Honours Update

July 2, 2024

Initial Proposed Plan

- The primary objective is to reproduce the strain vs. frequency graph from Fig. 4 Zhang et al. 2023 using Finesse 3
- Optical Cavity Testing
  - Tasks: Test an optical cavity & Change parameters and perform a sanity check.
  - Proposed Plan:
    1. Cavities
    2. Mach-Zehnder Interferometer
    3. Foucault
    4. Cavity + Mach-Zehnder (L-shape config)
    5. Recycling + Previous

Optical Cavity Understanding

An optical cavity, consisting of an arrangement of mirrors or other optical elements, serves as a resonant cavity for light waves. It is integral to laser systems, encasing the gain medium and providing essential feedback for laser operation.

Fabry-Perot Cavity

Involves a two-mirror optical cavity with an incident input laser. Utilises three photodiodes to monitor reflected, transmitted, and circulating power. Resonance is achieved by adjusting mirror tuning or scanning the input laser frequency.

Key Equations

Output Electric Field

$$E_{out} = E_{in} \frac{T_1 T_2 e^{i\phi}}{1 + R_1 R_2 e^{i\phi}}$$

Transmission Coefficient:

$$t_c = t_1 t_2 e^{-ikL} \sum_{n=0}^{\infty} \left(r_1 r_2 e^{-i2kL}\right)^n = \frac{t_1 t_2 e^{-ikL}}{1 - r_1 r_2 e^{-i2kL}}$$

Reflection Coefficient:

$$r_c = -r_1 + t_1^2 r_2 \sum_{n=0}^{\infty} \left(r_1 r_2 e^{-i2kL}\right)^2 = -r_2 + \frac{t_1^2 r_2}{1 - r_1 r_2 e^{-i2kL}}$$

Resonance Condition: The cavity reaches resonance when the maximum power is transmitted.

Response Functions:

Circulating Power:

$$F^{sc}_{circ} = \frac{E_{circ}}{E_{in}} = \frac{t_{im}}{1 - r_{im} r_{em} e^{i\phi}}$$

Reflected Power:

$$F^{sc}_{refl} = \frac{E_{refl}}{E_{in}} = \frac{r_{im} - r_{em} e^{i\phi}}{1 - r_{im} r_{em} e^{i\phi}}$$

Transmitted Power:

$$F^{sc}_{trans} = \frac{E_{trans}}{E_{in}} = \frac{t_{im} t_{em} e^{i\phi/2}}{1 - r_{im} r_{em} e^{i\phi}}$$

Coupling Conditions

- Under-coupled: $r_{im} > r_{em}$
- The system demonstrates lower efficiency due to impedance mismatch, causing the majority of input power to be reflected rather than transmitted.
- Impedance matched: $r_{im} - = r_{em}$
- Achieves optimal power transfer, minimising reflections and maximising transmission
- Over-coupled: $r_{im} > r_{em}$
- Although it results in high transmission, increased loss occurs, potentially destabalising the cavity.

Predictions for Non-Linear Cavities

- Phase Response: For a non-linear cavity with a folded mirror, the phase response will display unique characteristics depending on the degree of non-linearly and mirror configuration
- A folded mirror with 100% reflectivity over a length of 50 km would result in significant phase shifts and potential mode-matching issues due to the extensive propagation distance.

Summary of Honours Proposal (Moreso revision for myself)

Enhanced Sensitivity Interferometry for Probing Post-Merger Gravitational Waves: Investigating a New L-Shaped Interferometer Configuration

The proposal aims to significantly advance the detection capabilities of gravitational waves, specifically those emitted during the post-merger phase of binary neutron star collisions. The project presents a plan to develop and test an innovative interferometer configuration using advanced optical modelling techniques.

Abstract and Motivation

Gravitational waves, first observed in 2015, have transformed astrophysics, cosmology, and fundamental physics by offering a novel observational window into the universe. These waves are perturbations in spacetime produced by violent astrophysical events, such as the mergers of neutron stars or black holes. Detection of these waves has been achieved using large-scale interferometers like LIGO and VIRGO, which employ Michelson interferometers with Fabry-Perot cavities to boost sensitivity. Nonetheless, current detectors encounter sensitivity limitations, particularly at high frequencies where binary neutron star post-merger signals are most discernible.

Proposed Research Program

My research focuses on developing an optical model for a novel interferometer configuration to enhance sensitivity to gravitational waves from binary neutron star post-merger events. This model will be crafted using Finesse, a Python-based simulation tool tailed for interferometric configurations. This project builds on the work of Zhang et al. (2023), which demonstrated a marked improvement in high-frequency sensitivity using a 50 km Fabry-Perot-Michelson interferometer.

The research program is segmented into several key stages:

1. Literature Review and Familiarisation

   (a) *Need to read into more literature than Zhang 2023*

2. Model Development: The stage encompasses simulating the Fabry-Perot-Michelson interferometer, beginning with a basic Michelson configuration (*Pretty happy with this part so far and testing the transfer functions*), and progressively incorporating additional components to evaluate system behaviour (*Immediate next steps. First: Find equations for transfer functions of folded mirror*)

3. Calibration and Testing: The model will be calibrated against existing sensitivity data, following by Monte-Carlo simulations (*Have no clue how to implement these*) to estimate event detection rates and signal-to-noise ratios.

4. Comparison and Analysis: The strain sensitivity of the final design will be compared with current and future detectors to assess potential advantages.

Novel Configuration and Advantages

The novel L-shape interferometer configuration aims to surpass the limitations of existing designs by introducing supplementary mirrors and cavities to enhance optical power and signal extraction. This configuration includes a power recycling cavity at the input port (bright port) and a signal recycling cavity at the output port (dark port), collectively improving the interferometers sensitivity at high frequencies. The design also incorporates a sloshing-type Sagnac configuration to mitigate losses associated with the signal extraction cavity, a primary constraint in current interferometers.

This new configuring is anticipated to offer several advantages:

1. Enhanced High-Frequency Sensitivity: By optimising the optical layout, the interferometer can achieve superior sensitivity at frequencies where post-merger gravitational wave signals are most pronounced.

2. Improved Detection Rates: The heightened sensitivity will increase the detection rate of neutron star post-merger events, providing a wealth of data for astrophysical and cosmological investigations

3. Potential for Dark Matter Detection: The enhanced sensitivity range of the new detector may also facilitate the detection of dark-matter-induced neutron star collapse, presenting new opportunities for dark matter research.