History of Sensor Development at University of Birmingham

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Abstract

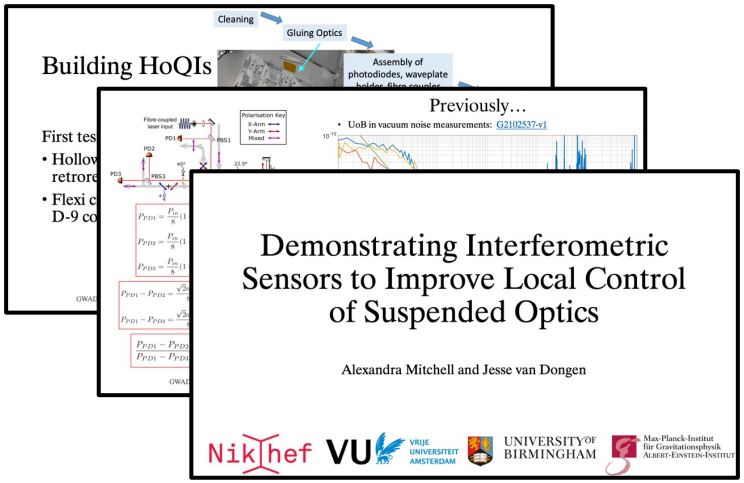
- Birmingham group has developed many sensors
- I will compare and discuss BOSEM, EUCLID, ILIAD, and HoQI
- I also introduce QUIMETT developed by Nagano-san and HDMI developed by Takano-san
- In the summary slide, we can fill in all the blanks in the table

Name of sensors	Motivation	Design & characteristics	Sensitivity at 1 Hz	Discussion & status
BOSEM				
EUCLID				
ILIAD				
HoQI				
QUIMETT				
HDMI				

Why did I choose this topic?

- Talk about HoQI at GWADW2022 was interesting
- Nagano-san's QUIMETT is similar to HoQI

  → I want to understand both HoQI and QUIMETT



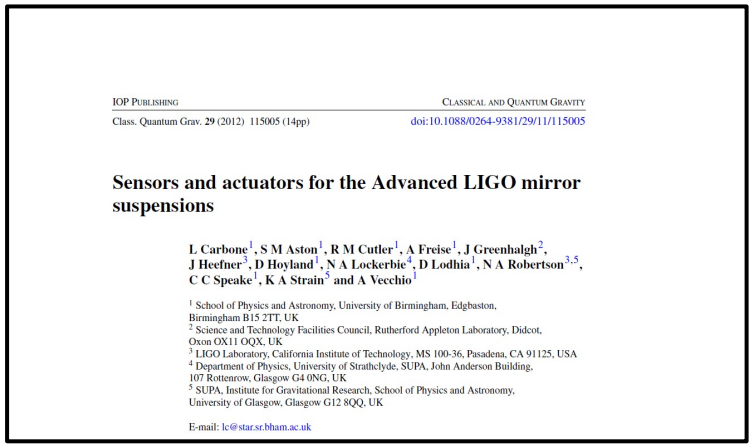
HoQI - GWADW2022

- I am confused about the difference between OSEM and BOSEM

  → I want to summarize sensors developed by Birmingham group

References

[1] (BOSEM)
L Carbone+, *Class. Quantum Grav.* **29** 115005 (2012)



IOP Publishing — Classical and Quantum Gravity
Class. Quantum Grav. **29** (2012) 115005 (14pp) — doi:10.1088/0264-9381/29/11/115005

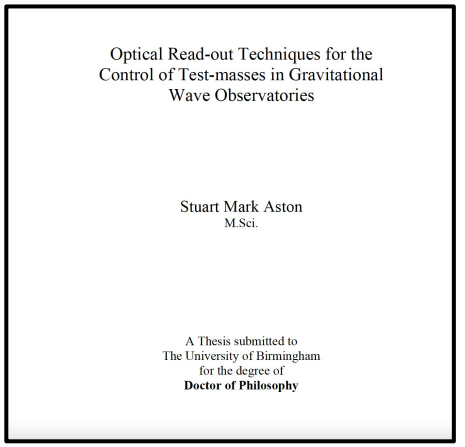
Sensors and actuators for the Advanced LIGO mirror suspensions

L Carbone[1], S M Aston[1], R M Cutler[1], A Freise[1], J Greenhalgh[2], J Heefner[3], D Hoyland[1], N A Lockerbie[4], D Lodhia[1], N A Robertson[3,5], C C Speake[1], K A Strain[5] and A Vecchio[1]

[1] School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
[2] Science and Technology Facilities Council, Rutherford Appleton Laboratory, Didcot, Oxon OX11 0QX, UK
[3] LIGO Laboratory, California Institute of Technology, MS 100-36, Pasadena, CA 91125, USA
[4] Department of Physics, University of Strathclyde, SUPA, John Anderson Building, 107 Rottenrow, Glasgow G4 0NG, UK
[5] SUPA, Institute for Gravitational Research, School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK

E-mail: lc@star.sr.bham.ac.uk

[2] (EUCLID)
S. M. Aston, Ph.D. thesis (2011)

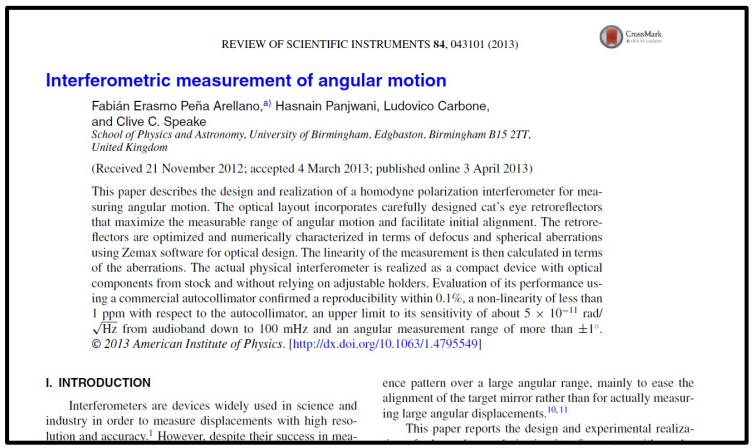


Optical Read-out Techniques for the Control of Test-masses in Gravitational Wave Observatories

Stuart Mark Aston
M.Sci.

A Thesis submitted to
The University of Birmingham
for the degree of
Doctor of Philosophy

[3] (ILIAD)
F. E. P. Arellano+, *Rev. Sci. Instrum.* **84**, 043101 (2013)



REVIEW OF SCIENTIFIC INSTRUMENTS **84**, 043101 (2013)

Interferometric measurement of angular motion

Fabián Erasmo Peña Arellano,[a)] Hasnain Panjwani, Ludovico Carbone, and Clive C. Speake
School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom

(Received 21 November 2012; accepted 4 March 2013; published online 3 April 2013)

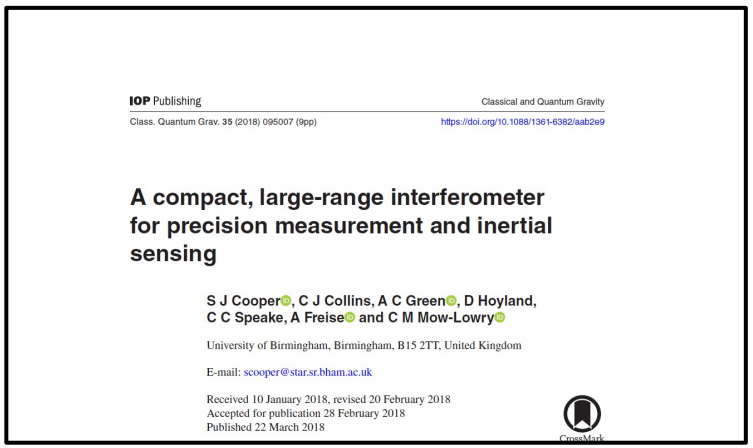
This paper describes the design and realization of a homodyne polarization interferometer for measuring angular motion. The optical layout incorporates carefully designed cat's eye retroreflectors that maximize the measurable range of angular motion and facilitate initial alignment. The retroreflectors are optimized and numerically characterized in terms of defocus and spherical aberrations using Zemax software for optical design. The linearity of the measurement is then calculated in terms of the aberrations. The actual physical interferometer is realized as a compact device with optical components from stock and without relying on adjustable holders. Evaluation of its performance using a commercial autocollimator confirmed a reproducibility within 0.1%, a non-linearity of less than 1 ppm with respect to the autocollimator, an upper limit to its sensitivity of about 5×10^{-11} rad/$\sqrt{\text{Hz}}$ from audioband down to 100 mHz and an angular measurement range of more than $\pm 1°$.
© *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4795549]

I. INTRODUCTION

Interferometers are devices widely used in science and industry in order to measure displacements with high resolution and accuracy.[1] However, despite their success in measurement over a large angular range, mainly to ease the alignment of the target mirror rather than for actually measuring large angular displacements.[10,11]

This paper reports the design and experimental realiza-

[4] (HoQI)
S. J. Cooper+, *Class. Quantum Grav.* **35** 095007 (2018)



IOP Publishing — Classical and Quantum Gravity
Class. Quantum Grav. **35** (2018) 095007 (9pp) — https://doi.org/10.1088/1361-6382/aab2e9

A compact, large-range interferometer for precision measurement and inertial sensing

S J Cooper, C J Collins, A C Green, D Hoyland, C C Speake, A Freise and C M Mow-Lowry

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Published 22 March 2018

- [5] (QUIMETT) Nagano-san's slides (internal)
- [6] (HDMI) Takano-san's midterm seminar

Contents

- BOSEM
- EUCLID
- ILIAD
- HoQI
- QUIMETT
- HDMI

Contents

- BOSEM
- EUCLID
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- HoQI
- QUIMETT
- HDMI

BOSEM: overview

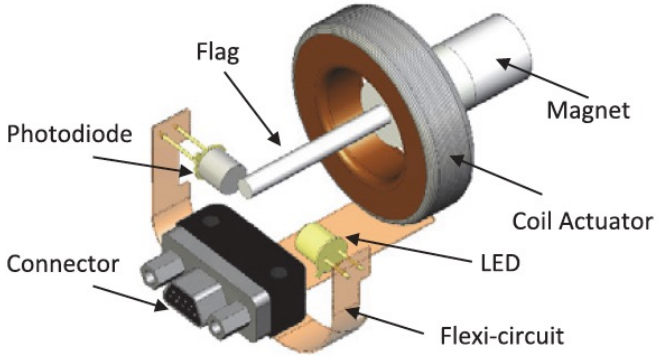
- BOSEM: Birmingham Optical Sensor and Electro-Magnetic actuator
- Developed by Birmingham group around 2010

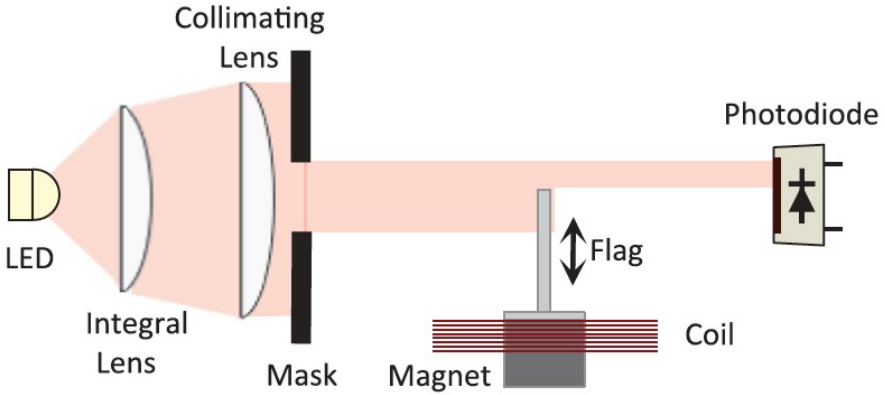
- Motivation: suspension control for Advanced LIGO
- Requirement: 3×10^{-10} m/$\sqrt{\text{Hz}}$ @1 Hz
  1×10^{-10} m/$\sqrt{\text{Hz}}$ @10 Hz

- Characteristics:
- Sensor and actuator are combined in a single unit
- Shadow sensor
- Coil-magnet actuator

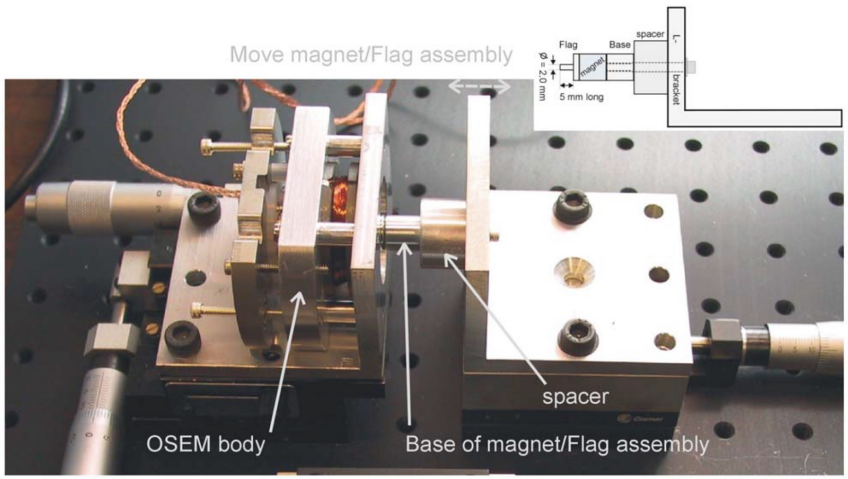
BOSEM: sensor design

- Magnet and “flag” are attached to a test mass
- When a test mass moves, a flag moves in a longitudinal axis and obscures a fraction of LED light onto a single-element PD





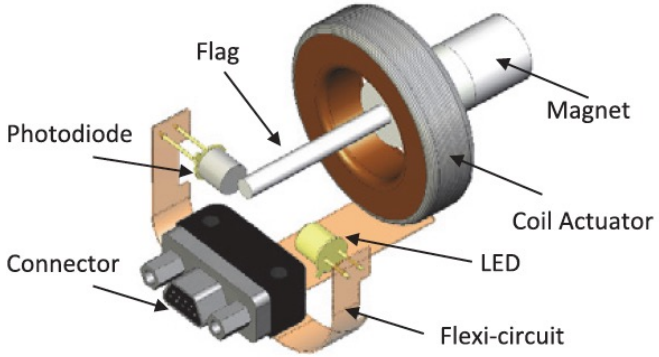
- LED: 950 nm,
  negligible emission at 1064 nm
- Lenses and mask:
  to collimate LED beam
- Flag: 25 mm × 3 mm aluminum cylinder

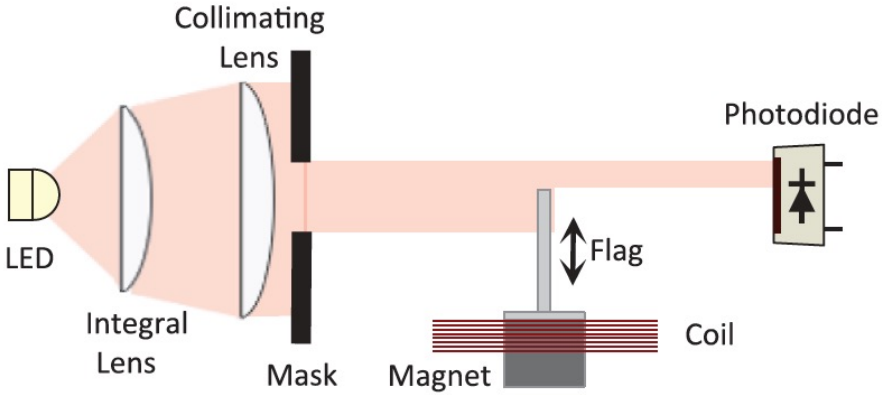


BOSEM: actuator design

- Coil-magnet actuator
- Actuation forces up to several hundreds of mN per actuator (4 BOSEMs per test mass)

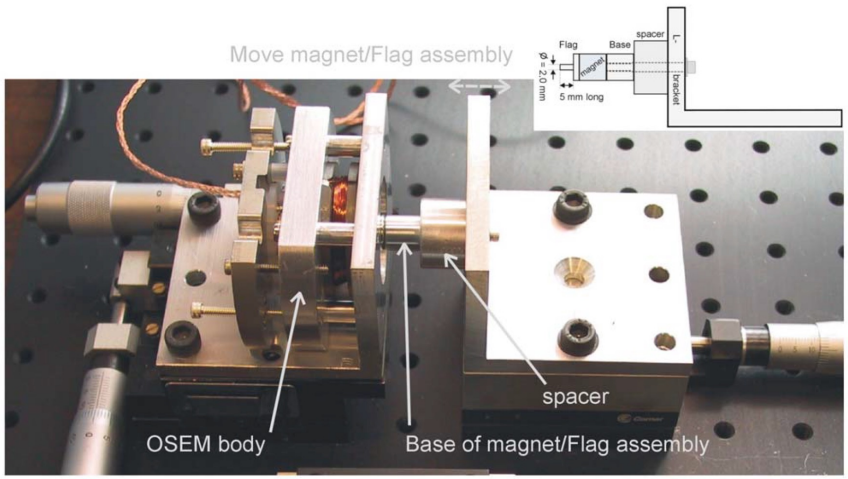
(cf. 5 mN per my coil-magnet actuator)





- Coil: 800 turns of
  polyimide-coated 32-AWG wire
- Magnet: 10 mm × 10 mm
  Nd-B-Fe cylindrical magnets
- Mechanical parts:
  low magnetic susceptibility Al6082

→ Residual magnetic forces below 5 mN

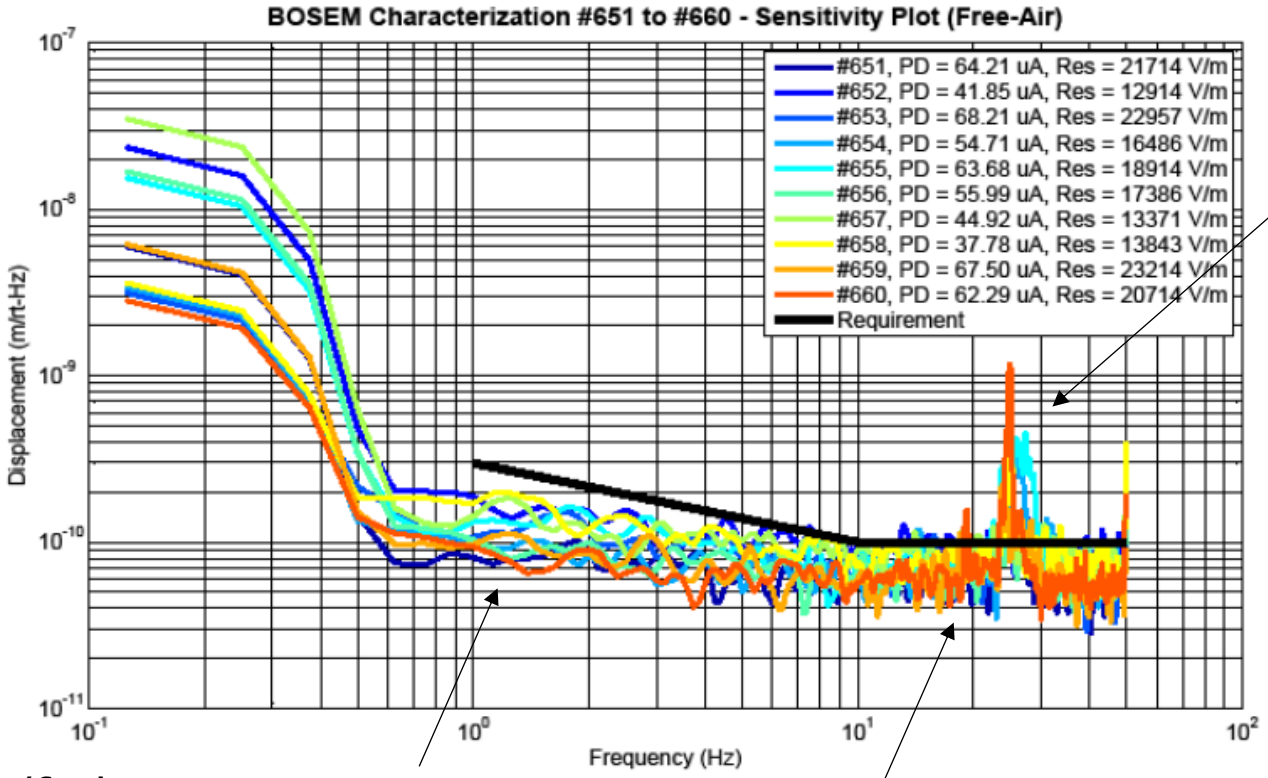


BOSEM: other design

- Compact design: less than 40 × 40 × 40 mm^3 volume and ~170 g mass
- During the installation process, we can align BOSEM 10 mm longitudinal and 1.5 mm lateral adjustments with respect to the flag position
- BOSEM can meet the requirement of the ultra-high vacuum environment
- 700 BOSEMs were delivered from Birmingham to aLIGO
  ← BOSEM components are easy to be assembled/disassembled

BOSEM: sensitivity

- 2×10^{-10} m/√Hz @1 Hz
- 1×10^{-10} m/√Hz @10 Hz
- Fulfilled the requirement



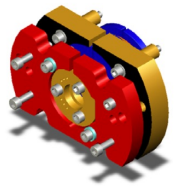
OSEM, AOSEM, BOSEM

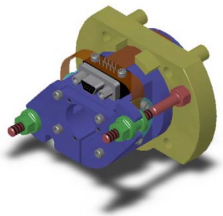
- OSEM, AOSEM, and BOSEM are very similar (shadow sensor + coil-magnet actuator) but a bit different

- OSEM: Optical Sensor and Electro-Magnetic actuator
- Developed by Birmingham group for Initial LIGO

- AOSEM: Advanced LIGO OSEM
- Improved by USA group for aLIGO to reduce assembly costs for mass production
- Coil: 400 turn → Force: ~10 mN per actuator

AOSEM



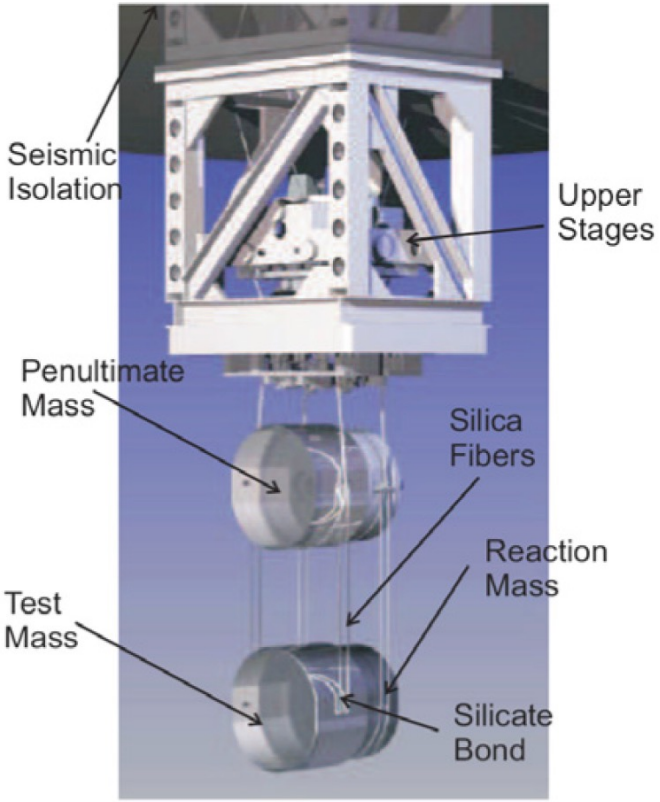


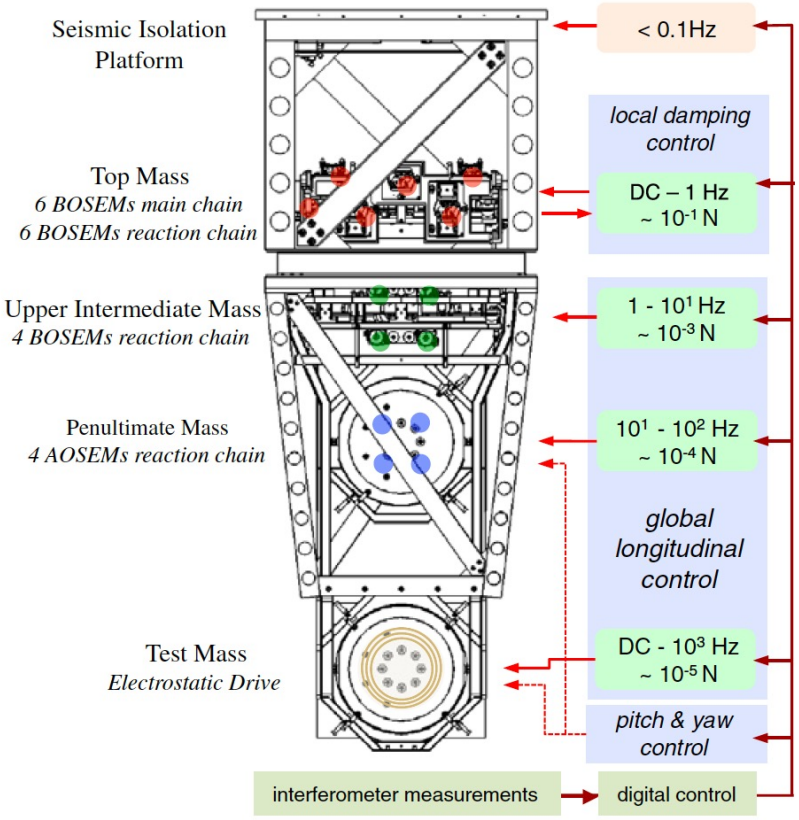
BOSEM

- BOSEM: Birmingham OSEM
- Developed by Birmingham group for Advanced LIGO
- Coil: 800 turn → Force: ~100 mN per actuator
- Larger and heavier than AOSEM

Suspension control by AOSEM & BOSEM

- Top and upper intermediate masses are controlled by BOSEM
- Penultimate mass is controlled by AOSEM because the required force is smaller





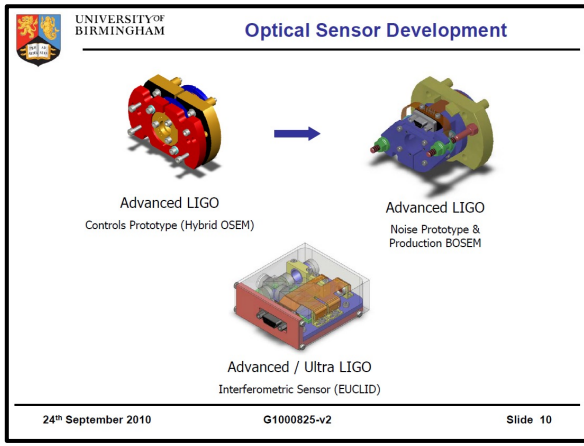
Contents

- BOSEM
- EUCLID
- ILIAD
- HoQI
- QUIMETT
- HDMI

EUCLID: overview

- EUCLID: Easy to Use Compact
  Laser Interferometric Device
- Developed by Birmingham group around 2010

- Motivation: suspension control for Advanced LIGO
- Requirement: same as BOSEM
- At first, BOSEM seemed not to meet the requirement
  → They started to develop EUCLID
  → After the success of BOSEM,
  the goal is to improve the sensitivity
  and control to lower test masses



LIGO Document G1000825-v2

- Characteristics:
- Quadrature homodyne interferometer with polarizing optics
- Cat's eye retroreflector to compensate for misalignment

Contents

- BOSEM
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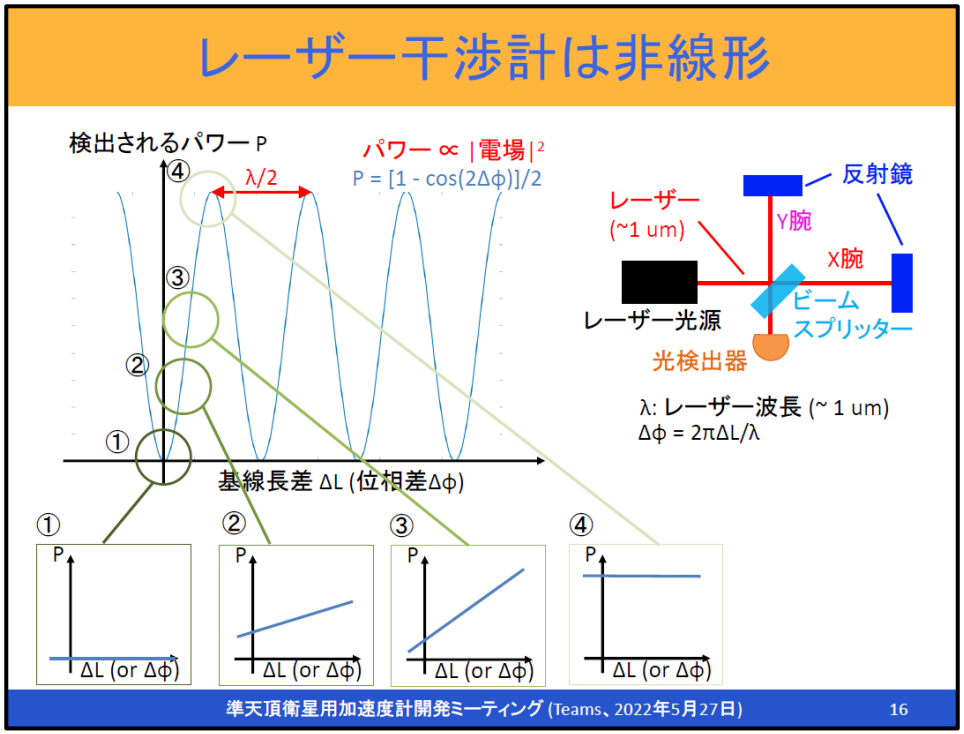
Michelson interferometer

- The response of MI has non-linearity → Small range
- We usually conduct feedback control to fix the operation point

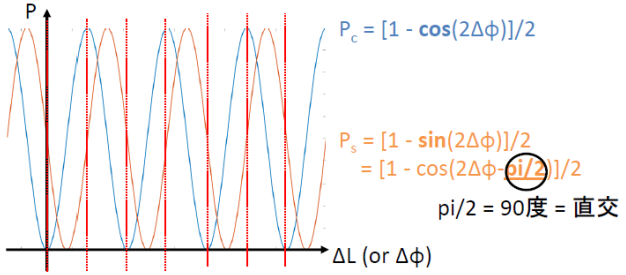


Quadrature interferometer

- When we obtain the quadrature signals (sin and cos), the information of phase can be calculated
- Range: infinity (theoretically), >10 mm (experimentally)
- No need to FB control
- Sensitivity worse than FB control method due to ADC noise

直交する位相の信号を取得する利点

- 直交する位相の信号とは:
  - –sinとcosを入れ替えた信号 (ただし、三角関数の1次の冪で書いたとき)
  - –つまり、片方が明or暗のとき、もう一方は中くらい。



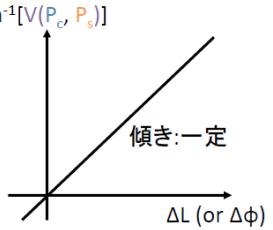
- $dP_c/d(\Delta L) = 0$の時は、$dP_s/d(\Delta L) \neq 0$ となる。(あるいはその逆)

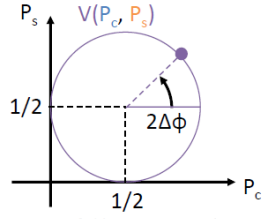
直交する位相の信号の使い方

- 直交する位相の信号 (直交位相信号) が取れれば、例えば以下の演算をすれば、ΔL (or Δϕ)が計測できる。

$$V(P_c, P_s) := \frac{P_s - 1/2}{P_c - 1/2} = \frac{\sin(2\Delta\phi)}{\cos(2\Delta\phi)} = \tan(2\Delta\phi) \xrightarrow{\text{逆関数}} \tan^{-1}[\tan(2\Delta\phi)] = 2\Delta\phi$$

実際、$\frac{d(\tan^{-1}[V(P_c, P_s)])}{d(\Delta\phi)} = 2$ となり較正係数は常に一定。(レンジが無限)





上の演算のイメージ図。

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  - Cat's eye retroreflector
- ILIAD
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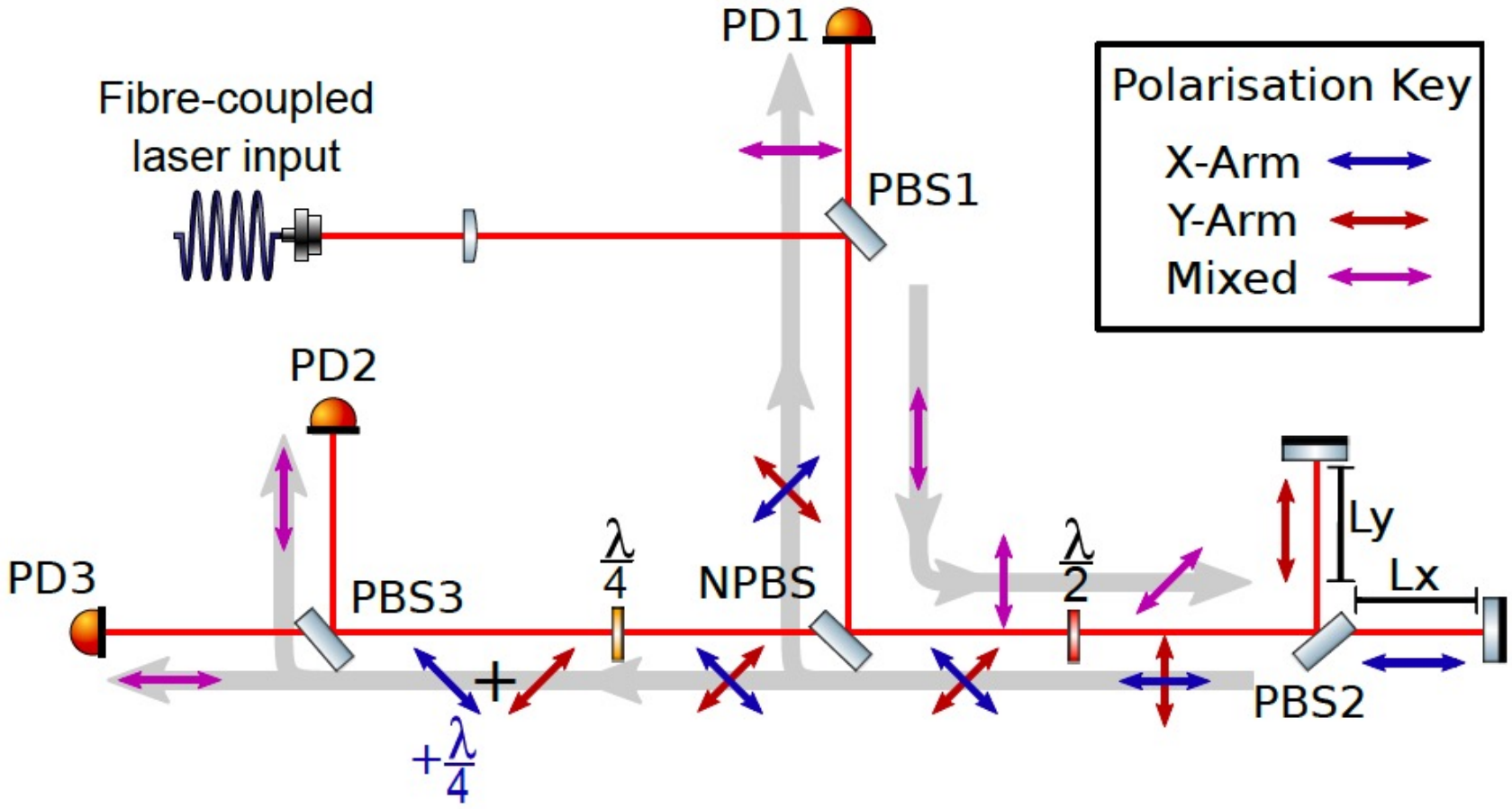
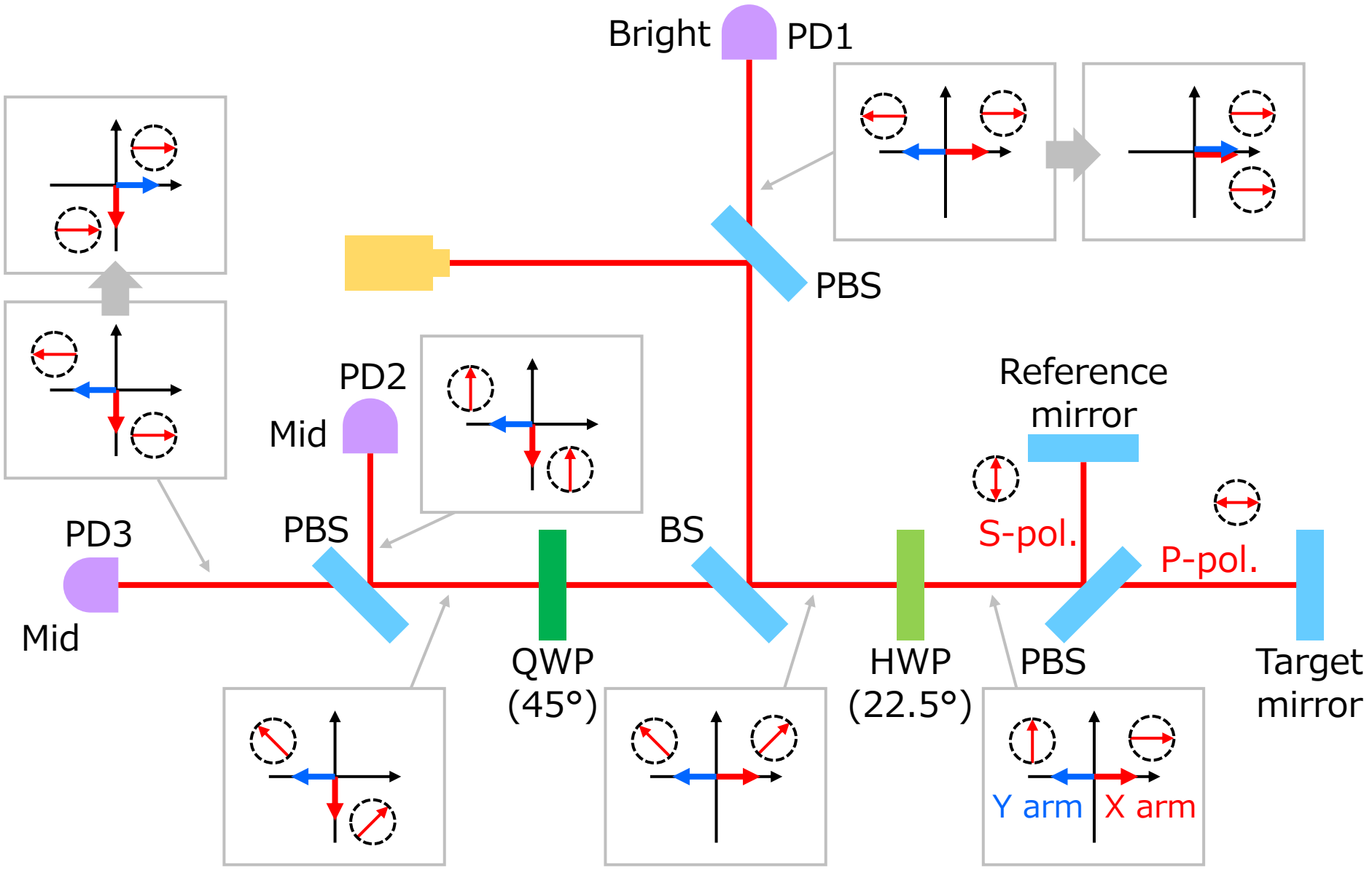
- QUIMETT
- HDMI

Design of HoQI

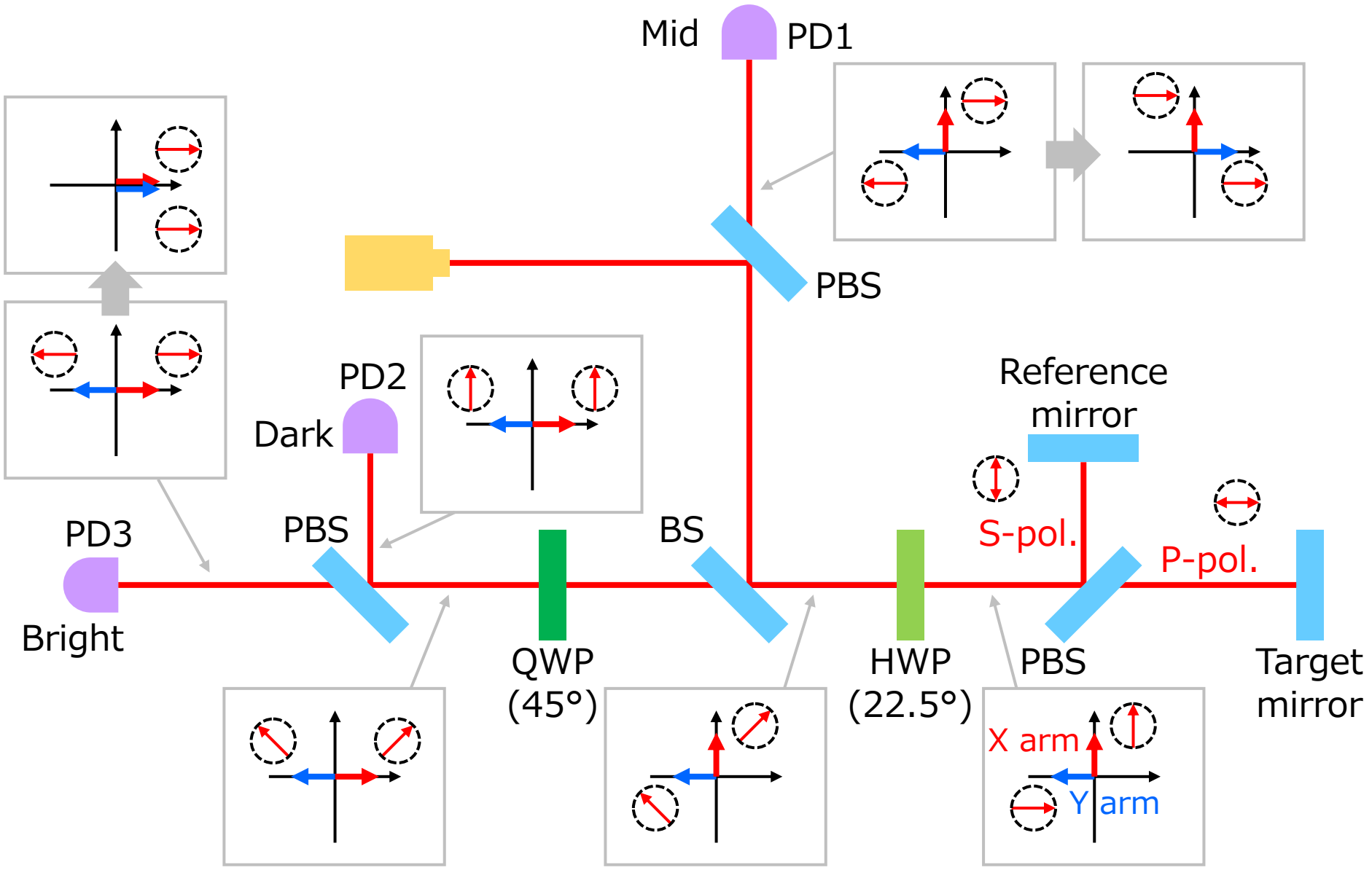
- HoQI is much simpler than EUCLID, so firstly I will explain the principle of HoQI



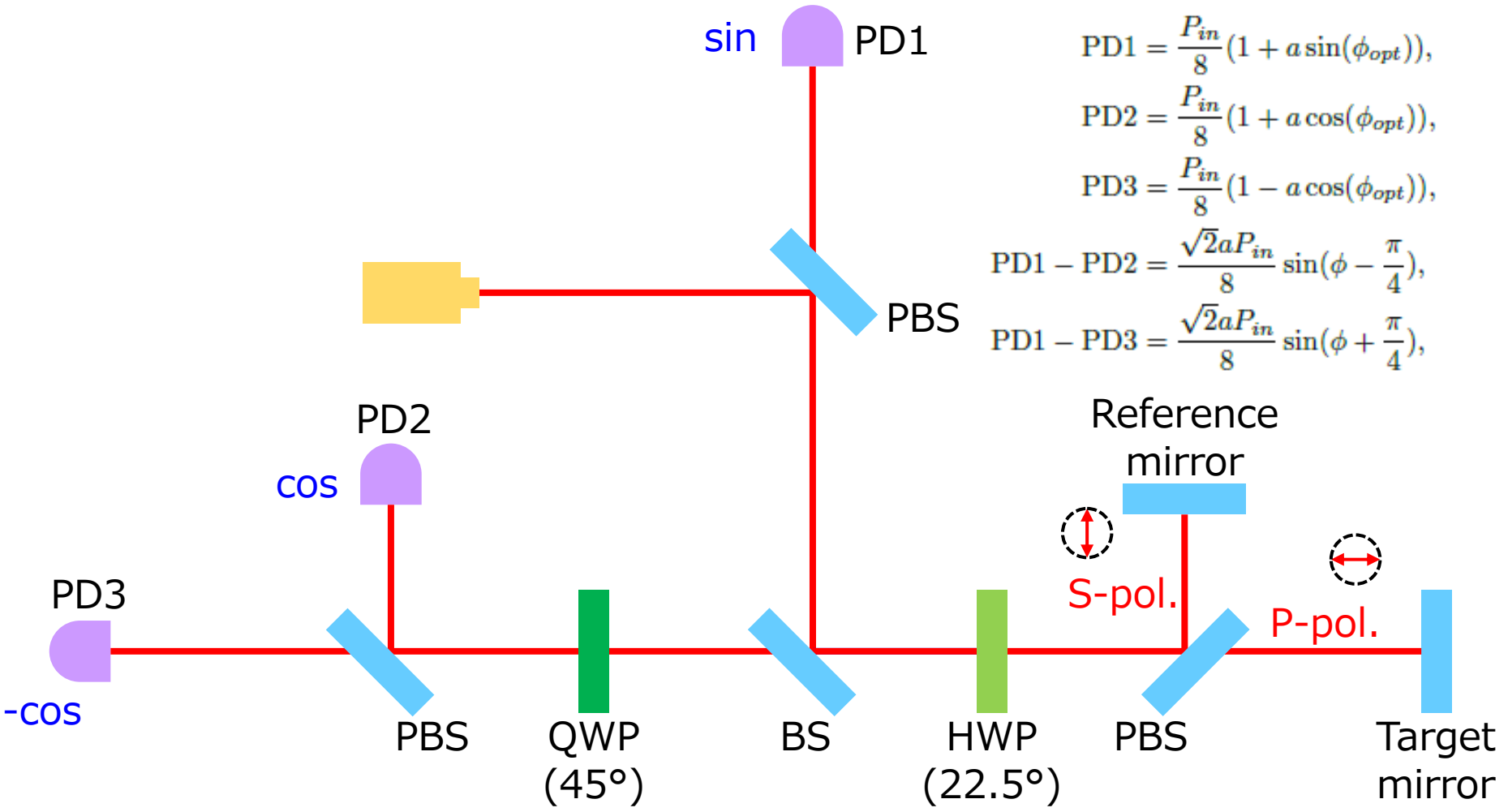
Interference condition (1)



Interference condition (2)



Response of HoQI



$$\mathrm{PD1} = \frac{P_{in}}{8}(1 + a\sin(\phi_{opt})),$$
$$\mathrm{PD2} = \frac{P_{in}}{8}(1 + a\cos(\phi_{opt})),$$
$$\mathrm{PD3} = \frac{P_{in}}{8}(1 - a\cos(\phi_{opt})),$$
$$\mathrm{PD1} - \mathrm{PD2} = \frac{\sqrt{2}aP_{in}}{8}\sin(\phi - \frac{\pi}{4}),$$
$$\mathrm{PD1} - \mathrm{PD3} = \frac{\sqrt{2}aP_{in}}{8}\sin(\phi + \frac{\pi}{4}),$$

- Common-mode rejection of laser intensity noise

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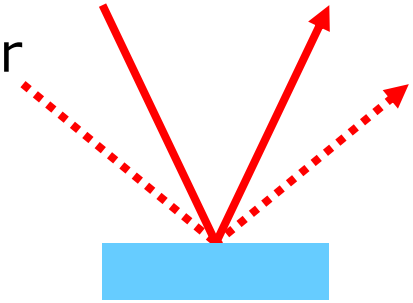
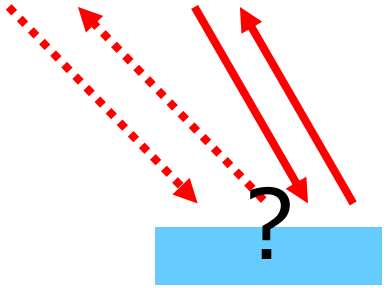
Retroreflector

- Retroreflector (再帰反射材) is used to compensate for misalignment

Nominal mirror



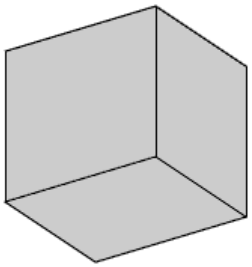
Retroreflector



- Most famous retroreflector is the cube-corner retroreflector
- This method cannot be used for a flat target mirror or with polarizing optics

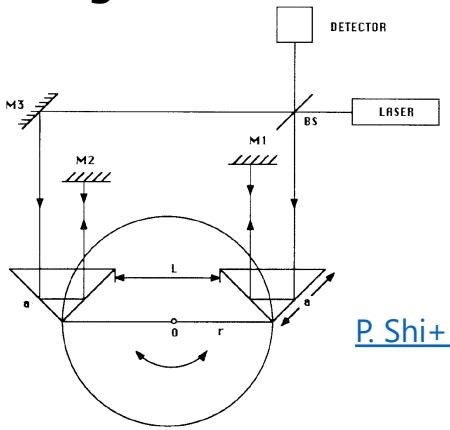
2D

3D



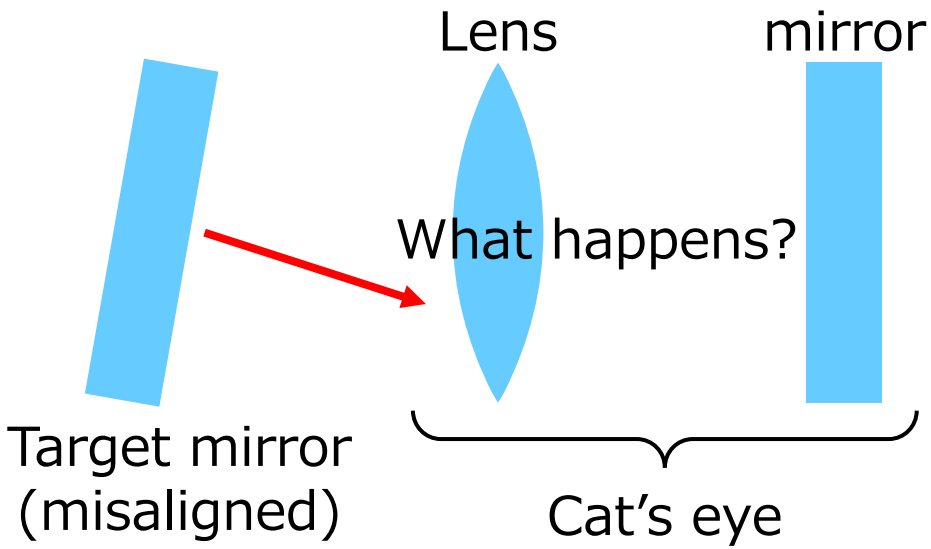
[コーナーキューブ - Wikipedia]

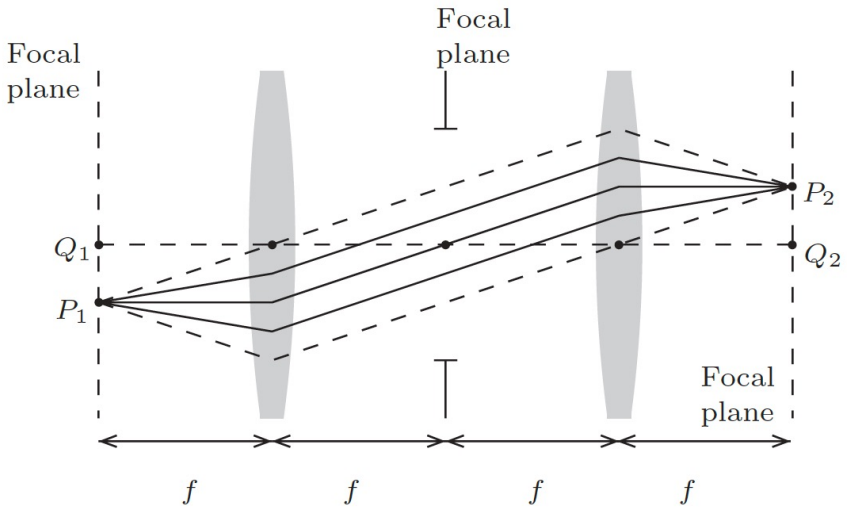
Michelson interferometer for rotation angle measurement



[P. Shi+ (1990)]

Cat's eye retroreflector





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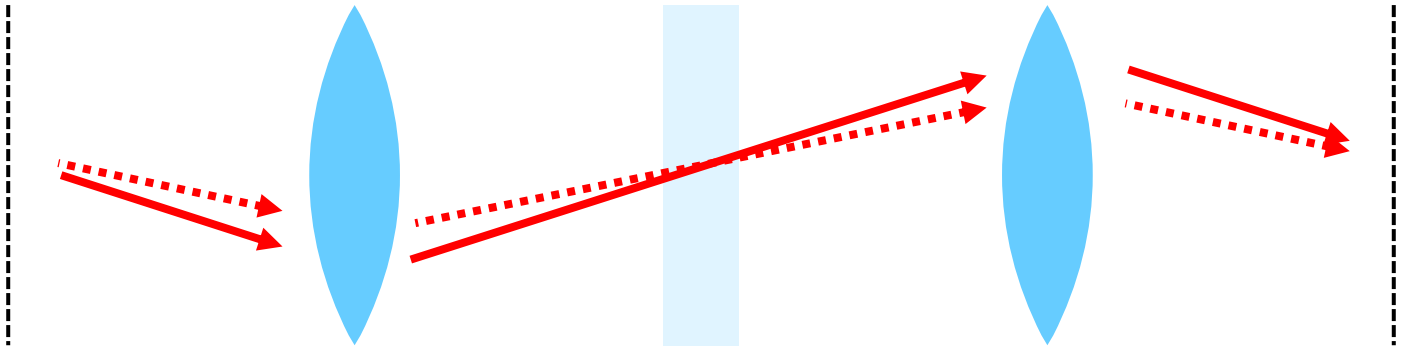
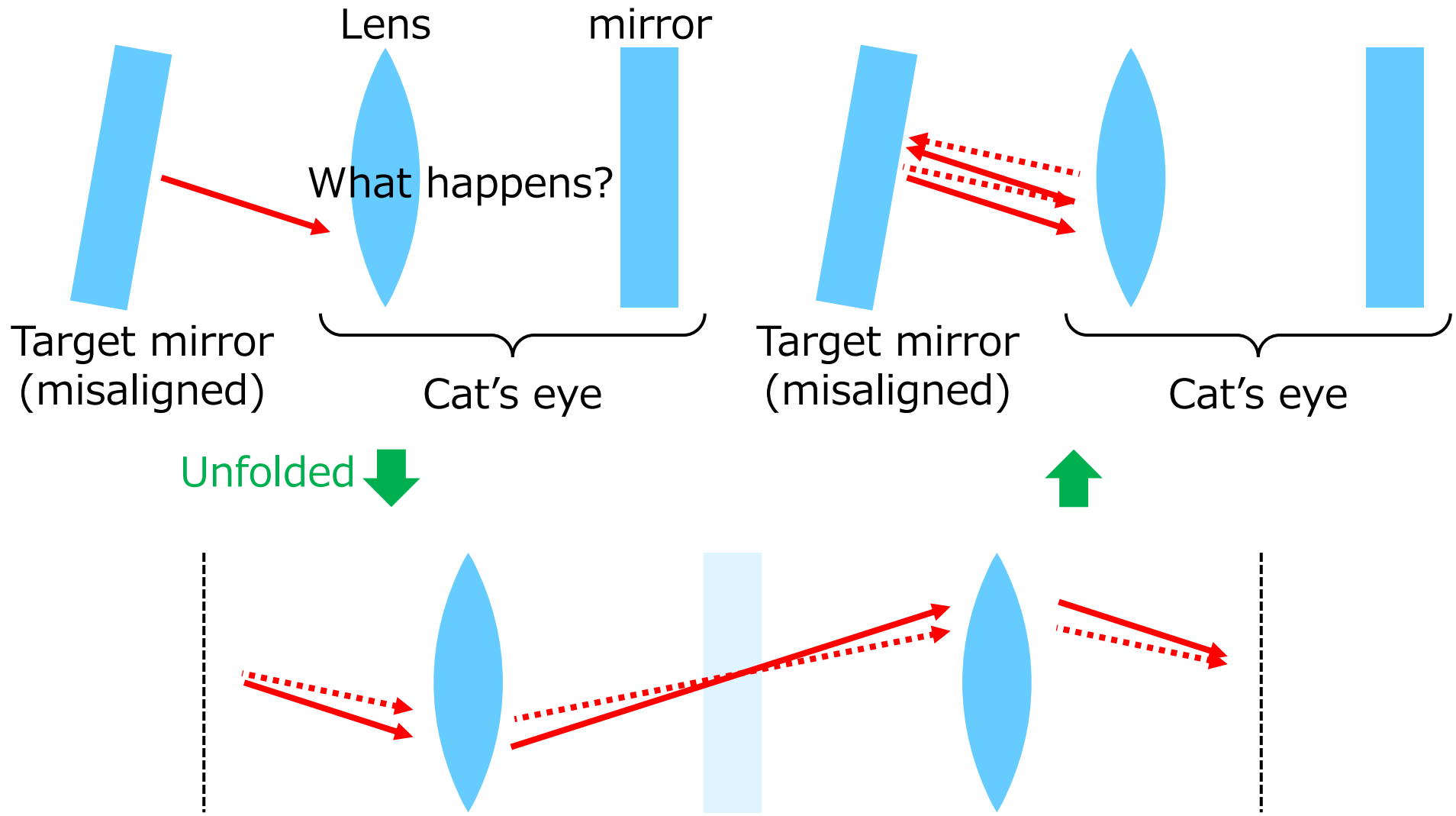
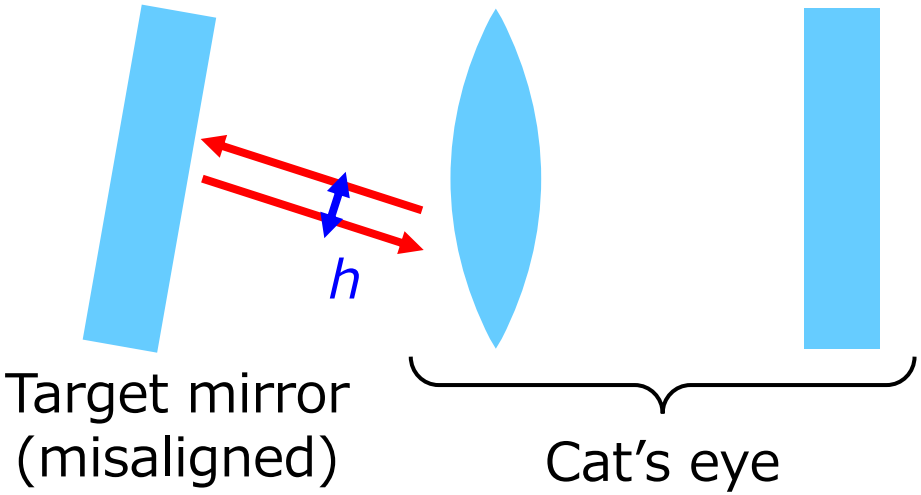
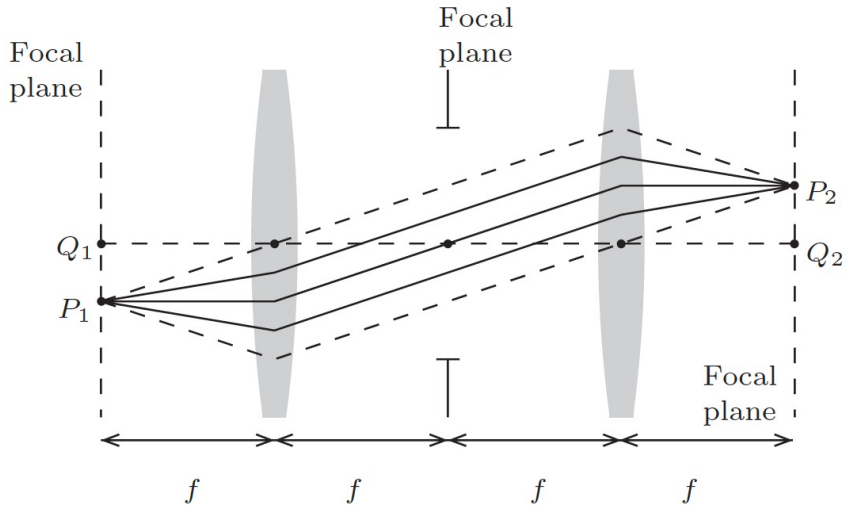


Cat’s eye retroreflector



Complete immunity for mirror tilt

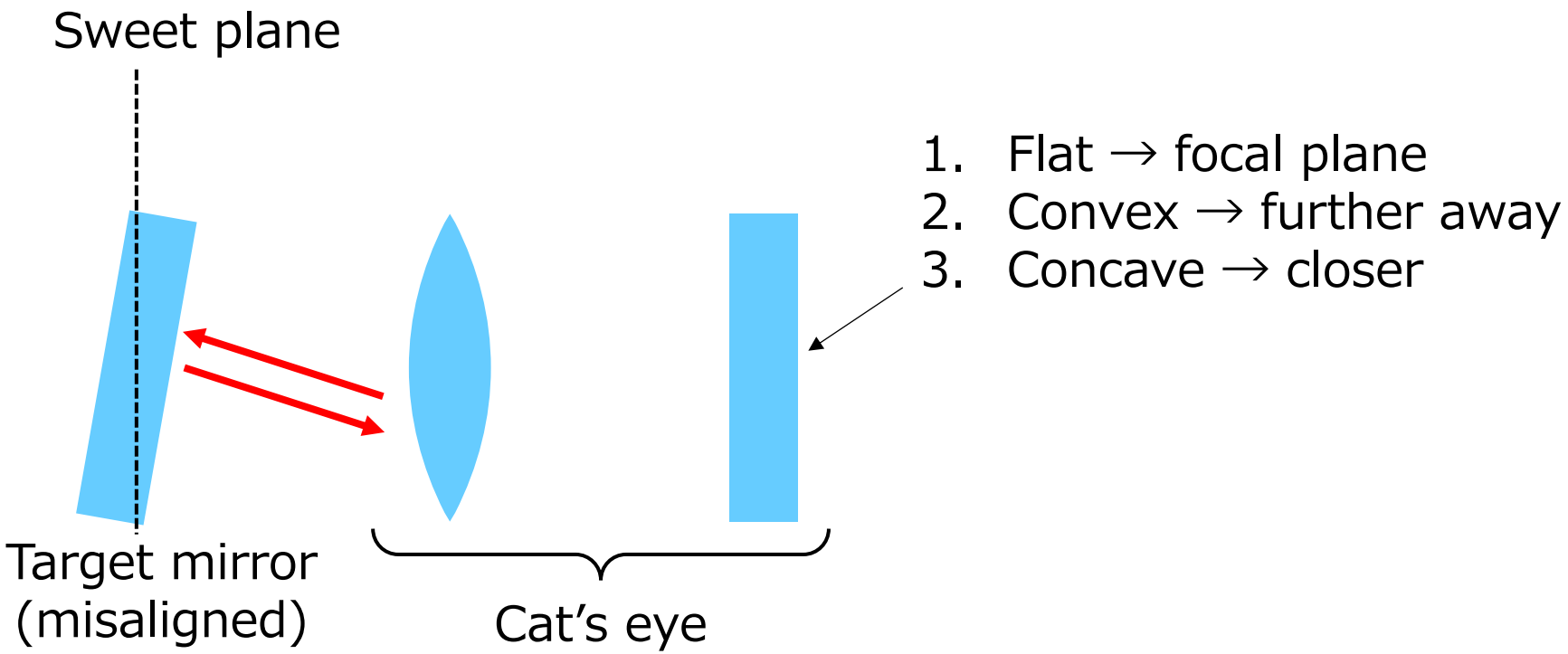




- In general, *h* is changed depending on the mirror tilt
- In the case of the cat's eye, P_1 and P_2 are conjugate points, and the optical path length is constant
  → We can choose the parameters of the components to make *h* always equal to zero

Sweet plane

- The effect of compensation of mirror tilt only happen when target mirror is located at a particular plane (sweet plane)



Cat's eye part of EUCLID

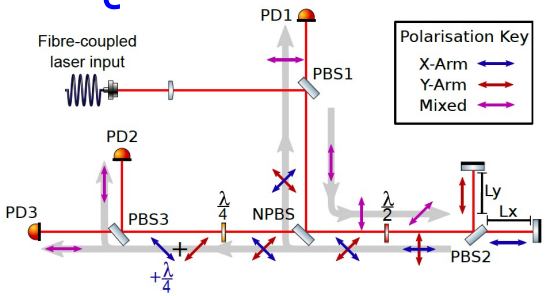
- H1 $\xrightarrow[\text{P-pol.}]{}$ A2 $\xrightarrow[\text{P-pol.}]{}$ Q2 $\xrightarrow[\text{Circle}]{}$ M2 $\xrightarrow[\text{Circle}]{}$ Q2 $\xrightarrow[\text{S-pol.}]{}$ A2 $\xrightarrow[\text{S-pol.}]{}$ cat's eye

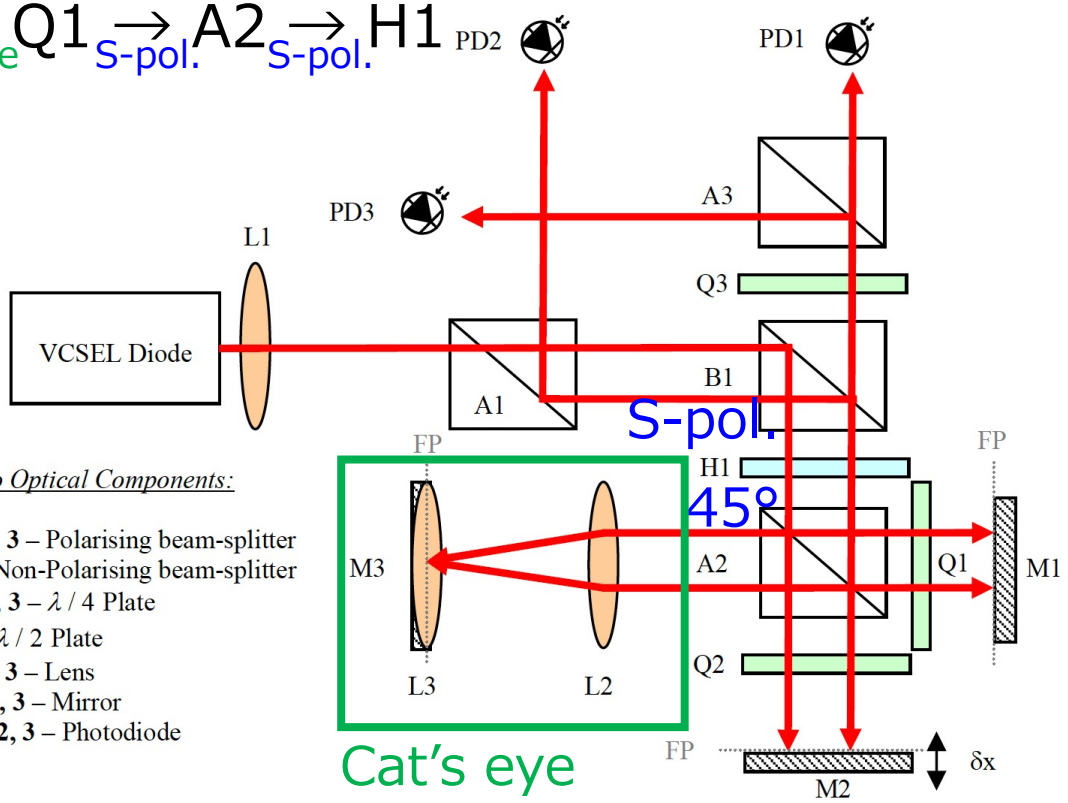
  $\xrightarrow[\text{S-pol.}]{}$ A2 $\xrightarrow[\text{S-pol.}]{}$ Q2 $\xrightarrow[\text{Circle}]{}$ M2 $\xrightarrow[\text{Circle}]{}$ Q2 $\xrightarrow[\text{P-pol.}]{}$ A2 $\xrightarrow[\text{P-pol.}]{}$ H1

- H1 $\xrightarrow[\text{S-pol.}]{}$ A2 $\xrightarrow[\text{S-pol.}]{}$ Q1 $\xrightarrow[\text{Circle}]{}$ M1 $\xrightarrow[\text{Circle}]{}$ Q1 $\xrightarrow[\text{P-pol.}]{}$ A2 $\xrightarrow[\text{P-pol.}]{}$ cat's eye

  $\xrightarrow[\text{P-pol.}]{}$ A2 $\xrightarrow[\text{P-pol.}]{}$ Q1 $\xrightarrow[\text{Circle}]{}$ M1 $\xrightarrow[\text{Circle}]{}$ Q1 $\xrightarrow[\text{S-pol.}]{}$ A2 $\xrightarrow[\text{S-pol.}]{}$ H1

HoQI

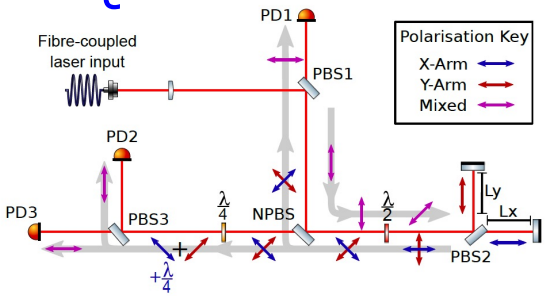


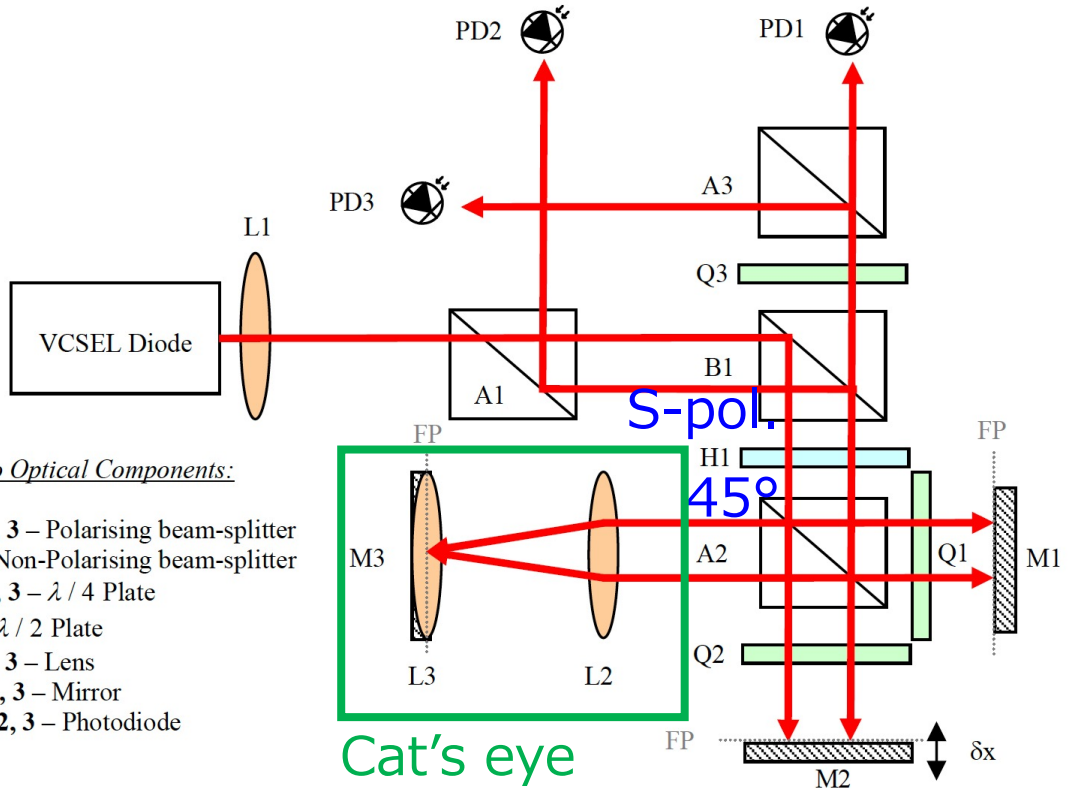


Cat's eye part of EUCLID

- QWPs (Q1, Q2) force the beams in each arm to be reflected from the cat's eye and their respective mirrors twice
- Cat's eye can cancel the tilt of mirrors (M1, M2)

HoQI





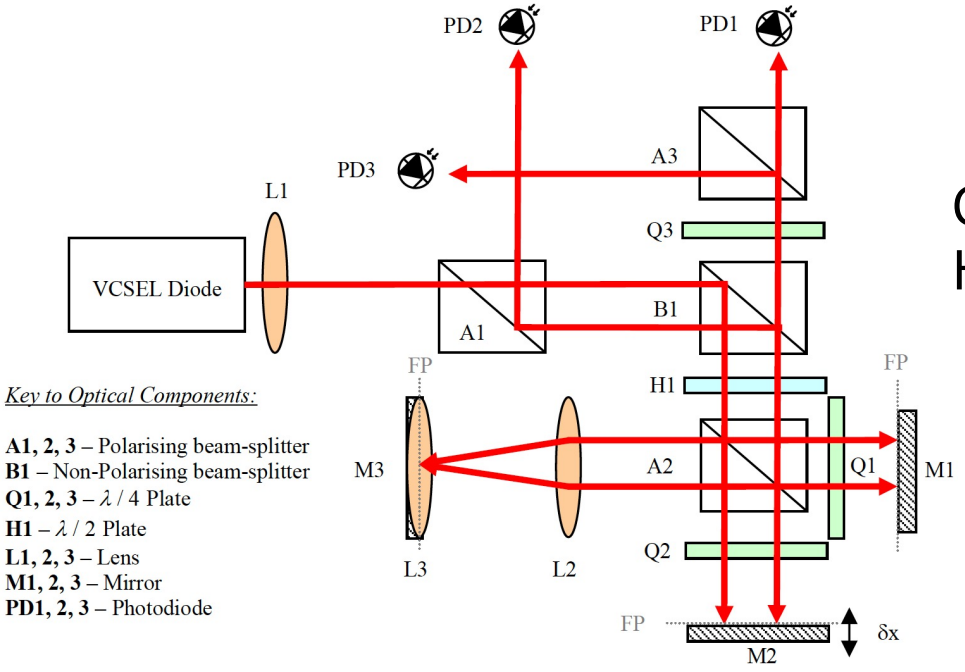
Key to Optical Components:

A1, 2, 3 – Polarising beam-splitter
B1 – Non-Polarising beam-splitter
Q1, 2, 3 – λ / 4 Plate
H1 – λ / 2 Plate
L1, 2, 3 – Lens
M1, 2, 3 – Mirror
PD1, 2, 3 – Photodiode

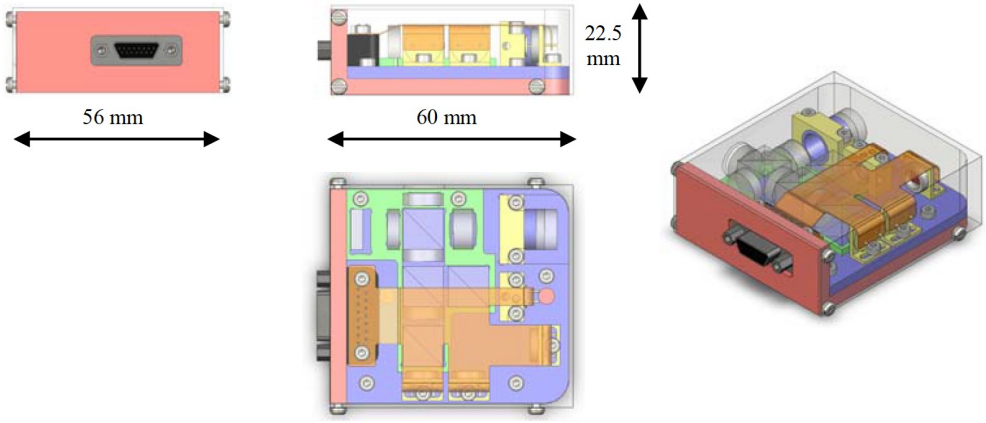
Contents

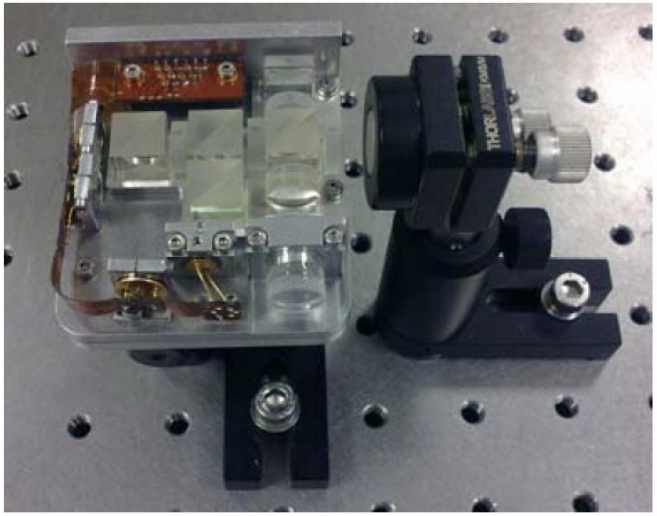
- BOSEM
- EUCLID
  - Quadrature interferometer
  - Quadrature homodyne interferometer with polarizing optics (HoQI)
  - Cat's eye retroreflector
- ILIAD
- HoQI
- QUIMETT
- HDMI

EUCLID: design



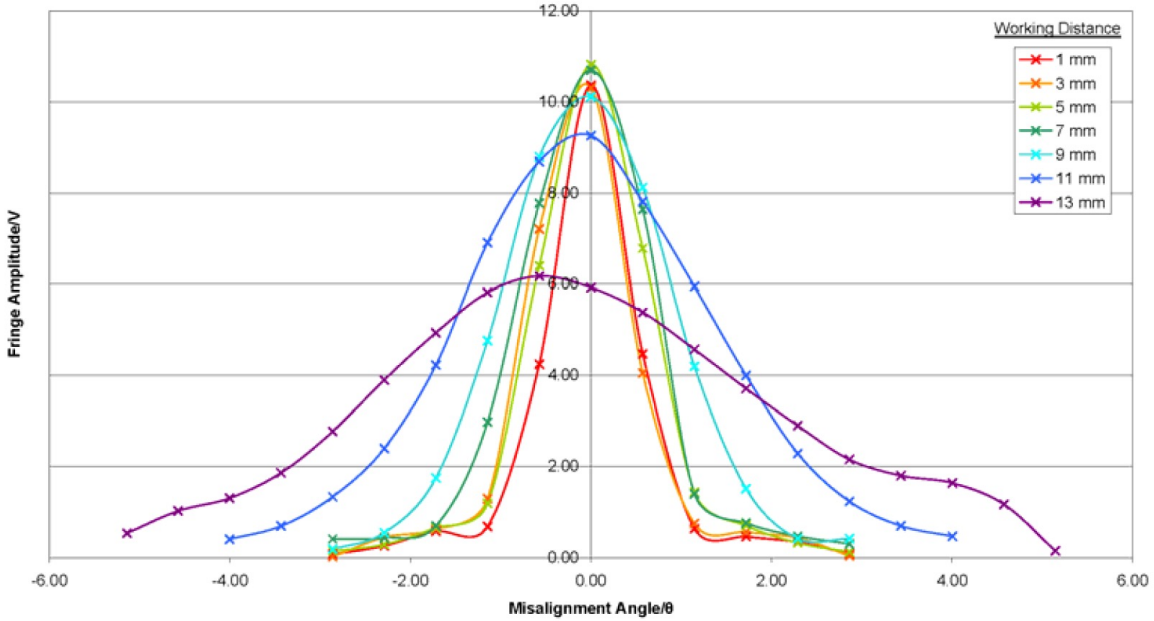
Combination of
HoQI and cat's eye

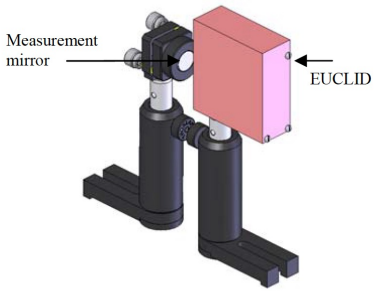


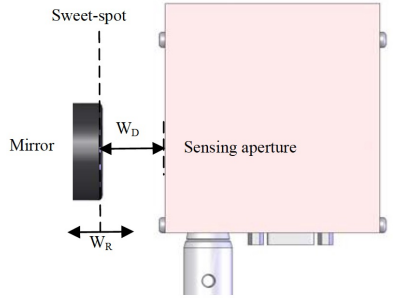


EUCLID: mirror tilt immunity

- EUCLID worked well for misalignment angles up to 1 deg
- EUCLID worked well even when the target mirror was 10 mm away from the sweet plane

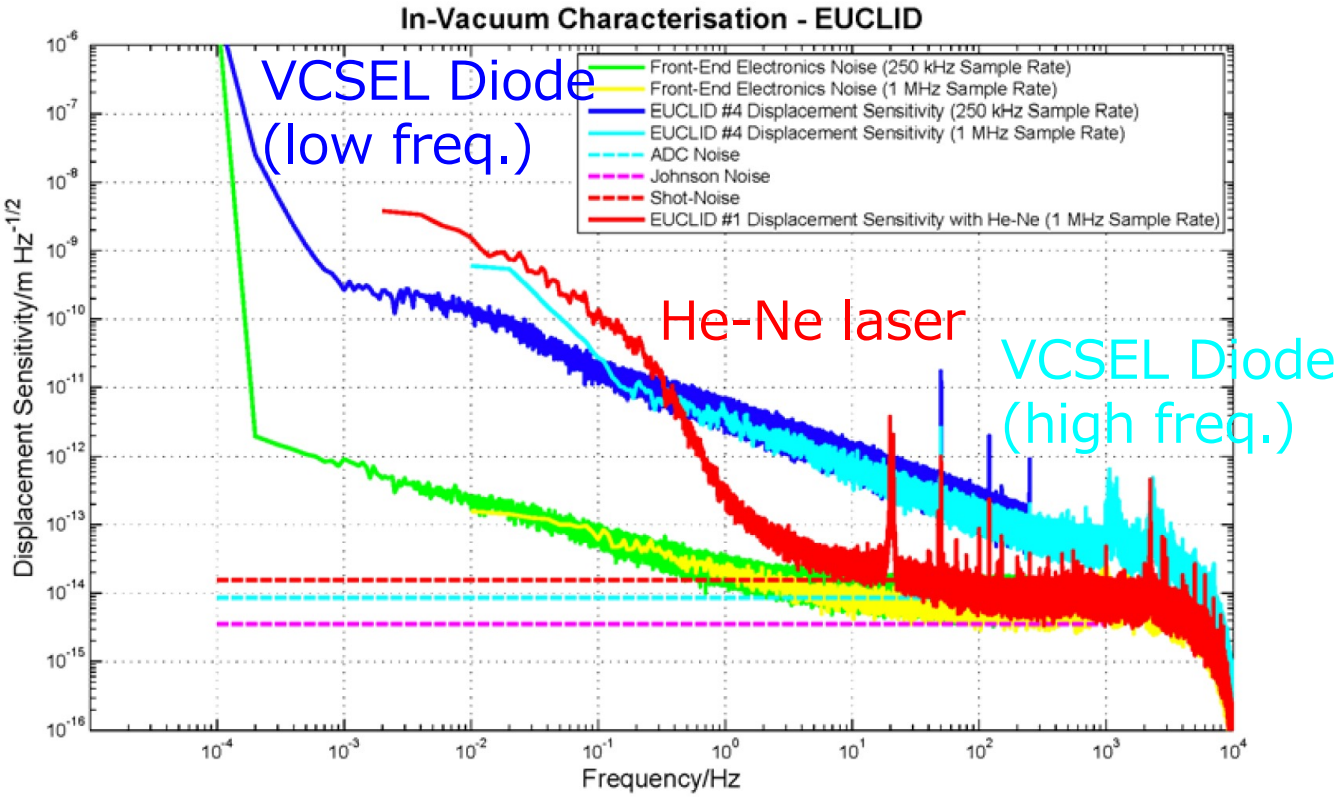






EUCLID: sensitivity

- 2×10^{-11} m/√Hz @0.1 Hz
- 1×10^{-12} m/√Hz @10 Hz
- Better than BOSEM
- Sensitivity was changed when VCSEL Diode was changed to He-Ne laser



EUCLID: discussion

- Sensitivity was changed when VCSEL Diode was changed to He-Ne laser
  → Better to use high quality laser
  → Mephisto laser is used for HoQI

- Cat's eye
  → Laser light passed through the arm twice
  → Large arm-length mismatch
  → Large freq. noise
  → No cat's eye for HoQI

- Too many polarization optics
  → difficult to assembly and expensive
  → Not suitable for mass production
  → No cat's eye and QWPs in the arms for HoQI

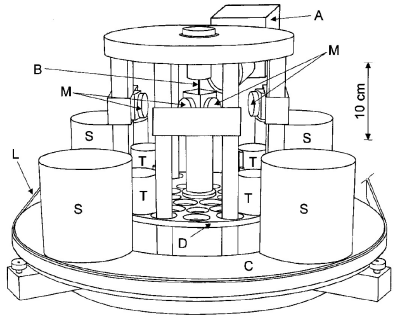
Contents

- BOSEM
- EUCLID
- ILIAD
- HoQI
- QUIMETT
- HDMI

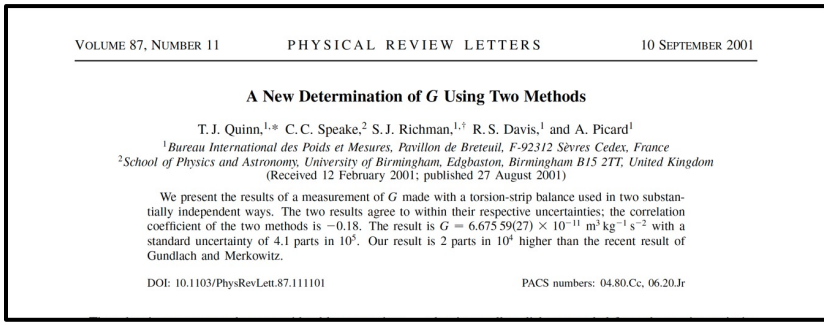
ILIAD: overview

- ILIAD: Innovative Laser Interferometric Angular Device
- Developed by Birmingham group around 2012

- Motivation:
  Newtonian Gravitational constant *G* measurement with a torsion pendulum
- After all, ILIAD was not installed for *G* measurement



T. J. Quinn+ (2001)



VOLUME 87, NUMBER 11 PHYSICAL REVIEW LETTERS 10 SEPTEMBER 2001

A New Determination of *G* Using Two Methods

T. J. Quinn,[1,*] C. C. Speake,[2] S. J. Richman,[1,†] R. S. Davis,[1] and A. Picard[1]
[1]*Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92312 Sèvres Cedex, France*
[2]*School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom*
(Received 12 February 2001; published 27 August 2001)

We present the results of a measurement of G made with a torsion-strip balance used in two substantially independent ways. The two results agree to within their respective uncertainties; the correlation coefficient of the two methods is -0.18. The result is $G = 6.675\,59(27) \times 10^{-11}\ \mathrm{m^3\,kg^{-1}\,s^{-2}}$ with a standard uncertainty of 4.1 parts in 10^5. Our result is 2 parts in 10^4 higher than the recent result of Gundlach and Merkowitz.

DOI: 10.1103/PhysRevLett.87.111101 PACS numbers: 04.80.Cc, 06.20.Jr

- Characteristics:
- Principle same as EUCLID
- Angular measurement with a non-planar interferometer

ILIAD: design

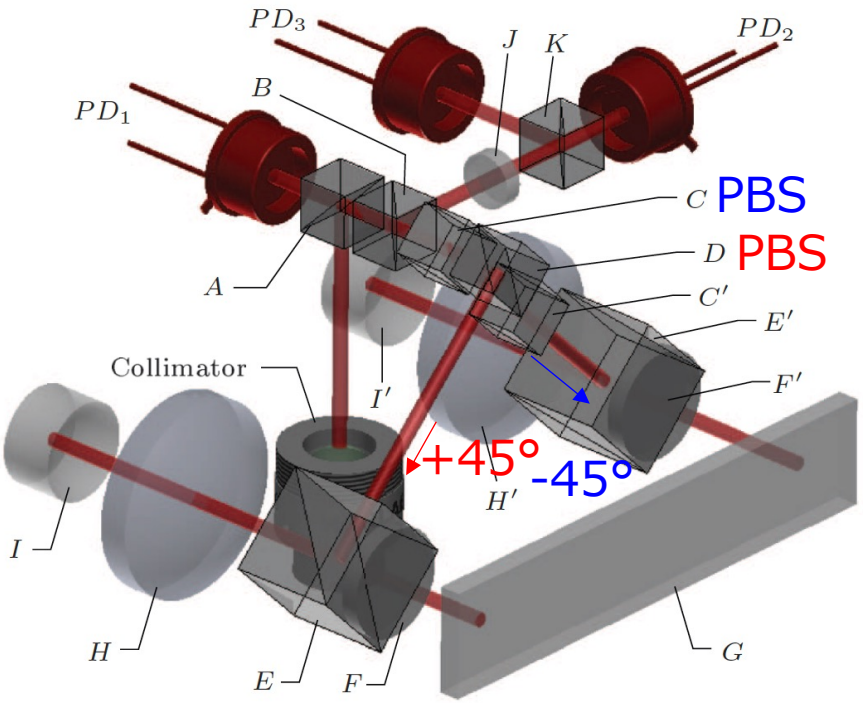


FIG. 3. Optical layout of the interferometer. A, C, D, E, E', K, polarizing beam splitters; B, beam splitter; C', compensation glass cube; F, F', J, quarter-wave plates; H, H', aspheric lenses; I, I', convex mirrors; G, target mirror; PD_1, PD_2, PD_3, photodiodes.

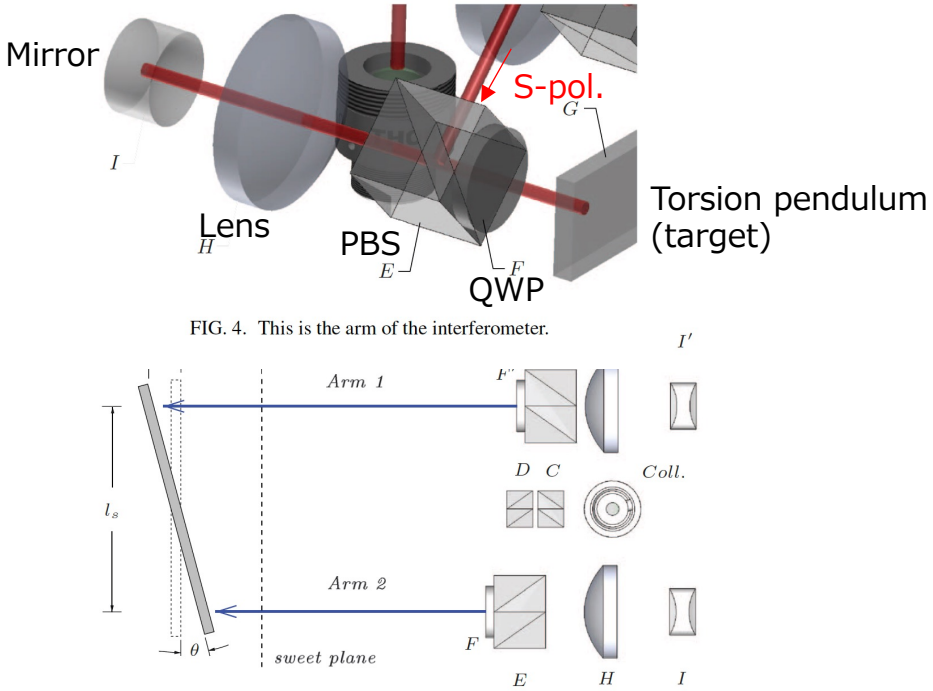
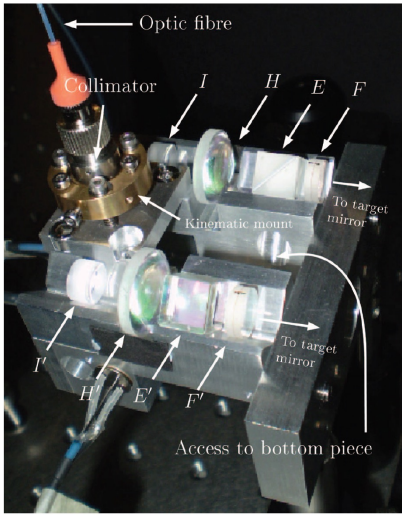


FIG. 4. This is the arm of the interferometer.

$$I_1 = b_1 + a_1 \sin\phi, \qquad \tan\phi = \frac{(a_2 b_3 + a_3 b_2)\, I_1 - b_1\,(a_2 I_3 + a_3 I_2)}{a_1\,(b_3 I_2 - b_2 I_3)},$$

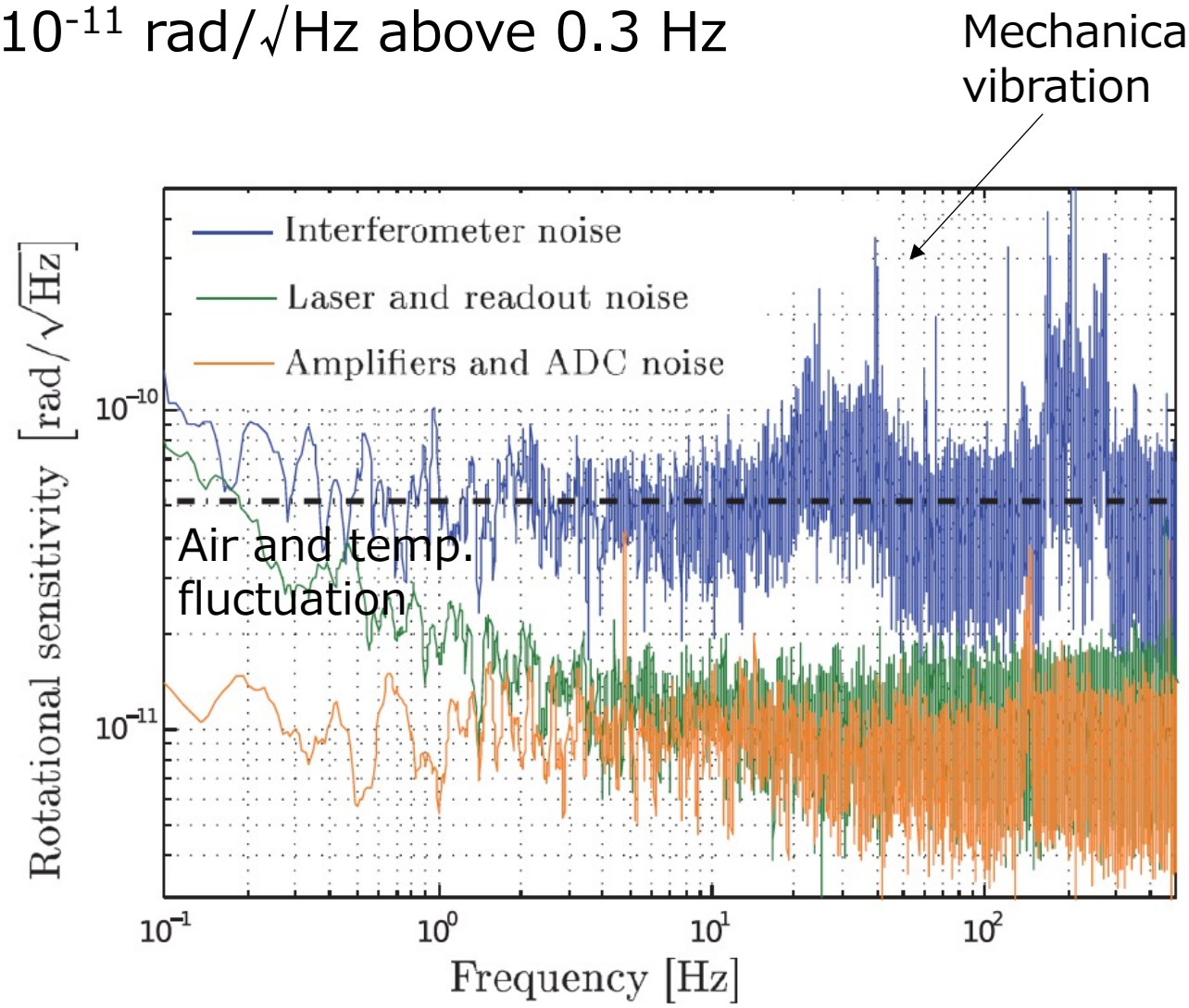
$$I_2 = b_2 + a_2 \cos\phi, \qquad \theta = \left(\frac{\lambda}{8\pi l_s}\right) \arctan\phi.$$

$$I_3 = b_3 - a_3 \cos\phi,$$



ILIAD: sensitivity

- 5×10^{-11} rad/√Hz above 0.3 Hz



Contents

- BOSEMAN
- EUCLID
- ILIAD
- HoQI
- QUIMETT
- HDMI

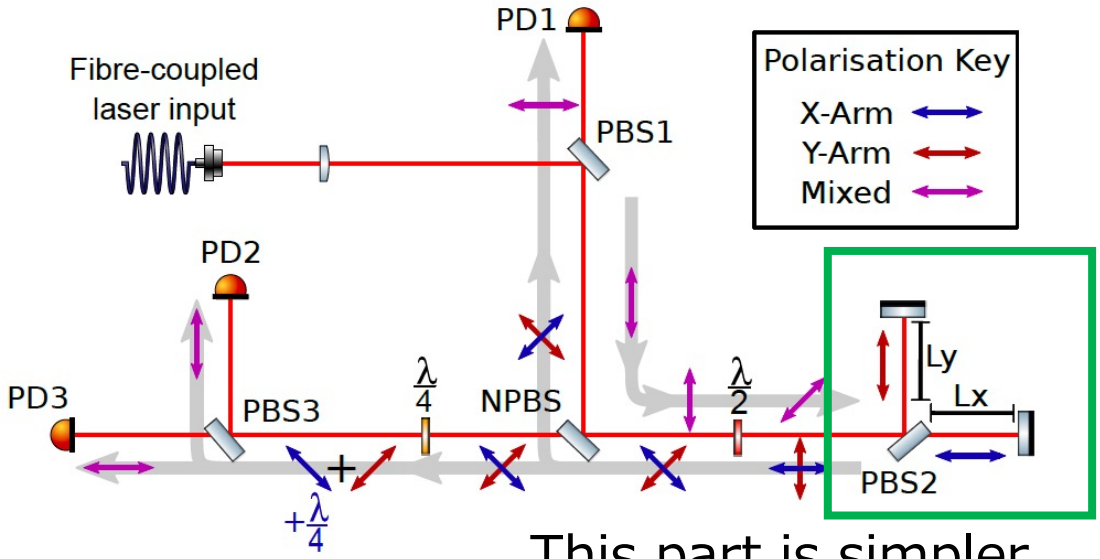
HoQI: overview

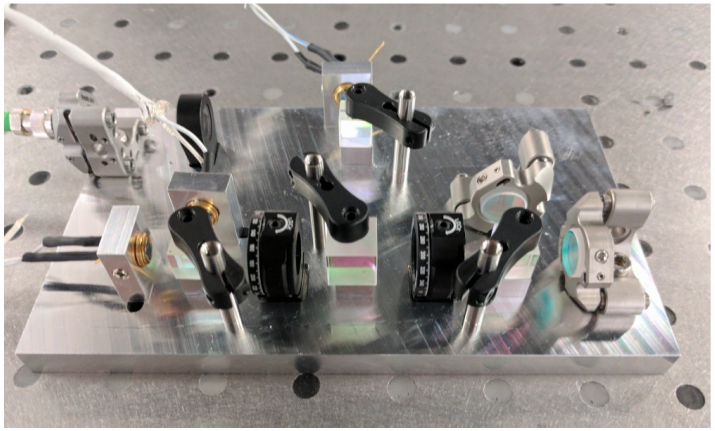
- HoQI: Homodyne Quadrature Interferometer
- Developed by Birmingham group around 2018

- Motivation: suspension control for Advanced LIGO
- Improve the sensitivity
- Replace BOSEM
- Control to lower test masses

- Characteristics:
- Improved based on reflections of EUCLID and ILIAD
- Mephisto laser
- Simple design to improve the sensitivity and to assemble easily for mass production

HoQI: design

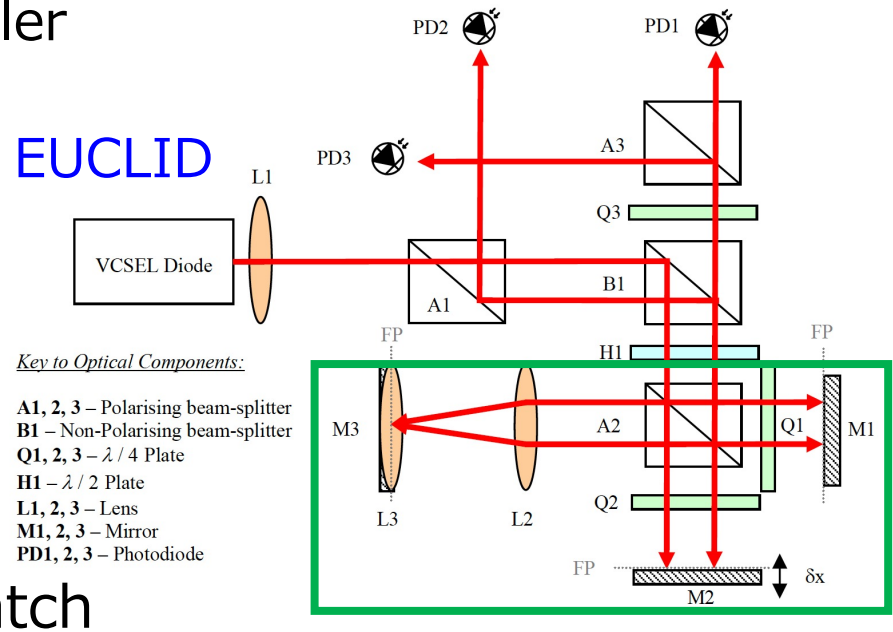




This part is simpler than EUCLID

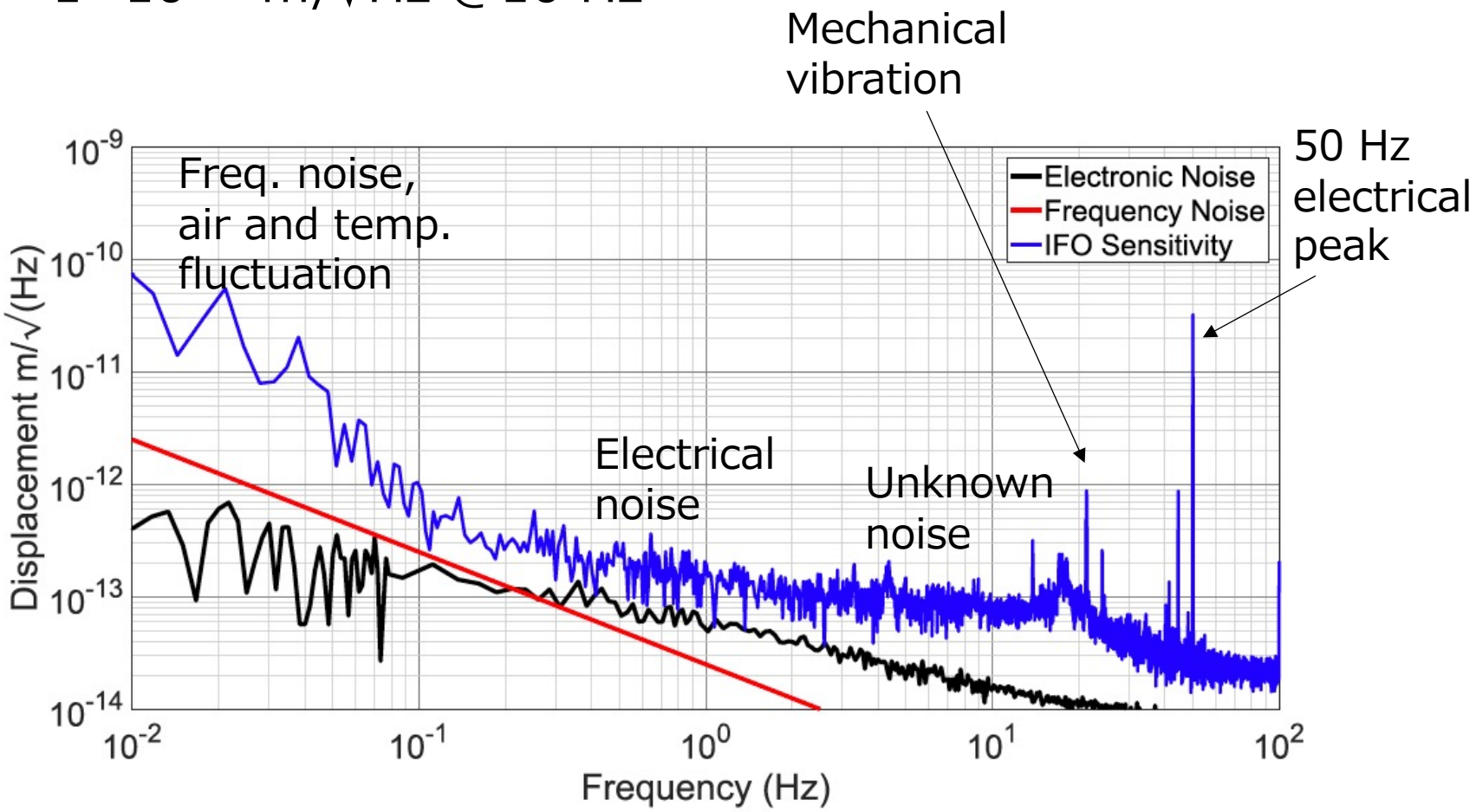
- Mephisto 500NE laser
- Simple optics
- Less birefringent optics
- No QWPs in arms
- No cat's eye
  → Small arm-length mismatch

EUCLID



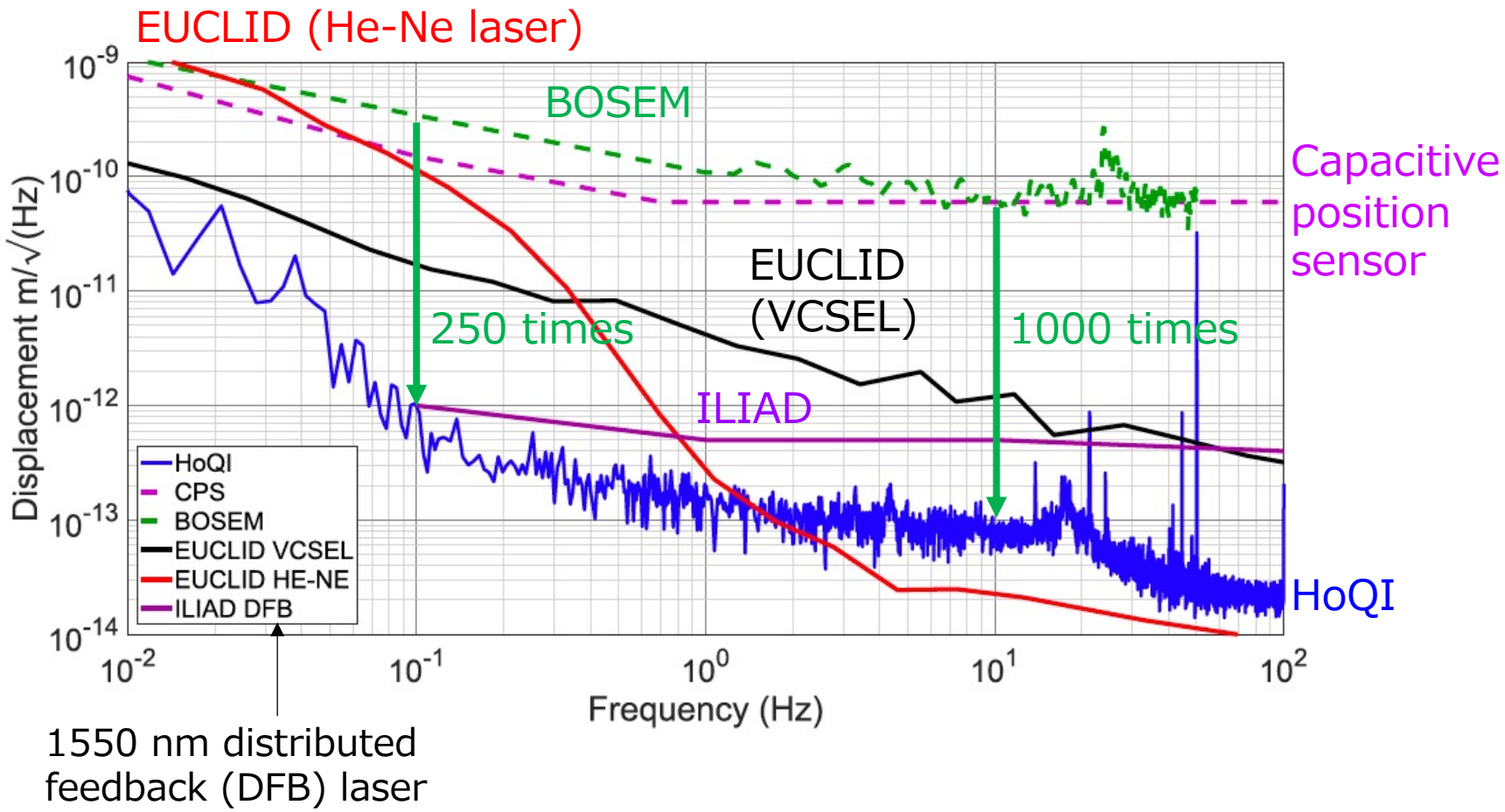
HoQI: sensitivity

- 1×10^{-12} m/√Hz @0.1 Hz
- 1×10^{-13} m/√Hz @10 Hz



HoQI: sensitivity comparison

- Much better than exiting displacement sensors



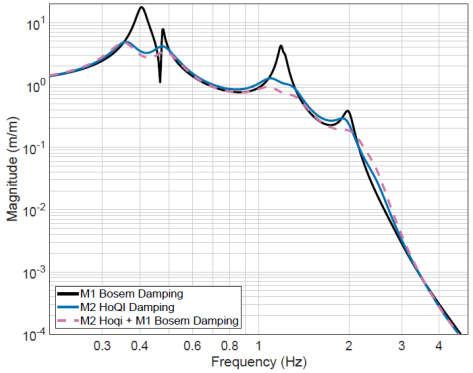
HoQI: status and application

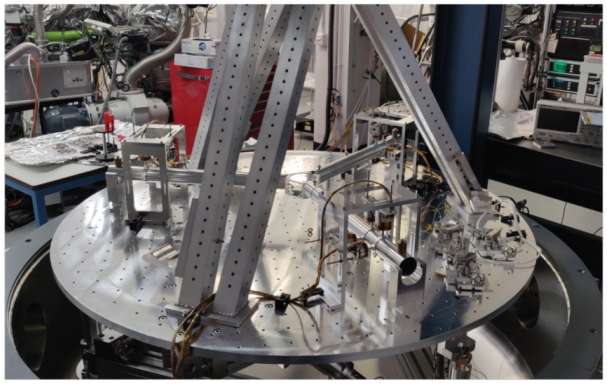
- Mass production of HoQI started



arxiv:2205.01434

- Simulation to aLIGO suspension (Journal club this week by Ono-kun)
- Six DoF seismometer S. J. Cooper+ (2022) arxiv:2207.10417
- Modified commercial L4-C geophone A. S. Ubhi+ (2022)






Contents

- BOSEM
- EUCLID
- ILIAD
- HoQI
- QUIMETT
- HDMI

QUIMETT: overview

Internal

QUIMETT: design

Internal

QUIMETT: angular measurement

Internal

QUIMETT: sensitivity

Internal

Contents

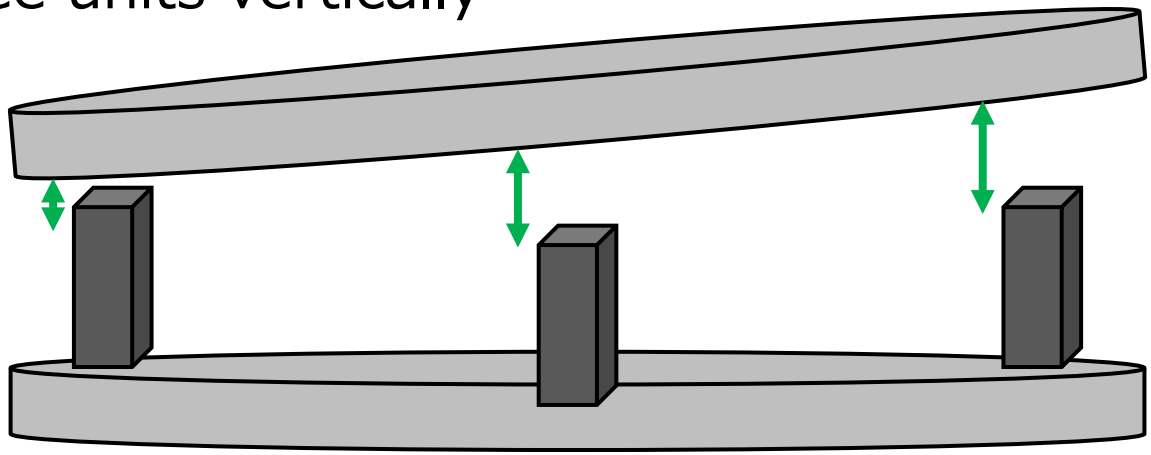
- BOSEM
- EUCLID
- ILIAD
- HoQI
- QUIMETT
- HDMI

HDMI: overview

- HDMI: Homodyne Dithered Michelson Interferometer
- Developed by Takano-san at Ando Lab around June 2020

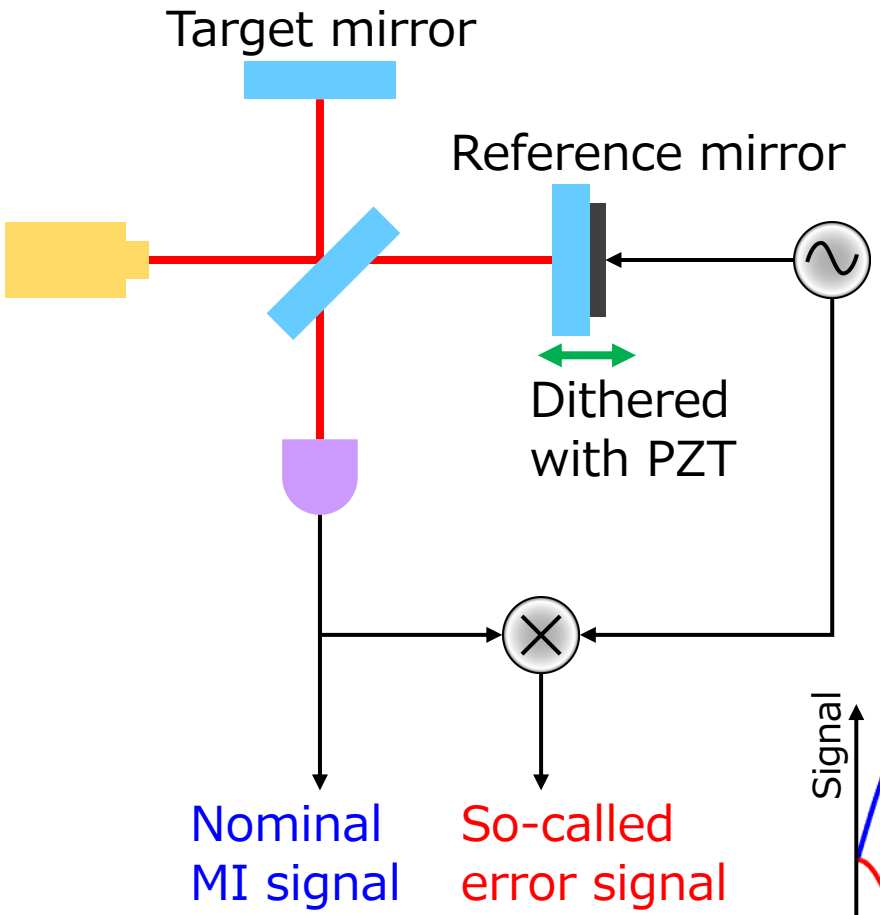
Related elog:
#4276 #4313
#4360 #4376

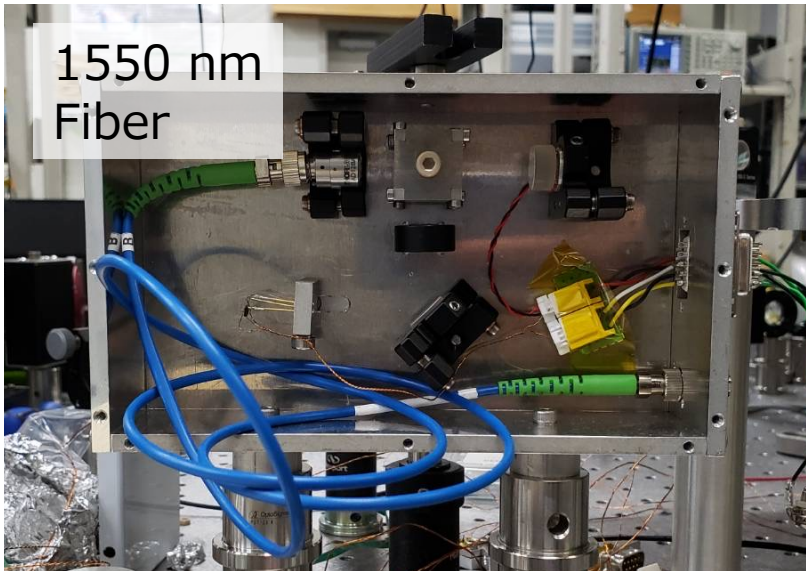
- Motivation: to measure the inclination for TOBA AVIT by placing three units vertically

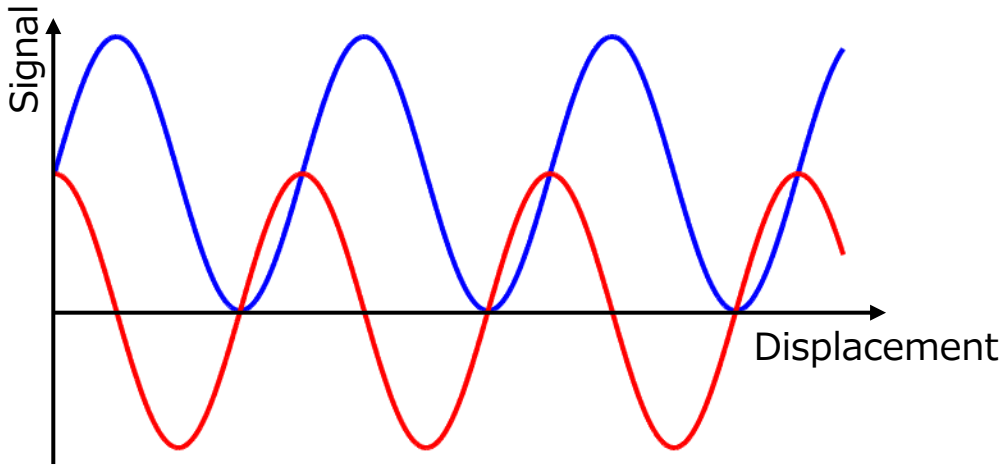


- Characteristics:
- No polarization optics
- Refence mirror is dithered to obtain quadrature signal

HDMI: design

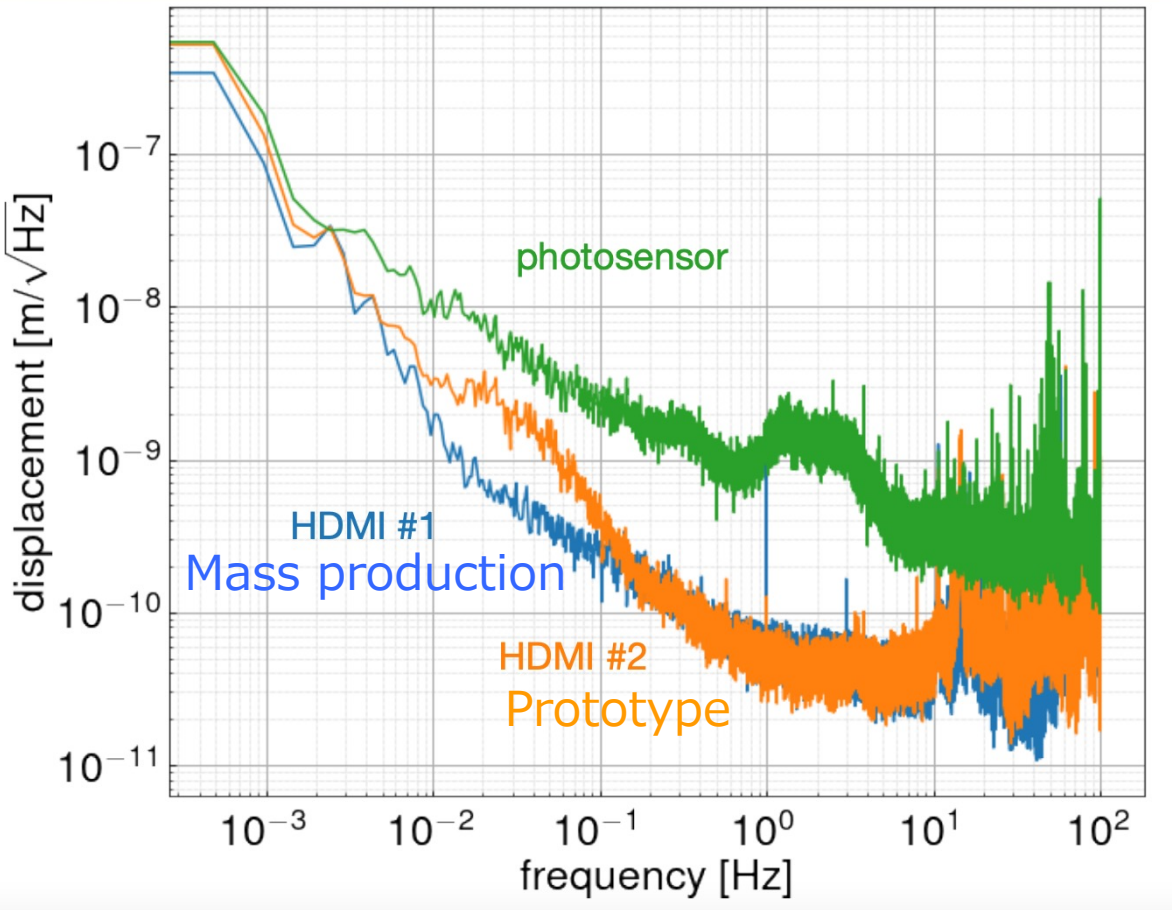

Target mirror
Reference mirror
Dithered
with PZT
Nominal
MI signal
So-called
error signal

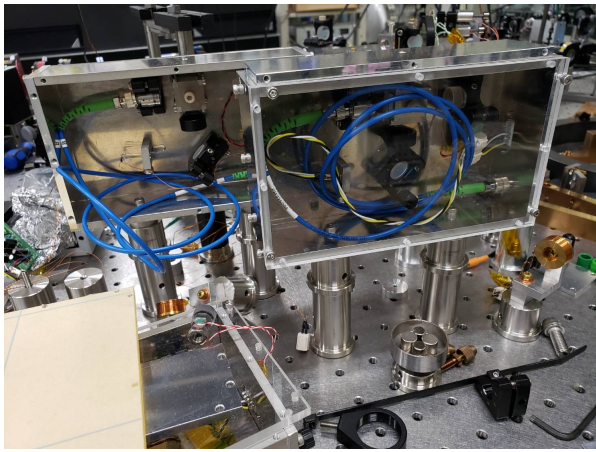

1550 nm
Fiber


Signal
Displacement

HDMI: sensitivity

- 3×10^{-10} m/√Hz @0.1 Hz
- 5×10^{-11} m/√Hz @10 Hz





Mass-produced, but not installed in AVIT yet

Summary

Sensors & references	Motivation	Design & characteristics	Sensitivity at 1 Hz	Discussion & status
BOSEM L Carbone+ (2012)	Suspension control for aLIGO	Shadow sensor, coil-magnet actuator	2×10^{-10} m/√Hz	Currently used
EUCLID S. M. Aston (2011)	Suspension control for aLIGO	Quadrature homodyne interferometer, polarizing optics, cat's eye retroreflector	4×10^{-12} m/√Hz	Improved to HoQI
ILIAD F. E. P. Arellano+ (2013)	*G* measurement with torsion pendulum	Same as EUCLID, Non-planar for angular measurement	5×10^{-13} m/√Hz	Not used for *G* measurement
HoQI S. J. Cooper+ (2018)	Suspension control for aLIGO	Simpler than EUCLID	2×10^{-13} m/√Hz	Replace BOSEM in the future
QUIMETT				
HDMI Slides	AVIT for TOBA	No polarizing optics, dither	5×10^{-11} m/√Hz	Mass-produced, not installed to AVIT