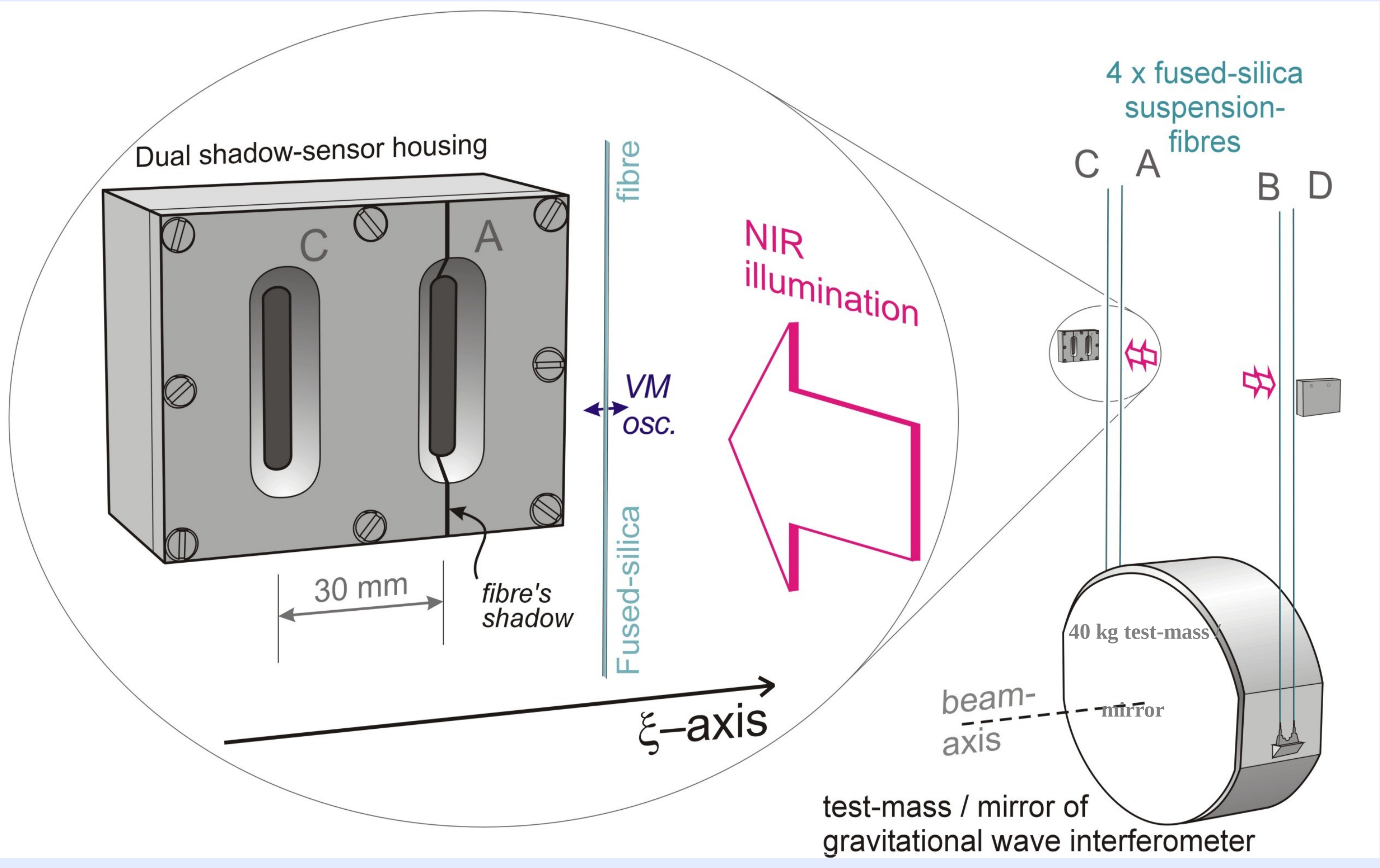
University of Strathclyde Glasgow

Shadow-sensing of Violin-Modes on an Advanced LIGO Suspension

SUPA LSC

The detection of shadows

Certain simple detectors of displacement comprise a collimated source of (often, Near Infra Red) light, and a photodiode (PD) detector, with the moving part interposed between them such that it casts a shadow onto the PD. When a silica suspension fibre's shadow, or the edge of a metallic flag's shadow in an OSEM (Optical Sensing ElectroMagnet), falls across the face of a PD, then clearly any subsequent lateral movement of the fibre or flag can cause a change in that PD's photocurrent—via the corresponding movement of the shadow. What may not be immediately apparent, however, is the fact that the PD's sensitivity to this lateral displacement depends upon the depth of the shadow only at the PD's optical edge(s), as explained below: -



Silica suspension-fibres and the *Violin-Mode* shadow-sensing arrangement. *VM* motion was sensed parallel to the ξ-axis.

Photodiode is mounted behind slit of area (width × height) = **w × h**.

Irradiance of incident NIR beam at PD = $\mathbf{I_0}$ [W.m^{-2}].

Photodiode's responsivity = ***r*** [A.W^{-1}].

Depth of fibre's shadow = **g(x)** — dimensionless number between 0 and 1 (0 ≡ transparent; 1 ≡ opaque).

x-axis is imagined to be fixed to the shadow.

The shadow is offset from centre of the aperture (or vertical 'slit') in the mask by a variable distance, **ξ**.

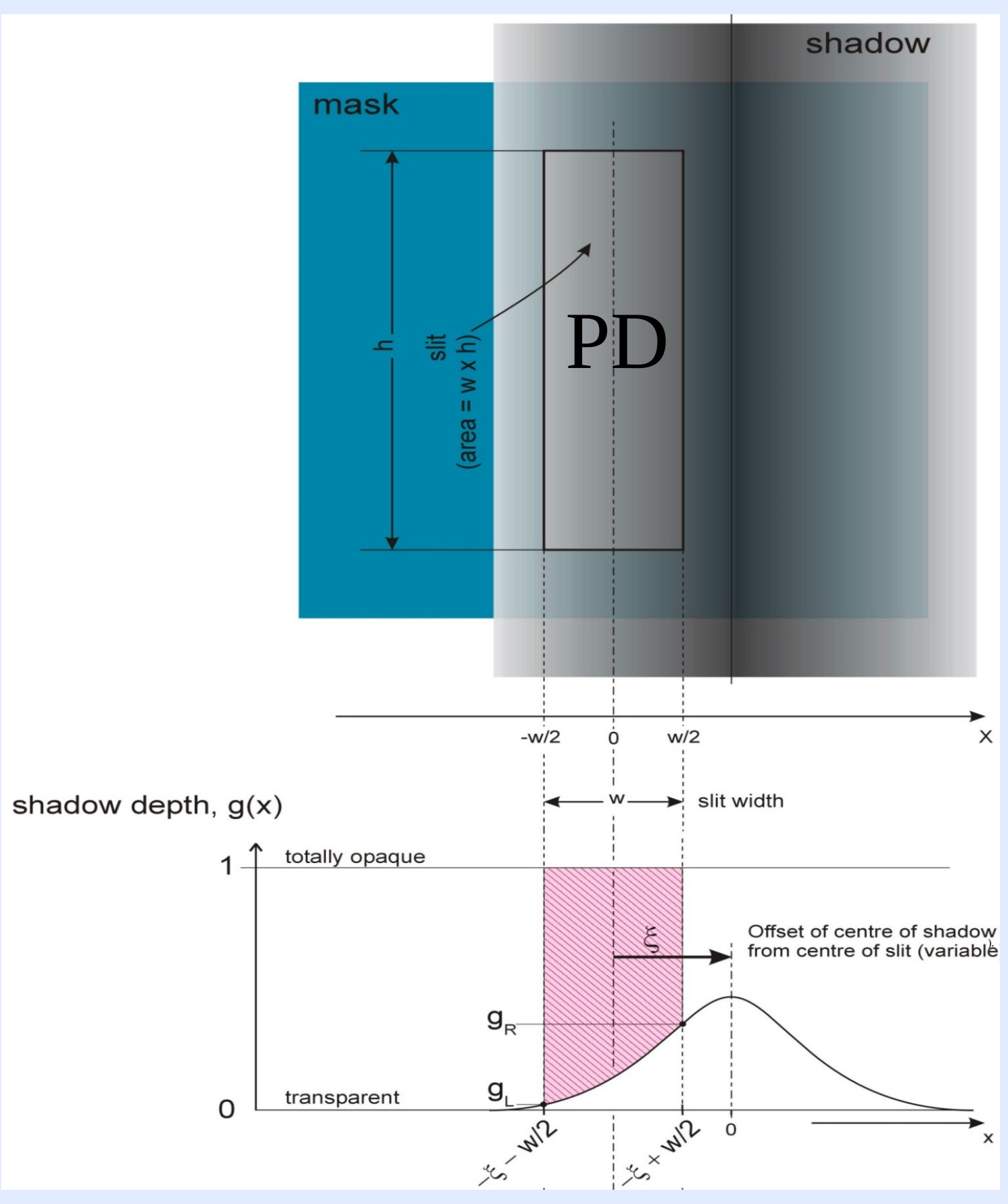
The PD's photocurrent, $\boldsymbol{i_{photo}}$, is then given by: -

$$i_{photo} = r.\mathrm{I}_0.\mathrm{h}.\left(\int_{-\xi-\mathrm{w}/2}^{-\xi+\mathrm{w}/2}(1-\mathrm{g}(\mathrm{x}))\mathrm{dx}\right)$$

, and therefore its rate of change with shadow position by: -

$$\frac{\partial i_{photo}}{\partial \xi} = r.\mathrm{I}_0.\mathrm{h}.\frac{\partial}{\partial \xi}\left(\int_{-\xi-\mathrm{w}/2}^{-\xi+\mathrm{w}/2}(1-\mathrm{g}(\mathrm{x}))\mathrm{dx}\right)$$

Using the Leibniz Integral Rule for differentiating under the integral sign...



$$\frac{\partial}{\partial \xi}\left(\int_{a(\xi)}^{b(\xi)} f(\mathrm{x},\xi).\mathrm{dx}\right) = \int_{a(\xi)}^{b(\xi)} \frac{\partial f}{\partial \xi}.\mathrm{dx} + f(b(\xi),\xi).\frac{\partial b}{\partial \xi} - f(a(\xi),\xi).\frac{\partial a}{\partial \xi}$$

...leading to

$$\frac{\partial i_{photo}}{\partial \xi} = r.\mathrm{I}_0.\mathrm{h}.\{\mathrm{g}(-\xi+\mathrm{w}/2)-\mathrm{g}(-\xi-\mathrm{w}/2)\}$$

, so that

$$\frac{\partial i_{photo}}{\partial \xi} = r.\mathrm{I}_0.\mathrm{h}.\{\mathrm{g_R}-\mathrm{g_L}\}.$$

If shadow does not overlap Left side of effective PD, then $\mathrm{g_L} = 0$,

and so **sensitivity to shadow displacement** becomes: -

$$\boxed{\frac{\partial i_{photo}}{\partial \xi} = r.\mathrm{I}_0.\mathrm{h}.\mathrm{g_R}}$$

If detector is shot-noise limited, photodiode's RMS noise current ∝ square-root of the exposed area of PD, so that

$$\boldsymbol{i_{shot\_N}} \propto \underline{\sqrt{\mathrm{w}\times\mathrm{h}}}\,,$$

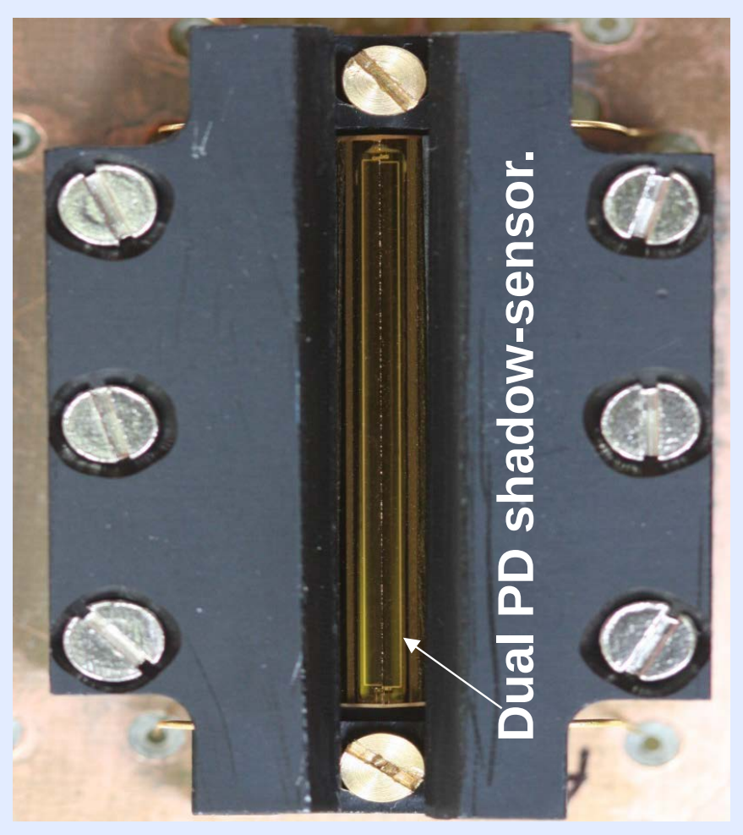
and the signal / noise ratio of the detector: $\propto \sqrt{\underline{\underline{\mathrm{h/w}}}}$ (also $\propto \sqrt{r.\mathrm{I}_0}$, and $\propto \mathrm{g_R}$)

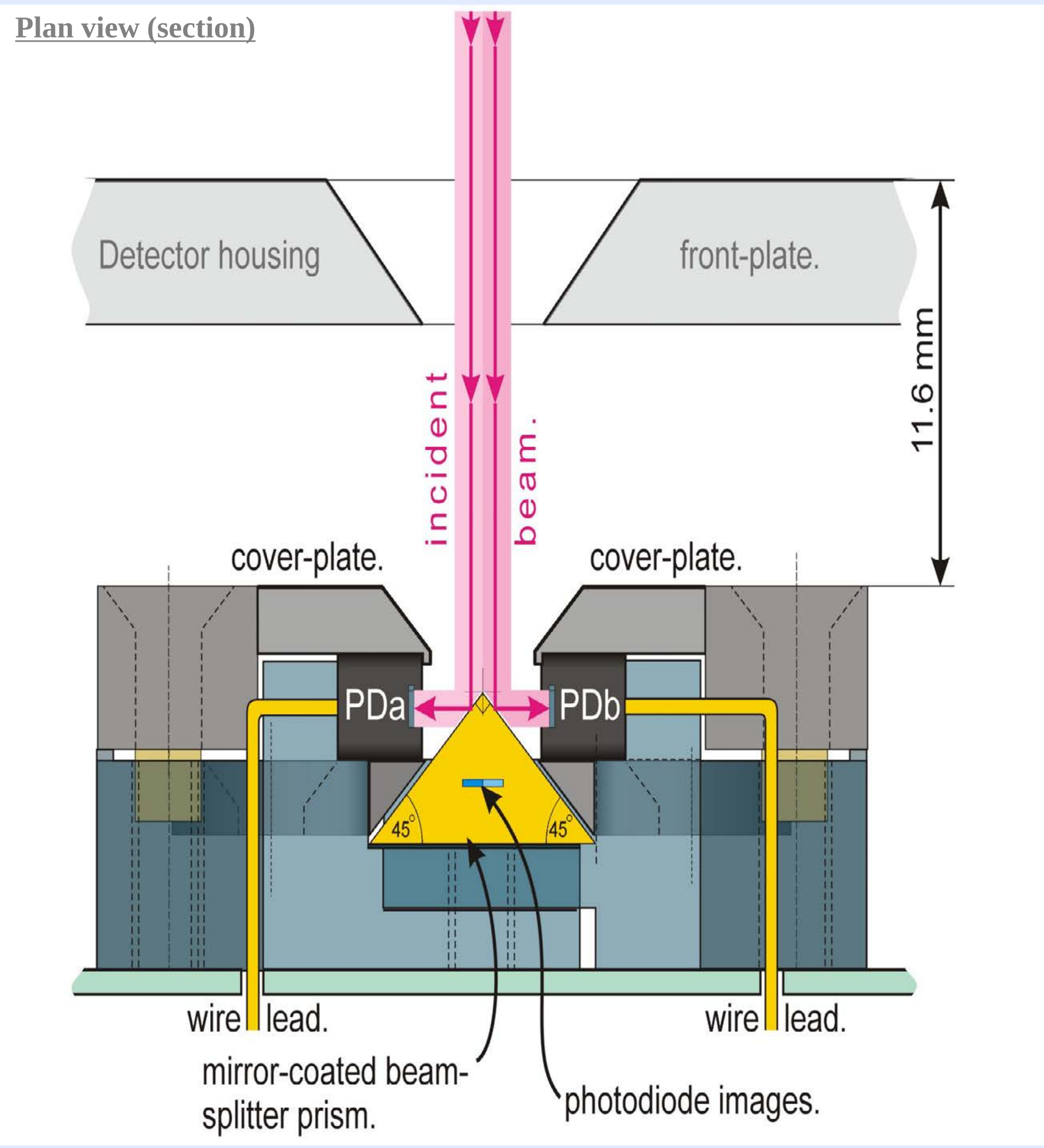
- Therefore, need 'tall-narrow' PD detectors, high irradiance, and deep shadows.

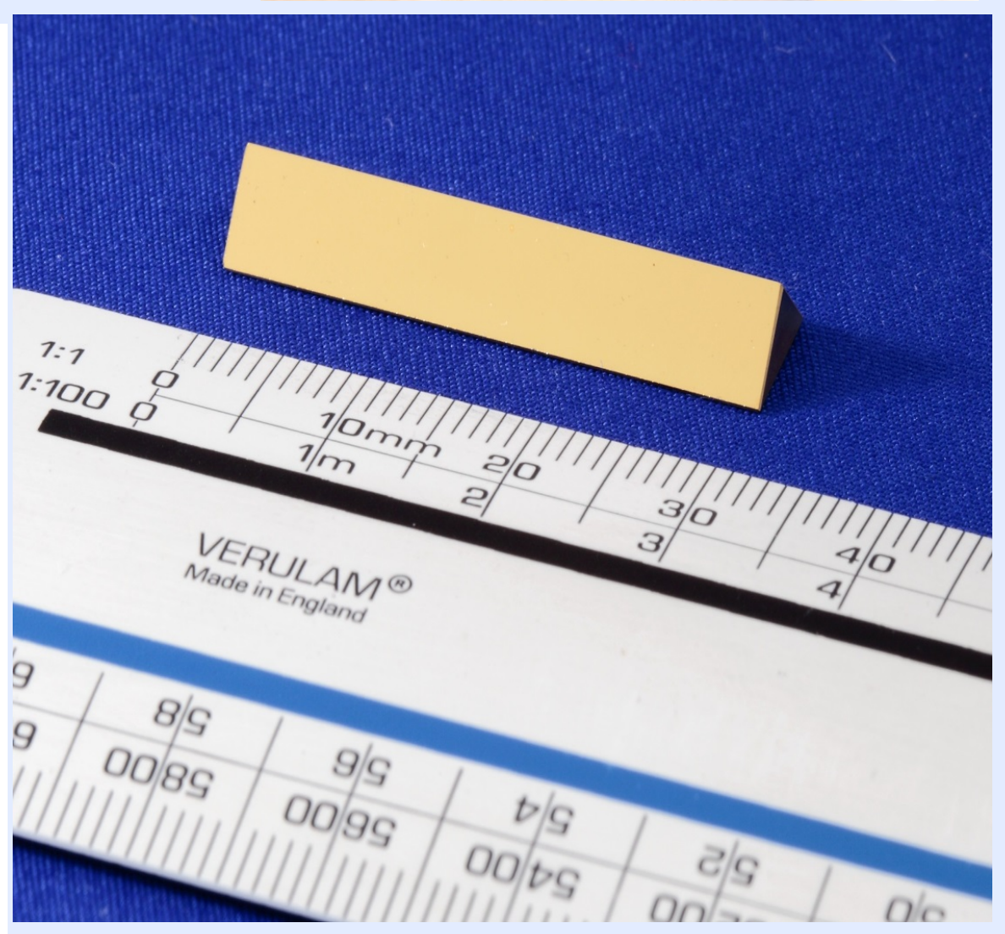
Moreover, in consequence the PD's sensitivity to displacement depends only on its length perpendicular to the sense of the displacement (here, labelled h), and not at all on its width (here, labelled w); but for best signal-to-noise h must be large and w small relative to h.

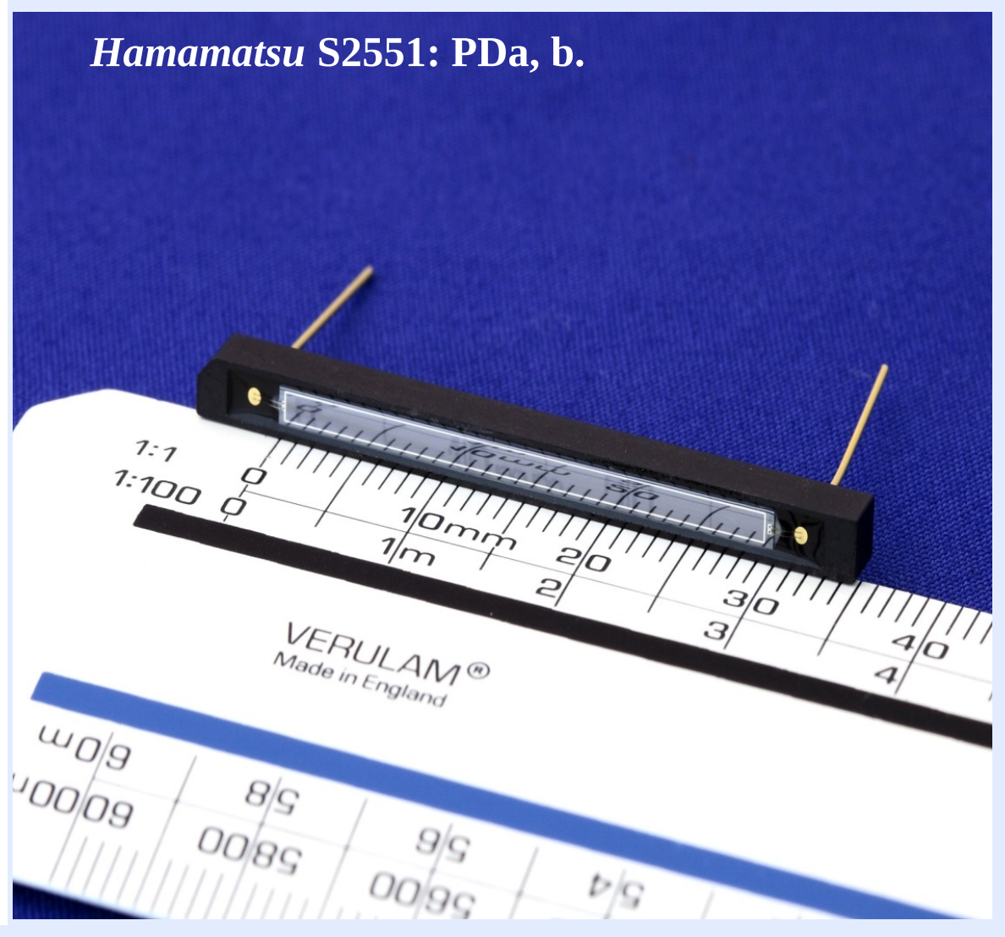
Violin-Mode oscillations

Seismic events, mechanical stress relaxation, etc., can ring-up sustained '*Violin-Mode' (VM)* oscillations in the four suspension fibres which support each GW detector's test-masses / mirrors. Although they may be present only at low levels, these oscillations may persist for days—preventing observation of gravitational waves during this dead-time.





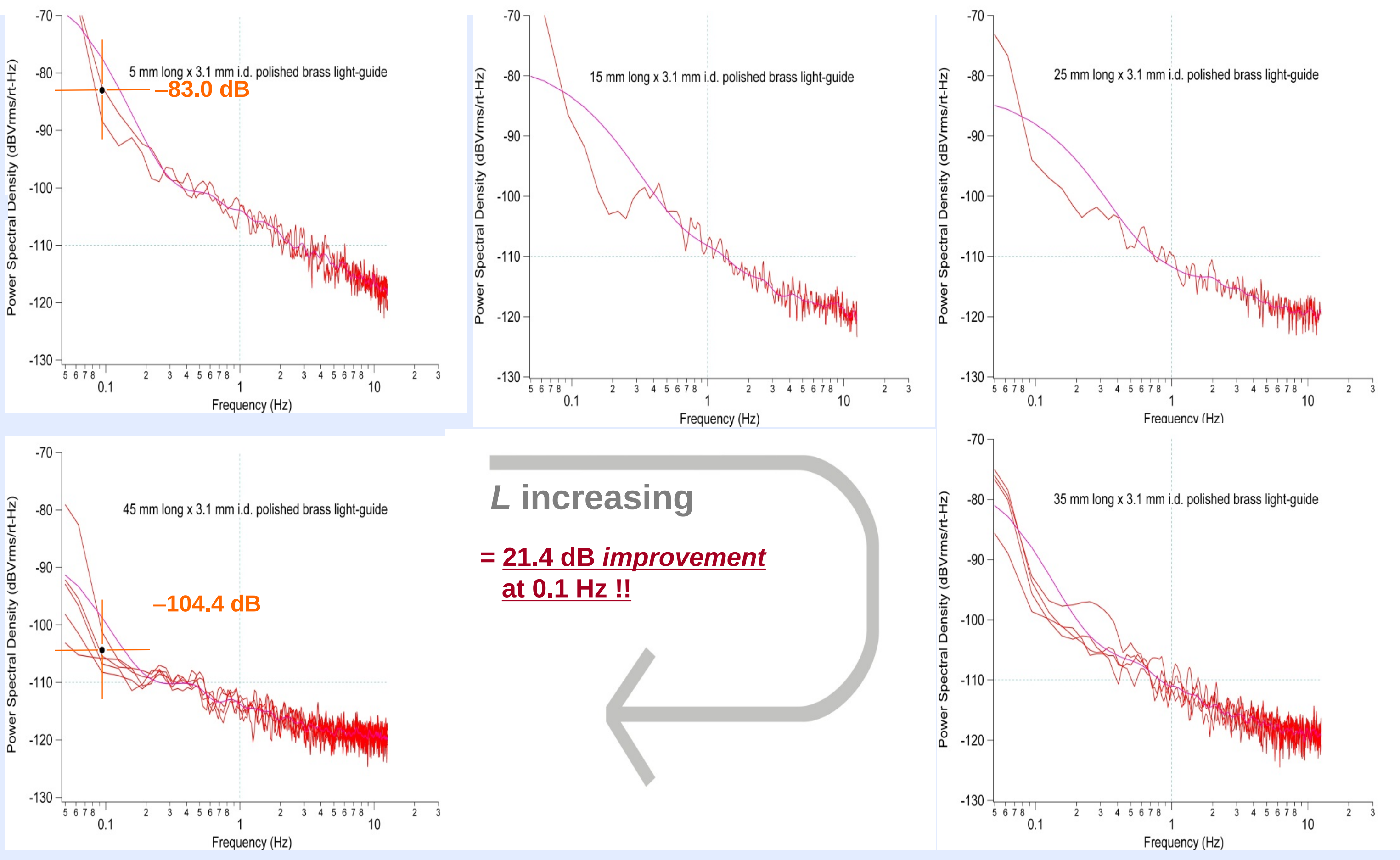




A 'split-photodiode' shadow detector was synthesized by reflection using two separate photodiodes (PDs) and an interposed 90º gold-coated prism. The illuminating source for each silica suspension fibre was a column of 8 × miniature Near Infra Red LEDs, plus a collimating lens.

In practice, a Violin-Mode displacement sensitivity of 69 ± 13 pm / sqrt-Hz was achieved at 500 Hz—over the 4 detectors of a full suspension—using the differential PD sensors, illustrated above.

OSEM noise

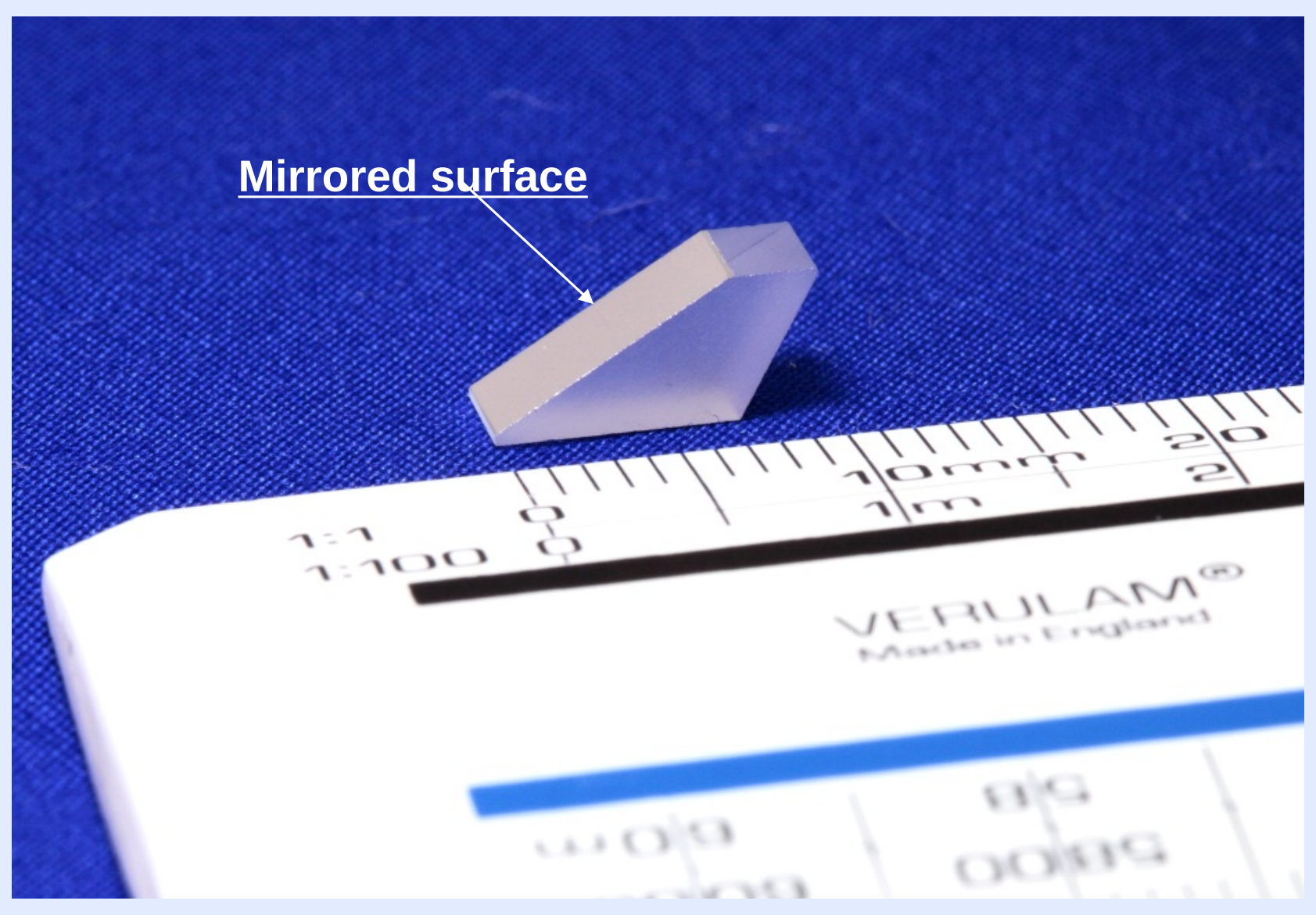


The noise PSD at 0.1 Hz was reduced progressively from -83.0 dBVrms/rt-Hz (*L* = 5 mm) to -104.4 dBVrms/rt-Hz (*L* = 45 mm).

Low frequency OSEM noise, on the other hand, is not 'white,' often exhibiting instead 1/f-like behaviour below frequencies ~10 Hz. Some of this is certainly due to 'beam-wandering' when NIR LEDs are used as the source of illumination; but common voltage regulators on the PD detection side can also produce significant levels of this noise—even at these low frequencies.

Displacement-doubling prism

Some sources of 1/f noise may be tackled successfully, as seen above; but in all cases, by placing this 'noiseless' displacement-doubling prism within an OSEM's flag, the displacement sensitivity of the OSEM may be doubled.



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