Optical Levers for Interferometric Inertial Isolation

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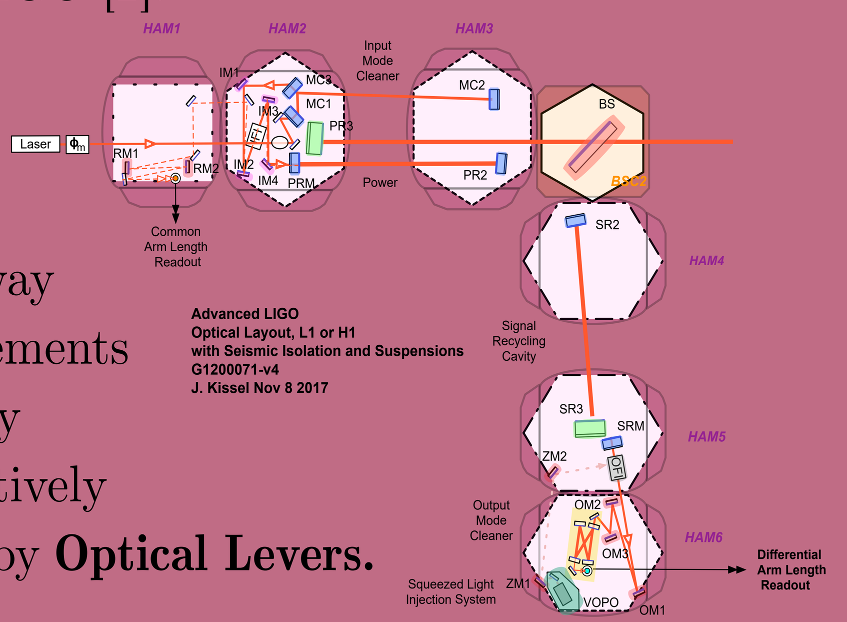
LVC Meeting - Maastricht 2018

INTRODUCTION

LIGO is noisy. Several stages of noise related to optics and benches, affecting measurements in the low frequency range ($<$ **10 Hz**). In particular, the suspension point motion of the HAM5 chamber is dominated by tilt above 1 Hz [1].
Getting a good estimate of ground motion is tricky because no rotational sensors able to measure the ground motion in rotation has been installed yet on LIGO [2].



However, there is a clever way to measure angular displacements of the benches very precisely ($10^{-12} rad/\sqrt{Hz}$) and to actively control them. This is done by **Optical Levers.**

OPTICAL LEVER WORKING PRINCIPLE

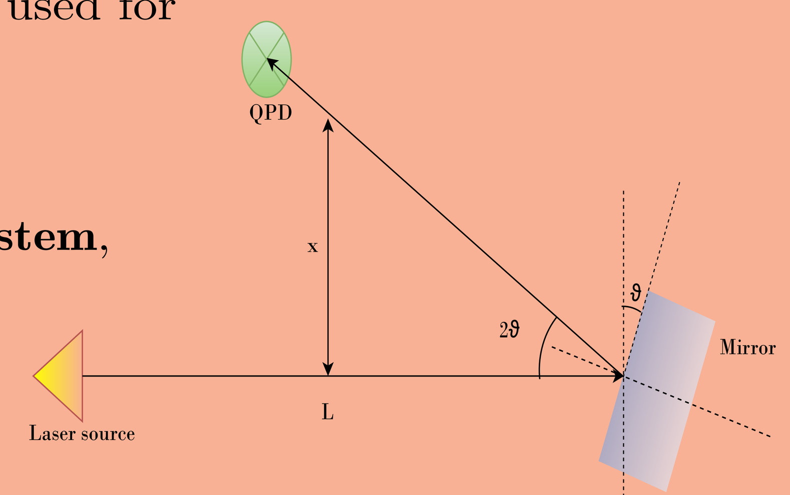
An optical lever is a convenient device to measure a **small displacement** and to measure angles accurately.

The light source is, generally, a laser or an SLD (Super Luminescent Diode) to avoid interference due to reflections.
The sensor used is a QPD (Quadrant Photodiode) measuring any small displacement of the spotlight.
When the mirror is tilted, a spot displacement is recorded and the angle can be computed.

Optical levers for GW interferometers are mainly used for

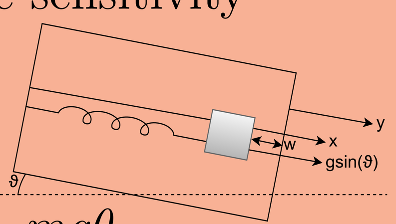
- a local angular control for each mirror;
- monitoring the mirror displacement.

They can also be used for the **seismic isolation system**, to measure the small tilt due to ground motion, affecting the seismometers that measure (and actively control) the seismic motion.



THE IDEA

The most important problem is the sensitivity of the horizontal accelerometers to rotation.



$$m\ddot{x} = -b(\dot{x} - \dot{y}) - k(x - y) + mg\theta$$

Applying the Laplace transform and using

$$w = x - y \qquad s = i\omega$$

$$m(W + Y)s^2 = -bWs - kW + mg\theta$$

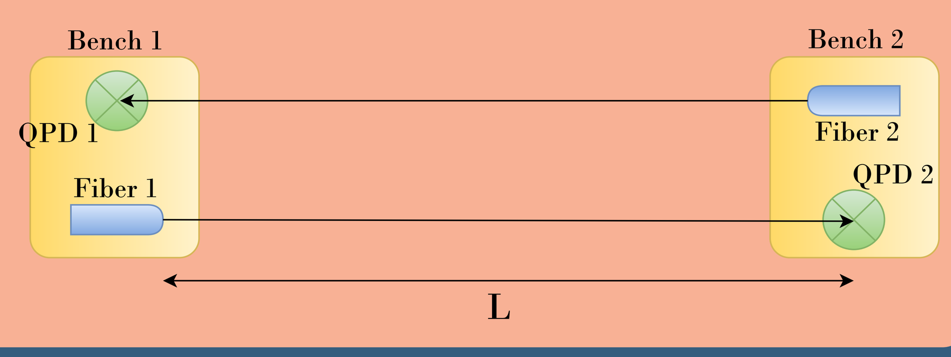
$$W(\omega) = \frac{-m\omega^2}{-m\omega^2 + ib\omega + k}\left(-y \boxed{-\frac{g}{\omega^2}\theta}\right)$$

Optical levers can **directly measure** extremely small tilt angles ϑ and apply corrections to the sensor. This study-in-progress system involves **sensing and actuation** for the seismic motion.

The QPD can not be set on the same bench 1 where geophones are, because it would be affected by the same ground motion. So it has to be placed on a bench 2, at some distance L, and actuation is associated to adjust the tilt of the bench 1.

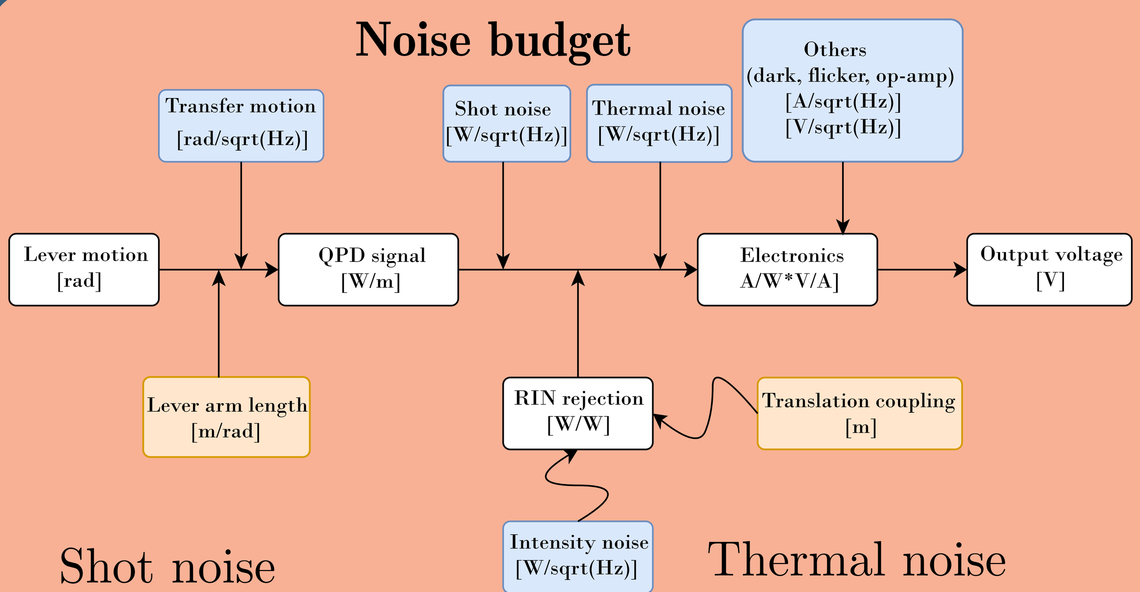
The longer L is, the better the sensitivity to small angles is.

Besides, also the bench 2 needs to be kept stable: another optical lever is placed on it, with the associated actuation.



NOISE BUDGET AND OPTICAL SIMULATION

Noise budget



Shot noise

$$\sigma_p = \sqrt{\frac{2\pi\hbar c P_0}{\lambda}}$$

$$\sigma_p = 1,4 \times 10^{-11}\,\frac{W}{\sqrt{Hz}}$$

λ = 1064 nm

P_0 = 1 mW

Thermal noise

$$V_{th} = \sqrt{\frac{4K_BT}{R}}\,\frac{A}{\sqrt{Hz}}$$

$$T_h = 1,47 \times 10^{-12}\,\frac{W}{\sqrt{Hz}}$$

R=1,3 $\times$ 10^4 Ω

T = 300 K

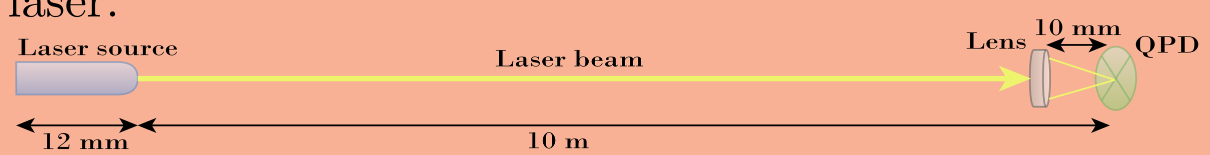
Spot position and displacement

$$P_{x,y} = \frac{P_0}{\pi w_{x,y}^2}\int_0^R e^{-2\left(\frac{x,y}{w_{x,y}}\right)^2} dx, dy \quad \text{Gaussian power}$$

$$\frac{\Delta P_x}{\Delta x} \approx \sqrt{2}\frac{P_0}{\pi w_x}[W/m] \qquad \frac{\Delta P_y}{\Delta y} \approx \sqrt{2}\frac{P_0}{\pi w_y}[W/m]$$

Optical simulation

The chosen source is a 1064 nm wavelength fiber-coupled Nd:YAG solid-state laser.



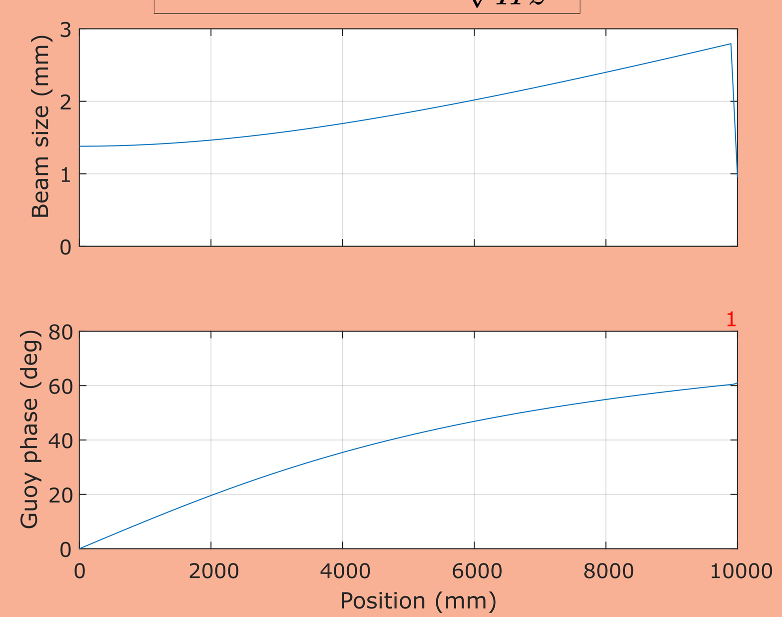
The beam size on the QPD is 1 mm, so a fiber collimator is used at the fiber output, and a 150 mm focal length lens is used to focus the beam.

Resolution

$$\alpha = shotnoise \times \frac{1}{signal} \times \frac{1}{Length},$$

$$\alpha = \sigma_p \times \frac{1}{\sqrt{2}\frac{P_0}{\pi w_y}} \times \frac{1}{L},$$

$$\alpha = 3 \times 10^{-12}\,\frac{rad}{\sqrt{Hz}}$$



PROTOTYPE DESIGN

To test the sensitivity of the QPD, a **prototype** of the Optical Lever has been designed. The whole setup could be placed in vacuum, so the system is **very compact**.

The aluminium basement is [75 cm $\times$ 36 cm].
The photodiode has a [4×12] mm^2active area.

NEXT STEPS

Experiment status

The prototype of the Optical Lever is going to be built and tested in the laboratories of the University of Birmingham.
The actuation system for the correction of angular motion of the bench will be designed and simulated.

Future perspectives for LIGO

The Optical Lever sensing and actuation system could be a good chance to improve the sensitivity of the interferometer at frequencies **below 10 Hz**.
This will allow the detection of Gravitational Waves in a range of frequency in which LIGO is currently blind.

References

[1] B. Lantz et al. Estimates of HAM-ISI motion for A+, T1800066-v2, March 2018

[2] S. Cooper et al. Ham ISI model, Technical note, University of Birmingham, March 2018

[3] B. Lantz et al. Review: Requirements for a Ground Rotation Sensor to Improve Advanced LIGO, Bulletin of the Seismological Society of America, Vol. 99, No. 2B, 2009