Waveguide Mirrors: Coupling of Transverse into Longitudinal Motion

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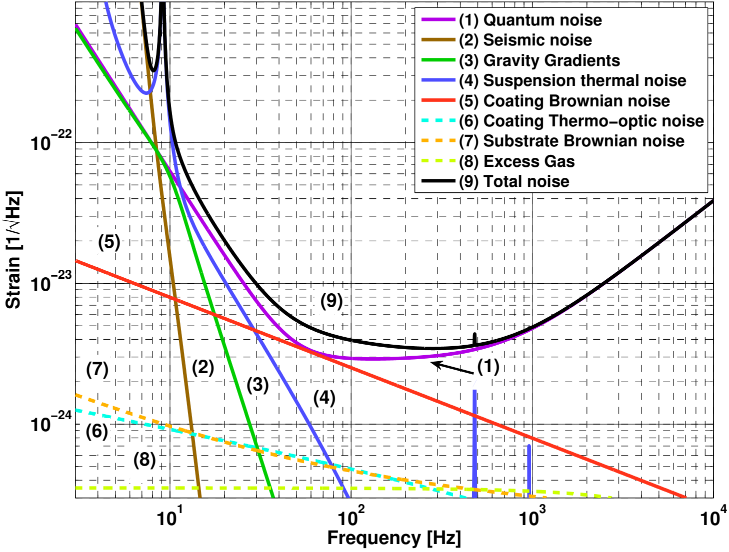
Thermal noise in the advanced detectors



Future thermal noise reduction

Potential reductions to mirror thermal noise (note that this is Stefan Hild's personal opinion, and not something approved/agreed by the GW community)

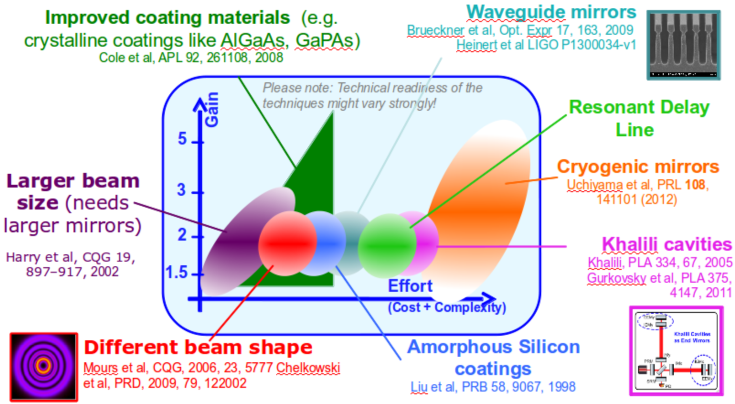


Image taken from Stefan Hild's talk given at GWADW, Elba, May 2013.

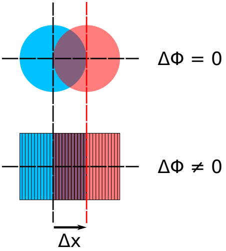
Grating Mirrors

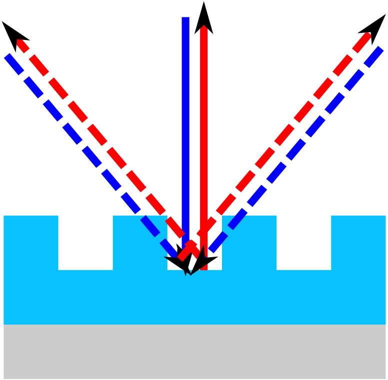
- Periodic, high refractive index structured material embedded on a low refractive index substrate
- Only need one coating with thickness of order λ (or none, if using silicon)
- Highly wavelength dependent

Grating Mirrors

Littrow Gratings

- Littrow gratings previously considered as arm cavity input couplers
- Suffer from additional noise effect due to transverse motion coupling arising from many allowed diffraction orders





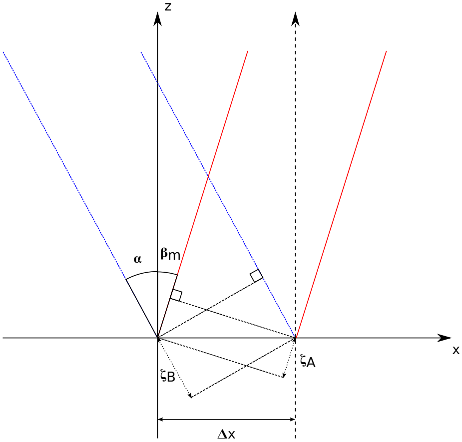


Figure : Freise et al, 2007.

Extra phase shift

$\Delta\phi\frac{\lambda}{2\pi} = \zeta_A + \zeta_B = \Delta x \left(\sin\alpha + \sin\beta_m\right)$ (Freise et al).

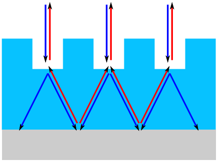
- Is this a problem? **Yes.**
- The effect has been known by short-pulse laser physicists for years but did not come to light in interferometry physics until recently
- **In gratings, this effect can swamp savings in thermal noise**

- **Can potentially fix this problem**
- Constrain grating period
- Light is forced into a single reflective diffraction order, the zeroeth
- In transmission, only the zeroeth and first diffraction orders are allowed
- Add waveguide below grating to allow **waveguide modes** inside material
- Light exists waveguide with a π phase shift compared to the zeroeth order light
- Phase shift invariant of sidemotion

Constraint

$$\frac{\lambda}{n_H} < \text{grating period} < \frac{\lambda}{n_L}$$

constructive interference



destructive interference

Waveguide Grating Mirrors

- Heinert et al calculation of thermal noise in waveguide grating mirrors
- For the geometries considered at 1064 nm and room temperature, no clear improvement in thermal noise
- Cryogenic temperatures at 1550 nm looks very different, offering **a Brownian thermal noise reduction of around a factor of 10**

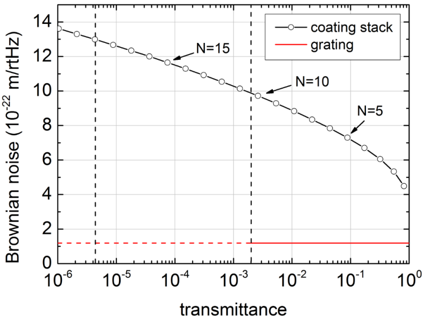
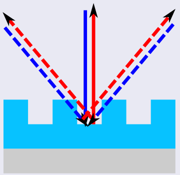


Figure : Room temperature 1064 nm silica/tantala bilayers vs cryogenic 1550 nm waveguide grating mirror at 100 Hz. Heinert et al, 2013.

Waveguide Grating Mirrors

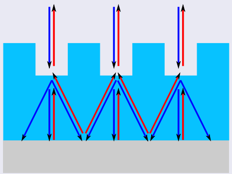
Brown et al showed in simulations that sidemotion noise in waveguide grating mirrors is reduced by 5 orders of magnitude over conventional gratings

Grating mirrors



Susceptible to sidemotion noise

Waveguide grating mirrors



Potentially cancel sidemotion noise

Need experimental verification of waveguide grating mirror sidemotion cancellation!

Determining a Waveguide Mirror's Sidemotion Coupling

Fabrication

- Collaboration with Jena and the AEI
- Tantala grating layer on top of a tantala waveguide layer, mounted on a fused silica substrate

Parameter	Value
Design λ	1064 nm
Grating depth	390 nm
Waveguide depth	80 nm
Etch stop depth	20 nm
Grating period	688 nm
Fill factor	0.38

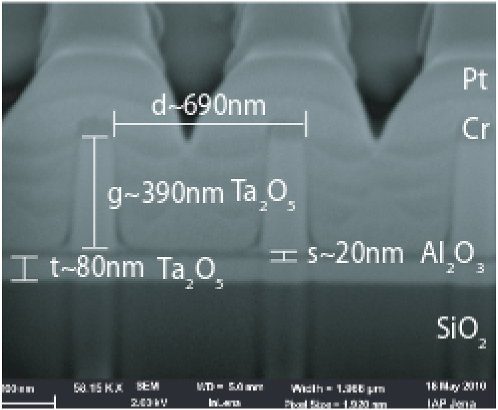
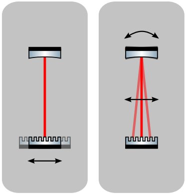


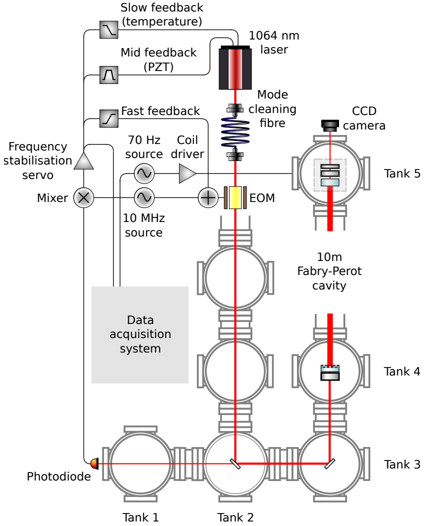
Figure : Friedrich et al, 2011.

Determining a Waveguide Mirror's Sidemotion Coupling

Experimental Setup

- We created a 10 m Fabry-Perot cavity with waveguide mirror as ITM and silica ETM
- ETM rotated to produce sidemotion
- The cavity length changes (where sidemotion effects would show up) were read out using an RF photodiode





Determining a Waveguide Mirror's Sidemotion Coupling

Understanding Mirror Phase Effects

All (near-)planar mirrors have longitudinal phase effects during rotation:

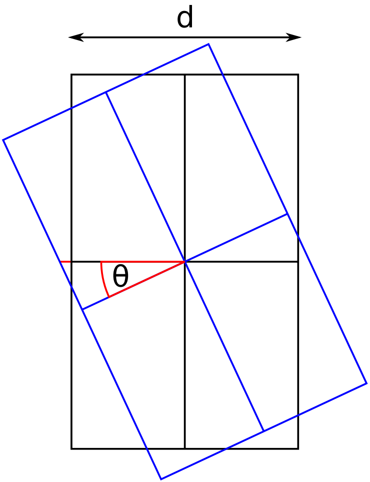
- Reflection from front surface on a mirror of depth d:

$$\frac{d}{4}\theta^2 \text{ (for small } \theta)$$

- Displacement of light beam from centre:

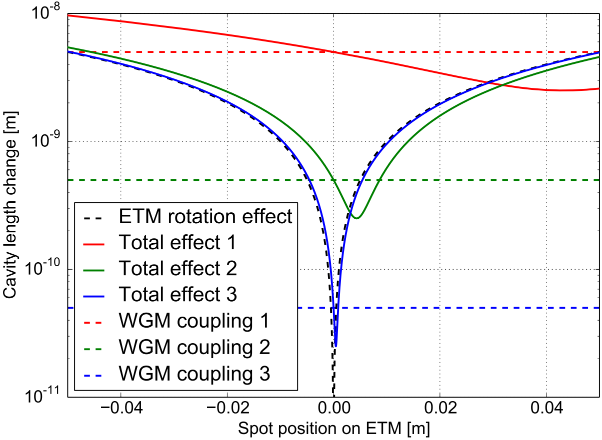
$$x_d \tan\theta \approx x_d\theta$$

Current and proposed future gravitational wave detectors can tolerate these noise sources as they are lower than the dominating sources.



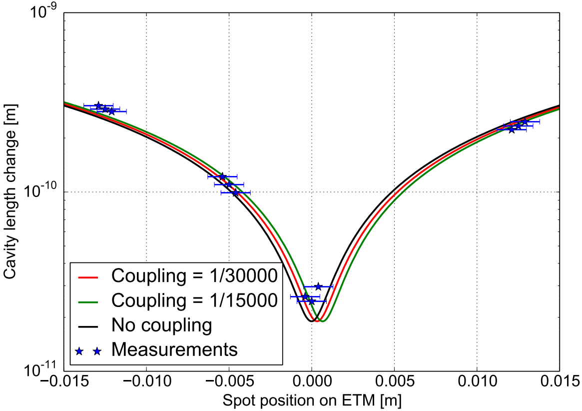
Determining a Waveguide Mirror's Sidemotion Coupling

- Expect to see notch due to phase interaction between waveguide coupling and mirror rotation
- Can imply waveguide mirror coupling from known rotation effects



Determining a Waveguide Mirror's Sidemotion Coupling

- Measurements taken with cavity aligned to 4 different spot positions
- Can compare to simulation of coupling to determine coupling
- Error on spot positions defines coupling level upper limit, i.e. worst fit through the data



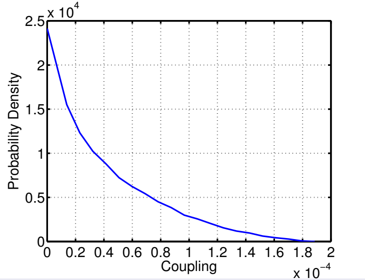
Determining a Waveguide Mirror's Sidemotion Coupling

- Model simulates effect of 'beam smearing' by assuming the spot moves in a Gaussian distribution across the waveguide grating mirror
- Cavity length signal (y-axis) scaling is arbitrary
- Fitting the model to the data therefore not straightforward since fit must fit scaling, spot movement standard deviation and coupling level
- A Bayesian approach is beneficial

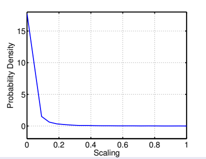
Determining a Waveguide Mirror's Sidemotion Coupling

- Can marginalise over three parameters:
  - sidemotion coupling
  - signal (y-axis) scaling
  - 'spot movement' standard deviation
- Markov-chain Monte-Carlo algorithm
- Produces three probability density distributions

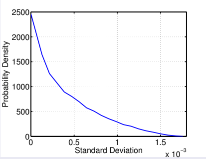
Coupling



Scaling

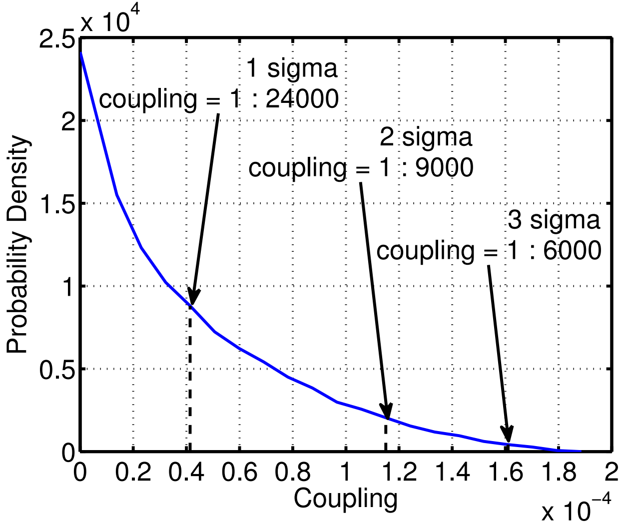


Std. Deviation



Determining a Waveguide Mirror's Sidemotion Coupling

Probability distribution of coupling level allows us to determine an upper limit.



Determining a Waveguide Mirror's Sidemotion Coupling

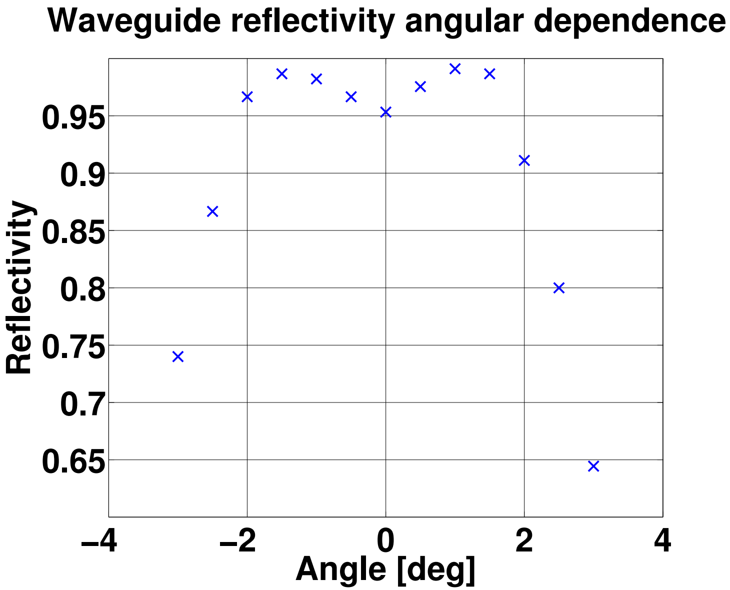
Standard Deviation	Side-to-Longitudinal Coupling
1	1 : 24000
2	1 : 9000
3	1 : 6000

- Within 3 standard deviations, the coupling level is at worst **1 : 6000**
- This represents a longitudinal phase shift comparable to the effect due to rotation at the centre (the $\frac{d}{4}\theta^2$ effect).
- Contrast this to the sidemotion coupling of the Littrow grating measured by Barr et al, which was of order **1 : 100**.
- Waveguide grating mirrors can still be considered for future interferometer applications

End

Extra Slides

Waveguide Reflectivity



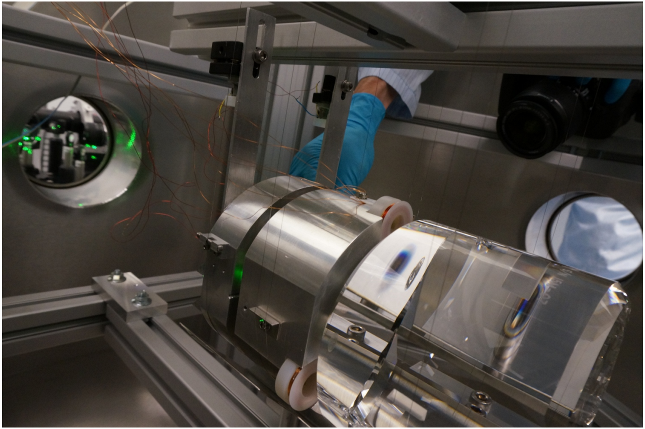


Figure : Courtesy of Jumpei Kato