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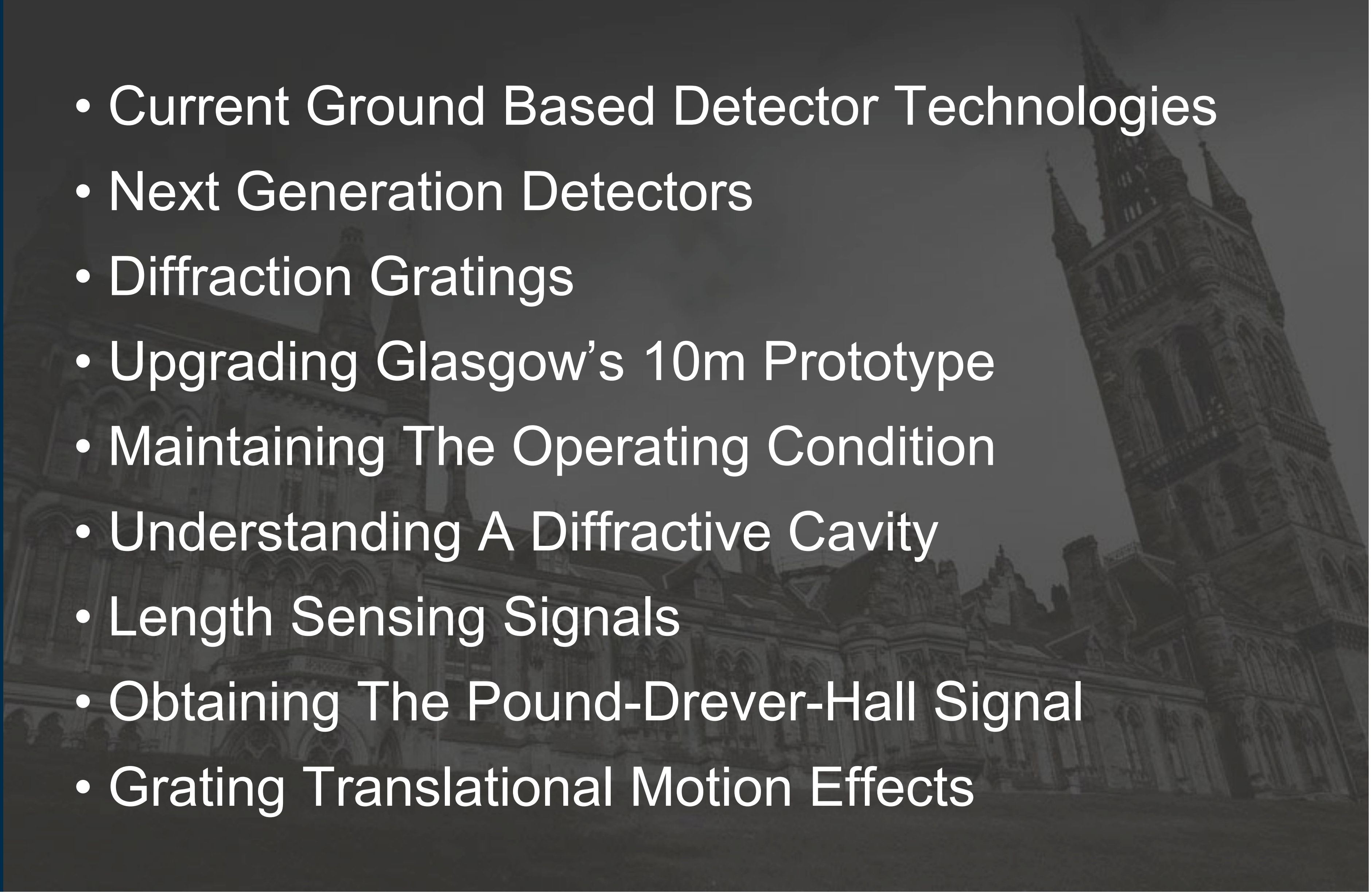
Demonstration of a suspended diffractively coupled Fabry-Perot cavity

Matthew Edgar



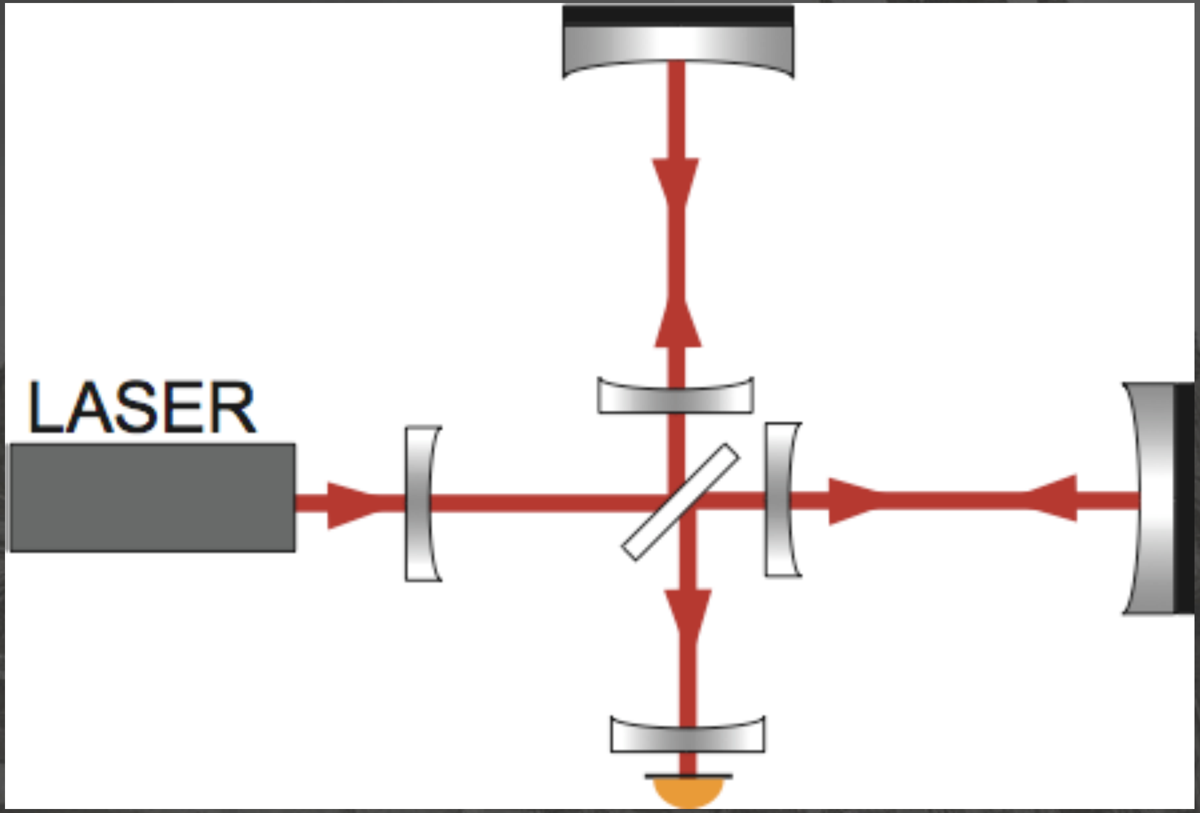
Overview

- Current Ground Based Detector Technologies
- Next Generation Detectors
- Diffraction Gratings
- Upgrading Glasgow’s 10m Prototype
- Maintaining The Operating Condition
- Understanding A Diffractive Cavity
- Length Sensing Signals
- Obtaining The Pound-Drever-Hall Signal
- Grating Translational Motion Effects

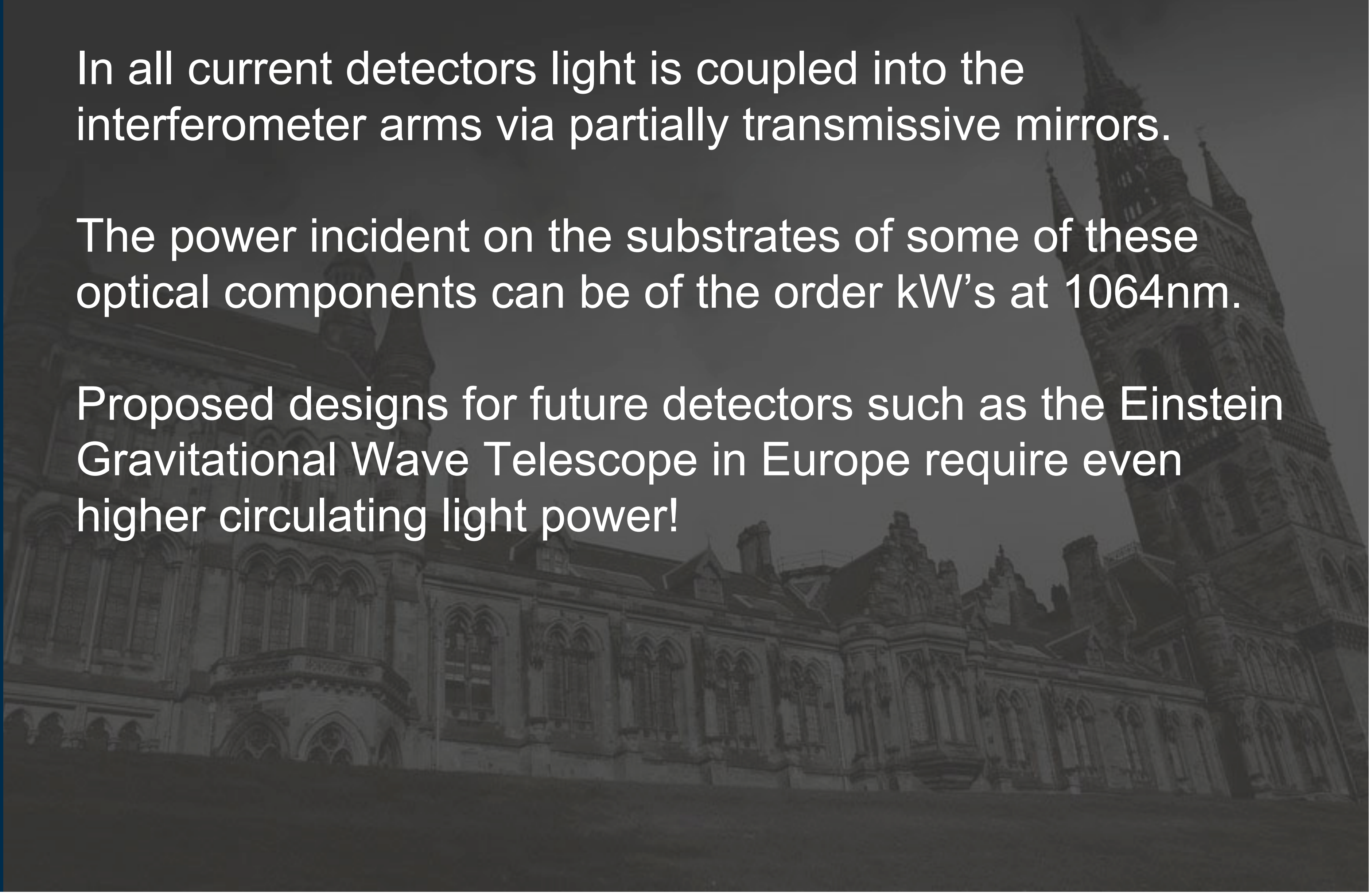
Current Ground Based Detectors

Based on enhanced Michelson topologies

- Optical cavities
- Power recycling
- Signal recycling (GEO600)



Current Ground Based Detectors



In all current detectors light is coupled into the interferometer arms via partially transmissive mirrors.

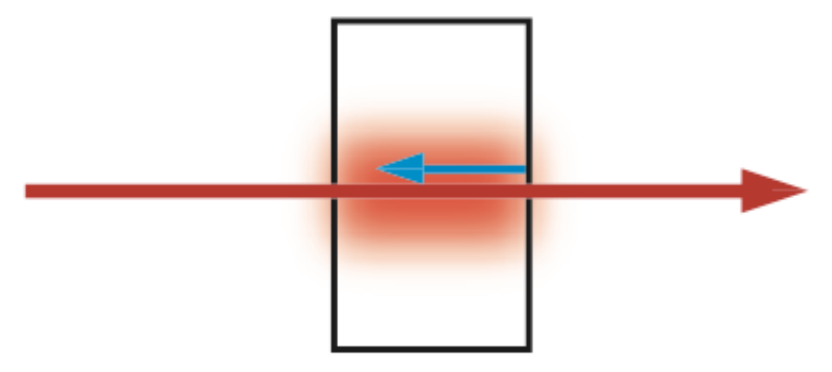
The power incident on the substrates of some of these optical components can be of the order kW’s at 1064nm.

Proposed designs for future detectors such as the Einstein Gravitational Wave Telescope in Europe require even higher circulating light power!

Next Generation Detectors

Increasing the stored light raises concern!

A constant small fraction is always absorbed by the optical substrates.



This leads to localised heating and produces thermal lenses caused by a change of refractive index with temperature.

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Diffraction Gratings

A non-transmissive mechanism must be found to avoid this issue.

A second motivation for using non-transmissive components arises if cryogenic techniques are to be used for reducing thermal noise.

One potential resolution is to use all-reflective devices, such as diffraction gratings, to avoid transmission through the substrates.

Diffraction gratings can be manufactured to serve various purposes inside interferometers:

Beam splitters

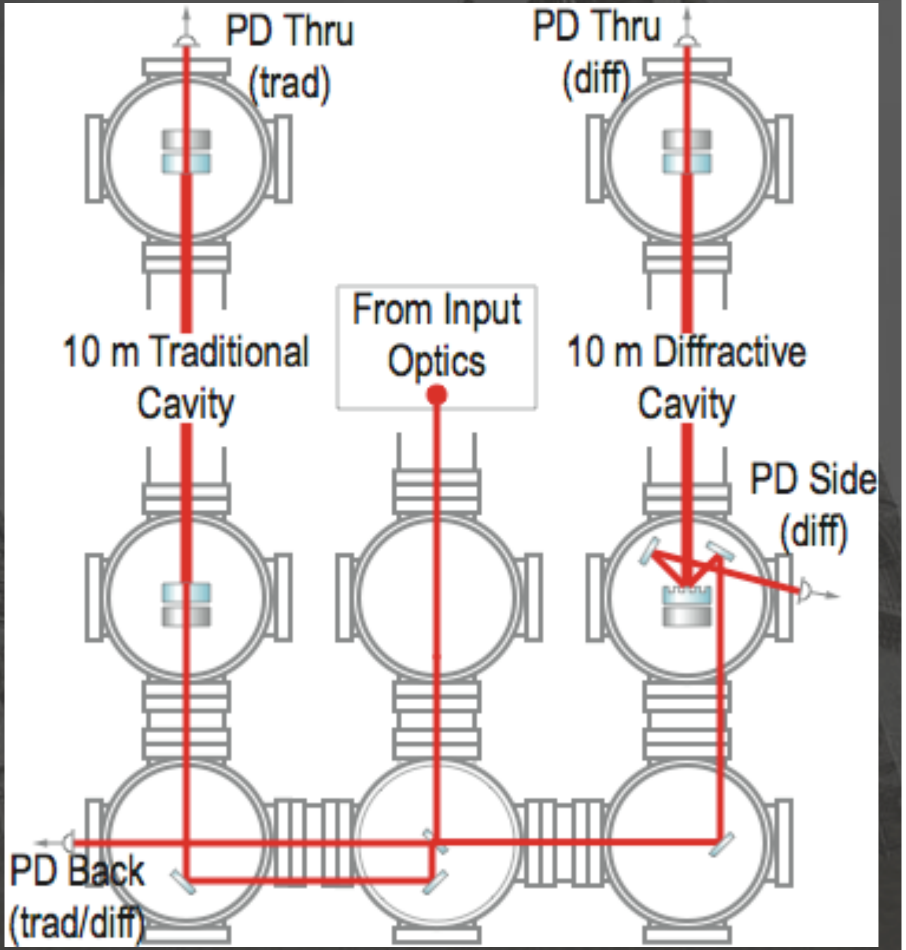
Cavity input couplers

Upgrading Glasgow's 10m Prototype

Several proof-of-principle [1] and bench-top [2] experiments have been carried out to demonstrate the principles of operation for diffractive cavities.

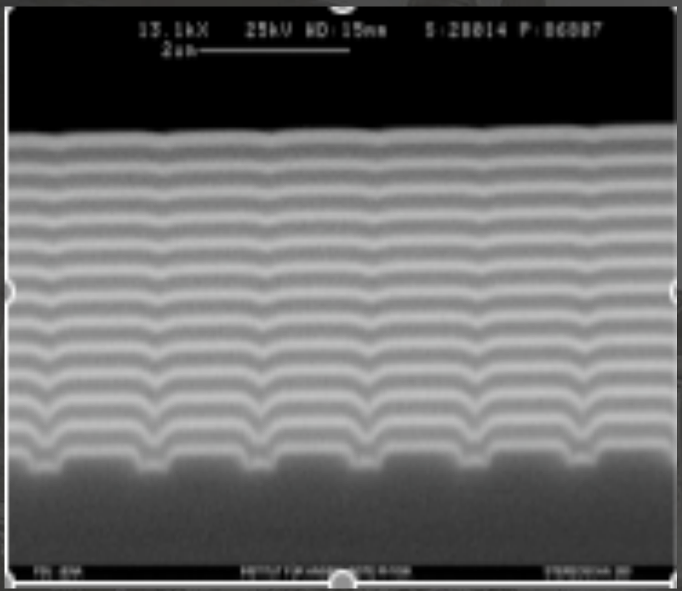
One of the interferometer arms at Glasgow was commissioned as a diffractively-coupled Fabry -Perot cavity.

All of the components are triple suspended, like GEO600, to ensure seismic isolation and freedom of motion.

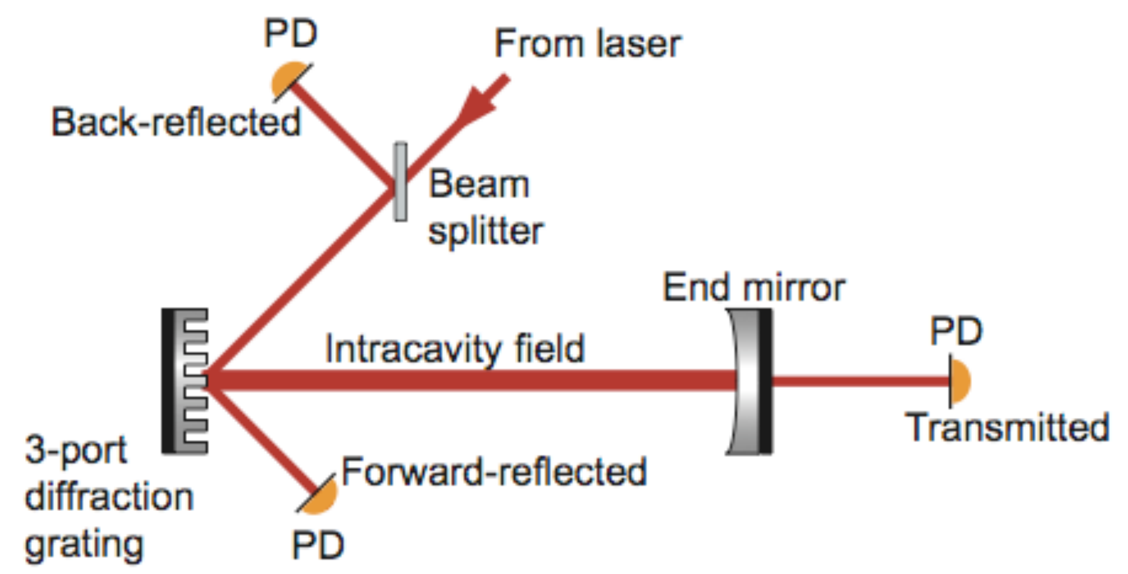


Upgrading Glasgow’s 10m Prototype

Our diffraction grating was manufactured at Jena University by etching a binary structure into a fused silica substrate then over-coating with multiple alternating layers of Ta_2O_5 and SiO_2.



Electron microscope image of diffractive optic [3].

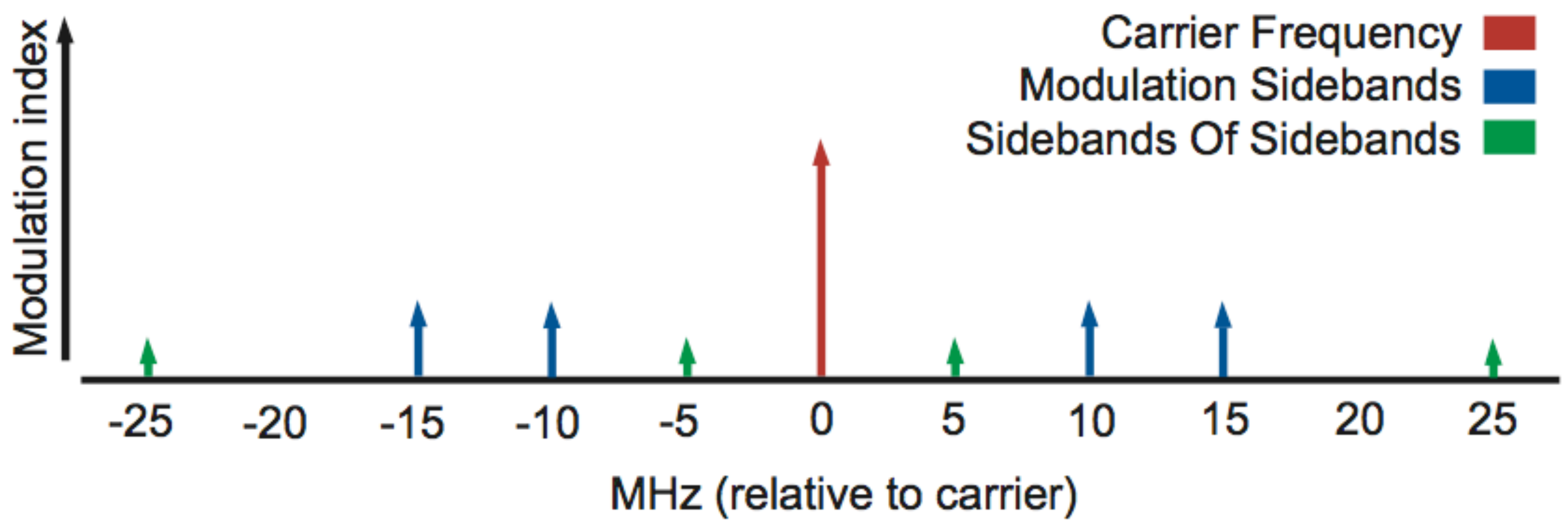


Simplified schematic of diffractive cavity [4].

Maintaining The Operating Condition

As with traditional transmissive systems, to maintain the diffractive cavity at the correct operating point requires modulating the laser light.

The light leaving the cavity is detected at the output ports and is then demodulated.



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Understanding A Diffractive Cavity

The scattering matrix of three-port grating can be represented by [5]:

$$b = \mathbf{S} \times a \quad (1)$$

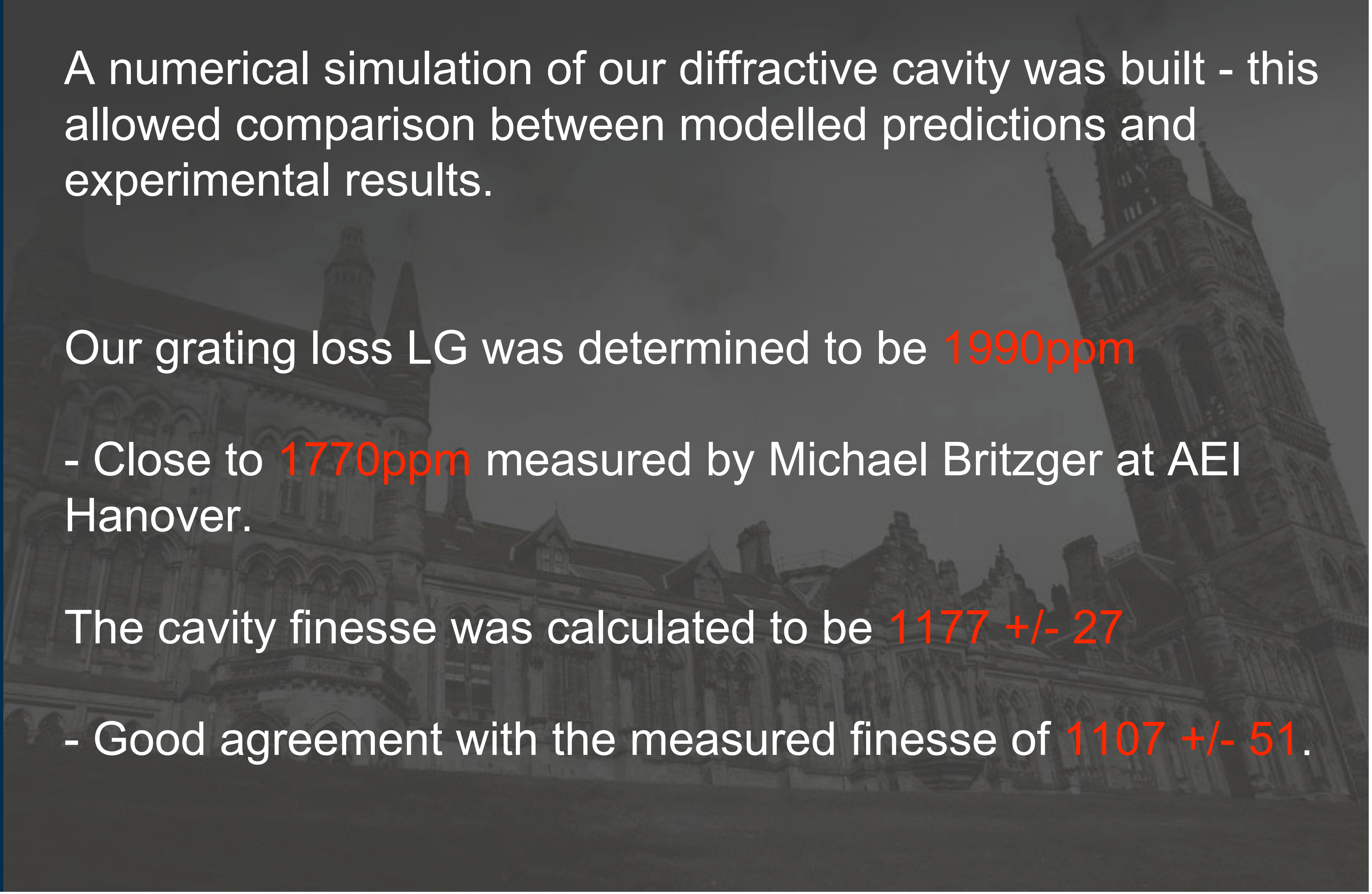
$$\mathbf{S}_{3p} = \begin{bmatrix} \eta_2 e^{i\phi_2} & \eta_1 e^{i\phi_1} & \eta_0 e^{i\phi_0} \\ \eta_1 e^{i\phi_1} & \rho_0 e^{i\phi_0} & \eta_1 e^{i\phi_1} \\ \eta_0 e^{i\phi_0} & \eta_1 e^{i\phi_1} & \eta_2 e^{i\phi_2} \end{bmatrix} \quad (2)$$

The input/output relations for a three-port diffractive cavity have been investigated at AEI Hanover and yield amplitudes for the fields at each port described by:

$$\begin{gathered} c_1 = \eta_2 e^{i\phi_2} + \eta_1^2 e^{2i(\phi_1+\phi)} d, \\ c_{2t} = i\tau_1 \eta_1 e^{i\phi_1} e^{\phi} d, \\ c_3 = \eta_0 + \eta_1^2 e^{2i(\phi_1+\phi)} d. \end{gathered} \quad (3)$$

Equations 2 and 3 have been taken from a recent paper [6]

Results



A numerical simulation of our diffractive cavity was built - this allowed comparison between modelled predictions and experimental results.

Our grating loss LG was determined to be 1990ppm

- Close to 1770ppm measured by Michael Britzger at AEI Hanover.

The cavity finesse was calculated to be 1177 +/- 27

- Good agreement with the measured finesse of 1107 +/- 51.

Length Sensing Signals

It was possible to sweep the cavity by at least one free spectral range using the laser frequency, and obtain the demodulated error signal for each output port.

The slope of this signal at the operating point gives the response for that output port, known as the effective optical gain.

The RF signal from each detection port can be demodulated in two orthogonal phases to give maximum signal (in-phase) and minimum signal (quadrature-phase).

The experimental and modelled results for each of these have been compared.

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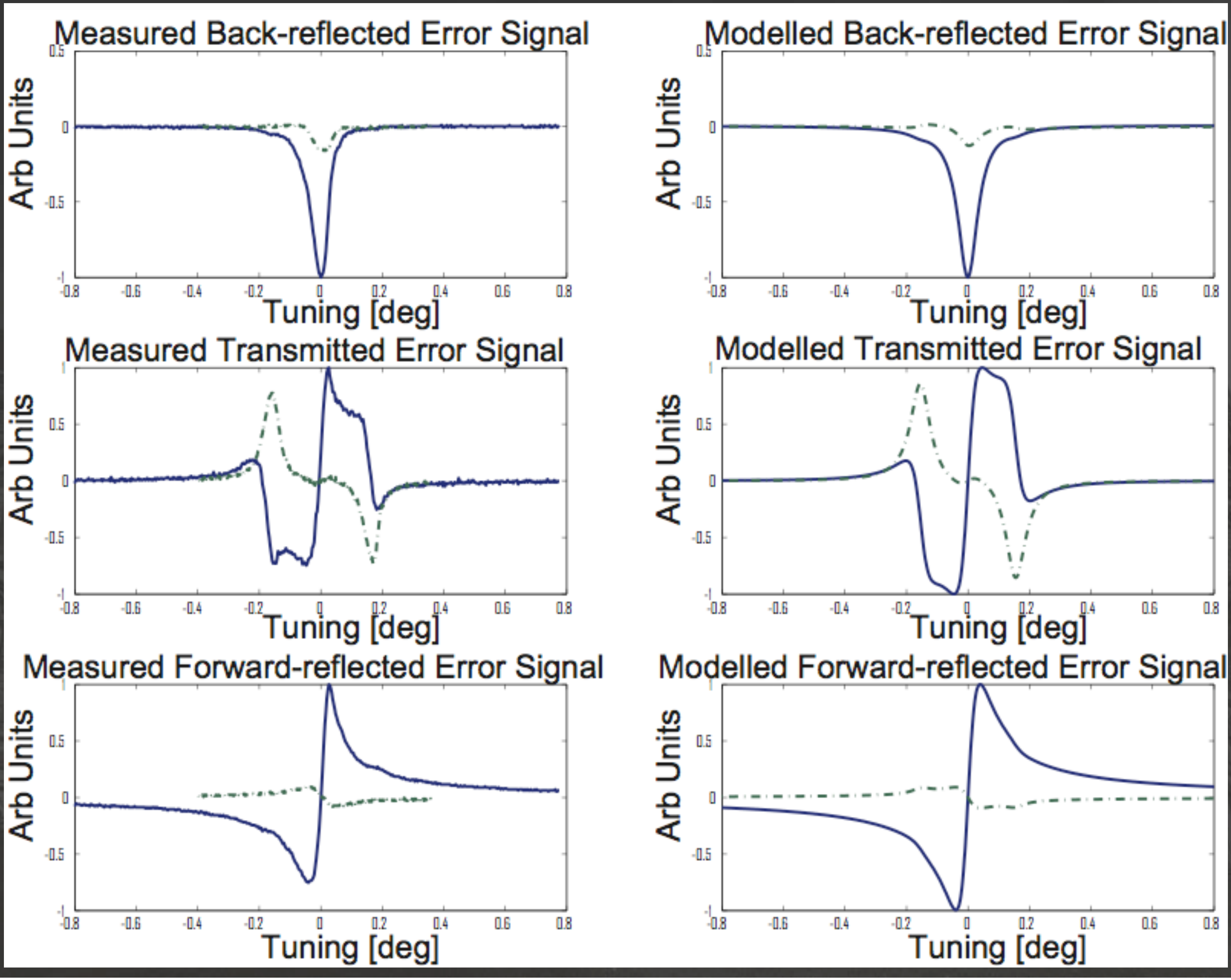
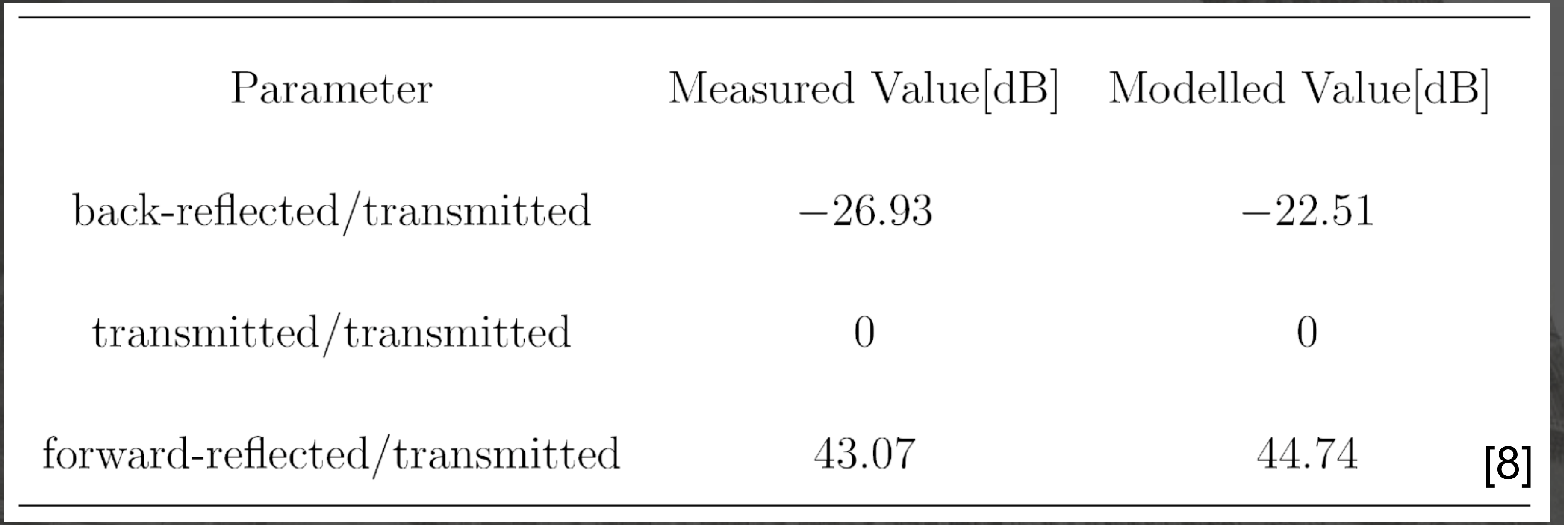
Results



[7]

Results

To calibrate the detected signals from all three ports, the in-phase slopes were compared to the slope of the signal from the transmitted port, which is symmetrical around the centre of resonance.



Parameter	Measured Value[dB]	Modelled Value[dB]
back-reflected/transmitted	-26.93	-22.51
transmitted/transmitted	0	0
forward-reflected/transmitted	43.07	44.74

[8]

This indicates a good quantitative agreement between the model and the experiment.

Obtaining The PDH Signal

Having demonstrated the validity of the model for this experimental configuration, we decided to investigate the effects of asymmetry on the demodulated output signals.

Interesting result is that by careful selection of the demodulation phase we can extract signals that exactly reconstruct a traditional PDH locking signal.

Due to the 2nd order amplitude diffraction efficiency in our case being close to the minimum possible we were able to lock to the forward reflected signal.

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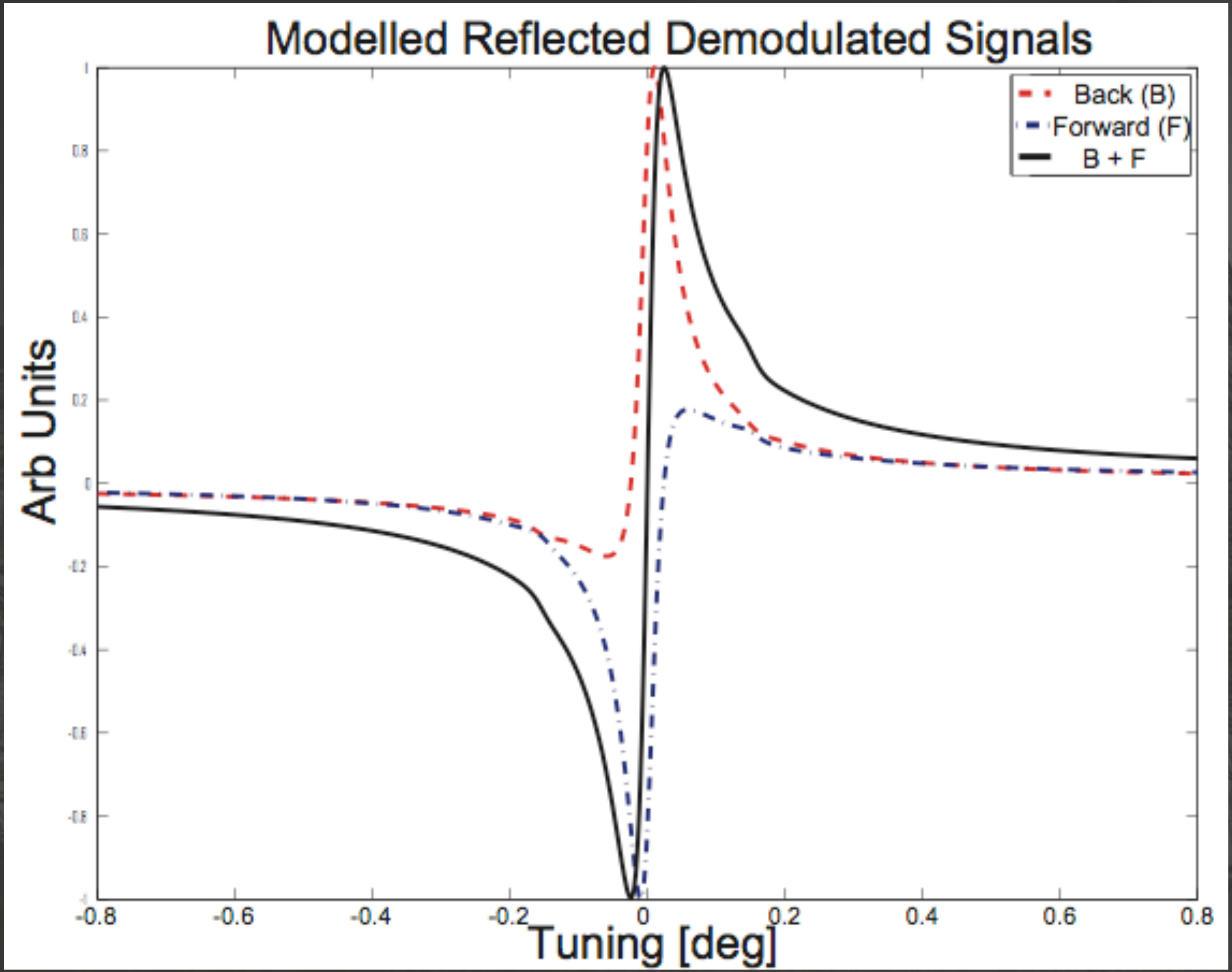
Results



[9]

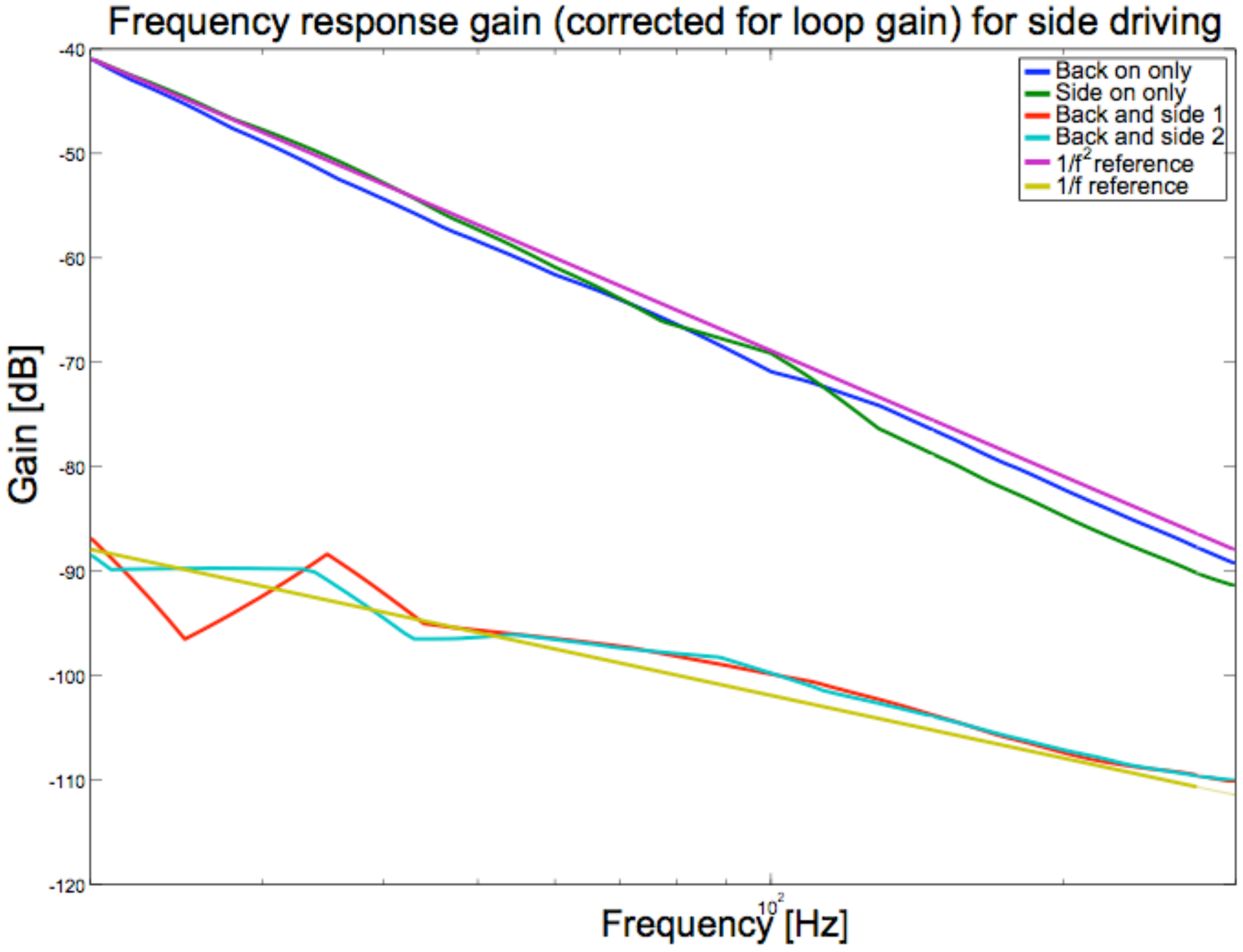
Translational Motion Of Grating

Although these results show that a diffraction grating has similar properties to a mirror in an optical cavity, there are also new features unique to gratings.

Considering translational motion of the input beam across the face of the grating or equivalently the grating with respect to the input beam, there are additional phase components that couple into the signal due to grating period.

This can be best illustrated when observing the magnitude of the frequency response when driving the mirror from side to side.

Translational Motion Of Grating



Grating Translational Motion Effects

Does this pose a problem?

- For our 10m system we were able to lock the diffractive cavity to TEM_{00} mode for hours without any issues.
- Work is ongoing to determine how this effect scales up to larger systems.
- Also investigating how the effect changes with diffraction efficiencies.

However, **rotational** motion will demand **better isolation** than otherwise required.

Conclusions & Future Work

We have shown that the framework for signal extraction from a diffractively coupled Fabry-Perot cavity is now well understood.

Utilising our numerical model we have also revealed the effects of signal asymmetry to the diffractive amplitude efficiencies.

Ongoing work involves extracting alignment signals from a diffractive cavity and building an auto-aligned system.

References

[1] Sun et al, 1998, All-reflective Michelson, Sagnac, and Fabry-Perot interferometers based on grating beam splitters

[2] Bunkowski et al, 2006, Demonstration of three-port grating phase relations

[3] Bunkowski et al, 2006, Diffractive optics for gravitational wave detectors

[4],[6],[7],[8],[9] Edgar et al, (not yet published), Experimental Demonstration of a suspended diffractively-coupled optical cavity

[5] Bunknowski et al, 2005, Input-output relations for a three-port grating coupled Fabry-Perot cavity