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Thermal noise in grating reflectors

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Outline

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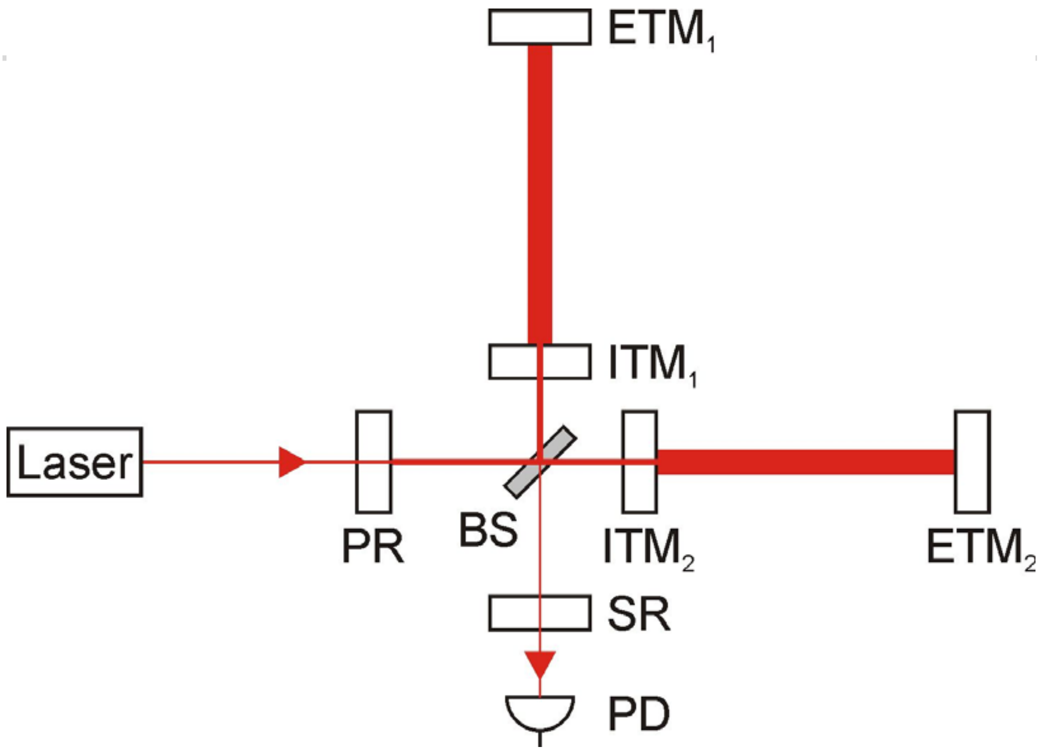
introduction

grating reflectors

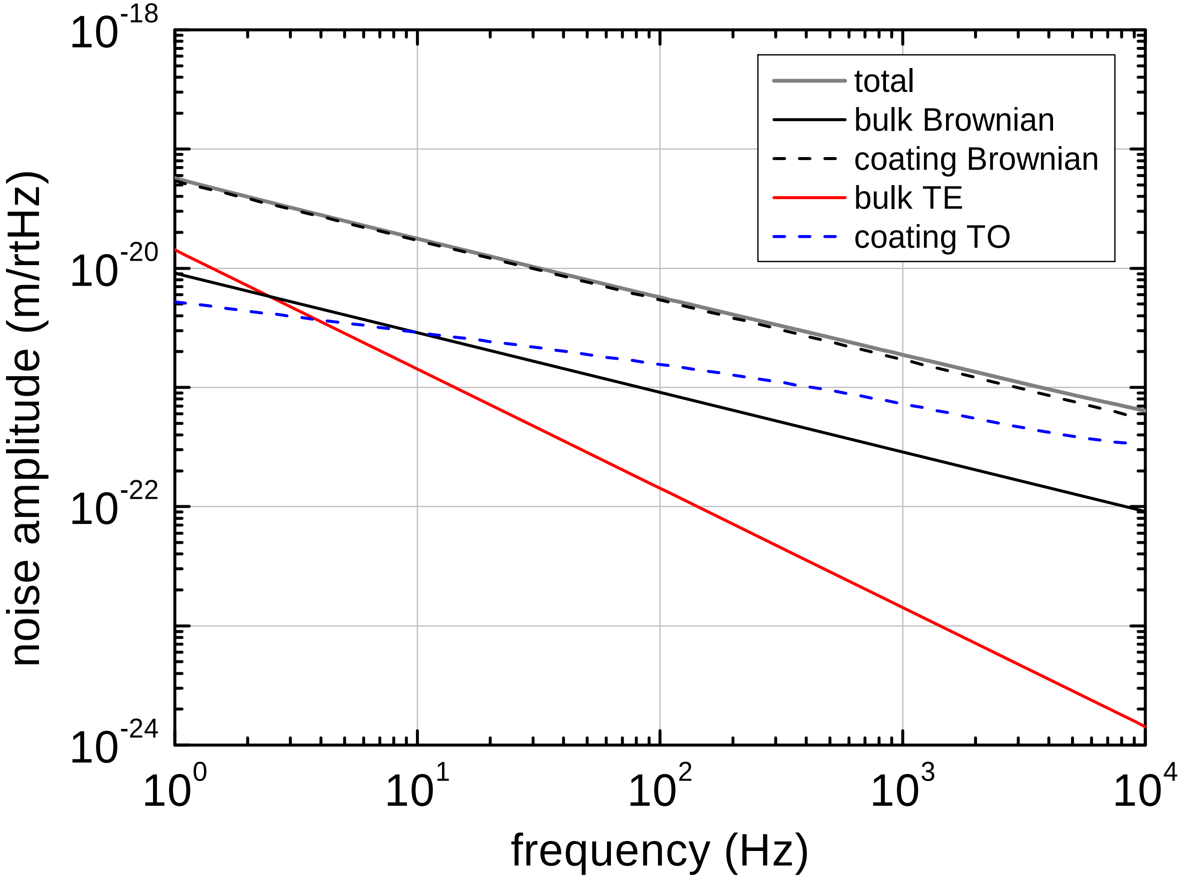
- functionality
- thermal noise calculation
- application to a GWD of the 3rd generation

conclusion

Detector scheme for 2nd generation detectors



Noise budget of ALIGO



Brownian coating noise represents the most critical contribution

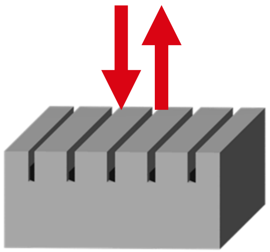
Brownian coating thermal noise of optical coating

$$S_z(f) \propto \frac{k_B T}{f} \frac{d}{r_0^2} \phi$$

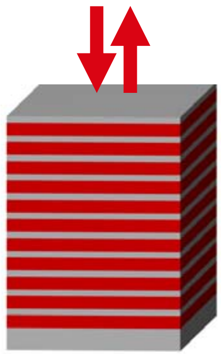
- T… temperature
- d…. coating thickness
- f… frequency
- r_0… beam radius
- ϕ… mechanical loss

Grating Concepts

IAP Jena



Crystalline Coatings

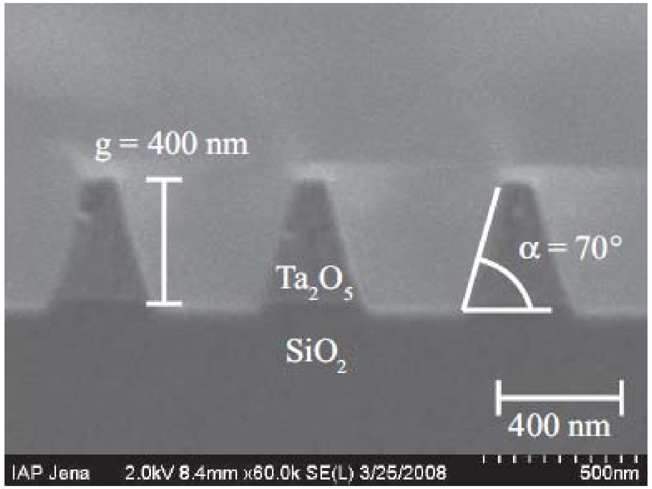


See talks by
G. Cole and A. Lin!

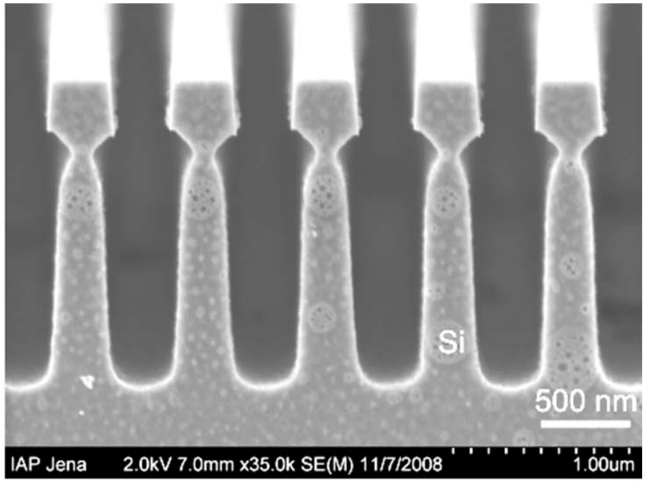
Levin, Phys. Rev. D (1998)
Harry et al. , CQG (2002)

Grating reflector topologies

non-monolithic 1D λ=1064 nm

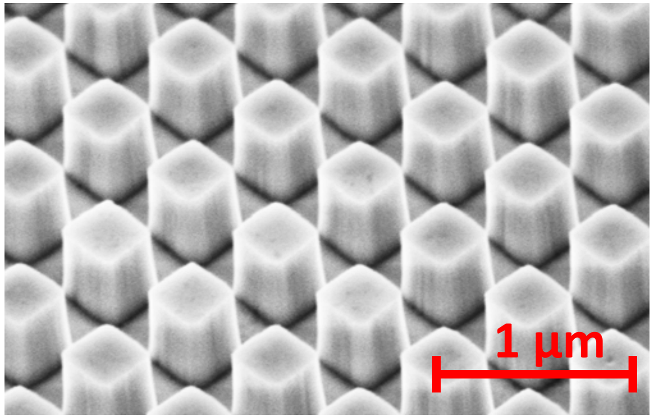


monolithic 1D λ=1550 nm

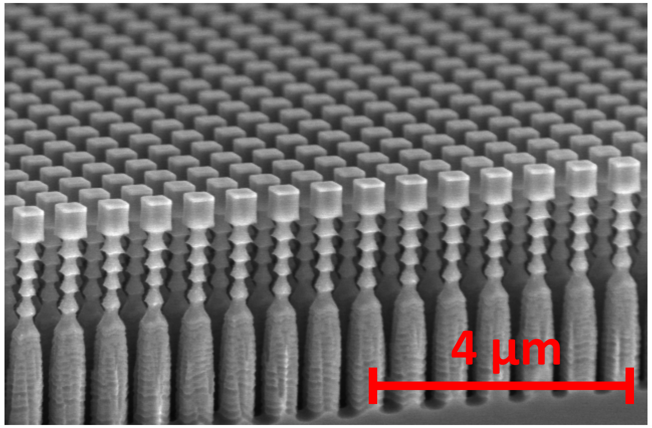


Brückner et al., Opt. Express (2008).
Brückner et al., Phys. Rev. Lett. (2010).

non-monolithic 2D λ=1550 nm

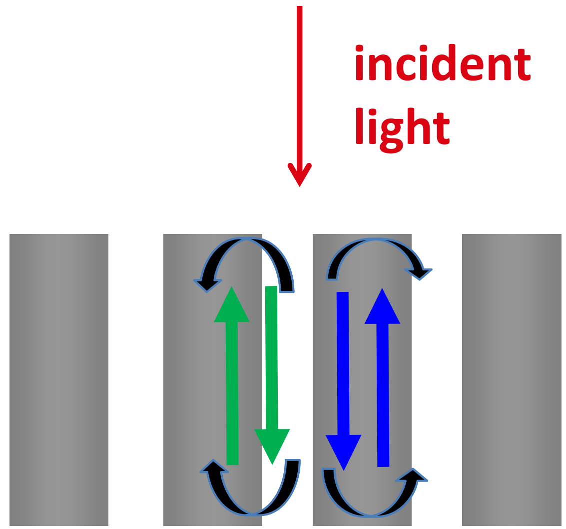


monolithic 2D λ=1550 nm

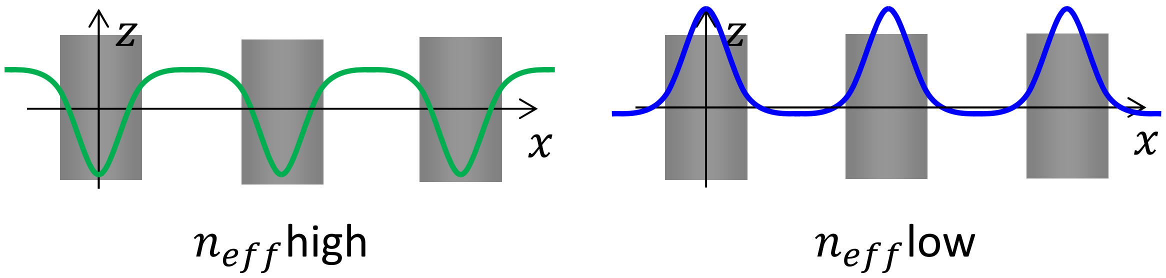


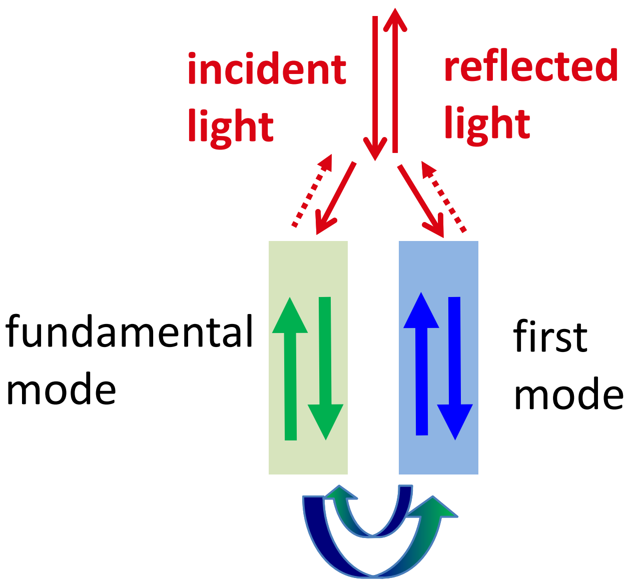
Kroker et al., Appl. Phys. Lett. (2013)

Two mode Fabry-Perot resonator



Grating = periodic array of slab waveguides





One mechanism for R=100%:

- cavities in antiresonance
- destructive interference at bottom
- intercoupling of modes

Lalanne , J. Lightwave Technol. (2007)
Karagodsky et al., Opt. Express (2010)

Optical properties of grating reflectors

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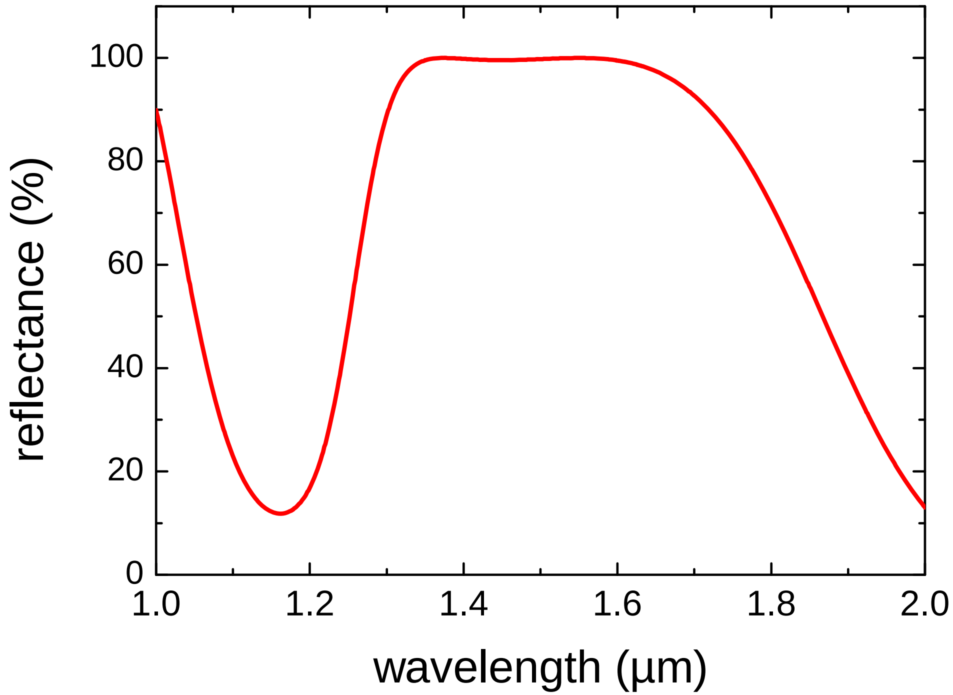
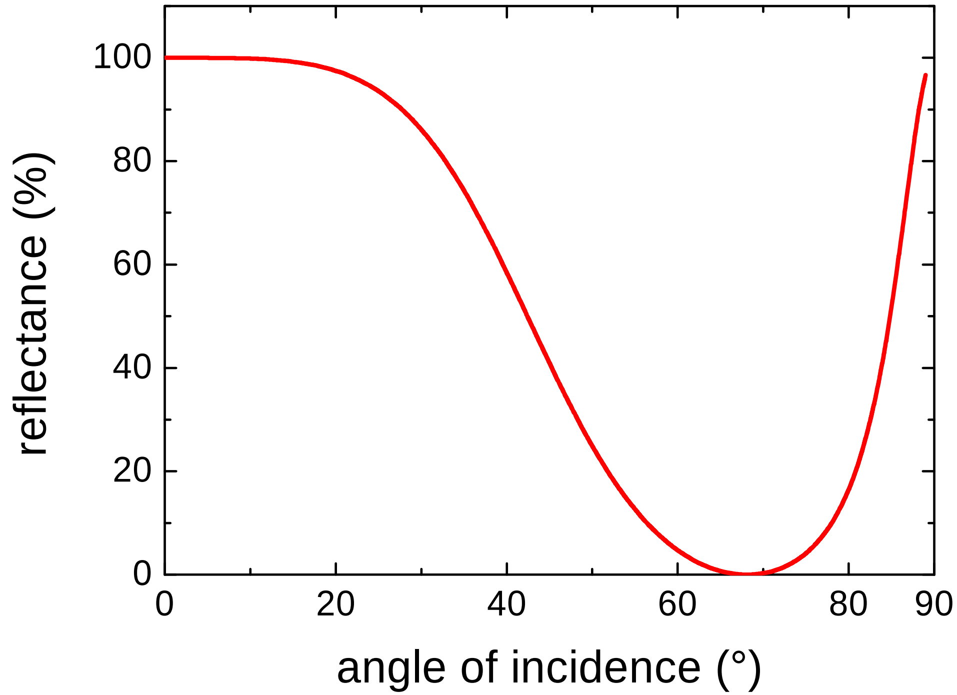
Free standing silicon reflector - broadband behavior due to high index contrast

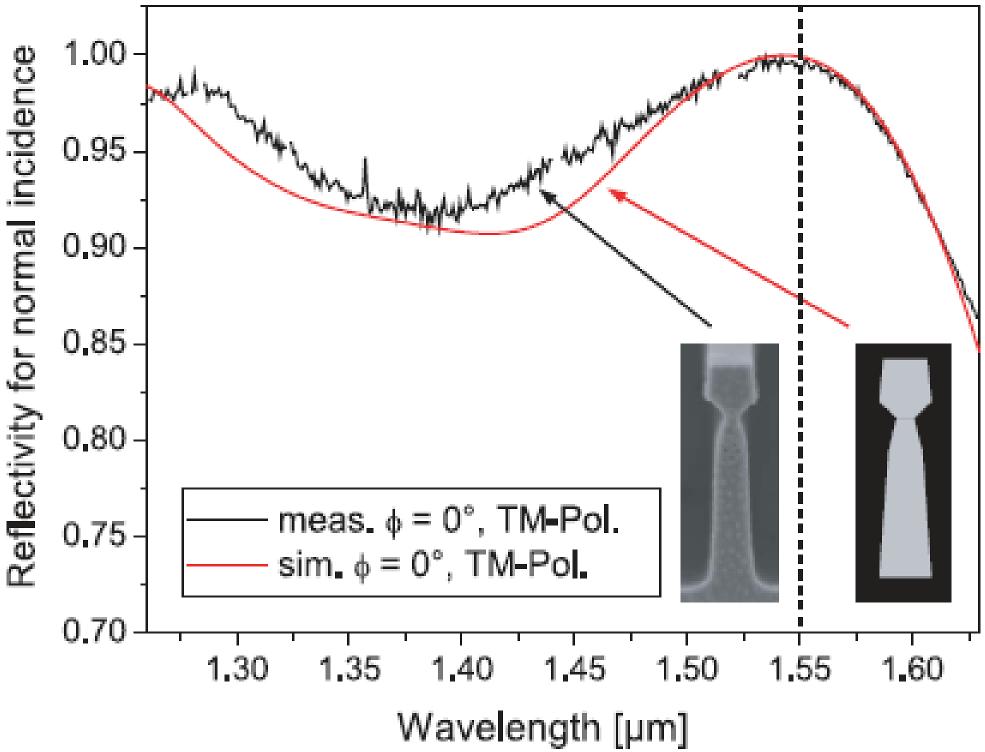
TM-polarization





Monolitihic silicon reflectors

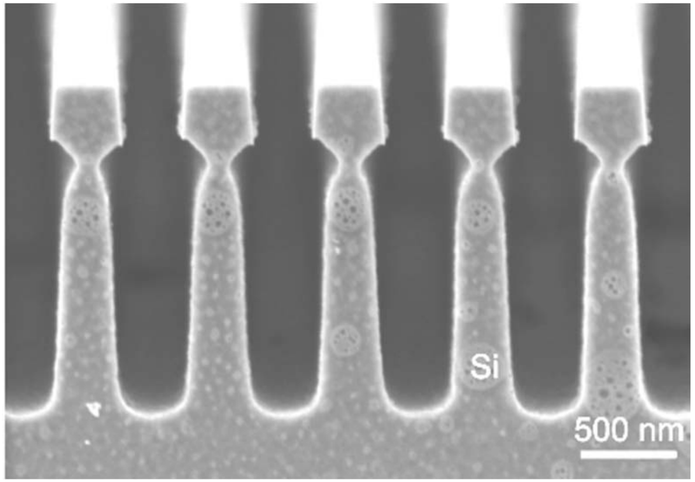
For scalability



same optical function as free ridges:

only one mode in lower grating

(~ effective medium)



$$R(1550\ nm) = (99.80 \pm 0.01)\%$$

Brückner et al., Phys. Rev. Lett. (2010)

Monolithic Silicon Reflectors with 2D periodicity

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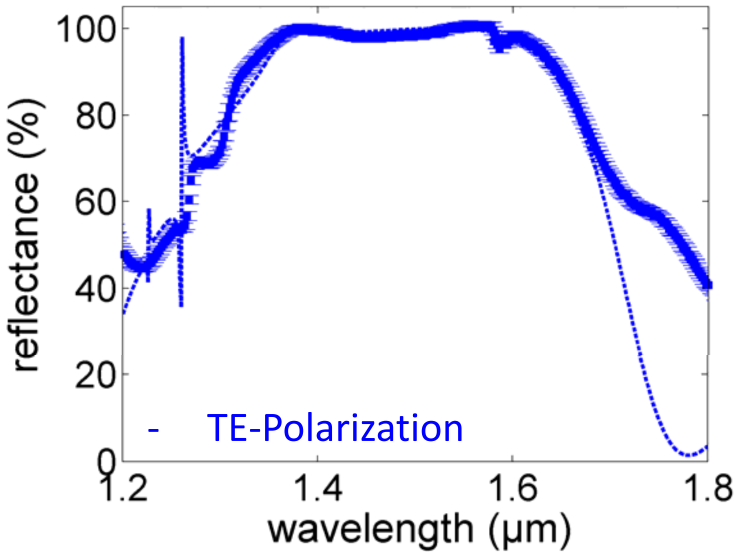
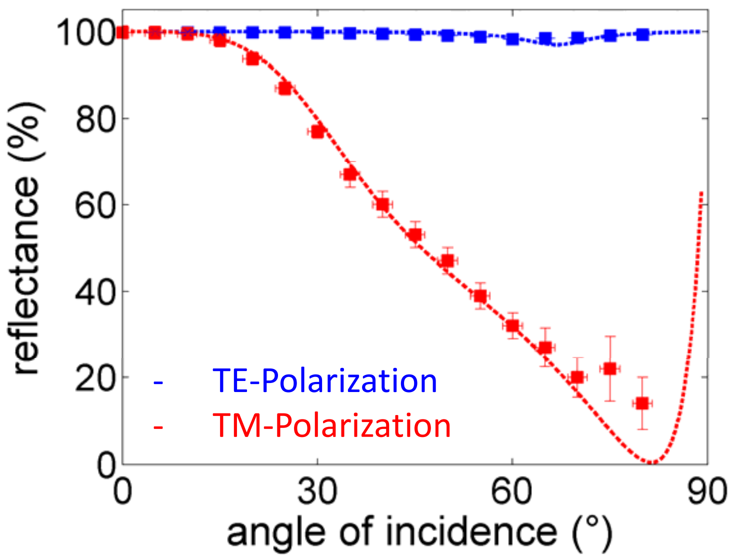
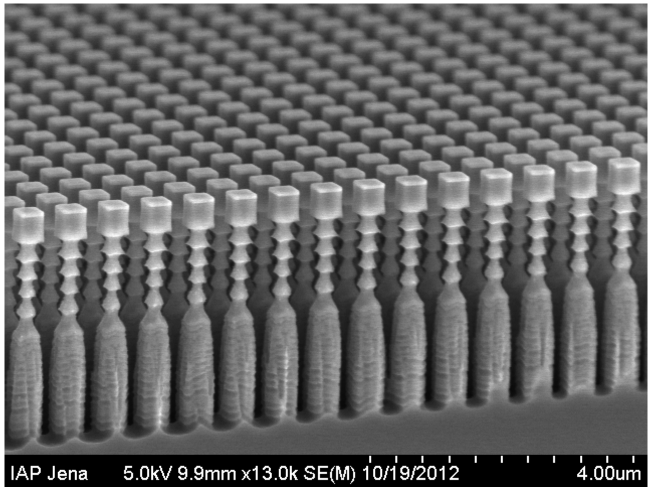
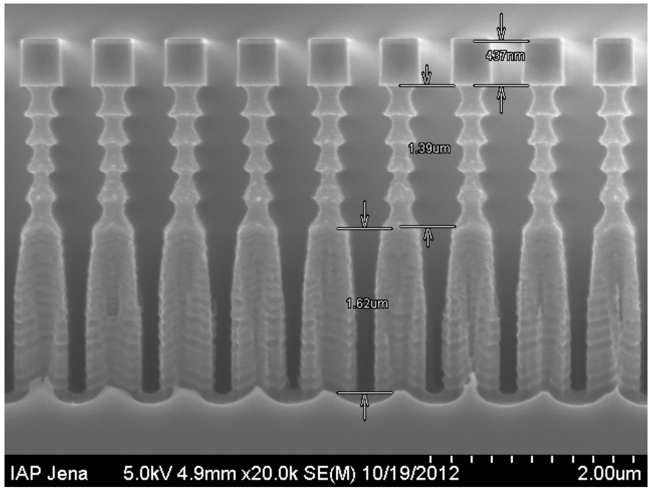








Kroker et al., Appl. Phys. Lett. (2013)

Thermal noise of grating reflectors

Brownian coating thermal noise of coated test mass:

$$S_z(f) \propto \frac{k_B T}{f} \frac{d}{r_0^2} \phi$$

→ lossy amorphous materials critical

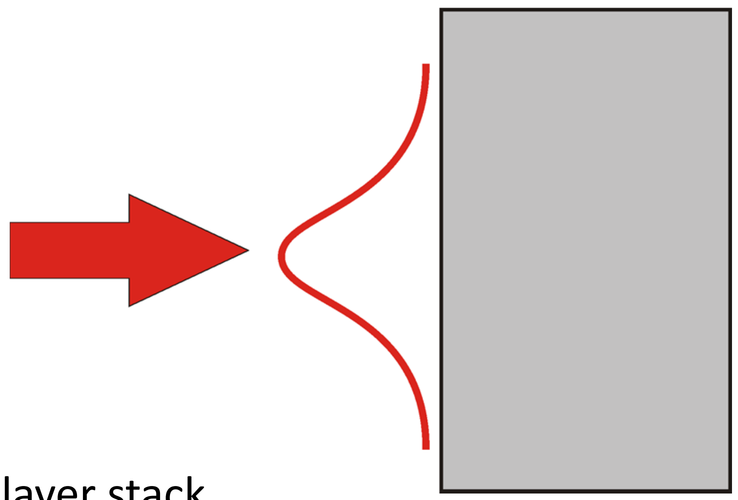
non-monolithic grating reflector:

$$d_{grating} \sim 0.1 \times d_{coatingstack} \qquad S_{grating} \sim 0.1 \times S_{coatingstack}$$

monolithic grating reflector:

$$d \rightarrow 0: \qquad S_{grating} \rightarrow 0$$

Fluctuation-Dissipation theorem



1. $p(r) = \frac{F_0}{\pi r_0^2} \exp\left(-\frac{r^2}{r_0^2}\right)$

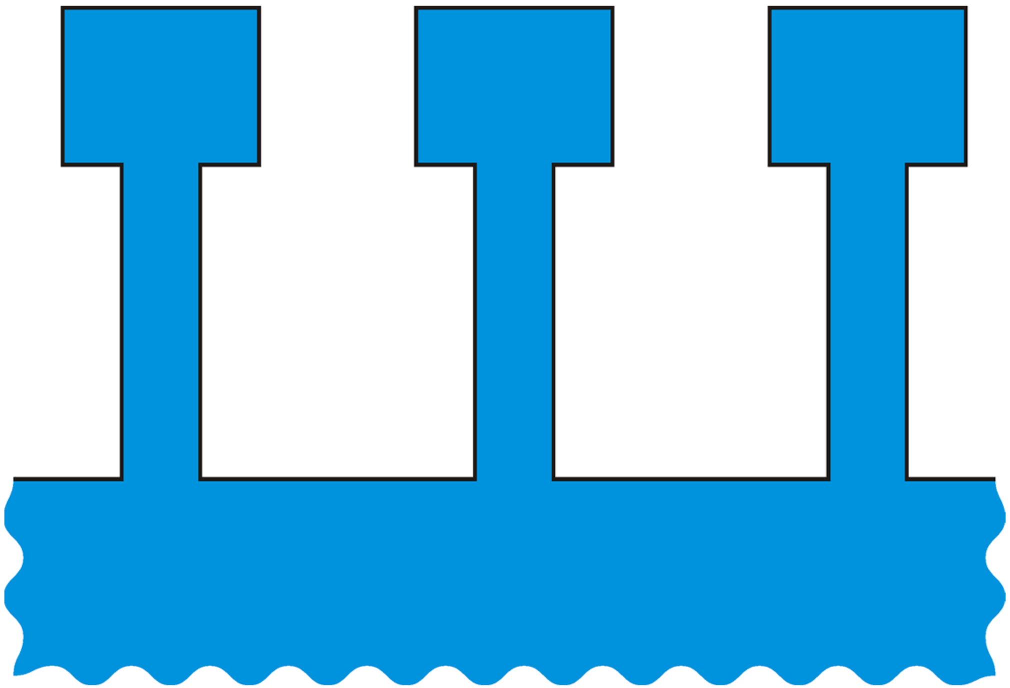
2. $\langle P_{diss} \rangle$

3. $S_z(\omega) = \frac{8 k_B T}{\omega^2} \frac{\langle P_{diss} \rangle}{F_0^2}$

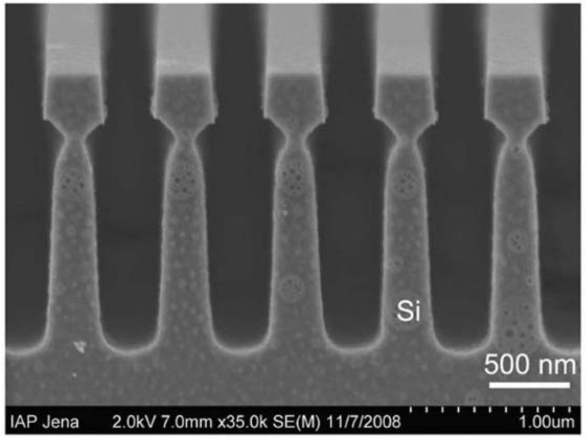
- Brownian coating noise: $S_z(\omega) \propto \frac{4 k_B T}{\pi \omega} \frac{d}{r_0^2} \frac{(1+\sigma)(1-2\sigma)}{E} \phi$

Levin, Phys. Rev. D (1998).

Chosen reflector geometry



design wavelength	1550 nm
period	688 nm
ridge height	350 nm
ridge width	388 nm
support height	800 nm
support width	200 nm

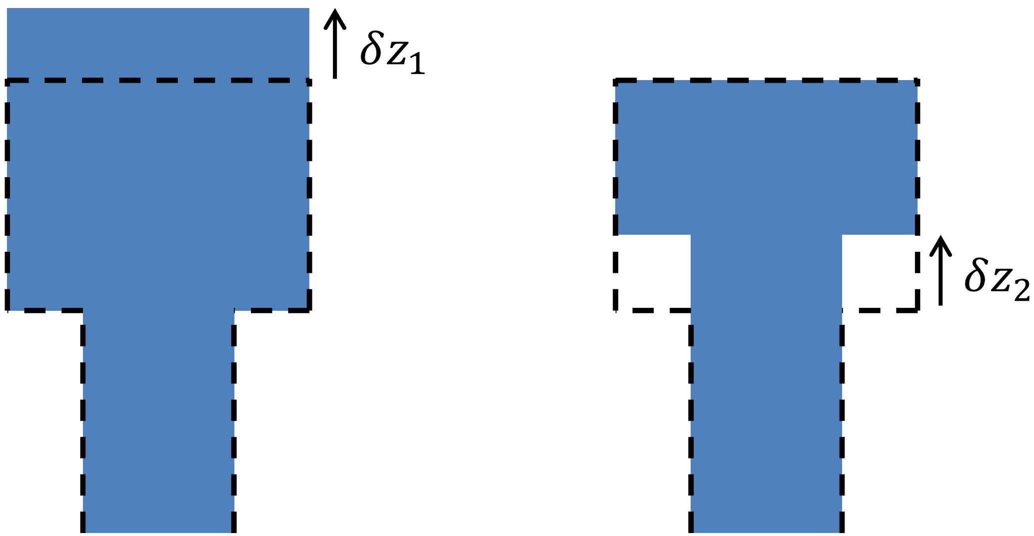


reflectivity 99.8%

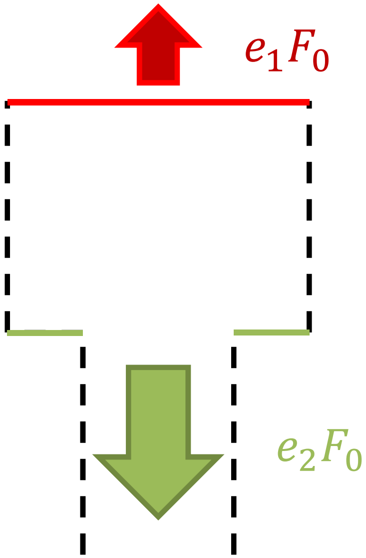
[F. Brückner et al., 2010, PRL 104, 163903]

Levin scheme for gratings – distribution of virtual forces

How do thermal structure fluctuations couple into the phase of the reflected light?



$\delta\varphi = K_{Br,1}\delta z_1$ $\delta\varphi = K_{Br,2}\delta z_2$



- weighting factors by **R**igorous **C**oupled **W**ave **A**nalysis (RCWA)

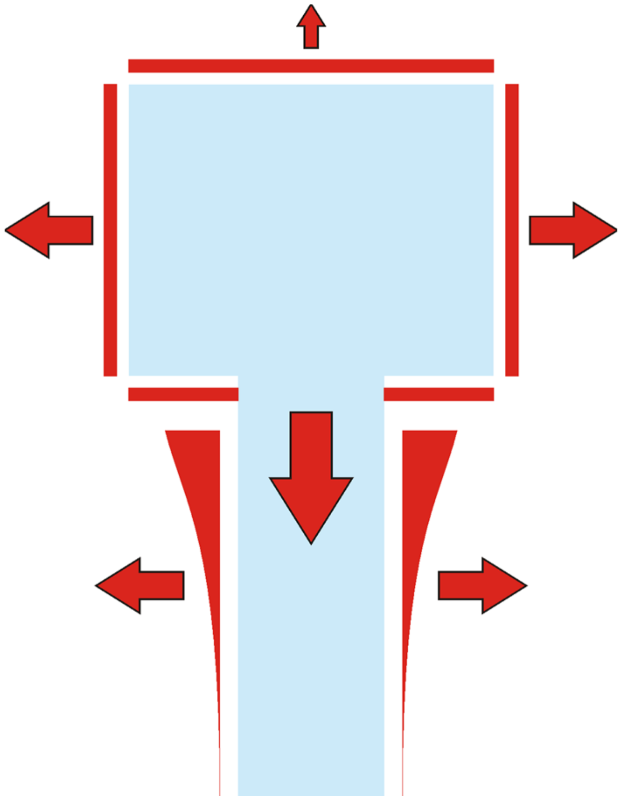
$$e = \frac{4\pi}{\lambda}K_{Br}$$ here: $e_1 = 0.02$ and $e_2 = 1.02$

- check of all kinds of surface fluctuations

Moharam et al., JOSA (1981).

Virtual load scheme

application of virtual loads



1. calculationofmechanicalenergy$E$
2. dissipated power $\langle P_{diss} \rangle = \omega \phi E$
3. Brownian noise power of the grating

$$S_z(\omega) = \frac{8 k_B T}{\omega^2} \frac{\langle P_{diss} \rangle}{F_0^2}$$

Temperature fluctuations – thermo-optic noise

Significant fluctuations on a scale larger thanthe thermal pathlength

$$r_{th} = \sqrt{\kappa / \rho C \omega}$$

κ… thermal conductivity
ρ… mass density
C … heat capacity

Values forsilicon($\omega = 2\pi \times 100$ Hz)

T [K]	κ [W/m/K]	C [J/kg/K]	r_{th} [mm]
300	148	713	0.37
10	2110	0.276	72

r_{th} ≫gratingdimensions (ridge/period)

→ homogeneoustemperaturedistributionalong a gratingridge

Temperature fluctuations

Scheme ofBraginsky et al. adapted

- Temperaturefluctuations in a thinlayer on top of a half spacesubstrate

$$S_T(\omega) = \frac{\sqrt{2} k_B T^2}{\pi r_0^2 \sqrt{\rho C \kappa \omega}}$$

Effectof a homogeneoustemperaturechange via RCWA

- Phase ofreflected light $\Delta\varphi = K_{TR} \beta \Delta T + K_{TE} \alpha \Delta T$
- Effectivedisplacementnoise

$$S_{z,TR}(\omega) = \left(\frac{\lambda_0}{4\pi} K_{TR} \beta \right)^2 S_T(\omega)$$

$$S_{z,TE}(\omega) = \left(\frac{\lambda_0}{4\pi} K_{TE} \alpha \right)^2 S_T(\omega)$$

Braginsky and Vyatchanin, Phys. Lett. A (2003).

Application to ET-LF

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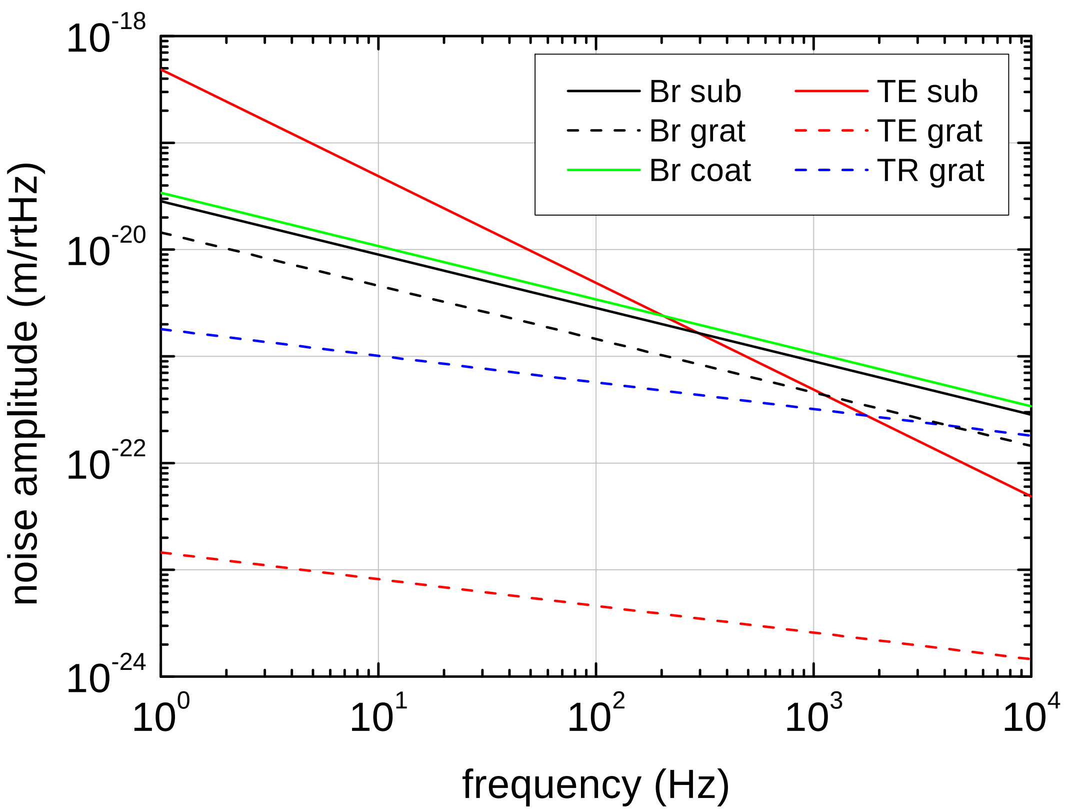
silicon substrate (diam. 50 cm x 46 cm, beam radius 9 cm) at 300 K



Application to ET-LF

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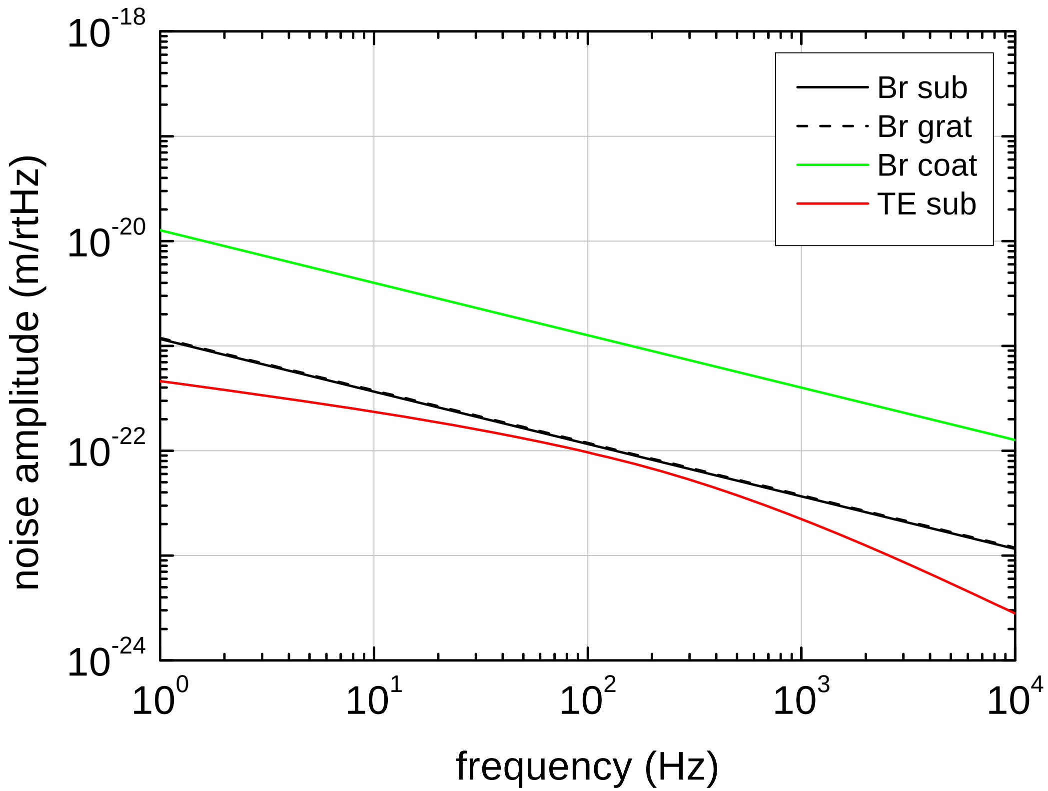
silicon substrate (diam. 50 cm x 46 cm, beam radius 9 cm) at 10 K

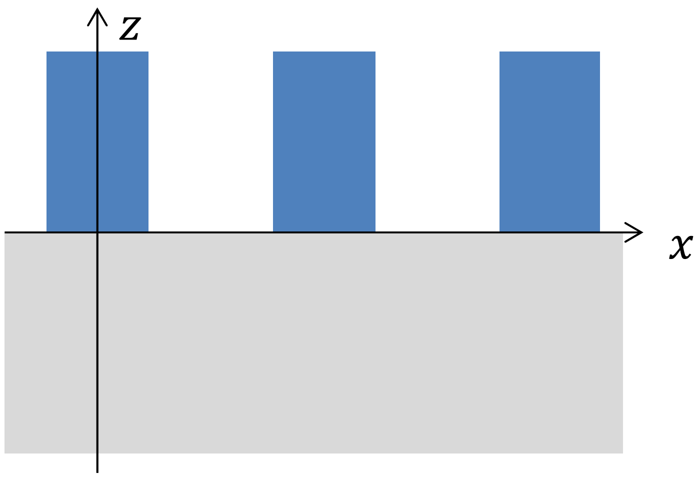


- possible decrease in noise amplitude by a factor of 10

Alternative grating design

Lamellar tantala grating on fused silica substrate

- Allows for a direct use in aLIGO (at 1064 nm and 300 K)



design wavelength	1064 nm
period	680 nm
ridgeheight	570 nm
ridgewidth	354 nm
$n_{tantala}$	2.1
$n_{substrate}$	1.45

Repeated estimate of Brownian, TR and TE noise

Thermal noise of tantala grating

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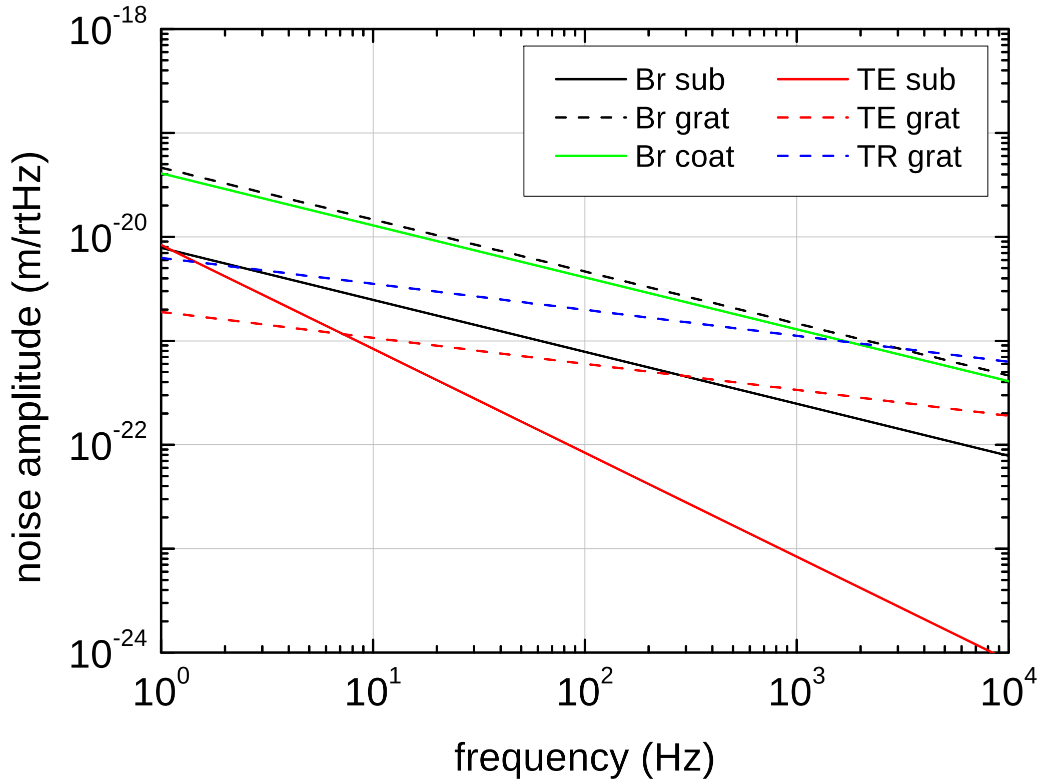
Noise curves for tantala grating



It is not just all about scaling layer thicknesses!

$$S_z(f) \propto \frac{k_B T}{f} \frac{d}{r_0^2} \phi$$

Coating thickness decreased by one order of magnitude – no benefit in Brownian TN for investigated configuration

Conclusion

Brownian coating noise is the dominating thermal noise process in current and future GWD‘s

grating reflectors circumvent lossy coating materials

a thermal noise reduction by a factor of 10 is predicted for the use of a monolithic silicon grating (demand cryogenics and 1550 nm)

Investigated tantala grating configuration on fused silica compatible with existing detectors but promise no noise benefit

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W. Gräf, D. Lehr, H. Schmidt, M. Banasch, W. Rockstroh, D. Voigt, T. Käsebier, N. Sergeev

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