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LIGO Laboratory / LIGO Scientific Collaboration

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Geometric OSEM Sensor Development

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of the Advanced LIGO Project, prepared by members of the UK team.

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1 Introduction

The work undertaken to design an opto-electronic sensor that will meet the sensitivity requirements of an advanced LIGO OSEM is based on experience gained by C. Speake and colleagues, whilst working at the International Bureau of Weights and Measures (BIPM), Paris. This note documents the progress made at the University of Birmingham over the past six months in developing and testing one of the detector candidates outlined in the original discussion paper by C. Speake. [1]

2 Optical Design

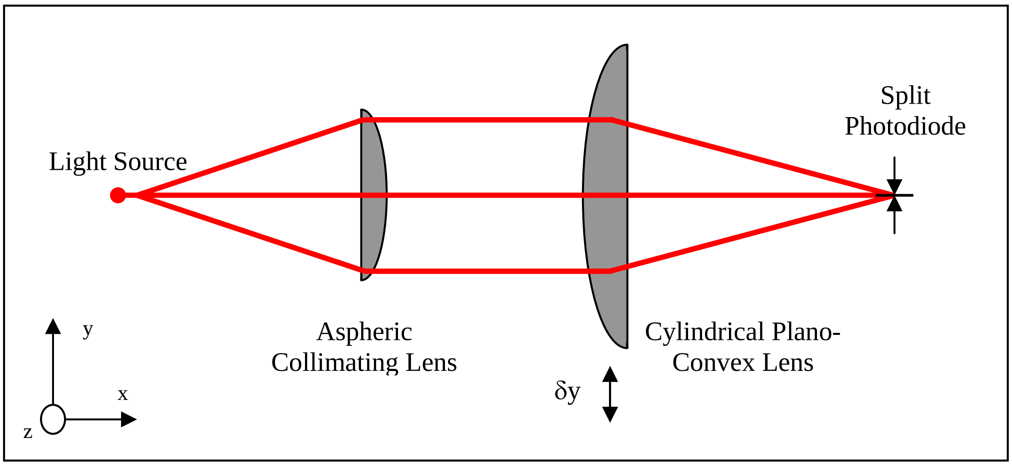


Figure 1. Optical Configuration.

Figure 1 shows the layout of the optical components of the geometric sensor. A cylindrical lens is employed to focus a beam from a collimated light source down onto a split photodiode. This cylindrical lens would be attached to the test mass / flag, thus enabling the image that is formed on the photodiode to move transversely, in *y*.

This method is advantageous since all light is collected by the photodiode and it is insensitive to displacement in the *x* and *z* planes. However, this system is sensitive to rotation of the test mass about the *z*-axis. This problem may be overcome by reducing the focal length of the cylindrical lens, but at the cost of reducing the magnification and dynamic range of the detector.

Another approach discussed by C. Speake[1] that improves on the image-sensor design is that of the shadow-sensor. This method is similar to the configuration shown in figure 1, except that an opaque cylindrical object is placed between the collimated light source and detector. This scheme has the great advantage of having little sensitivity to rotation of the object. However, it is likely that some of the optical power will be scattered by the object.

3 Electronics Design

The majority of testing that has been carried out for the geometric sensor, has been conducted using a commercial infrared (880nm) LED (OD-50L) by Opto Diode Corp.[2] This device has a typical power output of 50mW at 500mA forward current and is fairly well collimated, with a beam emission half-angle of 7^0. Off-the-shelf this device is available mounted in a TO-39 hermetically sealed package.

A UDT SPOT-9D[3] quadrant photodiode is employed as the split detector. The dead band between elements is 0.102mm and active area per element of $19.6mm^2$. This device has a spectral response in the range 350-1100nm and a maximum recommended incident power density of 100 W/m^2. Application of a reverse bias to the photodiode (photoconductive operation) allows for an increase in the linearity of the device response. The photodiode is supplied in a 1” diameter low-profile package.

The detector electronics follows the conventional approach of photodiode current amplification using trans-conductance amplifiers, with the output from each segment being passed through a unity gain differential amplifier, which ultimately provides the output signal corresponding to the voltage difference between the two segments. The trans-conductance output from each segment is also passed to a summing amplifier and IRLED driver circuit. This feedback loop is adopted so that we can enable the active intensity stabilisation of the IRLED source.

The electronics board constructed has 4-outputs (two trans-conductance, a summing, and a differential) for diagnostics / measurement purposes and a single reference voltage input, used to regulate the forward current through the IRLED device. Support electronics also provide regulated power supplies - required for operational amplifier supply rails and reverse biasing of the photodiode. Standard commercial specification components have initially been used to construct and test the prototype sensor. Low-noise operational amplifiers (OP07) are employed as trans-conductance, differential and summing amplifiers, as well as for the active stabilisation (voltage-following operational amplifier).

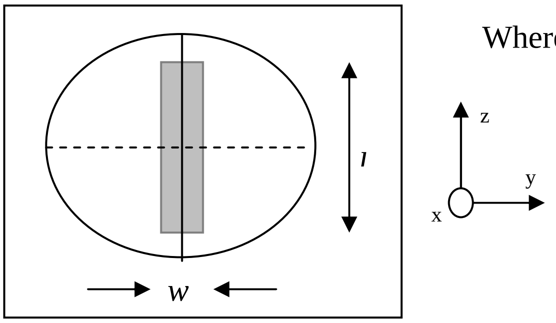
The dc reference voltage required for the active intensity stabilisation also has the provision that an ac signal can be modulated onto the IRLED output. This enables a modulated, ac “lock-in” technique to be adopted if required. Demodulation of the signal takes place at the differential output at the lock-in frequency (1kHz in this case).

Both schemes, modulated and un-modulated, have been investigated and the sensitivity performance of the opto-electronic geometric detector detailed in the results section.

4 Sensitivity Calculation

The fundamental physical constraint using the optical configuration described in section 2 is the limited incident intensity that can be focused onto the photodiode. For most commercial devices, as in this case, a linear response (to within 1%) is specified up to 10mW / cm^2. Incident power densities in excess of this rating will first cause non-linearity in the response and eventually lead to saturation of the device.

A maximum sensitivity estimate of the device, incorporating this photodiode limitation, can be derived as follows:



Where:

l, Length of image formed ≈ 10 mm

w, Width of image formed ≈ $\sqrt{2}$ mm

Split photodiode dead band = 0.102 mm

Figure 2. Photodiode Active Elements.

If the total incident power upon photodiode = P_T (W)

Then, the power density, $p = \dfrac{P_T}{wl}$ (W / m^2) (1)

Responsivity is given as, $\alpha = 0.65$ (A / W) @ 880 nm (IRLED)

Thus, currents induced (each side): $i_1 = \alpha p s_1$ & $i_2 = \alpha p s_2$ (2)

Where, the areas illuminated (each side): $s_1 = \left(\dfrac{w}{2} + y\right) l$ & $s_2 = \left(\dfrac{w}{2} - y\right) l$ (3)

Hence, the change in induced current: $$\Delta i = i_1 - i_2 = \alpha pl\frac{w}{2} + \alpha ply - \alpha pl\frac{w}{2} + \alpha ply \quad (4a)$$

$$\Rightarrow \Delta i = 2\alpha ply = \frac{2\alpha P_T y}{w} \quad (4b)$$

This leads to: $$\frac{d(\Delta i)}{dy} = \frac{2\alpha P_T}{w} \quad (5)$$

We now assume that any electrical noise sources and Johnson noise will be negligible compared to the shot noise of the system (i.e. shot noise limited).

Shot Noise limit, $$\sigma_{i_1,i_2} = \sqrt{2ei_{1,2}} \text{ (A/rtHz)} \quad (6a)$$

Where: e is the charge of an electron (1.602×10^{-19} C)

$$\Rightarrow \sigma_{i_1,i_2} = \sqrt{2e\alpha\left(\frac{P_T}{wl}\right)\left(\frac{wl}{2}\right)} = \sqrt{e\alpha P_T} \text{ (A/rtHz)} \quad (6b)$$

Adding the shot noise terms for each element in quadrature:

$$\sigma_{i_1,i_2} = \sqrt{\sigma_{i_1}{}^2 + \sigma_{i_2}{}^2} = \sqrt{2e\alpha P_T} \text{ (A/rtHz)} \quad (6c)$$

Thus, the sensitivity can be determined from:

$$\sigma_y = \frac{\sigma_{i_1,i_2}}{\left(\frac{d(\Delta i)}{dy}\right)} = \frac{\sqrt{2e\alpha P_T}}{2\alpha P_T} w = w\sqrt{\frac{e}{2\alpha P_T}} \text{ (m/rtHz)} \quad (7)$$

However, we can now substitute into (7) the limiting photodiode power density value, p_{max}, and responsivity, α.

Maximum power density, $p_{max} = \frac{P_T}{wl} = 10\,mW/cm^2 = 100\,W/m^2$

Hence, $$\sigma_y = w\sqrt{\frac{e}{2\alpha p_{\max} wl}} \text{ (m/rtHz)} \quad (8a)$$

Equivalently, $$\sigma_y = \sqrt{\left(\frac{e}{2\alpha p_{\max}}\right)}\sqrt{\left(\frac{w}{l}\right)} \text{ (m/rtHz)} \quad (8b)$$

Substituting in the correct values now enables us to obtain a sensitivity estimate of:

$$\sigma_y = \sqrt{\left(\frac{1.602\times10^{-19}}{2\times0.65\times100}\right)}\sqrt{\left(\frac{w}{l}\right)} = 1.3\times10^{-11} \text{ (m/rtHz)} \quad (9)$$

Where: Width of image formed, $w = \sqrt{2}$ mm
Length of image formed, l = 10 mm

This result demonstrates that our prototype sensor should be able to reach sensitivities of a similar order of magnitude (1×10^{-11} m/rtHz) to those specified by K. Strain in the interpretation of the OSEM requirements document,[4] whilst retaining an operating (displacement) range of $2\sqrt{2}$ mm (peak-peak). Note that, this result assumes we are using the specified linear range of the photodiode and are not saturating the device.

It was imperative that we build a prototype opto-electronic sensor using off-the-shelf components to determine if this sensitivity result, which we have obtained analytically, could be realised.

5 Results

The results following detail the performance of the prototype opto-electronic sensor as discussed in sections 2 and 3.

As noted in section 4, the fundamental noise source of the system is ideally the shot noise. However, other noise sources will also contribute, for example electronics noise in the form of Johnson noise and a 1/f contribution from the operational-amplifiers. Figure 3 shows the electronics noise performance of the system (measured with the IRLED emitter turned off). This corresponds to a current noise of approximately 40 pA/rtHz, which is slightly above the shot noise limit of 35 pA/rtHz, but sufficient so as to allow sensitivities of approximately 1×10^{-11} m/rtHz to be measured.

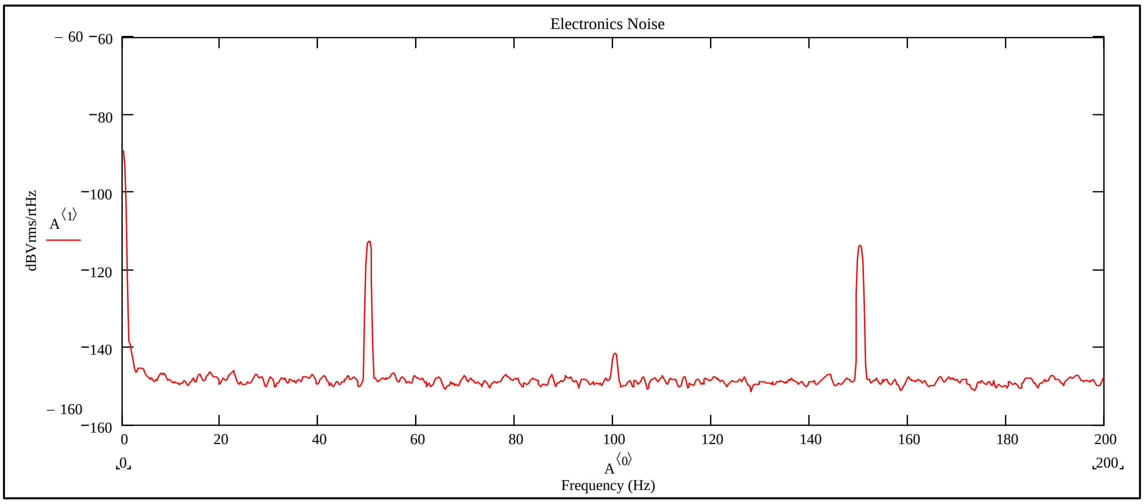


Figure 3. Electronics Noise.

Figure 4 shows the noise plots obtained for the geometric sensor with the dc un-modulated (red trace) and ac modulated, "lock-in" scheme (blue trace). The shot noise limit is denoted by the green trace.

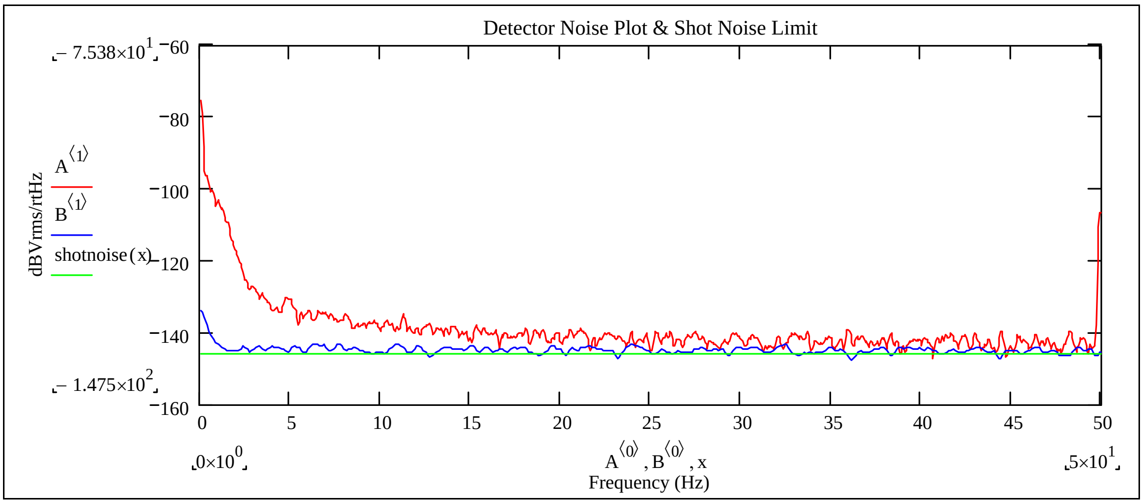


Figure 4. Geometric Sensor Noise.

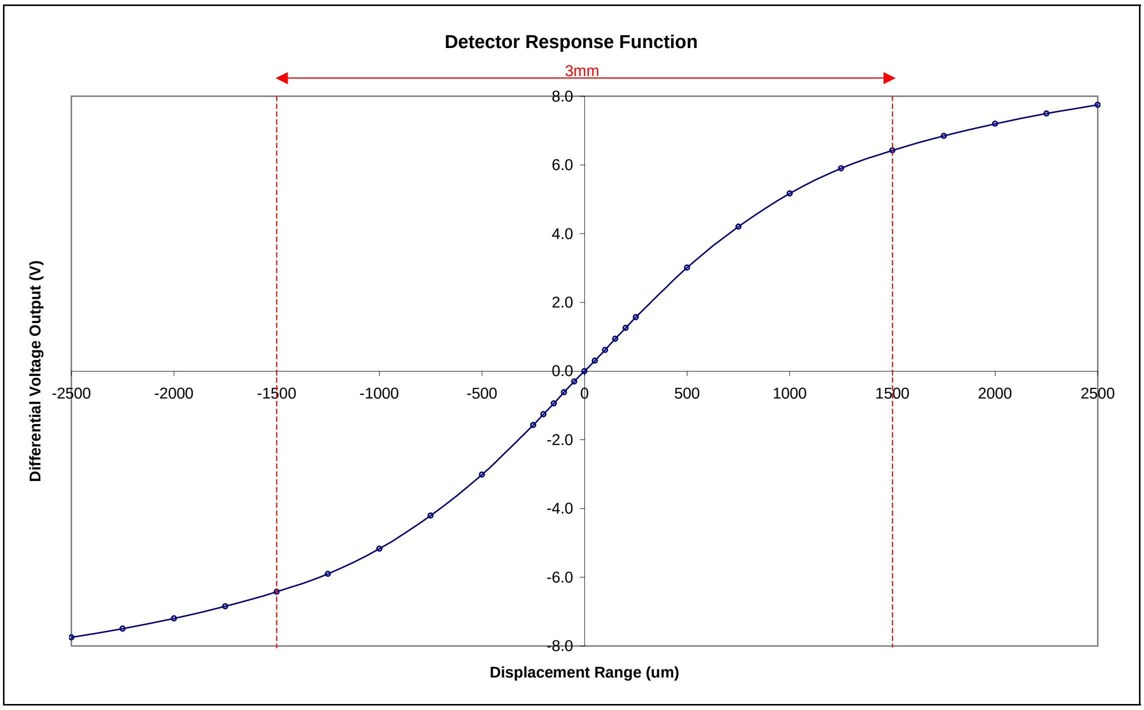


Figure 5. Detector Response Function.

Figure 5 shows the measured response function of the detector. The near-linear region corresponds to a maximum responsivity of approximately 4500 V/m over a 3mm peak-peak range. This is also equivalent to a full range voltage output of the differential amplifier equal to ± 7 Volts.

Now that the noise performance and response function of the detector have been measured, we are able to determine the sensitivity of the device. Again, using both un-modulated (red trace) and ac modulated, "lock-in" (blue trace) schemes, the sensitivity of the prototype geometric sensor is as shown in Figure 6. Note that, the broken black trace denotes the shot noise limited sensitivity.

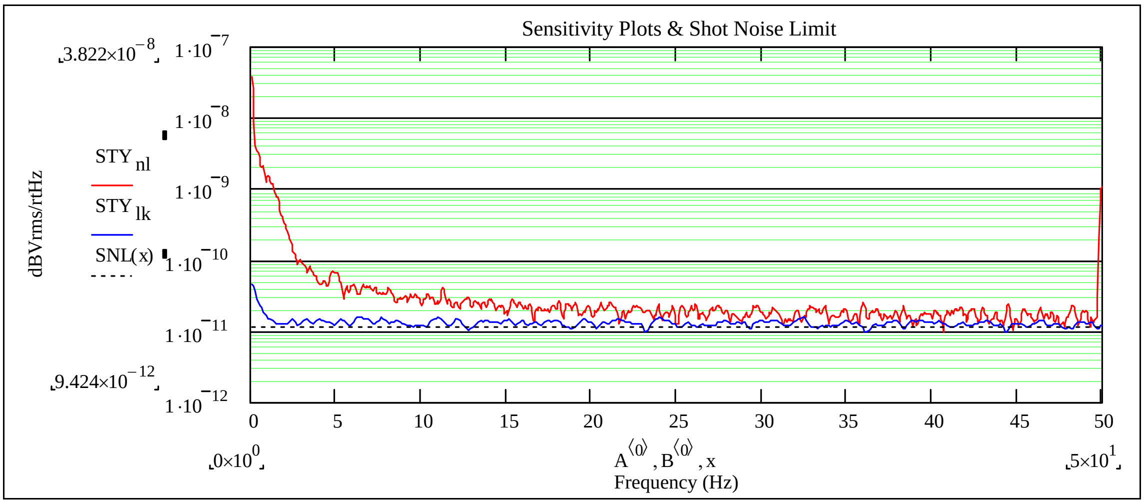


Figure 6. Detector Sensitivity.

6 Conclusions

It can be seen from figure 6 that the sensitivity performance of the un-modulated and lock-in methods are similar for frequencies >25Hz - with the exception of the 50Hz noise feature present in the un-modulated scheme. Both methods are able to achieve a maximum sensitivity of approximately $2x10^{-11}$m/rtHz at frequencies >25Hz. However, it is the low frequency performance (0-25Hz) of the ac modulated, "lock-in" scheme, that shows a significant improvement when compared to the dc un-modulated method over the same bandwidth.

To summarise, the sensor's ac performance can be characterised as follows:

- LIGO basic science mode performance, ≤ $1.5x10^{-11}$ m/rtHz (around 10Hz)
- LIGO control band noise performance, ≤ $1.5x10^{-11}$ m/rtHz (down to ≈ 1Hz)

These sensitivities have been achieved whilst coupling approximately 12mW of incident light intensity onto the photodiode. The IRLED emitter has a steady-state total power dissipation of ≈ 620mW.

Results obtained suggest that this detector concept is likely to fulfil the LIGO requirements for local control OSEMs. However, a significant issue surfaced during testing that constitutes a significant technical risk to using this approach.

Results presented within this document are all taken at the detectors optimal 'null' position, i.e. the image is formed at the centre of the photodiode (image falling across the dead-band). Movement of the detector away from the 'null' position proportionally raises the noise floor by a considerable margin. Hence the sensitivity performance detailed above could not be realised over the whole 3mm peak-peak range required for the instrument.

A similar "off-null" excess noise issue has also been observed with a similar prototype geometric sensor being developed by Nick Lockerbie at the University of Strathclyde. Both designs of geometric sensor share a key component, the IRLED emitter. It has initially been surmised that this could be the cause.

7 Future Work

Future work will be to undertake the task of continuing to characterise the noise performance of the opto-electronic sensor at low frequencies and identifying the optimal light source. Alternative approaches will also be tested and assessed, such as using Laser Diode sources. The possibility of using a fibre pigtailed laser diode or IRLED device is also under investigation, as well as using the shadow sensor configuration (see section 2).

Research into photodiode fabrication options has also been carried out and a proposal put forward by μAME.[5] The outcome of this is that we anticipate being able to obtain photodiodes with maximum power densities up to 100mW/cm^2, if required.

The most fundamental issue that requires further investigation is the "off-null" noise performance, in an attempt to identify the source of the excess noise.

8 References

[1] C. Speake, Opto-electronic Detectors; BIPM Designs, June 2003, University of Birmingham.

[2] Opto Diode Corp. web-link: http://www.optodiode.com/index.html (Current 29/01/04)

[3] UDT Sensors Inc. web-link: http://www.udt.com/multielementphotodetectors.htm (Current 29/01/04)

[4] K. Strain, Advanced LIGO suspensions general interpretation of requirements for sensors - for use as an initial planning aid by the UK project team V1.01, June 2003, University of Glasgow. ALUKGLA0005JUN03.

[5] Dr. Thor Erik Hansen, Technical Director, μAME. Kongeveien, Norway.