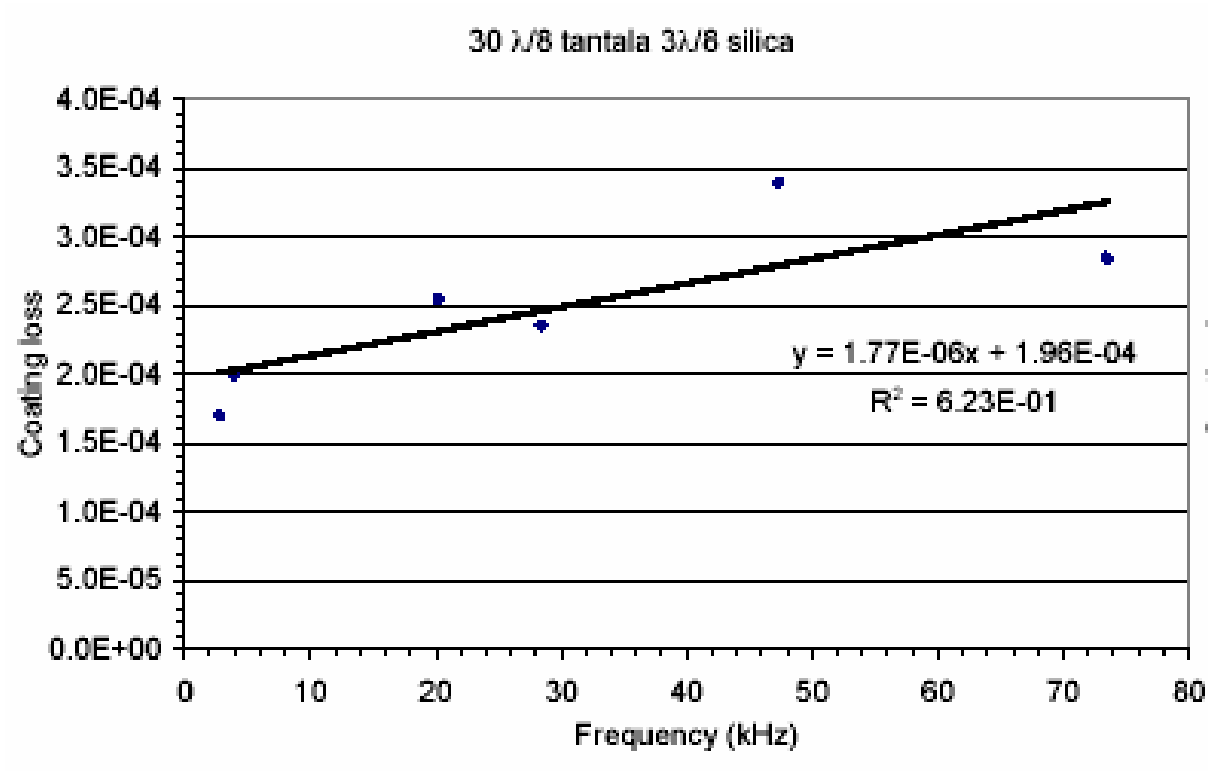
- *Loss is caused by internal friction in materials, not by interface effects*
- *Differing layer thickness allow individual material loss angles to be determined*

$\phi_{Ta2O5} = 4.6\ 10^{-4}$
$\phi_{SiO2} = 0.2\ 10^{-4}$
$\phi_{Al2O3} = 0.1\ 10^{-4}$
$\phi_{Nb2O5} = 6.6\ 10^{-4}$

Goal : $\phi_{coat} = 5\ 10^{-5}$

Frequency Dependence of Coating Loss

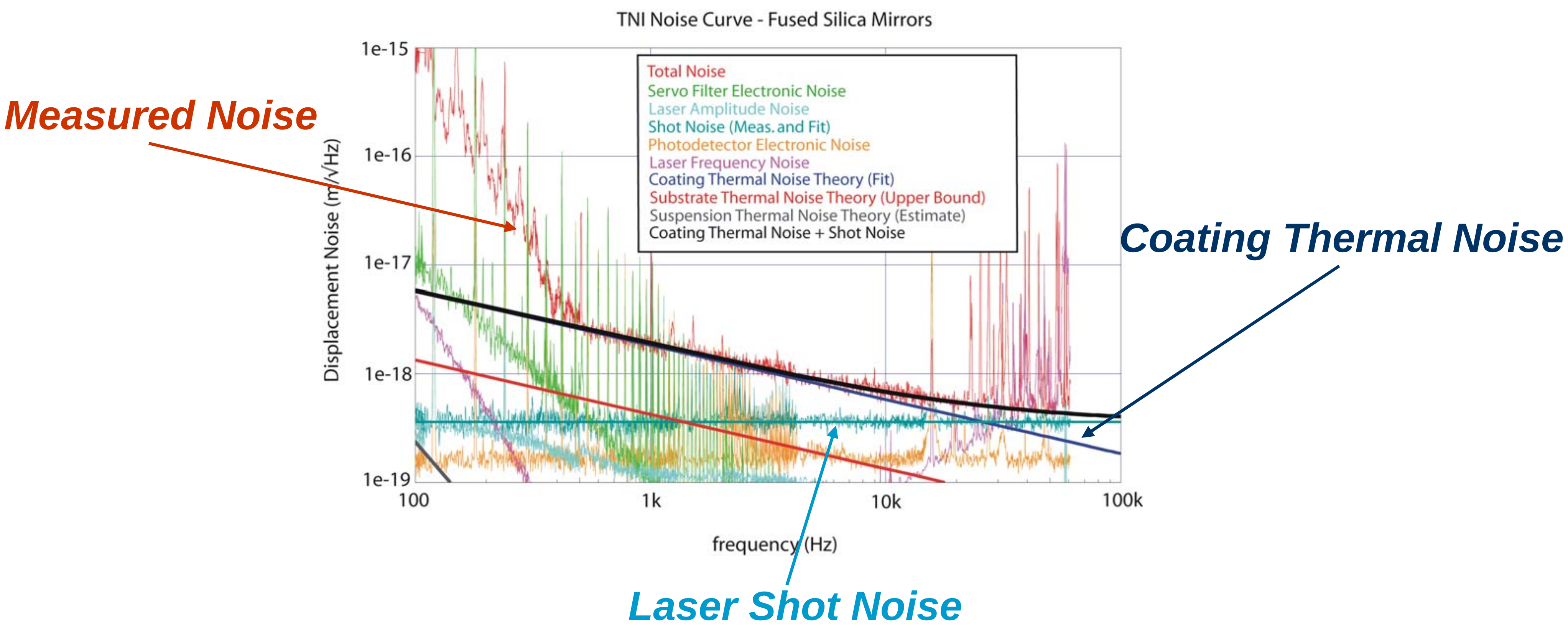
- *Evidence of frequency dependence of coating mechanical loss*
- *Coating loss lower at lower frequencies, so in LIGO's favor*
- *Primarily in SiO_2*
- *Frequency dependence known in bulk silica*
- *Results rely on small number of thin sample modes*



$$\phi_{Ta2O5} = (4.9 \pm 0.4)\, 10^{-5} - (1.8 \pm 2.5)\, 10^{-10}$$
$$\phi_{SiO2} = (2.7 \pm 5.7)\, 10^{-5} + (2.5 \pm 0.3)\, 10^{-9}$$

Direct Measurement of Coating Thermal Noise

- *LIGO/Caltech's Thermal Noise Interferometer*
- *1 cm long arm cavitites, 0.15 mm laser spot size*
- *Consistent with ~ 4 10^{-4} coating loss angle*



Advanced LIGO Coating Requirements

Need to develop low thermal noise coating without sacrificing optical performance.

Parameter	Requirement	Current Value
Loss Angle ϕ	$5\ 10^{-5}$	$1.5\ 10^{-4}$ [a]
Optical Absorption	0.5 ppm	1 ppm [a]
Scatter	2 ppm	20 ppm [b]
Thickness Uniformity	10^{-3}	$8\ 10^{-3}$ [b]
Transmission	5 ppm	5.5 ppm [b]
Transmission Matching	$5\ 10^{-3}$	$5\ 10^{-3}$ [b]

Current values are from

[a] *small laboratory samples*

[b] *installed optics in initial LIGO interferometers*

No single sample has demonstrated all values.

Titania Dopant in Tantala

Work done in collaboration with LMA/Virgo in Lyon, France as part of advanced LIGO coating research

$\lambda/4$ SiO_2 – $\lambda/4$ Ta_2O_5 Coatings with TiO_2 dopant

Dopant Conc.	*Loss Angle*
None	$2.7\ 10^{-4}$
Low	$1.8\ 10^{-4}$
Medium	$1.6\ 10^{-4}$
High	*?*

Increasing dopant concentration reduces mechanical loss

- ***How far can this effect be pushed?***
- ***Is there a better dopant?***
- ***Will this compromise optical performance?***

Secondary Ion-beam Bombardment

Work done in collaboration with CSIRO in Sydney, Australia as part of advanced LIGO coating research

$\lambda/4$ SiO_2 – $\lambda/4$ Ta_2O_5 Coatings

Mode	ϕ_{coat} Grid 1	ϕ_{coat} Grid 2
7	$4.1\ 10^{-4}$	$3.2\ 10^{-4}$
8	$4.2\ 10^{-4}$	$3.1\ 10^{-4}$
9	$5.0\ 10^{-4}$	$4.0\ 10^{-4}$
10	$4.1\ 10^{-4}$	$3.5\ 10^{-4}$
12	$4.4\ 10^{-4}$	$2.3\ 10^{-4}$

Grid was adjusted from 1 to 2 to increase uniformity

- *How far can this effect be pushed?*
- *Will this compromise optical performance?*

Future Plans

- *Continue with TiO_2 doped Ta_2O_5 up to stability limit of TiO_2 films*
- *Examine other dopants in Ta_2O_5*
- *Examine other high index materials*
- *Improve stoichiometry of Ta_2O_5, correlate with optical absorption*
- *Examine relationship between annealing and mechanical loss*
- *Need more input and collaboration with material scientists and optical engineers*