

Improving the optomechanics of a BAW resonator for quantum amplification within future gravitational wave detectors

Joseph Hocking

Supervisors: Prof. C. Zhao, Prof. Ju Li

A Research Proposal for the degree of
Master's in Experimental Physics



ARC Centre of Excellence for Gravitational Wave Discovery
Department of Physics
University of Western Australia
October 22, 2023

Contents

I. Introduction	2
II. Quantum Amplification through White Light cavities	3
A. Gravitational Wave Detector Noise	3
B. White Light Cavities	5
C. Overview of ND through Optomechanical Resonators	6
III. Preliminary Study	8
IV. Proposed Works	9
V. Conclusion	12
References	13

I. Introduction

Gravitational waves, ripples in the very fabric of space-time, were once thought to be the playground of theoretical physicists. That was until in September of 2015, when we first directly heard the rumblings of universe[15]. A true testament to the hard work and utter dedication of over half a century of international collaboration. We are now on the cusp of a new era of astronomy, the era of gravitational wave detection. It was Feynman[25], in a conference in 1957, described the first gravitational wave detector (GWD) in a mock thought experiment. Imagine a rigid rod, with two beads freely sliding (with friction), as the wave passes through the rod the rigidity of it does not allow it to move with the wave. However, the proper distance between the beads will move, and due to this some small amount of energy will be deposited within the system, energy from the wave itself. Thus it was realised that, theoretically at the minimum, one could detect gravitational waves. It was quickly noted, however, that due to the incredible stiffness of space-time, there existed no such material that could resist the motion of the wave.

The first experimental attempts at gravitational wave detections were through the use of *Resonant Mass Antennas*. These consist of a large bar precisely machine to have a resonant frequency matching that of expected gravitational wave sources. These achieved strain sensitivities on the order of $10^{-19} Hz^{-1/2}$, chiefly through the use of advanced seismic isolation systems, cryogenic cooling, and materials with extreme mechanical Q-factors.

The next generation of GWDs came in the form of large laser-based interferometers. These are a modified Michelson interferometer, with optical cavities within the arms. The end mirrors of the arms are tuned such that the phase of the two beams destructively interferes on the output (dark port) of the detector. When a gravitational wave passes through, differential stretching and squeezing of the two arms causes a phase difference in the beams, resulting in light at the output port. The current second generation interferometers, with newly implemented frequency dependent squeezing, are capable of reaching strain sensitivities of $10^{-24} Hz^{-1/2}$. However, for events such as binary neutron star coalescence, much of the information about the progenitor objects, the merger, and the resultant object is contained within the high frequency ring down above 1kHz[22]. Unfortunately, current detectors are limited to peak sensitivities below 500Hz by quantum noise mechanisms.

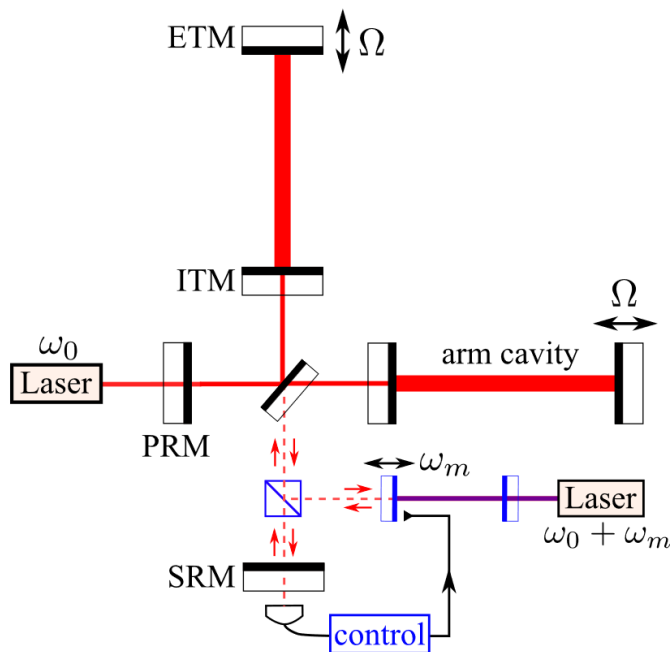


FIG. 1: A simplified schematic of an interferometric gravitational wave observatory. PRM, SRM, ITM, and ETM refer to the power recycling mirror, the signal recycling mirror, the initial test mass and the end test mass respectively. The optics drawn in blue show a proposed configuration of a white-light cavity scheme. In this configuration, the optomechanical resonator is the entry mirror to the optical cavity adjacent to the output, however in the WLC scheme explored here, the entry mirror is fixed and a separate resonator resides inside this optical cavity[19].

II. Quantum Amplification through White Light cavities

A. Gravitational Wave Detector Noise

The main categories of detector noise may be divided up into three rough frequency regimes. Within the **low frequency regime**, we are dominated by classical noise sources. This is largely related to the seismic motion of the ground coupling into the suspension system for the mirrors and so outside the scope of this work. In the **mid-frequency regime** we begin to see the radiation pressure back-action of the interferometer¹. Due to the quantum uncertainty of the photons' amplitude and arrival time, the radiation pressure exerted on the mirrors when they are reflected is noisy. As the interferometer is measuring the relative positions of the mirrors, this will become phase noise on the output and gives the radiation pressure noise seen within this frequency band. Finally, within the **high frequency regime**, we are limited by the quantum shot noise of the photons, or rather quantum uncertainty directly in the phase of the photons.² It is important to note that this noise source is independent of the frequency of gravitational

¹ Current detectors see thermal noise dominate here, however radiation pressure noise is not far behind, and as cryogenic test masses advance the radiation pressure noise will become more prominent

² Interestingly, this quantum noise does not in fact come from the bright port of the detector (where the laser is injected) as the quantum noise associated with this port will create in-phase noise down the two arms, while

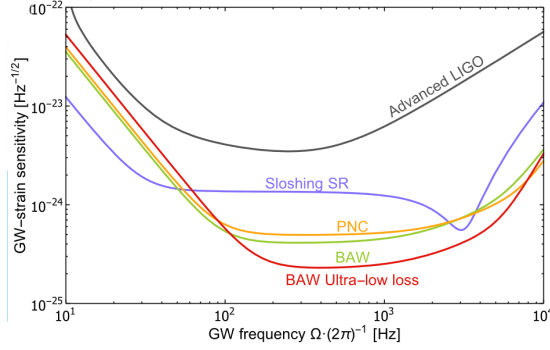


FIG. 2: The representative noise curves in current detectors and proposed WLC schemes. The mechanisms this proposal is concerned about are shown in red and green[22].

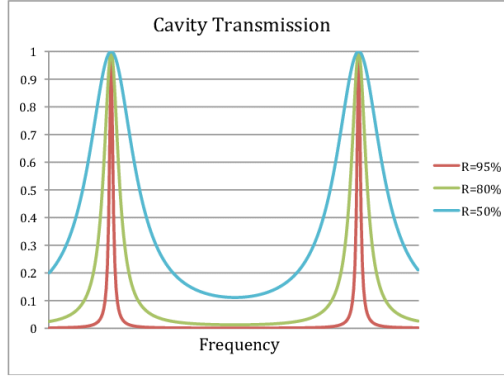


FIG. 3: A spectrum of a Fabry-Perot cavity[30]. The detector may be represented as such a cavity, where the laser frequency is resonant. When a GW passes through the detector, it introduces frequency sidebands that are separated by the GW frequency. If this frequency is smaller than the line-width of the cavity, then the sidebands will be amplified, if it is larger than the sidebands will be damped.

wave, however, it's effect on the strain sensitivity of the detector is not. To see how this can be, we must examine the response of the detector within the frequency domain.

The full detector is composed of many coupled cavities, however we will choose to simplify down to a single Fabry-Perot cavity with identical mirrors of power reflectivity R and power transmission T . This will have a normalised intensity of light within the cavity, as a function of light frequency ν , given by

$$I(\nu) = \frac{T}{1 + R^2 - 2R \cos(\Phi(\nu))}, \quad \Phi(\nu) = \frac{4\pi\nu L}{c}, \quad (1)$$

where L is the length of the cavity arm, and c is the speed of light. This is plotted in Fig 3,

will be destructively interfered. Instead the quantum noise is associated with the dark port of the detector, where the beam splitter will serve to shift the noise to be out of phase between the two arms. This is why squeezing is performed on a vacuum state and injected into the dark port

in which one can observe that the lower frequency gravitational wave signals are amplified by the cavity, while the higher frequency signals will be damped. This reduces the photon count at these high frequencies which, due to the Poisson counting statistics of the photons, will lead to a high relative uncertainty. This is the root cause of the shot-noise related strain noise.

Gain-Bandwidth Relationship

Moreover, assuming we are operating near the resonant frequency, that is the round-trip phase accumulation $\Phi(\nu_0) = 2n\pi$ for integer n , and the mirrors are near 100% reflectivity, we can simplify (1) down to

$$I(\nu_0) \approx \frac{4}{T}. \quad (2)$$

Additionally, the resonance condition will be met every free spectral range (FSR), that is $\nu_{FSR} = c/2L$. And so for finesse \mathcal{F} and cavity bandwidth ν_{FWHM} we have

$$\nu_{FWHM} = \frac{\nu_{FSR}}{\mathcal{F}} = \frac{c/2L}{\pi r/(1-R)} \approx \frac{c/2L}{2\pi/T} \implies \nu_{FWHM} \propto T. \quad (3)$$

By examining (3) and (2), we can see that the higher the gain, the lower the bandwidth. Thus we must either sacrifice on peak strain sensitivity for the sake of a larger bandwidth, or prioritise peak sensitivity over broadband sensitivity. Real GWDs are much more complicated than this, but the argument still remains the same. Ideally we would like to have a high gain, whilst maintaining a high bandwidth. This would be incredibly insightful into the the pre-merger and post-merger remnants of gravitational wave events, allowing us to see the full waveform of the in-spiral and merger. To do so, we must go beyond the classical physics described here.

B. White Light Cavities

In 1997, Whicht et al. proposed a concept, from herein referred to as a White Light Cavity or WLC, to utilize a quantum amplification scheme to break this gain-bandwidth relationship. The proposed scheme would introduce a medium into the signal recycling cavity that would correct the phase such that $\Phi(\nu) \approx n\pi$ for a large range of ν , whilst maintaining the frequency shift induced by the gravitational wave. The corrected photons would then be fed back into the arm cavities for further amplification. Such a medium would be said to have an anomalous (also called negative) dispersion effect (AD or ND), that is the phase shift would be inversely proportional to frequency. This would, in effect, widen the bandwidth of the arm cavities whilst maintaining the same high gain. Mathematically, for carrier laser frequency ω_0 , the detectors arm length, L_{arm} , is tuned such that

$$\frac{\omega_0 L_{arm}}{c} = n\pi, \quad n \in \mathbb{Z}. \quad (4)$$

When a gravitational wave of frequency Ω couples into the detector, our signal now has a frequency $\omega_0 + \Omega$, these photons will therefore experience a phase shift of $\phi_{shift} = 2\Omega L_{arm}/c$. So ideally, our negative dispersion medium will have a frequency dependent phase shift of

$$\phi_{ND} = -\frac{2\Omega L_{arm}}{c}. \quad (5)$$

AD is traditionally observed around strong absorption lines, so along with their proposal for the WLC scheme, Which et al. suggested that an atomic media, held near absorption by a pump beam, may create a sufficient negative dispersion effect, however it was later shown that, when implemented into a interferometric system, optical instability would place unrealistic constraints on the media, making it unsuitable for use within a WLC scheme. An alternative proposed method of inducing negative dispersion is through the use of an optomechanical filter, this has been the focus of WLC research as of recently. There are three candidate optomechanical resonators that may be used to create the unstable filter:

Phononic Membrane: This is a small membrane made from an already highly reflective material, in which a lattice of holes are punched into the surface such that they create a mechanical band gap that traps phonons within a defect in the lattice. This benefits from low mass and high mechanical Q factor, but suffers from large thermal heating due to its small heat capacity.

Micro-Resonators: Micron-scale suspended mirrors, which utilise a pendulum mode for the mechanical motion. There are two types being explored by UWA within this category: the Cat-flap, which is a rectangular AlGaS pendulum, and the lollipop, which is a circular AlGaS pendulum.

Bulk Acoustic Wave (BAW) Resonator: This is the focus of this proposal, and will be explained in detail further on, but as a brief description: The BAW resonator is a plano-convex quartz crystal that is able to form a bulk phonon wave³, this allows for a large mechanical Q, and its relatively large mass is beneficial for reducing the effect of laser heating. The large mass, on the other hand, also results in low optomechanical coupling, requiring large amounts of laser power for sufficient negative dispersion to occur.

C. Overview of ND through Optomechanical Resonators

For any cavity optomechanical interaction, we may model it through a 3-mode interaction, which have an input-output relation of

$$\hat{a}_{out} = \frac{\Omega + i(\gamma_m + \gamma_{opt})}{\Omega + i(\gamma_m - \gamma_{opt})} \hat{a}_{in} + \hat{n}_{th}, \quad (6)$$

where our mechanical damping is given by $\gamma_m \equiv \omega_m/Q_m$, with Q_m being the mechanical Q factor of our optomechanical filter. And our negative optomechanical damping is given by $\gamma_{opt} \equiv g^2/\gamma_f$, where γ_f is the filter cavity bandwidth, and g is the optomechanical coupling of the resonator. Included in this equation is the thermal noise term, \hat{n}_{th} , this will be ignored for now but will place further requirements on the resonator. Note that this only applies within the resolved sideband regime, that is, when $\omega_m \gg \gamma_f \gg \Omega$, for filter cavity bandwidth γ_f . Additionally, by operating as an unstable optomechanical filter, which by definition is the regime such that $\gamma_{opt} \gg \gamma_m$, we can make the following approximations

$$\hat{a}_{out} \approx \frac{\Omega + i\gamma_{opt}}{\Omega - i\gamma_{opt}} \hat{a}_{in} \approx -\exp\left(\frac{-2i\Omega}{\gamma_{opt}}\right) \hat{a}_{in}. \quad (7)$$

³ This is a mode of the resonator in which the nodes of motion (that is, locations of very little motion) are located at the edges, leading to very low coupling between the resonator and the mounting structure.

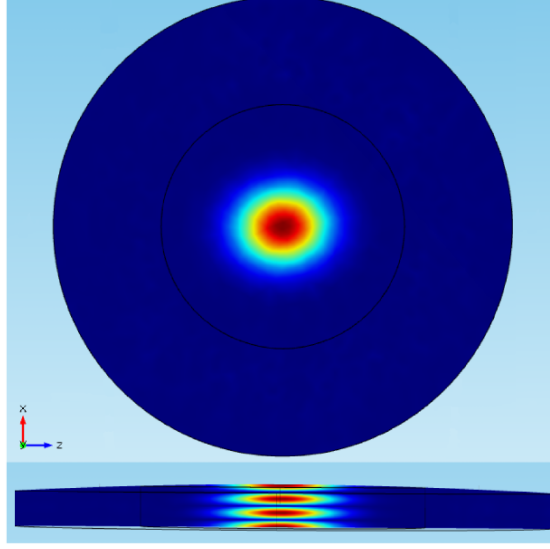


FIG. 4: A schematic of a BAW resonator[8].

That is, our output experiences a phase shift of $\phi = -2\Omega/\gamma_{opt}$ so to satisfy the requirements outlined in Eqn (5), we have

$$\gamma_{opt} = \frac{c}{L_{arm}} = \frac{g^2}{\gamma_f}, \quad g^2 = \left(\frac{d\omega}{dq}\right)^2 x_{xpf}^2 \bar{a}^2 \quad (8)$$

$$\Rightarrow P_c = 2 \frac{m\omega_m c \Omega L_{arm}}{\mathcal{F}\omega_0}. \quad (9)$$

Additionally, we can examine the restrictions placed on the mechanical Q-factor of the resonator, Q_m , through the effect of thermal noise. \hat{n}_{th} , the thermal noise operator from Eqn (6), is uncorrelated with the input optical field, and so to make it such that the effect does not dominate over any benefit from the WLC scheme, we require that

$$\frac{8k_B T_{envir}}{Q_m} < \hbar \gamma_{IFO}, \quad (10)$$

where γ_{IFO} is the detector bandwidth prior to the implementation of the unstable filter, and T_{envir} is the resonator temperature. This provides a convenient figure of merit for optomechanical filters to be used in the WLC scheme, T/Q . As an order of magnitude estimate, to maintain near the sensitivities of current generation interferometers, we require $T/Q \sim 6 \times 10^{-10} K$. That is, if we operate our mechanical filter at 1K, we would require a mechanical Q factor of 6×10^{10} .

The BAW as an unstable optomechanical filter

Previous study on the feasibility of a BAW resonator within this role had been performed with Ref [22], in which the authors identified a nominal value for the peak coupling strength associated with the resonator and thus inferred a minimum filter cavity power requirement. For a crystal, of refractive index n_Q , centre position $x_p = (x_1 + x_2)/2$, and a crystal thickness q , held

within a cavity of length L_f and at resonant laser wave number k , then the resonance condition is given by:

$$\frac{n_Q \tan[k(x_p - q/2)] - \tan[n_Q k(x_p - 1/2)]}{1 + n_Q \tan[k(x_p - q/2)] \tan[n_Q k(x_p - 1/2)]} = \frac{n_Q \tan[k(x_p + q/2 - L_f)] - \tan[n_Q k(x_p - 1/2)]}{1 + n_Q \tan[k(x_p - q/2)] \tan[k(x_p + q/2 - L_f)]}. \quad (11)$$

Assuming a small motion of q , we can take dw/dq to be linear and negative. For typical values of quartz, as described in Ref [22], we can expect to see a coupling of $d\omega/dq \approx 2\pi \times 0.018 \text{GHz nm}^{-1}$ for a 20mm table top experiment as will be described in later sections of this proposal. For a realistic filter cavity length of 5cm, this coupling drops down to $2\pi \times 0.0075 \text{GHz nm}^{-1}$, which implies a filter cavity optical intensity requirement of $P_c \sim 17 \text{MW cm}^{-2}$. Theoretically, quartz and the AlGaAs coatings should withstand these high intensities, however it is unclear whether the laser heating within the quartz would breach the strict thermal noise requirements described above. This issue motivates the need to induce higher optomechanical coupling of the BAW resonator, through the application of reflective coatings onto the crystal, this would reduce the power requirement, but would also lead to a degraded mechanical Q factor of the resonator, and so requiring a balance to be found between these competing issues. This research proposal will seek to examine the relationship between the increase of coupling strength through the application of further silicon nitride coatings and the degradation of the mechanical Q-factor, along with experimental measurements of the radiation pressure excitement of mechanical modes of the BAW.

III. Preliminary Study

A forthcoming paper will discuss the experimental comparison of an uncoated BAW resonator ($R_m \approx 4\%$) and a resonator coated with a single thin layer of silicon nitride ($R_m \approx 16\%$). Firstly, a novel approach to simulating the coupling strength of a BAW resonator is presented, as well as a comparison of the theoretical predictions to the experimental results. These experimental measurements were made with the crystals placed within a $\sim 20\text{mm}$ cavity, whose length was scanned to map the resonances as the crystal position was actuated.

To simulate the coupling of the cavity, an approximation of the system was made to a double membrane in the middle (dMIM) cavity. This was made under the assumption that the optomechanical interaction only occurs at the interfaces of the resonator, and not within the bulk structure of the crystal⁴. A dMIM configuration within a cavity has already been well studied by Ref [14], which should the transmission of such a cavity is given by

$$\mathcal{T}_c = \frac{(1 - R)^2(1 - R_m)^2}{|\mathcal{D}|^2}, \quad (12)$$

where

$$|\mathcal{D}|^2 = A\chi^2(kL) + B\chi(kL) + C, \quad (13)$$

⁴ This is approximately true within the MHz range, however Ref [12] demonstrated high coupling through Brillouin scattering within the GHz regime, unfortunately these modes have too low of a Q-factor to be considered for a WLC scheme.

in which

$$\begin{aligned}
\chi(kL) &= \sin(kL) - R_m \sin(kL - 2kq) \\
A &= 4R \\
B &= 8\sqrt{RR_m}(1 + R) \cos(2kQ) \sin(kq) \\
C &= 8RR_m \cos(4kQ) \sin^2(kq) - 2R(1 - R_m)^2 + (1 + R^2)[1 - 2R_m \cos(2kq) + R_m^2]. \quad (14)
\end{aligned}$$

Where $q, Q \equiv x_p$ are the effective (that is, corrected for the refractive index of quartz) thickness and position of the resonator. As before k is the laser wavenumber, and L is the cavity length. R is the power reflectivity of the cavity mirrors, with R_m being the power reflectivity of each surface of the BAW. Note that, unlike the analysis done in Ref [14], here the phase shift due to the coating is not considered due to the thinness of the single layer. These expressions are a generalisation of the understanding of coupling mechanism described in Ref [22], not only allowing for arbitrary reflectivities of the crystal interfaces, but also the analysis of two different modes of motion: position mode, where the position of the crystal is actuated, and thickness mode, where the thickness of the crystal is modulated. The transmission heatmap is shown in Figure 5.

For experimental confirmation of these simulations, a BAW resonator was placed into an approximately $\sim 20\text{mm}$ long cavity. The length was scanned whilst actuating the position of the crystal to map the resonances of the position mode. This measurement was made for both an uncoated resonator and the coated one. The transmission heatmap is shown in Figure 5. The experimental results were found to be in good agreement with the simulation's predictions.

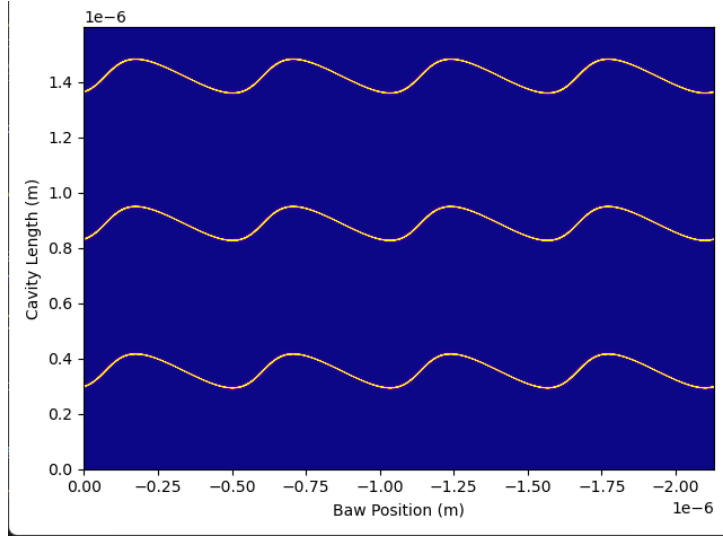
Now that the simulation's assumption have proved to be experimentally valid, the position mode was simulated and the gradient $d\omega/dq$ calculated in Fig 6. This is the coupling relevant for a WLC scheme. It was found that the quadrupling of the power reflectivity resulted in an approximate doubling of the gradient. This suggests that the power requirement decrease proportionate to the power reflectivity.

IV. Proposed Works

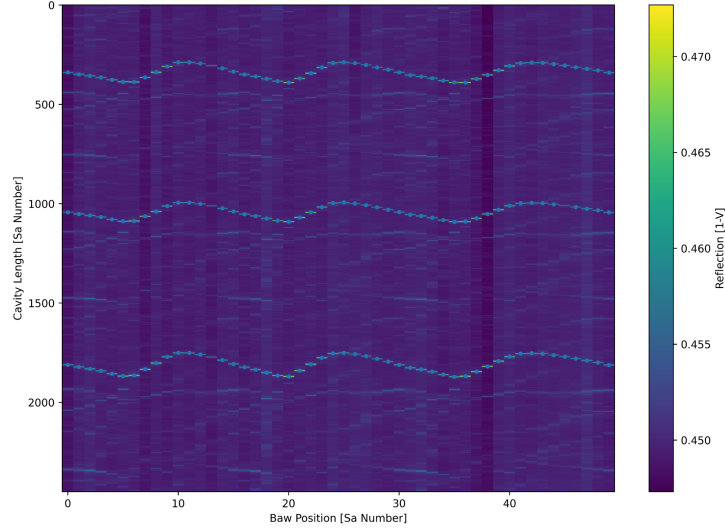
There are two avenues to be pursued for further development of this WLC scheme. The first is to investigate, through simulation, the relationship between the increase of optomechanical coupling through the application of further silicon nitride coatings and the degradation of the mechanical Q-factor. Secondly, is to probe the experimental details of the implementation of the BAW as a potential candidate for a WLC scheme, namely verify that there exists sufficient coupling for radiation pressure excite of the mechanical resonance.

Details of the mechanical Q-factor of BAW resonators operating at cryogenic temperatures is not particularly novel, however there are many unknowns that may be introduced when applying reflective coatings. Ref [8] derived an approximate expression to determine the excess mechanical loss induced by thin film coatings and quartz resonators. However, a more systematic approach may be required when applying greater than the single coating to the crystal, as may be required if the single coating does not increase the optomechanical coupling sufficiently. Thus a finite element simulation software such as ANSYS or COMSOL may be required to determine a more accurate estimate of the mechanical Q-factor. This, in conjunction with the previously developed simulations, should enable a more methodical optimisation between the coupling and mechanical Q-factor.

The experimental verification of radiation pressure driving will likely take the majority of efforts within this proposal. There has been previous attempts made to excite a mechanical resonance through the amplitude modulation of the laser within the experimental setup used to



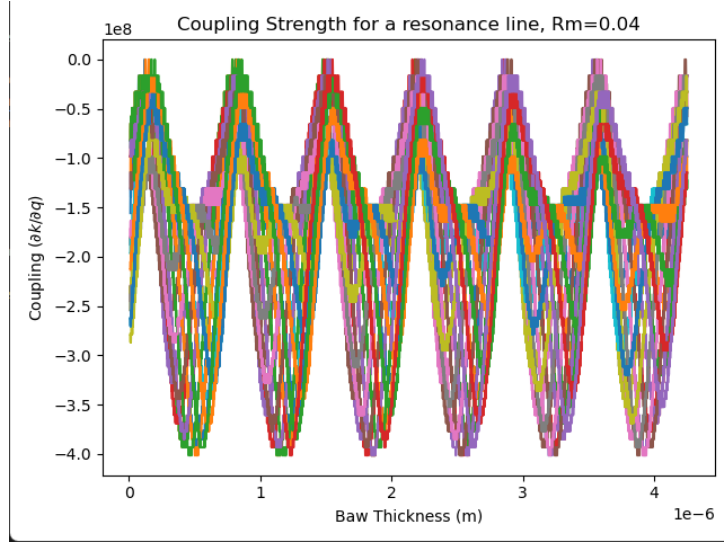
(a) Simulated transmission of the BAW cavity.



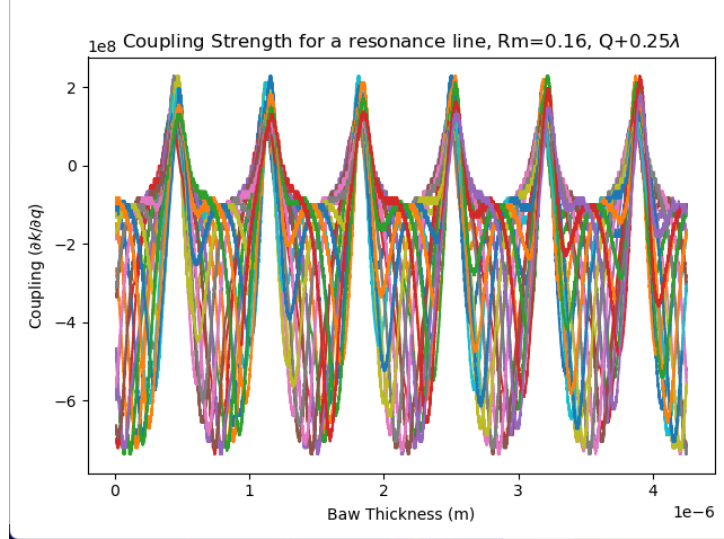
(b) Experimental transmission of the BAW cavity. Note that this measurement is reflection, and so has been inverted by $1 - V_{ref}$. The detected resonances are marked with a blue dot.

FIG. 5

take the measurements above. However, this was done using the uncoated resonator as well as in air. Hence the first step will be to place the optical cavity, now containing the coated resonator, and place it into a vacuum chamber. The vacuum will increase the mechanical Q -factor of the resonator by approximately an order of magnitude (going from $\sim 10^5$ in air to $\sim 10^6$ in vacuum). Additionally, the use of the coated resonator, with it's doubled optomechanical coupling, will hopefully allow measurement of the radiation pressure driving of the BAW resonator. If this is not the case, then more coatings of the resonator will be required until the coupling is sufficient



(a) The uncoated resonator.



(b) The coated resonator.

FIG. 6: Simulated gradient of the thickness mode of the BAW cavity, of both the uncoated and the coated resonator. The peak absolute value for the coupling strength for the uncoated resonator was $\sim 4 \times 10^8 dk/dq$, and for the coated one was $\sim 7.5 \times 10^8 dk/dq$.

to see this radiation pressure driving. Once this is confirmed, that development of a cryogenic system will begin to take place. This is likely beyond the time frame of a Master's research project, but will be a crucial stage moving forward. The cryogenic system will allow for the move towards the required Q-factor of $\sim 10^{10}$ that had been demonstrated in Ref [9].

V. Conclusion

Future gravitational wave detectors will be targeting the high frequency regime, and a serious method for achieving broadband sensitivity increases is through the use of a WLC scheme. The proposed method for the creation of a WLC scheme is through unstable optomechanical filters, of which the BAW is a potential candidate. The BAW suffers from a low optomechanical coupling and a high resonator mass, requiring large optical intensities that may introduce excess laser heating. Previously, an increase in this optomechanical coupling has been experimentally demonstrated through the use of reflective coatings, and more importantly, a method of simulating the optomechanical coupling from an arbitrary reflectivity of the BAW was devised. This research is proposed to be focused on two main objectives: to investigate the effect on mechanical Q-factor of the application of further coatings to the BAW through finite element analysis, and to attempt to experimentally measure the radiation pressure excite of the mechanical resonance of the BAW. This second objective will be completed through first placing the existing optical cavity within a vacuum chamber, and then, if need be, applying more silicon nitride coatings to the resonator.

-
- [1] Gaurav Bahl and Tal Carmon. Brillouin optomechanics. In *Cavity Optomechanics: Nano- and Micromechanical Resonators Interacting with Light*, pages 157–168. Springer Berlin Heidelberg, January 2014. arXiv: 1309.2828.
 - [2] Joe Bentley, Philip Jones, Denis Martynov, Andreas Freise, and Haixing Miao. Converting the signal-recycling cavity into an unstable optomechanical filter to enhance the detection bandwidth of gravitational-wave detectors. *Physical Review D*, 99(10):102001, May 2019. Publisher: American Physical Society.
 - [3] Eric D. Black. An introduction to Pound–Drever–Hall laser frequency stabilization. *American Journal of Physics*, 69(1):79–87, January 2001. Publisher: American Association of Physics Teachers (AAPT).
 - [4] Jérémy Bon, Leonhard Neuhaus, Samuel Deléglise, Tristan Briant, Philippe Abbé, Pierre François Cohadon, and Serge Galliou. Cryogenic optomechanic cavity in low mechanical loss material. *Journal of Applied Physics*, 124(7), August 2018. Publisher: American Institute of Physics Inc.
 - [5] Xu Chen. Tabletop Investigation of Parametric Instability and Light Scattering Phenomena in Gravitational Wave Detectors.
 - [6] J. A. Clark, A. Bauswein, N. Stergioulas, and D. Shoemaker. Observing gravitational waves from the post-merger phase of binary neutron star coalescence. *Classical and Quantum Gravity*, 33(8):085003, March 2016. Publisher: IOP Publishing.
 - [7] E.P. EerNisse. Analysis of thickness modes of contoured doubly rotated, quartz resonators. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 48(5):1351–1361, September 2001.
 - [8] Serge Galliou, Samuel Deléglise, Maxim Goryachev, Leonhard Neuhaus, Gianpietro Cagnoli, Salim Zerkani, Vincent Dolique, Jérémy Bon, Xavier Vacheret, Philippe Abbé, Laurent Pinard, Christophe Michel, Thibaut Karassouloff, Tristan Briant, Pierre-François Cohadon, Antoine Heidmann, Michael E. Tobar, and Roger Bourquin. A new method of probing mechanical losses of coatings at cryogenic temperatures. *Review of Scientific Instruments*, 87(12):123906, December 2016.
 - [9] Serge Galliou, Maxim Goryachev, Roger Bourquin, Philippe Abbé, Jean Pierre Aubry, and Michael E. Tobar. Extremely low loss phonon-trapping cryogenic acoustic cavities for future physical experiments. *Scientific Reports*, 3(1), July 2013.
 - [10] Maxim Goryachev and Michael E. Tobar. Effects of geometry on quantum fluctuations of phonon-trapping acoustic cavities. *New Journal of Physics*, 16, 2014. Publisher: Institute of Physics Publishing.
 - [11] A. M. Jayich, J. C. Sankey, B. M. Zwickl, C. Yang, J. D. Thompson, S. M. Girvin, A. A. Clerk, F. Marquardt, and J. G. E. Harris. Dispersive optomechanics: a membrane inside a cavity. May 2008. arXiv: 0805.3723.
 - [12] Prashanta Kharel, Glen I. Harris, Eric A. Kittlaus, William H. Renninger, Nils T. Otterstrom, Jack G. E. Harris, and Peter T. Rakich. High-frequency cavity optomechanics using bulk acoustic phonons. *Science Advances*, 5(4):eaav0582, April 2019.
 - [13] Dustin Kleckner, Brian Pepper, Evan Jeffrey, Petro Sonin, Susanna M. Thon, and Dirk Bouwmeester. Optomechanical trampoline resonators. *Optics Express*, 19(20):19708, September 2011.
 - [14] Jie Li, André Xuereb, Nicola Malossi, and David Vitali. Cavity mode frequencies and strong optomechanical coupling in two-membrane cavity optomechanics. *Journal of Optics*, 18(8):084001, August 2016.
 - [15] LIGO Scientific Collaboration and Virgo Collaboration. Observation of gravitational waves from a binary black hole merger. *Phys. Rev. Lett.*, 116:061102, Feb 2016.
 - [16] Mikhail D. Lukin, Michael Fleischhauer, Marlan O. Scully, and Vladimir L. Velichansky. Intracavity electromagnetically induced transparency. *Optics Letters*, 23(4):295, February 1998.
 - [17] Yiqiu Ma, Shtefan L. Danilishin, Chunnong Zhao, Haixing Miao, W. Zach Korth, Yanbei Chen, Robert L Ward, and D.G. Blair. Narrowing the Filter-Cavity Bandwidth in Gravitational-Wave Detectors via Optomechanical Interaction. *Physical Review Letters*, 113(15):151102, October 2014.

- [18] Yiqiu Ma, Haixing Miao, Chunnong Zhao, and Yanbei Chen. Quantum noise of a white-light cavity using a double-pumped gain medium. *Physical Review A*, 92(2):023807, August 2015. Publisher: American Physical Society.
- [19] Haixing Miao, Yiqiu Ma, Chunnong Zhao, and Yanbei Chen. Enhancing the Bandwidth of Gravitational-Wave Detectors with Unstable Optomechanical Filters. *Physical Review Letters*, 115(21):211104, November 2015. Publisher: American Physical Society.
- [20] Bhagya Nair, André Xuereb, and Aurélien Dantan. Cavity optomechanics with arrays of thick dielectric membranes. *Physical Review A*, 94(5):053812, November 2016.
- [21] Michael Page, Jiayi Qin, James La Fontaine, Chunnong Zhao, Li Ju, and David Blair. Enhanced detection of high frequency gravitational waves using optically diluted optomechanical filters. *Physical Review D*, 97(12):124060, June 2018. Publisher: American Physical Society.
- [22] Michael A. Page, Maxim Goryachev, Haixing Miao, Yanbei Chen, Yiqiu Ma, David Mason, Massimiliano Rossi, Carl D. Blair, Li Ju, David G. Blair, Albert Schliesser, Michael E. Tobar, and Chunnong Zhao. Gravitational wave detectors with broadband high frequency sensitivity. *Communications Physics*, 4(1), December 2021. arXiv: 2007.08766 Publisher: Nature Research.
- [23] Michael A Page, Maxim Goryachev, Haixing Miao, Yanbei Chen, Yiqiu Ma, David Mason, Massimiliano Rossi, Carl D Blair, Ju Li, David G Blair, Albert Schliesser, Michael E Tobar, and Chunnong Zhao. Supplementary Information for "Gravitational wave detectors with broadband high frequency sensitivity". Technical report.
- [24] G. S. Pati, M. Salit, K. Salit, and M. S. Shahriar. Demonstration of a Tunable-Bandwidth White-Light Interferometer Using Anomalous Dispersion in Atomic Vapor. *Physical Review Letters*, 99(13):133601, September 2007. Publisher: American Physical Society.
- [25] John Preskill and Kip S Thorne. Foreword to Feynman Lectures on Gravitation.
- [26] W. H. Renninger, P. Kharel, R. O. Behunin, and P. T. Rakich. Bulk crystalline optomechanics. *Nature Physics*, 14(6):601–607, June 2018. arXiv: 1703.08231 Publisher: Nature Publishing Group.
- [27] D. S. Stevens and H. F. Tiersten. An analysis of doubly rotated quartz resonators utilizing essentially thickness modes with transverse variation. *Journal of the Acoustical Society of America*, 79(6):1811–1826, 1986.
- [28] Brian D ' Urso, Oskar Painter, John O'brien, Tom Tombrello, Amnon Yariv, and Axel Scherer. Modal reflectivity in finite-depth two-dimensional photonic-crystal microcavities. Technical report, 1998.
- [29] S. Weis, R. Riviere, S. Deleglise, E. Gavartin, O. Arcizet, A. Schliesser, and T. J. Kippenberg. Optomechanically induced transparency. *Science*, 330(6010):1520–1523, December 2010. arXiv:1007.0565 [quant-ph].
- [30] Ken Wharton. Quantum Theory without Quantization. 2011. Publisher: arXiv Version Number: 1.
- [31] A Wicht, K Danzmann, M Fleischhauer, M Scully, G Müller, and R. H Rinkleff. White-light cavities, atomic phase coherence, and gravitational wave detectors. *Optics Communications*, 134(1):431–439, January 1997.
- [32] A. Wicht, M. Müller, R. H. Rinkleff, A. Rocco, and K. Danzmann. Experimental demonstration of negative dispersion without absorption. *Optics Communications*, 179(1):107–115, May 2000.
- [33] Stacy Wise, G. Mueller, D. Reitze, D. B. Tanner, and B. F. Whiting. Linewidth-broadened Fabry–Perot cavities within future gravitational wave detectors. *Classical and Quantum Gravity*, 21(5):S1031, February 2004.
- [34] Stacy Wise, V. Quetschke, A. J. Deshpande, G. Mueller, D. H. Reitze, D. B. Tanner, B. F. Whiting, Y. Chen, A. Tünnermann, E. Kley, and T. Clausnitzer. Phase Effects in the Diffraction of Light: Beyond the Grating Equation. *Physical Review Letters*, 95(1):013901, June 2005. Publisher: American Physical Society.
- [35] Haibin Wu and Min Xiao. White-light cavity with competing linear and nonlinear dispersions. *Physical Review A*, 77(3):031801, March 2008.
- [36] Ma Ke Ying, Xu Chen, Yu Ying Hsu, Dung Sheng Tsai, Huang Wei Pan, Shiuh Chao, Andrew Sunderland, Michael Page, Benjamin Neil, Li Ju, Chun Nong Zhao, and David Blair. Cat-flap micro-pendulum for low noise optomechanics. *Journal of Physics D: Applied Physics*, 54(3), January 2021. Publisher: IOP Publishing Ltd.
- [37] H. N. Yum, J. Scheuer, M. Salit, P. R. Hemmer, and M. S. Shahriar. Demonstration of White Light Cavity Effect Using Stimulated Brillouin Scattering in a Fiber Loop. *Journal of Lightwave*

- Technology*, 31(23):3865–3872, December 2013. Conference Name: Journal of Lightwave Technology.
- [38] Minchuan Zhou and Selim M. Shahriar. Optomechanical resonator as a negative dispersion medium for enhancing the sensitivity bandwidth in a gravitational-wave detector. *Physical Review D*, 98(2):022003, July 2018.
- [39] Minchuan Zhou, Zifan Zhou, and Selim M. Shahriar. Quantum noise limits in white-light-cavity-enhanced gravitational wave detectors. *Physical Review D*, 92(8):082002, October 2015. Publisher: American Physical Society.