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A+ LIGO Output Mode Cleaner Cavities and Investigation of Polarisation Balanced Homodyne Detection

T. Seetharamu[1,2], S. Appert[2], K. Arai[2], M. Barrios[4], M. Barton[1], A. Bell[1], G. Billingsley[2], P. Fritschel[5], G. Hammond[1], R. Jones[1], C. Makarem[2], M. Nakano[2], E. Polini[2], K. Strain[1], C. Torrie[2], G. Vajente[2], S. Webster[1]

[1] SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom
[2]LIGO Laboratory, Caltech, Pasadena, USA
[4]University of California, Berkeley, USA
[5]LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

E-mail: t.seetharamu.1@research.gla.ac.uk

Abstract. The A+ upgrade of the Advanced LIGO detectors introduces balanced homodyne readout (BHD) and aims for improved levels of squeezed vacuum injection to enhance gravitational-wave sensitivity. A crucial component in achieving these goals is the Output Mode Cleaner (OMC), which filters higher-order modes and RF sidebands while preserving the carrier TEM_{00} mode. We present recent OMC build results with transmission consistently above 98%, an essential step towards stable 6 dB squeezing in A+ and $\sim$ 10 dB for next-generation detectors. Furthermore, we report on the ongoing experimental investigation of a polarisation-based BHD scheme, which could reduce system complexity by eliminating the need for dual OMCs, while also mitigating birefringence-induced noise.

1 Introduction

Current LIGO gravitational-wave detectors employ a DC readout scheme, which relies on slight differential arm detuning to provide the local oscillator (LO) light at the output port. Although effective, DC readout has key limitations: it couples LO intensity noise, introduces intentional IFO asymmetry, and restricts the usable homodyne phase range. To address these issues, the A+ upgrade will implement balanced homodyne detection (BHD), where an external LO is combined with the IFO output on a beam splitter [1]. BHD is one of the major upgrades to LIGO and is planned to take place starting this year ahead of the O5 run. THe BHD scheme provides freedom to choose the optimal readout quadrature, improved noise mitigation, and compatibility with stable squeezed-light injection. Alongside BHD, improved Output Mode Cleaner (OMC) cavities are critical to achieving the A+ sensitivity goals. Since each site requires two OMCs to perform BHD, this introduces complexities. Polarisation BHD is an idea [2] where the LO and IFO signal beams, kept at orthogonal polarisations and are mixed together using half wave plates (HWP) to perform BHD.

2 Output Mode Cleaner Improvements

2.1 Role of the OMC

The OMC is a monolithic bowtie optical cavity (see Figure 1) that transmits the IFO's carrier light while rejecting RF sidebands and higher-order spatial modes. Achieving throughput level beyond 98% is vital for preserving squeezed states, as any optical loss directly degrades the squeezing level. Current Advanced LIGO detectors have demonstrated squeezing levels up to 5.2 dB at Hanford and 6.1 dB at Livingston, although maintaining stable operation at these levels remains challenging [3]. The measured OMC efficiency is approximately 98% at Livingston and 96% at Hanford. For the A+ upgrade, the target is stable 6 dB of squeezing, which requires improved mode matching, active misalignment control, and reduced optical loss in the OMC and other components. Looking further ahead, next-generation gravitational-wave detectors will aim for squeezing levels of 10 dB or more [4].

2.2 Build Results

The recent build progress across six OMCs have consistently demonstrated $> 98\%$ transmission. This marks a significant improvement over aLIGO OMCs ($< 97\%$) and represents an essential milestone for reaching A+ squeezing targets. The results are summarised in Table 1.

2.3 Optimisation Strategies

The performance of the OMCs has been improved through a combination of reduced optical losses from improved coatings (confirmed by higher cavity transmission), tighter screening to identify scatter and absorption sites using Total Integrated Scatter (TIS) and transmittance measurements, enhanced characterisation via ZYGO interferometry to determine mirror radii of curvature and optimise alignment, and rigorous cleanliness protocols, including detailed inspection and "first contact" cleaning prior to power budget measurements.

Table 1: Measured OMC parameters (OMC1–OMC6).

	Finesse	**OMC unit throughput**	**OMC loss per mirror (ppm)**
OMC1	390	0.991 ± 0.005	16 ± 11
OMC2	375	0.9798 ± 0.0054	43.49 ± 11.44
OMC3	380	0.983 ± 0.002	32 ± 10
OMC4	380	0.988 ± 0.007	23.25 ± 14.25
OMC5	387	0.986 ± 0.008	27 ± 17
OMC6	378	0.9836 ± 0.0049	31 ± 10

3 Polarisation BHD

3.1 Motivation

Conventional BHD in A+ requires two OMCs in the readout chain, increasing hardware complexity and potential asymmetry-induced noise coupling (reducing common-mode rejection) [1]. Polarisation BHD is an idea [2] to reduce the necessity for two OMCs (Figure 1) and potentially much simpler than A+ BHD. The reduction in number of OMCs comes from co-propagation of LO and IFO signal beams unlike in the nominal BHD setup (see Figure 1). But polarisation BHD comes with it's own problem of birefringence noise but we show how this can be reduced by doing balanced rotation before and after the OMC. This enables cancellation of birefringence-induced noise while preserving net 45° rotation required for performing BHD with orthogonally polarised LO and IFO beams.

3.2 Concept

The scheme uses HWPs before and after the OMC to achieve a net 45° rotation between s- and p-polarised fields. This preserves the BHD signal while cancelling birefringence-induced displacement noise (Figure 1). The total noise can be written [5]:

$$\frac{\partial(P_1 - P_2)}{\partial x} = -\left(P_{\mathrm{LO}} + P_{\mathrm{IFO}}\right)\sin(4\theta)\,\frac{\Delta f_0\, f_{\mathrm{FSR}}}{f_c^2 \lambda} + \sqrt{P_{\mathrm{IFO}} P_{\mathrm{LO}}}\,\cos(4\theta)\sin\delta\,\frac{4\,\Delta\mathcal{F}}{\lambda}. \tag{1}$$

The first term here represents noise coupling due to birefringence induced difference in resonance frequencies of the cavity for s- and p- beams and the second term the same due to difference in finesses for the two polarisations. Setting this to zero gives the optimal first HWP angle:

$$\theta_{\text{opt}} = -\frac{1}{4}\arctan\left(\sqrt{\frac{P_{\text{IFO}}}{P_{\text{LO}}}}\cdot\frac{4\,\Delta\mathcal{F}}{f_{\text{FSR}}}\cdot\frac{f_c^2}{\Delta f_0}\cdot\sin\delta\right). \tag{2}$$

where $\Delta\mathcal{F}$ and Δf_0 are difference in cavity finesse and cavity resonance frequencies for s- and p- beams respectively, f_c and f_{FSR} are cavity pole and cavity free spectral range respectively and P_{IFO} and P_{LO} are IFO and LO beam powers respectively. And δ is the homodyne angle.

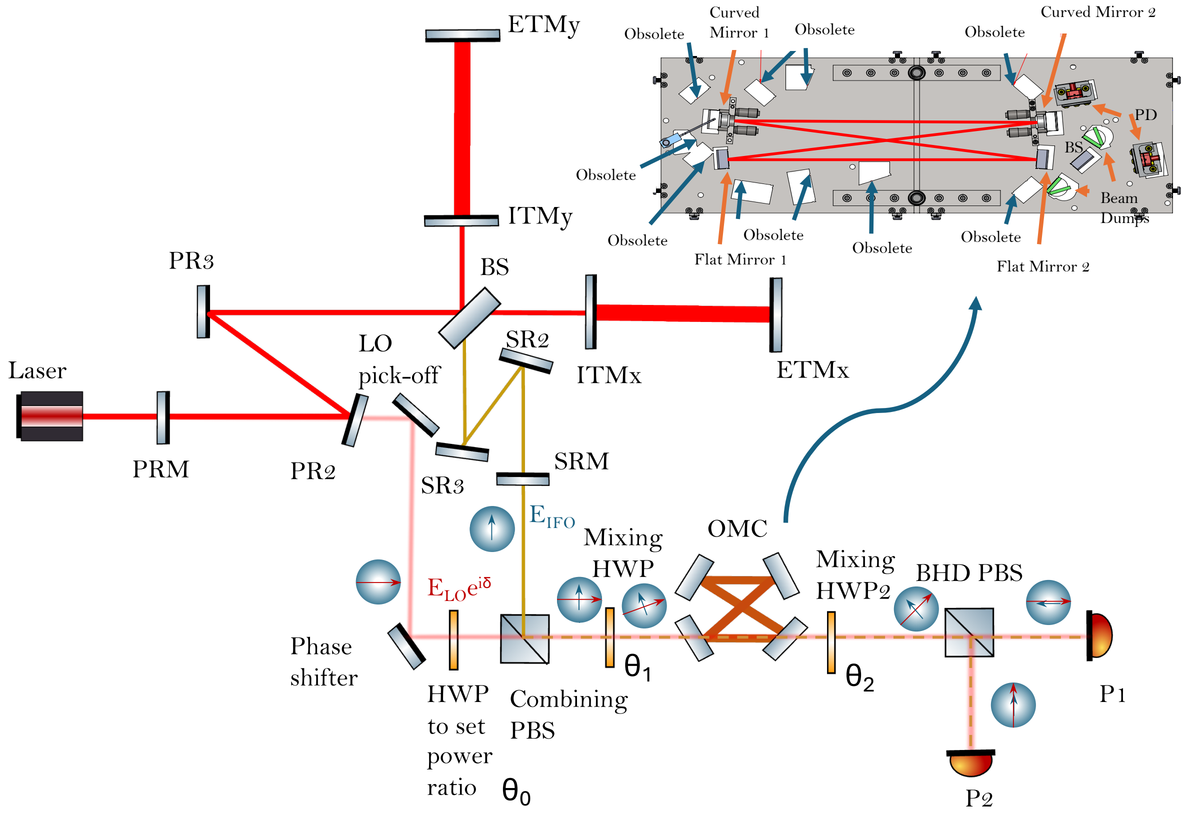

Figure 1: Schematic of the A+ IFO output with polarisation homodyne readout (HWP both sides of OMC fast axes angles at θ_1 and θ_2 respectively). The LO and IFO beams are p- and s- polarised respectively.

3.3 Experimental Progress

We measured the birefringence parameters of OMC1 in July 2024 and explored mitigation of OMC length-noise coupling to the BHD signal using an HWP and a quarter wave plate (QWP) to set phase and power ratio between s and p. The results are summarised in Table 2.

Table 2: Measured cavity birefringence parameters. Δf_0 and finesse difference were obtained by injecting a 45° linearly polarised beam and scanning the cavity to detect both p and s polarisations; parameters were extracted by fitting the difference of two Lorentzians to the s–p signal.

Parameter	**Value**
Δf_0 (kHz)	6.488 ± 0.165
Finesse difference	3.182544 ± 0.585646

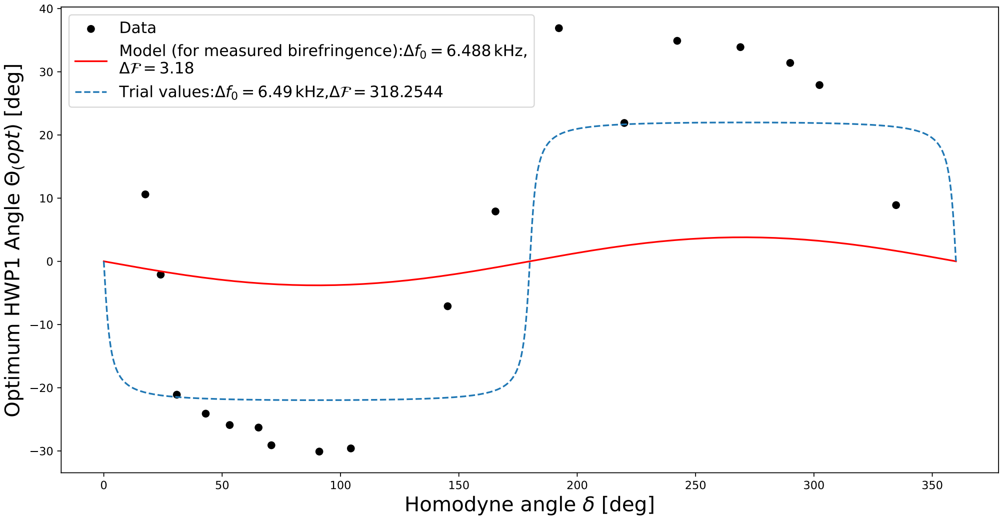

Figure 2: Optimum HWP1 angle Θ_{opt} as a function of homodyne angle δ. Black markers represent experimental data points. The solid red line shows the model curve based on measured birefringence parameters ($\Delta f_0 = 6.49, \mathrm{kHz}$, $\Delta\mathcal{F} = 3.18$). The dashed blue line corresponds to a trial parameter set, illustrating the deviation of the measured optimum HWP1 mixing angles from the measured birefringence values. Unfortunately the measured angles don't agree with the theoretical prediction and further measurements are planned this month.

As shown in Figure 2, substituting the measured birefringence values of OMC1 into equation 2 does not reproduce the observed scatter of the optimum HWP1 mixing angle that minimises the coupling between OMC length fluctuations and homodyne signal fluctuations. To address this discrepancy, a new series of measurements is planned for August 2025 using OMC6, with improved modelling and a more refined experimental procedure.

4 Conclusion

All six OMCs have now been successfully constructed and are scheduled for delivery to the LIGO sites in the near future. The experimental investigation of polarisation-based BHD is ongoing, and further details will be reported in forthcoming work.

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