LIGO

Optical Coatings for Gravitational Wave Detection

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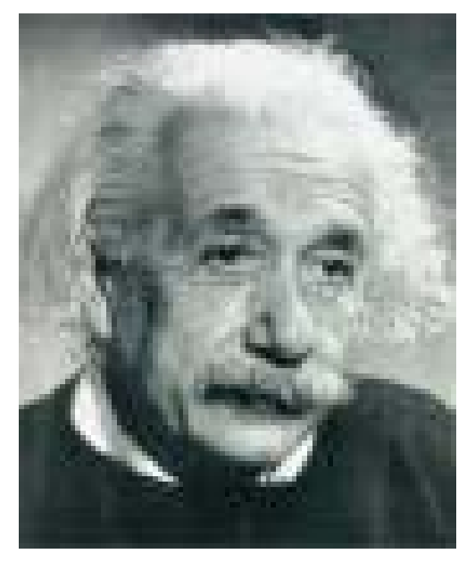
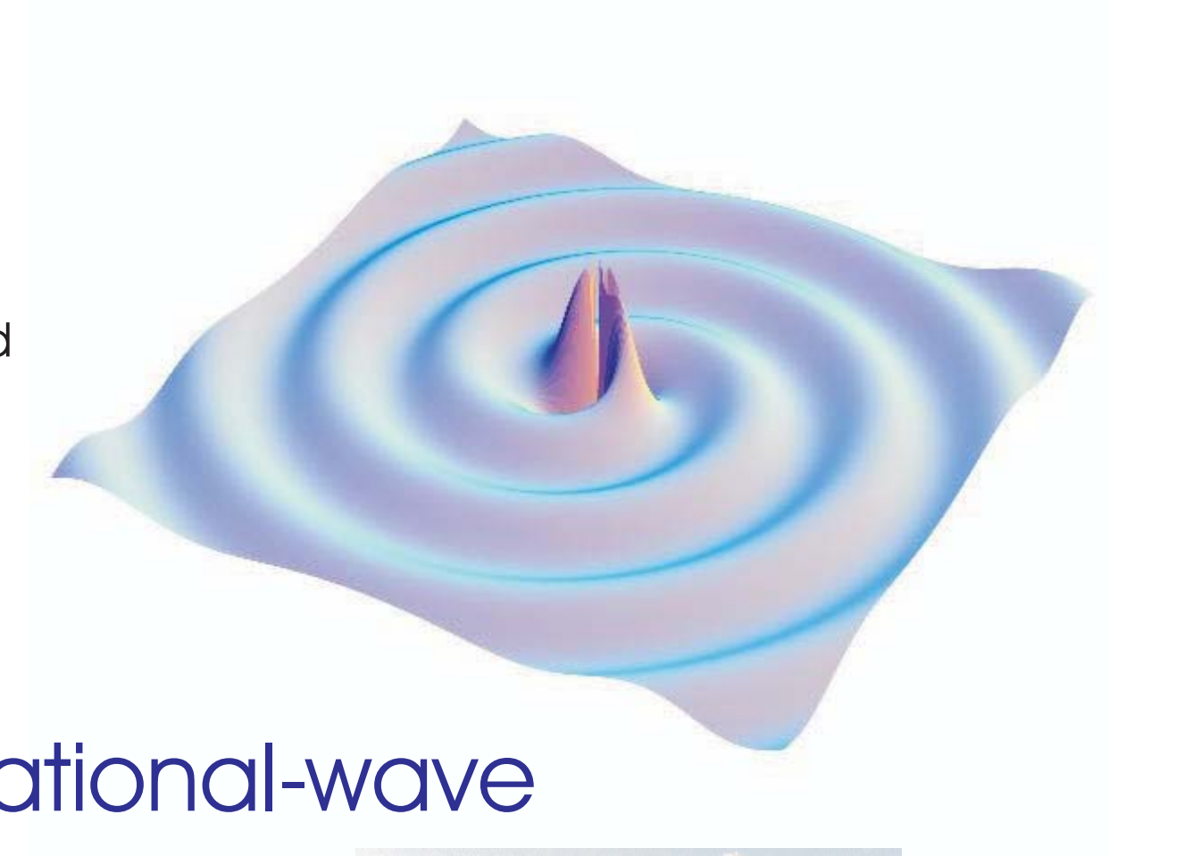
Gravitational Wave Detection



Gravitational waves are a prediction of Einstein's theory of General Relativity. An oscillating mass will cause waves in space-time that propagate out at the speed of light. The amplitude of this wave is a strain, so large spatial separations will be changed more than small ones. This strain will occur in both directions perpendicular to the direction of the wave's travel. The oscillations in these two directions will be 180° out of phase, so as the X direction contracts, the Y direction will expand.



Astronomical sized masses moving near the speed of light are needed to produce detectable gravitational waves. Possible sources include[1]

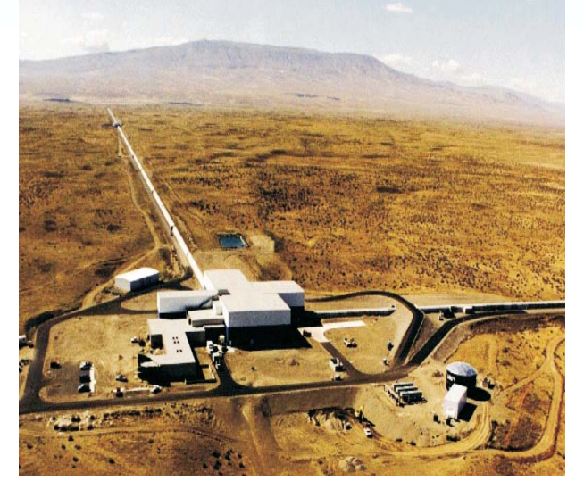
- Inspiralling binary neutron stars or black holes
- Supernova explosions
- A stochastic background from the big bang
- Asymmetric pulsars

A typical strain at the Earth from an astronomical source is 10^{-21}, or 1 millionth the diameter of an atomic nucleus.

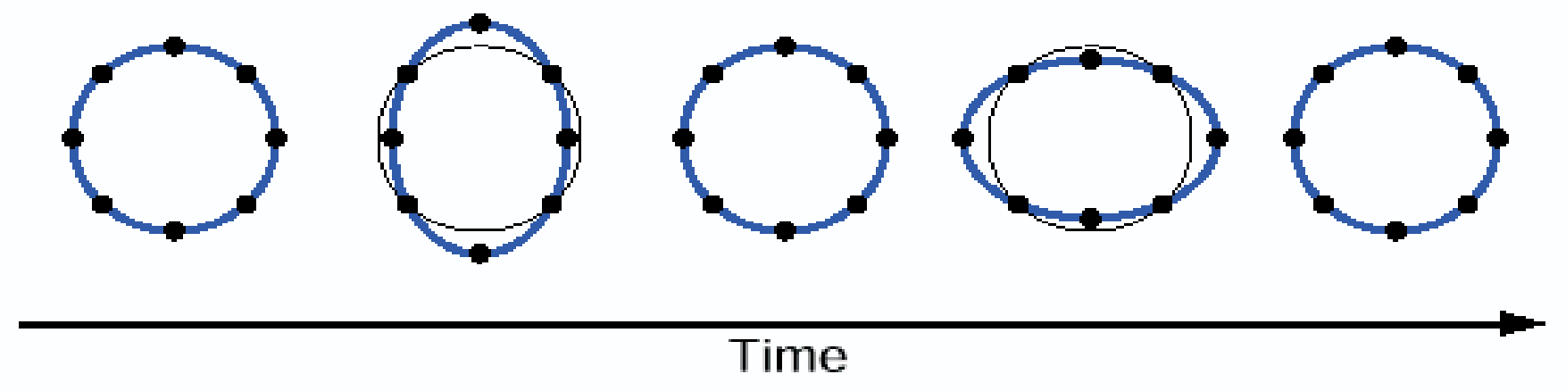
Laser Interferometer Gravitational-wave Observatory (LIGO)

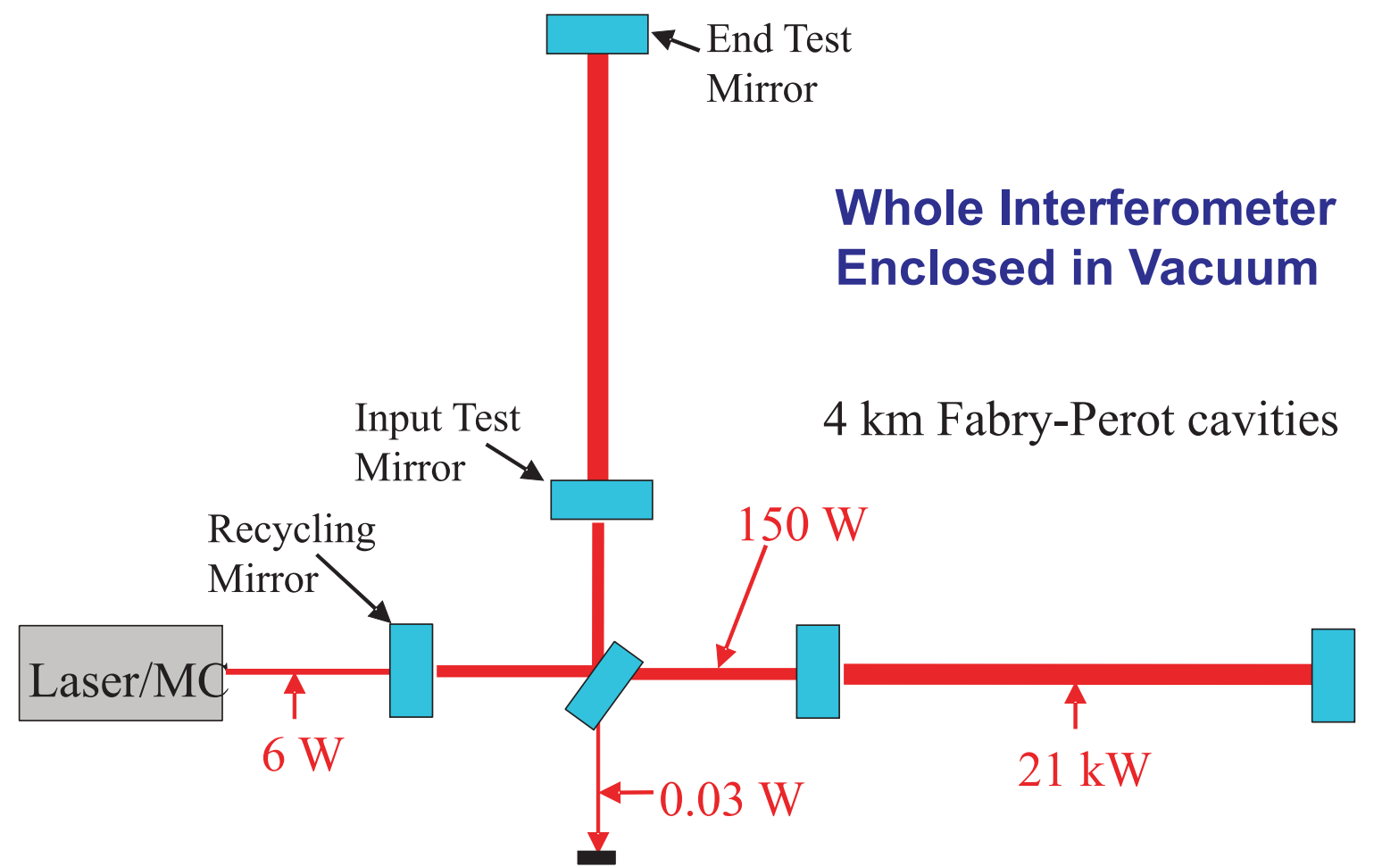
Livingston LA

LIGO (Laser Interferometer Gravitational wave Observatory) has built three Michelson interferometers at two sites in the US to detect gravitational waves. Each arm is a 4 kilometer long Fabry-Perot cavity enclosed in vacuum. The mirrors are 10 kg silica cylinders, coated with silica/tantala dielectric coatings. A MOPA Nd:YAG laser is used to illuminate the interferometer.[2,3]



Hanford WA



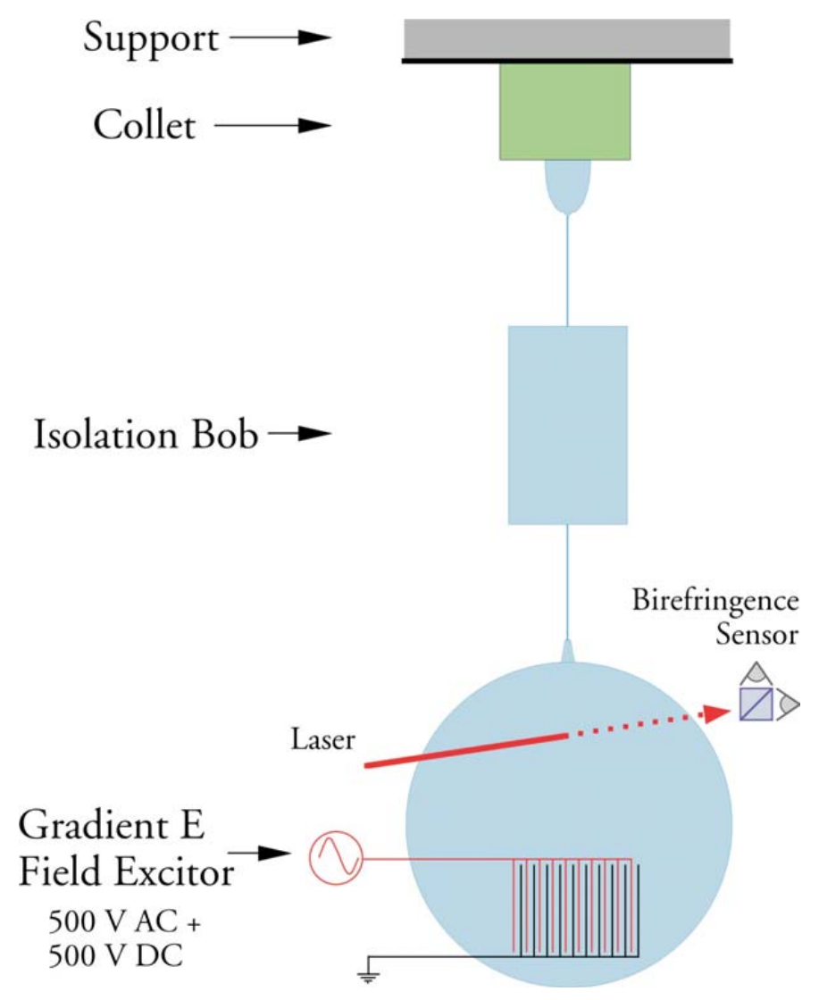


Gravitational waves create a characteristic tensor strain field, so distances along the X axis are stretched while along the Y axis are compressed. An interferometer with perpendicular arms can detect this effect.

The extremely small displacement caused by a gravitational wave (1 part in 10^{18} m for 4 kilometer long interferometer arms) makes reducing noise the critical design criterion. Noise from seismic motion, thermal vibrations of the mirrors and suspensions, and optical shot noise are the limiting sources.

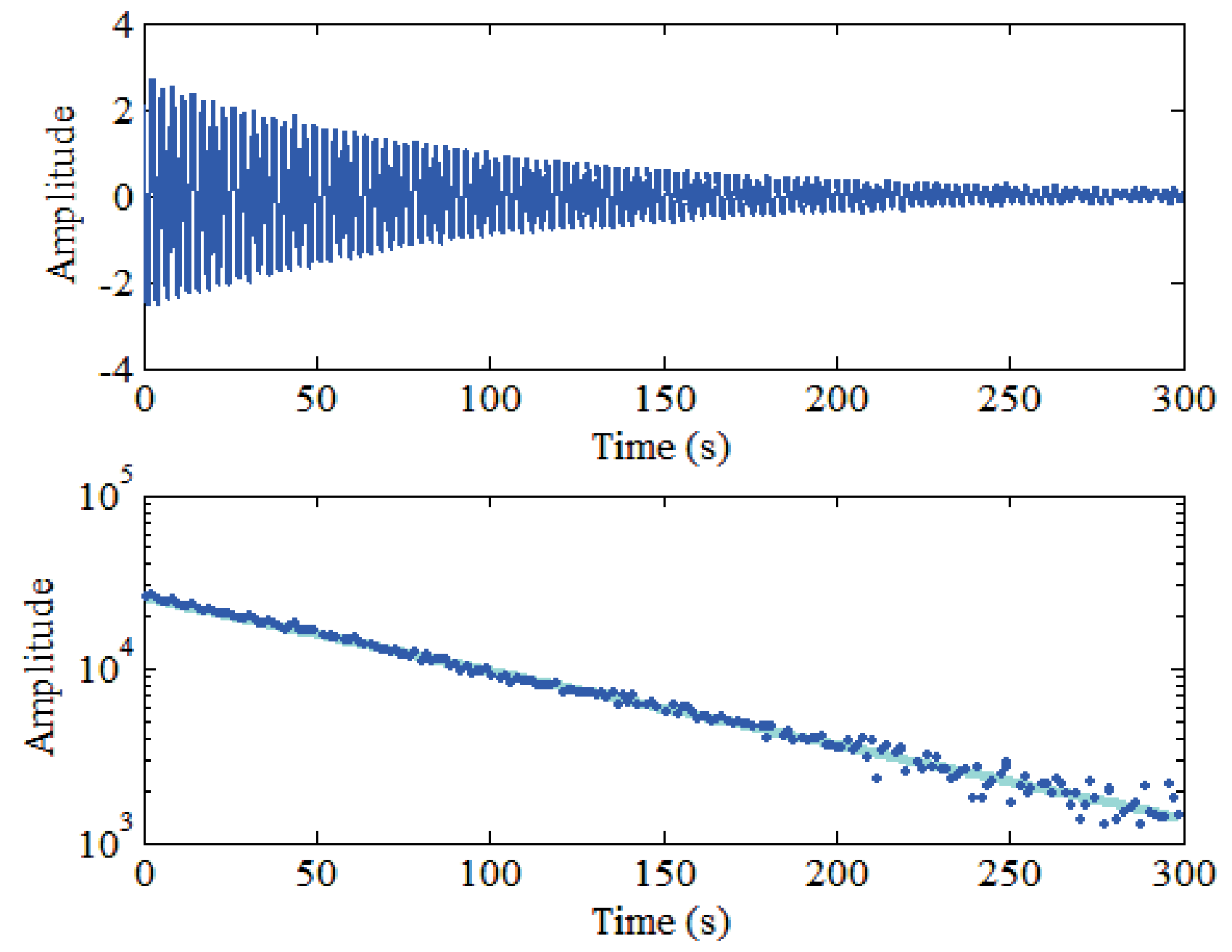
$$\frac{\Delta L}{L} \sim 10^{-21}$$

Mechanical Loss Measurements

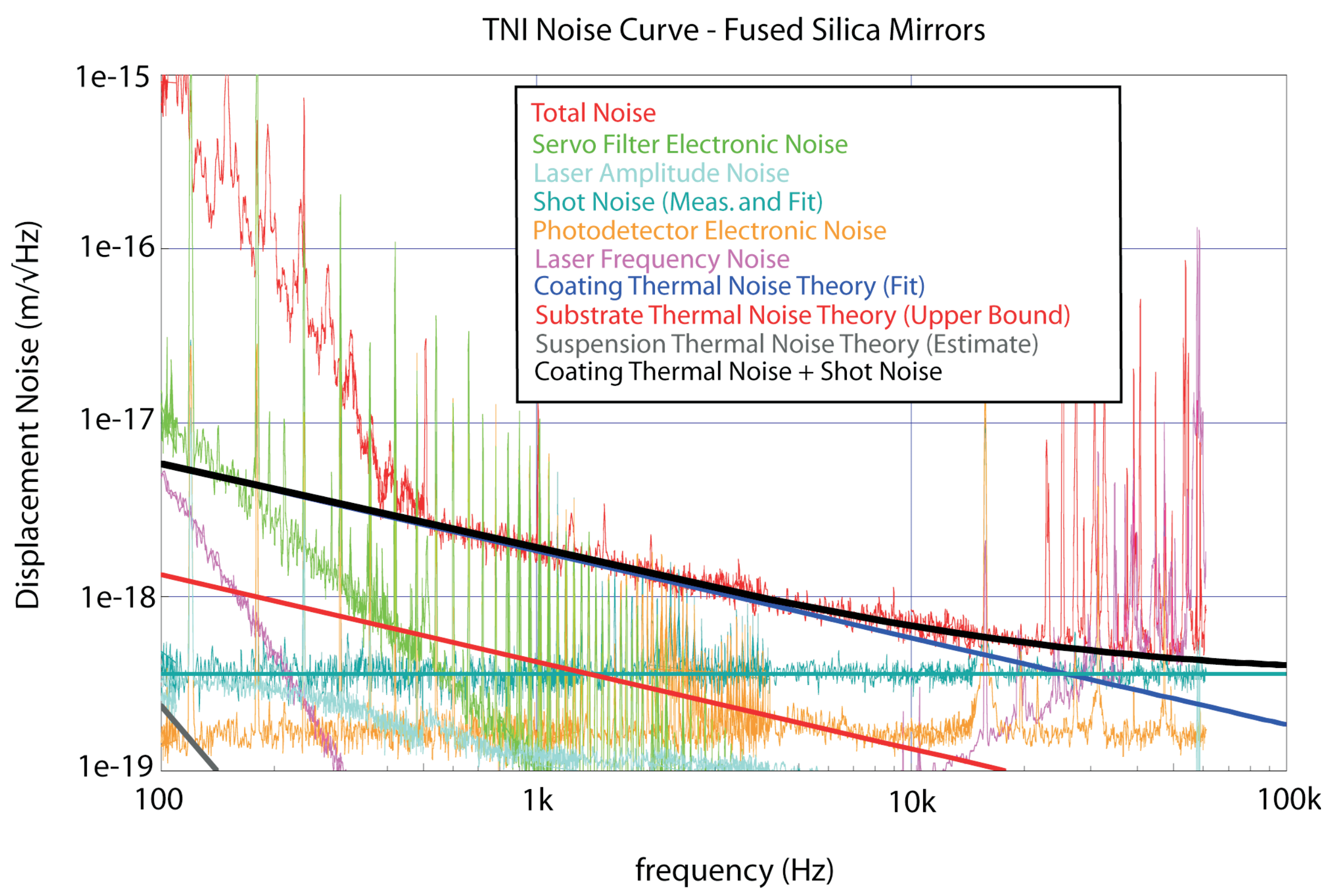


Internal friction in the coating is determined by measuring modal quality factors, Q, of silica samples, both coated and uncoated. The modal frequencies are between 2 kHz and 50 kHz, above the frequency range where thermal noise will be important for LIGO. The samples are suspended to reduce friction, either in a wire sling or from a welded silica fiber. The sample's normal modes are rung up by a comb capacitor, and the ringdown is monitored by either a birefringence readout or a simple interferometer. The Q of the mode is found from the ringdown time, τ. The loss angle of the coating material is found from the change in Q between coated and uncoated, taking into account the amount of energy stored in the coating for the particular mode. This energy is found from a finite element model of the sample[5,6].

$$Q = \pi f \tau$$



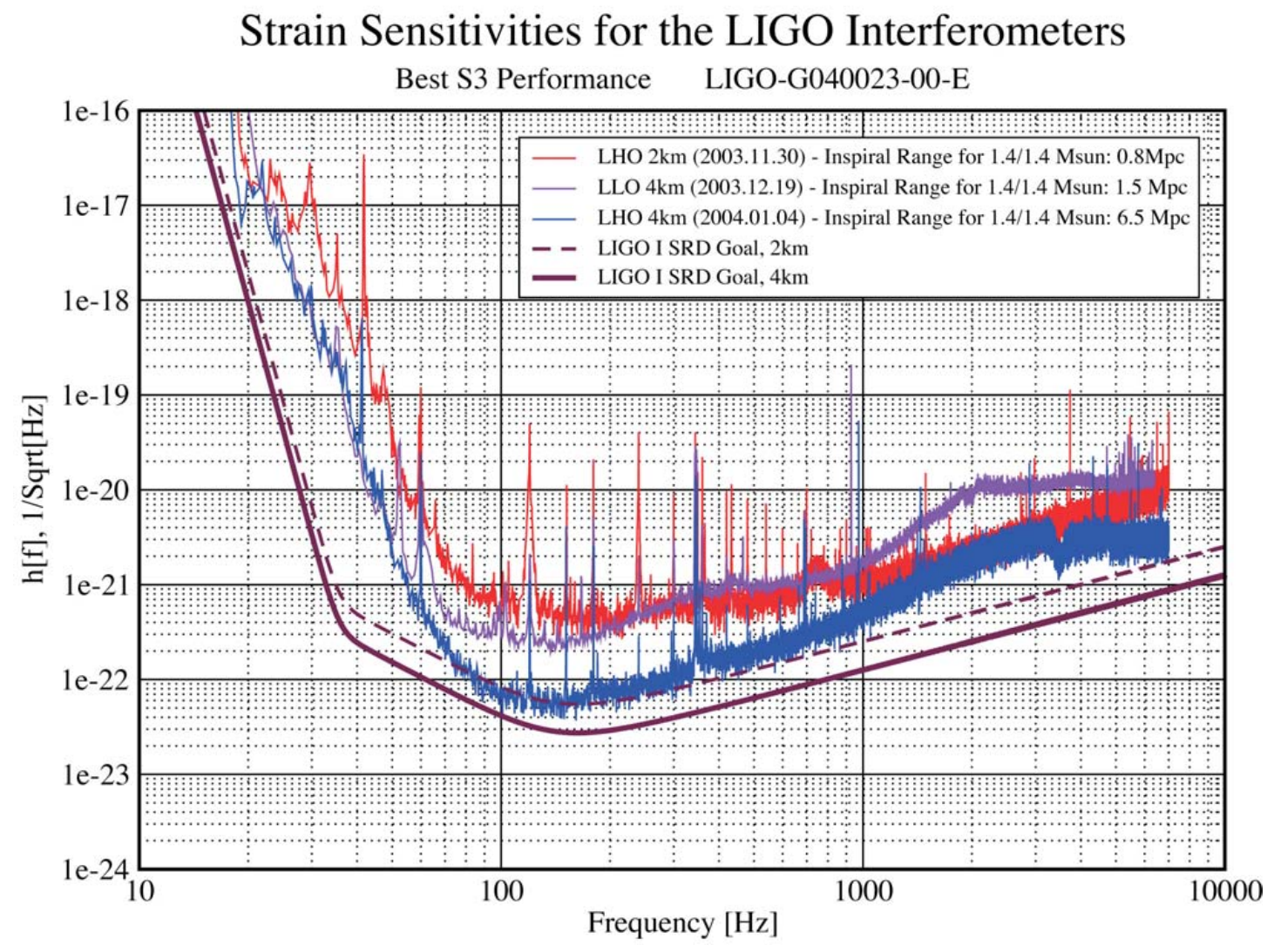
Typical modal ringdown



Direct measurement of coating thermal noise made by LIGO's Thermal Noise Interferometer. A silica/tantala coating is deposited on four mirrors, arranged similarly to LIGO as two Fabry-Perot cavities in a Michelson interferometer, although with 1 cm long arms rather than 4 km. With a much smaller laser spot size, which minimizes the area averaged over and enhances the noise, coating thermal noise can be seen in this prototype interferometer. The Thermal Noise Interferometer has a spot size of 0.15 mm, compared to 40 mm in initial LIGO, and a planned 60 mm in advanced LIGO. The observed thermal noise has the correct frequency dependence of $1/\sqrt{f}$ and is consistent with $4.2\ 10^{-4}$ for the coating loss angle.[7]

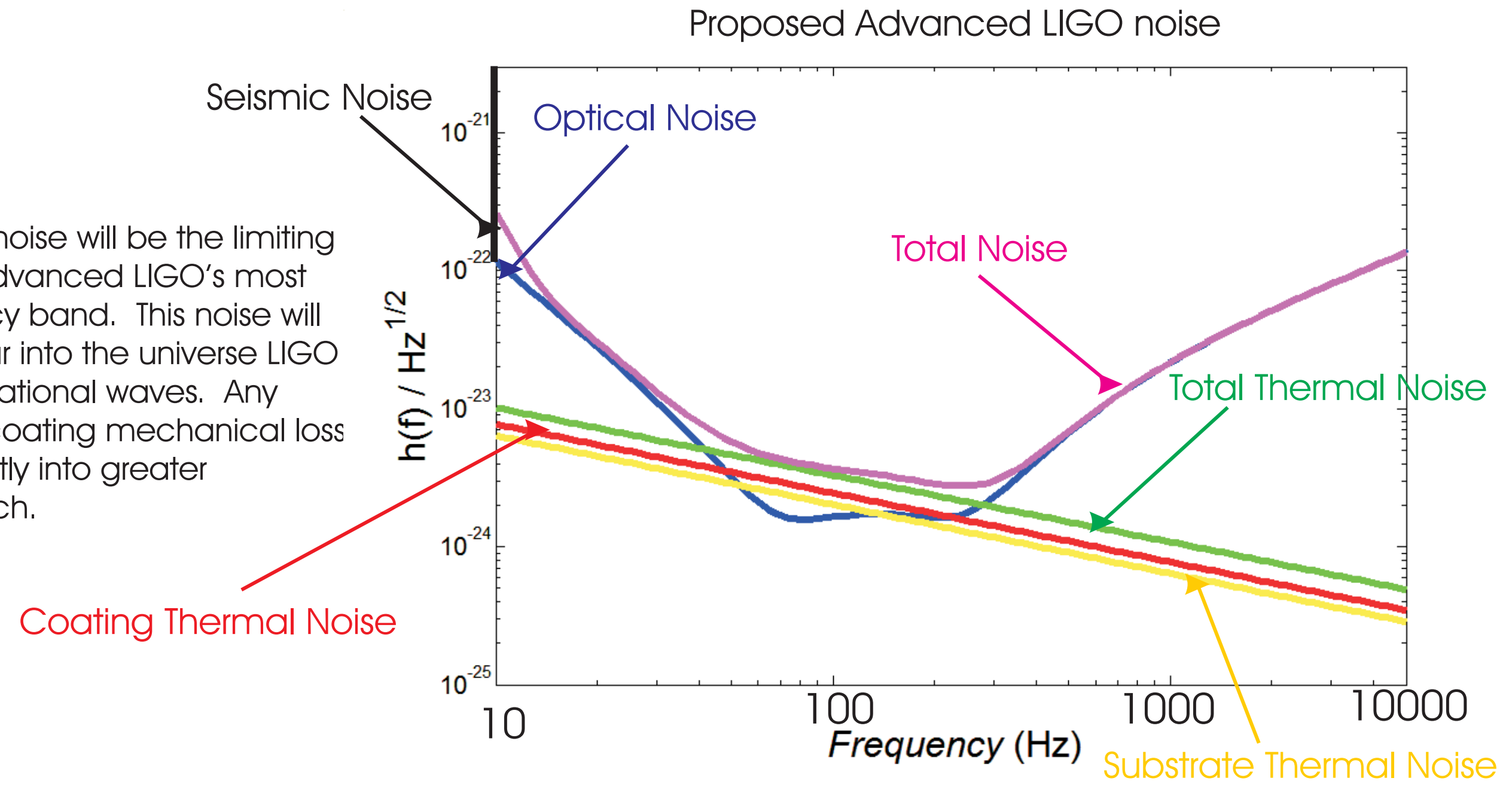
$$S_x(f) = 4\, k_B\, T\, d\, \phi / (\pi^2 f\, w^2\, Y)$$

Interferometer Noise



Initial LIGO interferometers noise and sensitivity January 2004. The solid line shows the design sensitivity of the 4 km interferometers, the dashed for the 2 km.

Coating thermal noise will be the limiting noise source in Advanced LIGO's most sensitive frequency band. This noise will determine how far into the universe LIGO can detect gravitational waves. Any improvement in coating mechanical loss will translate directly into greater astronomical reach.



Coating Requirements

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

Thermal Noise

Thermal noise comes from dissipation in the system, according to the Fluctuation-Dissipation Theorem of Callen and Green[4]. This noise can take many forms; electrical resistance gives rise to Johnson noise, viscosity causes Brownian motion in a fluid, and internal friction in materials gives rise to a stochastic thermal force, which causes position noise. Internal friction is indicated by an imaginary component of an elastic constant, $Y\,(1+i\,\phi)$, where ϕ is called the material loss angle. Many material values contribute to coating thermal noise (Young's modulus, index of refraction, thermal conductivity, etc.) but the material loss angle is the least measured and understood.

$$S_F(f) = 4\, k_B\, T\, \mathrm{Re}[Z]$$

Results

Coating	Loss Angle (ϕ_{coat})	Optical Absorption
[a]30 layer $\lambda/4$ SiO_2- $\lambda/4$ Ta_2O_5	$2.7\ 10^{-4}$	
[a]60 layer $\lambda/8$ SiO_2- $\lambda/8$ Ta_2O_5	$2.7\ 10^{-4}$	
[a]2 layer $\lambda/4$ SiO_2- $\lambda/4$ Ta_2O_5	$2.7\ 10^{-4}$	
[a]30 layer $\lambda/8$ SiO_2- $3\lambda/8$ Ta_2O_5	$3.8\ 10^{-4}$	
[a]30 layer $3\lambda/8$ SiO_2- $\lambda/8$ Ta_2O_5	$1.7\ 10^{-4}$	
[b]30 layer $\lambda/4$ SiO_2- $\lambda/4$ Ta_2O_5	$3.1\ 10^{-4}$	0.7 ppm
[c]30 layer $\lambda/4$ SiO_2- $\lambda/4$ Ta_2O_5	$4.1\ 10^{-4}$	
[d]30 layer $\lambda/4$ SiO_2- $\lambda/4$ Ta_2O_5	$5.3\ 10^{-4}$	
[b]30 layer $\lambda/4$ SiO_2- $\lambda/4$ Nb_2O_5	$2.8\ 10^{-4}$	0.3 ppm
[e]43 layer $\lambda/4$ Al_2O_3- $\lambda/4$ Ta_2O_5	$6.4\ 10^{-5}$	1.5 ppm
[a]30 layer $\lambda/4$ SiO_2- $\lambda/4$ Ta_2O_5 w/ low [TiO_2] dopant	$1.8\ 10^{-4}$	1 ppm
[a]30 layer $\lambda/4$ SiO_2- $\lambda/4$ Ta_2O_5 w/ high [TiO_2] dopant	$1.6\ 10^{-4}$	1 ppm

[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

These results indicate that the mechanical loss in the coating is coming from the internal friction in the coating materials, not from any interface effects between coating layers or between the coating and the substrate.

The results from the silica/tantala coatings with different ratios of silica to tantala allow the individual material ϕ's to be determined. From these loss angles for tantala and silica, ϕ values can be found for alumina, niobia, and the 2 different titania-doped tantala formulas.[8]

Material	Loss Angle ϕ
Ta_2O_5	$4.6\ 10^{-4}$
SiO_2	$0.2\ 10^{-4}$
Al_2O_3	$0.1\ 10^{-4}$
Nb_2O_5	$6.6\ 10^{-4}$
Ta_2O_5 - low TiO_2	$2.8\ 10^{-4}$
Ta_2O_5 - high TiO_2	$2.4\ 10^{-4}$

Future Plans

Work with LMA/Virgo on further titania doped tantala. Explore other dopants for tantala, and other high index materials.

Work with CSIRO on improving the stoichiometry of tantala. Examine the effects of different annealing temperatures and cycles on mechanical loss.

Verify low thermal noise in candidate coatings using the Thermal Noise Interferometer at Caltech.

Need more input from and collaboration with material scientists on reducing mechanical loss in coatings while preserving low optical loss.

Bibliography

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