LIGO SURF Summer Project Plan: Homodyne Detector Characterization

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1. Introduction

The LIGO experiment makes use of large laser interferometers in order to observe gravitational waves (GW), as predicted by Einstein's theory of General Relativity. After the goals of Initial LIGO were accomplished in 2007, a series of improvements were made in effort to progress from Initial LIGO to Advanced LIGO [1]. These upgrades included an increase in laser power, a thermal lensing compensation system, an output mode cleaner, an angular sensing and control system, and a migration to a homodyne readout scheme [1]. Currently the Advanced LIGO detectors employ a homodyne DC readout scheme (DCR) to sense the GW signal at the dark, or anti-symmetric, port.

Homodyne detection, in general, makes use of a local oscillator field (LO) that is directly sampled from the main carrier field, so the mixed output of the two signals is around 0 Hz. The homodyne detection methods have advantage over older methods by reducing susceptibility to various technical noise couplings, and lowering quantum noise [2]. Although the transition to DCR offered significant advancements, this detection method is still subject to several challenges.

The fact that the static carrier field is present at the anti-symmetric port (AS) in DCR creates vulnerability. Any amount of light that enters back into the interferometer can create noise at the main output port, and the carrier also produces a signal in the photodiode segments that must be subtracted to find the arm alignment signal [2]. Additionally, the fact that DCR requires a slight difference in arm lengths allows for an increase of the coupling of laser intensity fluctuations at the output, which can impose more stringent requirements on laser noise [2]. Evans gives the following relation for the static LO field (A_{DC}), the gravitational wave field (A_{GW}), and the power at the AS port photo detector (P_{AS}) [2].

$$P_{AS} = \bar{P}_{AS} + 2\mathcal{R}e(\bar{A}_{DC}(A_{GW} + \varepsilon\bar{A}_{DC})^*) \tag{1}$$

The amplitude modulation resulting from technical noise at the output is indistinguishable from the gravity wave signal, and the phase of the LO field relative to the phase of the gravitational wave signal is constant [2].

As opposed to DCR, a balanced homodyne detection scheme (BHR) makes use of interferometer arms that are held in resonance, with interference of the LO and AS fields occurring at a second beam splitter in the output path [1,2]. The LO signal can be picked off (A_{PO}) of the main interferometer light and propagated to the dark port for this interference, where the second beam splitter directs the signal to two photodiodes with power P_A and P_B. As shown by Evans [2],

$$P_A - P_B = 2\mathcal{R}e\left(e^{i\phi}\bar{A}_{PO}A^*_{GW}\right) \quad (2)$$

Equation 2 demonstrates that, with BHR, the LO phase is no longer constrained to the GW phase, and the GW signal is insensitive to noise on the LO signal [2]. These two results present an advantage over DCR, but pose new challenges. Since the LO field is no longer propagated along the same path as the signal field, the LO phase needs to be measured and controlled, and the LO field is not automatically co-aligned and mode-matched to the signal field [2]. In similar experiments, these issues have been addressed by propagating RF sidebands with the signal field to measure its phase difference with the LO field, which is then detected by the photodiodes and fed into a servo control loop that adjusts the angle of the second beam splitter [2]. A mode cleaning cavity can also be used in the LO path for mode-matching the LO with the signal field [2].

2. Objectives

In order to reap the benefits of BHR, a high fidelity combination of the LO and signal fields is required at the dark port, achieved with the addition of a homodyne detector similar to the one which will be investigated. The signal balancing required to realize equation 2 can be affected by technical issues such as:

1. Beam splitter alignment. The second beam splitter must be carefully and exactly tuned to divide the combined LO and AS signals between the two photodiodes as equally as possible. In the case of perfectly equal splitting, the photodiodes should produce the same amount of current, which would cancel the mode noise mentioned above.

2. Equal scattering of light from the beam splitter. Alignment requirements of the second beam splitter can be investigated, as the reflective properties of the beam splitter material can vary with incidence angle. The impact of scattering from the beam splitter must also be assessed, and proper mitigations can be construed to ensure that the photodiodes receive the same light.

3. Optimized electronic performance of the circuit. The electronic current subtraction between the two diodes can be characterized and optimized to yield the highest amount of mode cancellation. The detection scheme's overall level of noise immunity can be determined and maximized with all of these assessments.

3. Approach

- A setup to test the noise suppression capabilities of a homodyne detector will be built in the lab.
- In the test setup, an NPRO laser will be used, with intensity stabilization and the capability of injecting signal noise as the ε term in equation 1.
- Digital data will be collected and analyzed using an Advanced LIGO style DAQ.
- The homodyne detector electronics are an example of a design that could potentially be used as a BHR detection scheme in the full scale LIGO interferometer.

4. Project Schedule

Activity	**Time Allotted**
Learn about the interferometer and gravity wave detection	1 week
Assemble the experimental setup in the lab and stabilize the laser	2 weeks
Measure detector noise performance	5 weeks
Model the effect of detector noise performance on the full interferometer	2 weeks

5. References

[1] Fricke, Tobin T. *Homodyne Detection for Laser-Interferometric Gravitational Wave Detectors*. Louisiana State University, Baton Rouge. 2011.

[2] Matthew Evans, Peter Frischel, and Valery Frolov. *Balanced Homodyne Readout for Quantum Limited Gravitational Wave Detectors*. LIGO Laboratory, Massachusetts Institute of Technology, Cambridge. 2013.