Optical Gyroscopes for Ground Tilt Sensing in Advanced LIGO

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The need for low frequency tilt sensing

The optics in Advanced LIGO's suspensions must be very well isolated from the seismic motion of the ground. At 10Hz, approximately 9 orders of magnitude isolation is required to achieve design sensitivity [1].

At lower frequencies, as the interferometer length is altered away from the correct operating point, there is a non-linear coupling of mirror motion to output signal. At the extremes of this, the detector will no longer be able to lock. To reduce such effects to an acceptable level, the length of the 4km arms must be held to better than $1x10^{-14}$m [1] despite much larger fluctuations arising, for example, from tidal deformation of the Earth's crust.

The low frequency isolation is achieved actively, with seismometers being used to feed forward to the hydraulic HEPI actuators. The sensitivity of the seismometers to horizontal motion at low frequencies is good enough to achieve the required isolation. However coupling of rotations, or ground tilt, into horizontal seismometer signals at low frequency are problematic. For a horizontal seismometer the ratio of sensitivity to rotation, to sensitivity to horizontal motions at a frequency ω, is given by:

$$\frac{rotation\ sensitivity}{horizontal\ sensitivity} = -\frac{g}{\omega^2}$$

Below some frequency we may expect that the response of the seismometers will become dominated by tilt. If this signal is fed forward into the system, it may execute horizontal translations in response to these erroneous signals.

By using a rotation sensor in parallel with the seismometers, it will be possible to remove the rotation component of the signal that is fed forward to the active stage.

In order to calculate the rotational sensitivity required, we shall assume that noise from the rotational sensor must contribute only 1/10th of the total noise in the horizontal direction. Using the above equation we can express this as:

$$\Omega_{sensitivity} = \frac{1}{10}\frac{\omega^2}{g}x_d$$

where x_d is the horizontal sensitivity requirement. At 0.2Hz, this gives a goal of $3\times10^{-9}\ rad/\sqrt{Hz}$.

Current gyroscope technology

Laser based gyroscopes operate on the sagnac principle, whereby the path length for light travelling round a ring is altered as it rotates. Beams sent in opposite directions round the ring are interfered at the output giving a beat frequency that is proportional to the rotation rate.

They are commonly used in a variety of applications, from weapons guidance to consumer products and are based on ring laser, passive cavity, or fibre gyro designs. Generally the requirement is for a small, rugged unit capable of measuring relatively large rotation rates. However, research is also taking place into larger scale, high sensitivity gyroscopes for geophysical measurements. The Ring Laser Group at the University of Canterbury, operating the worlds largest ring laser ($800m^2$), has achieved sensitivities of $4\times10^{-9}\ rad/\sqrt{Hz}$ [2,3], while the 'G-Ring', a $16m^2$ ring laser built in Germany reached $10^{-10}\ rad/\sqrt{Hz}$

Design of externally excited laser gyro

Our research is focussed on producing a passive ring gyroscope using fixed mirrors. The two counter propagating beams, will each be locked to a triangular cavity.

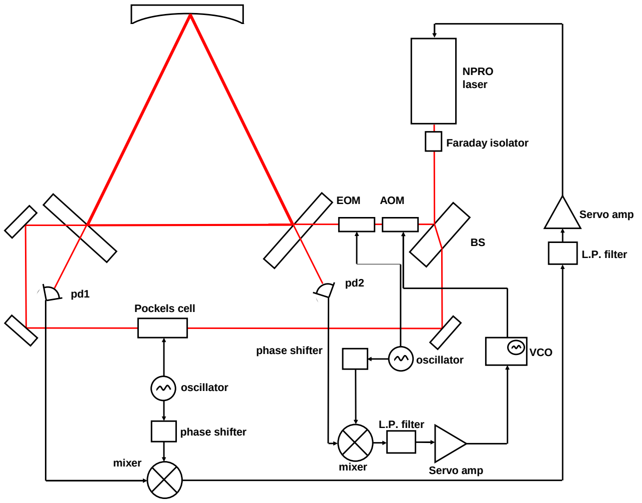

Fig. 1 Diagram of externally excited laser gyroscope

The counter clockwise beam (CCW) is modulated using an EOM to produced sidebands that allow PDH locking to the cavity by altering the laser frequency. The CW beam is likewise modulated, and locked using an AOM to shift the frequency. The beat frequency between the modulation frequencies is dependent on the rotation rate, Ω, and is given by:

$$\Delta f = \frac{4A}{\lambda P}\Omega$$

where A is the area of the ring, P is the length of the perimeter of the ring and Ω is the rotation rate. To avoid lock-in problems [4], where the frequency of the two counter propagating beams lock together, different modulation frequencies will be used for each beam.

Sensitivity calculations

The sensitivity of a shot noise limited passive laser gyroscope is given by [5]:

$$\delta\Omega = \left(\frac{\lambda P}{4A}\right)\frac{\sqrt{2}\Gamma}{\sqrt{(n_{ph}\eta\tau)}}$$

Γ, is the bandwidth, n_{ph} is the number of photons arriving at the detector, η is detector efficiency, and τ is integration time. Assuming a triangular cavity with 1m sides and finesse of 1000, the sensitivity achieved will be $\sim1\times10^{-10}\ rad/\sqrt{Hz}$.

Acknowledgements

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References

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