Coupling of Longitudinal Phase Shift from Sidemotion of Waveguides

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- Problems associated with grating mirrors
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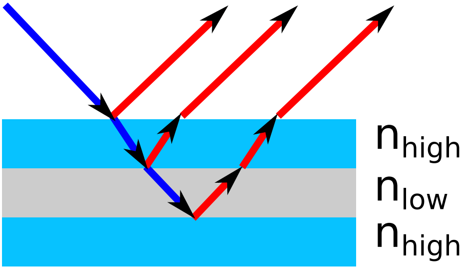
- Traditional dielectric mirrors utilise **stacks of $\frac{\lambda}{4}$ coatings** to create highly reflective surfaces
- Each stack's coatings contribute noise due to mechanical loss
- This is the **limiting factor** in current gravitational wave detectors' most sensitive frequency bands, where dielectric mirrors with many coating layers are used



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

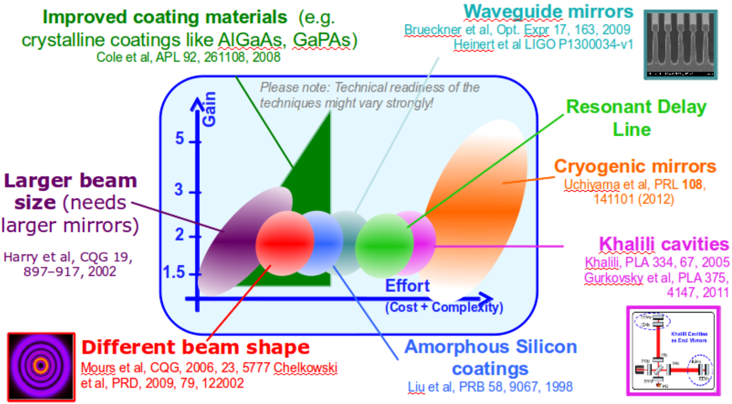


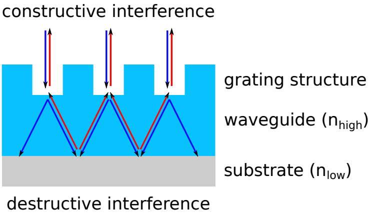
Image taken from Stefan Hild's talk given at GWADW, Elba, May 2013.

Dielectric Mirrors and their Alternatives

An Alternative: Waveguide Mirrors

- Waveguide mirrors use a **periodic surface** and a **resonant structure** exhibiting high reflectivity at certain angles and certain wavelengths
- Crucially only uses **one layer of material** of similar thickness to a dielectric stack, with overall thickness of order λ
- Composed of a thin, high refractive index structured material embedded on a low refractive index substrate
- First proposed for our field in 2006 (Bunkowski et al) and demonstrated in 2009 (Brückner et al).
- Potentially useful for ET, **but challenges remain**.

- Carefully chosen grating parameters create high reflection
- Light is forced into a single reflective diffraction order, the zeroeth
- In transmission, only the zeroeth and first diffraction orders are present
- The transmitted light undergoes total internal reflection due to the boundary between the high and low refractive index material
- The reflected transmitted light exits through an adjacent grating block



With carefully chosen parameters, such waveguide mirrors can in theory be 100% reflective, **with a fraction of the material** of a typical gravitational wave detector's reflective surface.

- There has been a recent study to calculate the thermal noise of waveguide gratings by Heinert et al.
- For the geometries considered at $1064\,\mathrm{nm}$ and room temperature, no clear improvement was found
- But for cryogenic temperatures and with $1550\,\mathrm{nm}$, this looks very different, where **a noise reduction of around a factor of 10** is calculated compared to a dielectric mirror with 19 pairs of silica and tantala layers (similar to the Advanced LIGO specification)

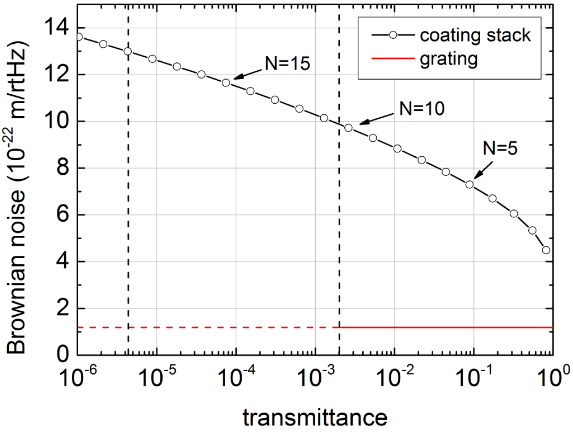


Figure: Thermal noise in a waveguide mirror at $1550\,\mathrm{nm}$ and a dielectric mirror similar to the Advanced LIGO specification as a function of transmittivity. Image from Heinert et al, 2013.

Problems Associated with Grating Mirrors

- Waveguide mirrors are similar to grating mirrors studied in the past
- Dielectric mirrors are usually cylindrically symmetric such that translations of the mirror surface do not induce additional phase terms in the reflective light
- Grating mirrors only display this invariance for translation in the direction of the grating grooves
- For perpendicular translations, **an additional term is introduced** depending on Δx, the translation transverse to the optical axis
- This can look like a gravitational wave!

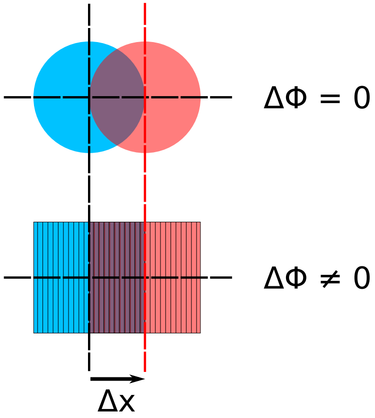


Figure: Comparison between dielectric and waveguide mirror during sidemotion

Problems Associated with Grating Mirrors

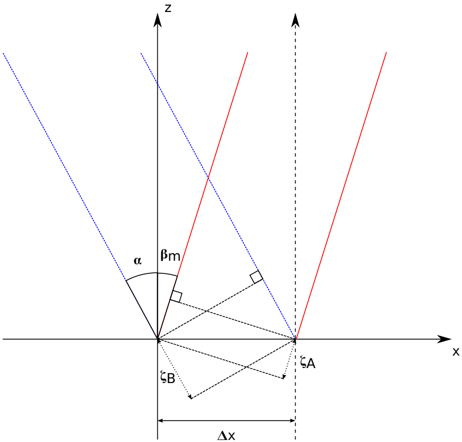


Figure: Light path length change during reflection on a three port grating. Diagram reproduced from Freise et al, 2007.

- The extra effect is $\Delta\phi\frac{\lambda}{2\pi} = \zeta_A + \zeta_B = \Delta x\,(\sin\alpha + \sin\beta_m)$ (Freise et al).
- Is this a problem? **Yes.**
- The effect has been known by short-pulse laser physicists for years (where it is called 'group delay') but did not come to light in interferometry physics until recently.
- The phase effect is enough to swamp any savings in thermal noise.

Problems Associated with Grating Mirrors

This effect was experimentally verified with the 10 metre prototype in the University of Glasgow in 2011 (Barr et al). Its presence makes it difficult to consider grating mirrors for future gravitational wave detectors due to the stringent stability and alignment requirements.

Problems Associated with Grating Mirrors

Waveguide Mirrors

- Waveguide mirrors might be different: the light is forced into first order diffraction, where the waveguide resonance can potentially **cancel out** the effect, i.e. $\zeta_A = -\zeta_B$, so $\Delta x = 0$.
- A recent paper by Brown et al (University of Birmingham) simulated a waveguide mirror and found the sidemotion effect to be **5 orders of magnitude lower** than that of a grating mirror, equivalent to a phase difference of less than $1 \times 10^{-7}\,\mathrm{rad}$, a result limited by numerical precision.
- **Is this also true in practice?**

- In collaboration with Universität Jena and the AEI in Hannover, a set of waveguide mirrors were produced to the specification used in the previous demonstration of a suspended $10\,\mathrm{m}$ cavity in Glasgow (Friedrich et al).
- The mirrors were made from a tantala grating layer on top of a tantala waveguide layer, mounted on a fused silica substrate. An additional etch stop layer of $20\,\mathrm{nm}$ was mounted on top of the waveguide layer to assist the fabrication process.

Parameter	**Value**
Design λ	$1064\,\mathrm{nm}$
Grating depth	$390\,\mathrm{nm}$
Waveguide depth	$80\,\mathrm{nm}$
Etch stop depth	$20\,\mathrm{nm}$
Grating period	$688\,\mathrm{nm}$
Fill factor	0.38

Table: The waveguide design parameters

- The set of waveguide mirrors were fabricated with slightly different parameters to increase the likelihood of a waveguide with suitable qualities being available.
- Only one of the waveguide mirrors was suitable, possessing a reflectivity of around 96%. The others had significantly worse reflectivities at the desired incidence and wavelength (0° and $1064\,\mathrm{nm}$).
- Reflects the difficulty of manufacture

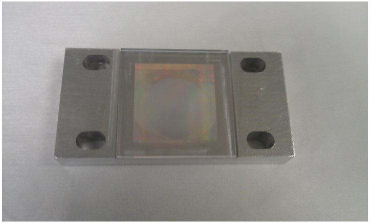
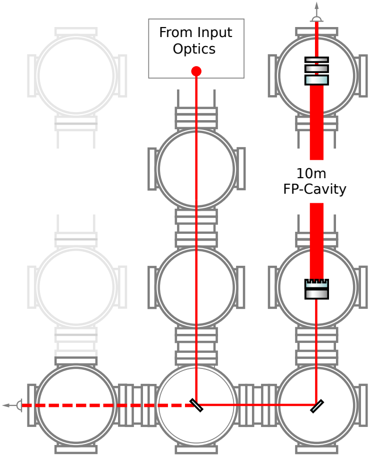


Figure: The waveguide used in the experiment, mounted on an aluminium base.

Determining a Waveguide Mirror's Sidemotion Coupling

Experimental Setup

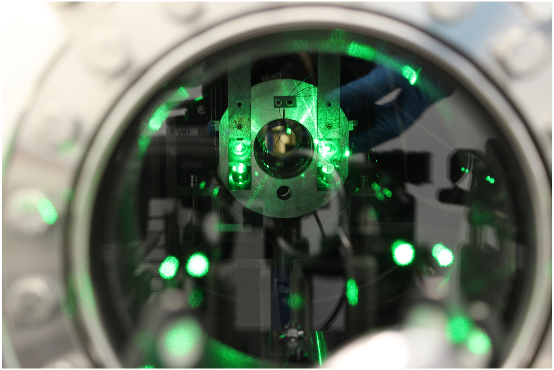
- We created a $10\,\mathrm{m}$ Fabry-Perot cavity in our prototype facility using the waveguide mirror as the ITM and a highly reflective fused silica mirror as the ETM.
- The ETM was rotated to scan the light across the waveguide's grooves
- The cavity length changes (where sidemotion effects would show up) were read out using an RF photodiode



Determining a Waveguide Mirror's Sidemotion Coupling

Experimental Setup

We also installed a pair of suspended Michelson interferometers behind the ETM's reaction mass in an attempt to read out its rotation



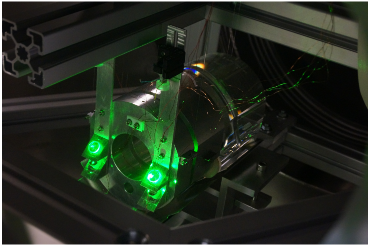


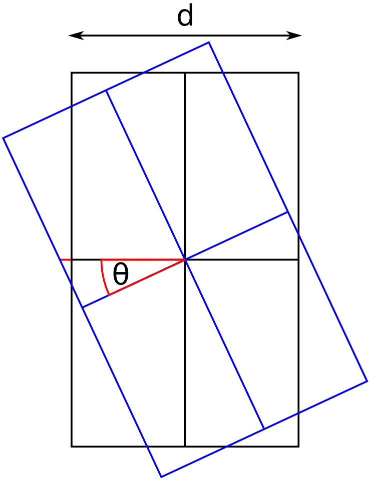
Figure: Courtesy of Jumpei Kato

Understanding Mirror Phase Effects

All (near-)planar mirrors have longitudinal phase effects during rotation due to the mirror geometry:

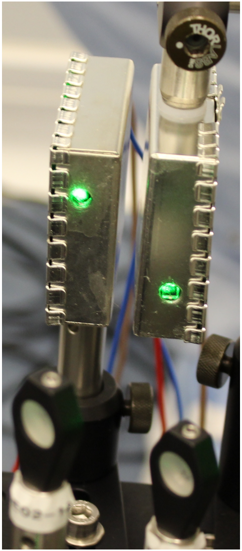
- One effect comes from the mirror's depth d, as the reflective surface of the mirror is displaced from the mirror's centre of rotation: $\frac{d}{4}\theta^2$ (when θ is small)
- Another effect comes from the light beam's displacement from the centre of reflective surface in plane with the centre of rotation, due to the non-zero longitudinal motion of a mirror's surface at that point: $x_d \tan\theta \approx x_d\theta$

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



Calibrating Rotation using Michelson Interferometers

- The initial analysis of this positional readout has proved tricky to interpret, perhaps due to the sensitivity of the interferometer's alignment to PZT actuation coupled to the large spot size in relation to the photodiodes used.
- Instead, for the preliminary results the rotational information has been inferred from the longitudinal signal measured during in-phase coil actuation (i.e. longitudinal pushing rather than rotation).



Sidemotion Coupling in our Waveguide

These are **PRELIMINARY** results!

- We found our waveguide to have a coupling of side to longitudinal motion of about $32\,500\,\mathrm{at}$ the centre, meaning that a sidemotion of 1 (arbitrary unit) would result in a longitudinal phase shift equivalent to a length of $\frac{1}{32500}$.
- Off-centre positions are still to be analysed (correcting for longitudinal effects due to off-centre rotation) but follow the expected trends.
- In comparison to the grating reflector measured by Barr et al, this represents a suppression of this source of noise of the order 1×10^4.
- This represents a longitudinal phase shift comparable to the effect due to rotation at the centre (the $\frac{d}{4}\theta^2$ effect).

If our results are valid, this means that **waveguide mirrors can be considered for the main optics** in future gravitational wave detectors such as ET.

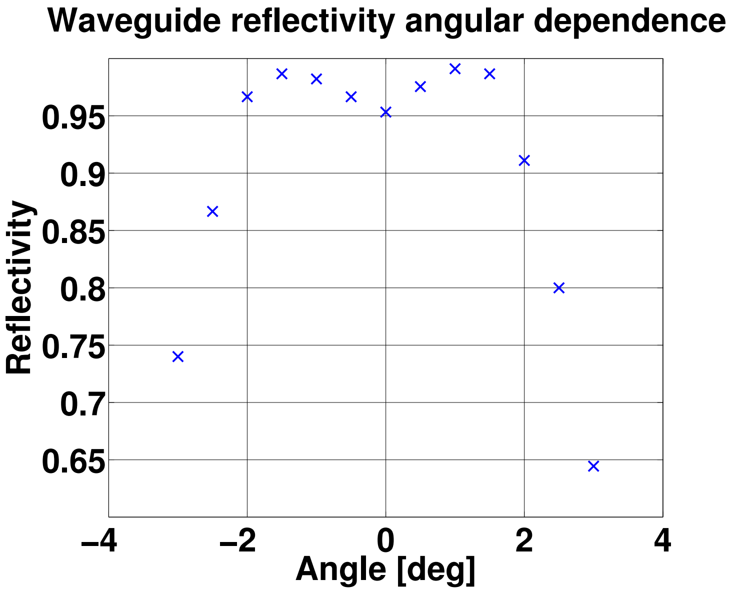
End

Thanks to **Russell Jones**, **Colin Craig**, **Stephen Craig** and **Jumpei Kato** for their assistance during the experiment!

Any questions?

Extra Slides

Waveguide Reflectivity



Determining a Waveguide Mirror's Sidemotion Coupling

Experimental Setup

- The high reflectivity $2.7\,\mathrm{kg}$ fused silica mirror formed a cavity with the waveguide mirror with finesse of $\sim$75.
- The input laser power was approximately $70\,\mathrm{mW}$.
- The RF photodiode was resonant at $10\,\mathrm{MHz}$ and produced signals large enough to control with a PDH setup designed for very high finesse cavities.
- The waveguide was aligned on the ITM such that its gratings were parallel to the vertical direction.

Determining a Waveguide Mirror's Sidemotion Coupling

Experimental Setup

- Both the ITM and ETM were suspended via a triple stage cantilever, and behind the ITM was placed a $2.7\,\mathrm{kg}$ steel reaction mass.
- The ETM used a thinner reaction mass along with the 'Michelson' mass housing the two interferometers.
- Coils on the reaction mass lined up to magnets on the ETM, allowing for rotational and tilt control.

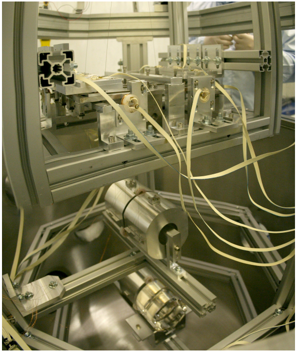


Figure: A triple suspension in the Glasgow $10\,\mathrm{m}$ prototype

- Rather than translating the waveguide sideways, the ETM was rotated by actuating the coils on its reaction mass.
- This prevented the need to calibrate out roll from slight coil actuation mismatch.
- Rotating the ETM scanned the cavity light across the waveguide, simulating sidemotion.

- The cavity was locked using the Pound-Driver-Hall technique (with $10\,\mathrm{MHz}$ sidebands), feeding back to the laser's PZT and crystal temperature to maintain resonance.
- The RF signal from a photodiode placed in the path of the reflected light from the ITM was recorded using a data acquisition system (LIGO CDS).
- Rotational signals were injected at a frequency high enough to avoid the pendulum modes but low enough to have a large signal

- The cavity length signal was calibrated using the recorded reflected cavity RF and laser PZT feedback signals, along with the cavity length of approximately $10\,\mathrm{m}$ and the mirror's parameters (mass, moment of inertia, coil position).
- The laser has a well-defined PZT response, and at the injection frequency the PZT follows the cavity length.
- From this it is possible to calculate the change in length for a given signal using the relation $\frac{\Delta f}{f} = \frac{\Delta L}{L}$.

- The rotation of the ETM determines the level of sidemotion applied to the waveguide. This was calculated using the calibrated cavity length signal during longitudinal pushing. The force applied to the mirror per volt during longitudinal pushing was analysed on the mirror in terms of rotational pushing to work out the angle.
- Using the simulation package FINESSE, the spot movement on the ITM $10\,\mathrm{m}$ away was obtained from the angle and mirror radius of curvature.

The Michelsons

ETM Masses

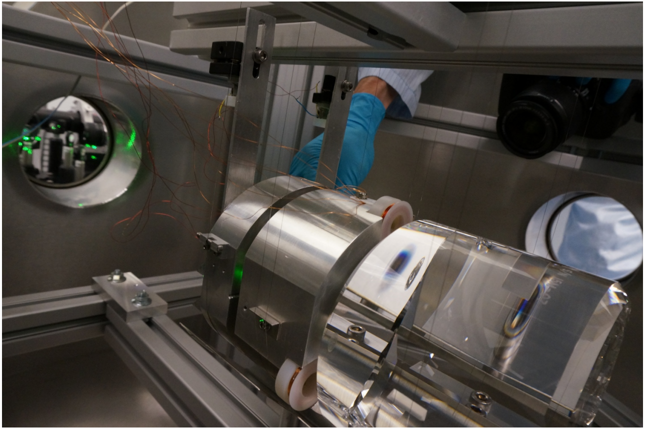


Figure: Courtesy of Jumpei Kato