Reviewers' comments:

Reviewer #1 (Remarks to the Author):

This manuscript addresses the challenge of enhancing the sensitivity of a laser interferometric gravitational wave detector over the frequency band of 1 to 5 kHz, which is important for detecting certain events of significant importance in the field of gravitation wave astronomy. Specifically, it presents a set of detailed analyses, purporting to show that such enhancement may be feasible, via optomechanics-based white light signal recycling, using two different resonators that have been recently demonstrated. The topic covered in this manuscript is of great interest to the community of scientists interested in gravitational wave astronomy.

I have some concerns regarding the content of this manuscript, as delineated in the questions/comments below. If the authors are able to address these issues in a satisfactory manner, I would be willing to recommend this paper for publication.

1. The manuscript consider two different resonators. One is a silicon nitride membrane acoustically isolated from the environment by a bandgap in a phononic crystal. The second is a single-crystal, plano-convex quartz crystal lens that supports bulk acoustic longitudinal waves. From the analyses presented, it is clear that the quartz lens has many potential challenges, including but not limited to the optical power requirement. It has not been established by the authors that there are clear pathways to overcome these challenges, given the current state of technologies. As such, they should consider focusing on only the membrane approach in this paper, and present the details of the lens based approach in a separate, lower impact paper.

2. A critical issue for realizing optomechanics-based white light signal recycling is the need for implementing a multi-variable feedback system to control the instability, as noted by the authors. Accounting for the time delay in such a feedback process introduces readout noise, also noted by the authors. It appears that this issue has been glossed over in this manuscript. However, this is one of the most important hurdles in implementing a white light signal recycling scheme for enhancing the sensitivity. Details of exactly how such a control system would have to be implemented, and the noise implications thereof, must be addressed carefully, in order to establish the experimental feasibility of the overall approach proposed here. It would be acceptable for such an analysis to be presented as a supplement.

Reviewer #2 (Remarks to the Author):

Dear Editor,
Some of the authors of the submitted manuscript have proposed few years ago (in a publication on The Phys. Rev. Lett. dated 2015) an optical scheme that incorporates an unstable optomechanical cavity in the output field path of advanced Gravitational-Wave detectors. Their scheme would significantly increase the sensitivity in the high frequency band (hundreds to thousands of Hz), but is very demanding in terms of optomechanical properties.
After the initial proposal, the same authors (with other colleagues) have published other articles, analyzing the performance of different kinds of optomechanical resonators, mostly exploiting optical dilution to improve the thermal properties.
The present manuscript extends the analysis to two kinds of mechanical resonators, working at cryogenic temperature without the need of optical dilution. The two resonators (SiN membranes incorporating a phononic acoustic filter, and bulk single-crystal quartz) are indeed well known by the optomechanical community for their excellent performance, and are used respectively for quantum optomechanical experiments, and for metrological purposes. Representatives of the frontrunning teams working on the two platforms have joined the historical authors to guarantee a reliable analysis. The manuscript shows that the target sensitivity is achieved with more realistic assumptions with respect to the previous works.
The article is clear, well structured and the analysis is detailed. However, the amount of novelty is not enough to deserve the interest of a general audience. The physical concepts, the main experimental scheme and the relevant expressions for calculating the achievable spectral

sensitivities are already published. Even the main parameters, performance and limitations of the considered optomechanical staff are well explored in the literature. Putting everything together and showing a relevant improvement of the detectors can be obtained with challenging, yet realistic setup is surely a useful work for the community that is planning the next generation of GW detectors, and deserves publication on a specialized journal, but I do not recommend it for Communications Physics.

Reviewer #3 (Remarks to the Author):

“Gravitational wave detectors with broadband high frequency sensitivity” by Page et. al., presents an important potential advance in interferometric gravitational-wave instrumentation. Conventional wisdom in the field has maintained that sensitivity improvements at shot-noise dominated higher frequencies made via signal recycling are necessarily narrow in bandwidth. One must choose a narrow frequency range to enhance, which is limiting if one either does not know the best frequency to target or if the interesting gravitational wave features are both at frequencies of a few kHz and broad band, such as those produced by supernovae or the object resulting from a binary neutron star collision. This paper describes two specific technologies that can perform white light signal recycling (WLSR), overcoming the previously assumed narrow-band enhancement limitation of signal recycling and providing a path towards significant broad band sensitivity improvements in future detectors.

The two technologies accomplish WLSR by use of an optomechanically coupled negative dispersion filter. The first technology is a phononic crystal (PNC) resonator and the second is a bulk acoustic wave (BAW) resonator. Both types of resonators have been tested and demonstrated to have the characteristics necessary for WLSR. The contribution of this paper and its supplementary material is to calculate the optimum characteristics of these resonators when used in gravitational wave interferometers and show the effect they would have on the sensitivity curves of near-current and future detectors. The two types of resonators are both important because, while the BAW resonator has the potential for greater noise reduction, its low optomecanical coupling makes it a more suitable technology for the longer arms and higher powers planned for the next generation of interferometric detectors while the PNC resonator would be practical for near-term Advanced+ detectors.

The paper is well motivated and thorough in its descriptions of how the PNC and BAW resonators should be designed to provide optimal WLSR sensitivity improvements. The supplementary material provides sufficient detail to back up the design choices and describes how the design choices made for the next generation of interferometers will influence the improvements that are possible with WLSR. The paper should be of significant interest to those interested in interferometer design and also those gravitational wave astronomers who would like to see broad band improvements in the high frequency regime.

Below are some suggestions for minor changes:

1) The abstract and introduction of the paper use the binary neutron star coalescence GW170817 to motivate the need for broad band sensitivity improvements at frequencies of a few kHz since the post-merger gravitational wave signal containing information about the merger remnant would have been at those frequencies but was too weak to detect. I recommend that the authors include a reference to https://journals.aps.org/prx/abstract/10.1103/PhysRevX.9.011001 in support of this argument since this paper describes how the lack of sufficient sensitivity at these frequencies rendered any post-merger signal undetectable.

2) On lines 26 and 30 of the paper “new born” should be one word “newborn”.

3) On lines 361-363 of the paper it is stated that “An optomechanical negative dispersion filter for WLSR is currently under development at the University of Western Australia.” It is a bit unclear if this filter is based on PNC or BAW. The next sentence implies that it is based on PNC but both technologies are mentioned earlier in the paragraph.

4) On line 213-214 of the supplementary material “corresponding 1064 nm wavelength” should be changed to “corresponding to a 1064 nm wavelength”.

Dear editors and reviewers,

We thank you for your consideration of our manuscript regarding gravitational wave detectors with broadband high frequency sensitivity using the method of white light signal recycling, and would like to address the comments brought forth by the reviewers.

The first reviewer has recommended publication on the grounds that our manuscript is of *"of great interest to the community of scientists interested in gravitational wave astronomy"*, but have asked us to address two critical items related to the optomechanical design in our proposal.

The first issue regards the inclusion of the quartz bulk acoustic wave (BAW) resonator in the design of the optomechanical technologies in the manuscript. The reviewer argues that the quartz BAW has many challenges to overcome before it can be used in optomechanically enhanced gravitational wave detectors, chiefly that of the high circulating optical power used within its optical filter cavity module. Recognising their valid concerns, which were already part of our analysis, we have emphasised discussion in the supplement which gives evidence and arguments as to why such power is not in principle unfeasible when used with quartz resonators. In particular, we estimate that the low temperature requirement can be maintained based on the intrinsic optical absorption properties of quartz. We note that future long-arm detectors will have a reduced filter cavity power requirement as per equation 3. Also, the BAW resonator's large size makes it more advantageous for mode matching, which was noted in the original discussion as a particular concern in the design of future detectors. As detailed in our list of changes, we have highlighted the presence of these arguments in the revised manuscript.

The third reviewer agrees that the supplementary items in the original submission were sufficient to justify the inclusion of the BAW resonator in the manuscript, stating that *"The supplementary material provides sufficient detail to back up the design choices and describes how the design choices made for the next generation of interferometers will influence the improvements that are possible with WLSR"*. The third reviewer also identifies our argument that BAW resonator technology is *"a more suitable technology for the longer arms and higher powers planned for the next generation of interferometric detectors"*. We thus conclude that BAW optomechanics should remain in the manuscript as a viable technology, especially for longer arm gravitational wave detectors such as Einstein Telescope and Cosmic Explorer.

The second major issue raised by the first reviewer is the control scheme for the unstable filter cavity. In particular, they state *that "accounting for the time delay in such a feedback process introduces readout noise, also noted by the authors. It appears that this issue has been glossed over in this manuscript"*. We would like to add further clarification regarding this issue. The main text refers to the paper by J. Bentley *et al.*, Phys. Rev. D **99** 102001 (2019), which states that the time delay in a local control scheme for an unstable filter introduces readout noise into the gravitational wave signal. However, Bentley's paper also points to a manuscript in preparation that claims that the readout noise can be cancelled by ideal combination of the local control and GW signal readouts in postprocessing. We have made sure to highlight this development in the main text. We also draw attention to a new idea that the unstable filter can be controlled coherently, eliminating the quantum control noise at a fundamental level. Given the complexity and subtlety of the problem, we think it is more appropriate to present a thorough analysis in separate works. This paper is instead focusing on addressing the fundamental thermal noise of the mechanical oscillator.

Dr Michael A. Page
Research Associate, University of Western Australia
35 Stirling Highway, Crawley, Perth, 6009, Australia
mpagephys@gmail.com / michael.page@uwa.edu.au

The second reviewer stated that our manuscript is *"clear, well structured and the analysis is detailed"*. However, they decline to recommend publication on the grounds that *"the amount of novelty is not enough to deserve the interest of a general audience. The physical concepts, the main experimental scheme and the relevant expressions for calculating the achievable spectral sensitivities are already published"*. Given that the other two reviewers accept the novelty of our paper, we would like to clarify its broad appeal, in relation to other white light signal recycling designs that have already been published. This paper is the first to demonstrate the possibility of white light signal recycling using mechanical resonator structures that already exist, and have promising thermal noise properties. All other papers on this topic have outlined design principles, but use hypothetical materials that assume a large degree of improvement in intrinsic mechanical loss versus state-of-the-art. Indeed, the first reviewer states that "*enhancement may be feasible, via optomechanics-based white light signal recycling, using two different resonators that have been recently demonstrated. The topic covered in this manuscript is of great interest to the community of scientists interested in gravitational wave astronomy*."

The third reviewer recommended publication and did not offer any major revisions. Their judgement has been presented in our response to the arguments of the first two reviewers. We thank them for their comments that have helped us strengthen the manuscript.

Yours sincerely,

Dr Michael A. Page, on behalf of the authors

Dr Michael A. Page
Research Associate, University of Western Australia
35 Stirling Highway, Crawley, Perth, 6009, Australia
mpagephys@gmail.com / michael.page@uwa.edu.au

Gravitational wave detectors with broadband high frequency sensitivity - List of changes

Michael A. Page[1], Maxim Goryachev[2], Haixing Miao[3], Yanbei Chen[4], Yiqiu Ma[5], David Mason[6], Massimiliano Rossi[7], Carl D. Blair[1], Li Ju[1], David G. Blair[1], Albert Schliesser[7], Michael E. Tobar[2], and Chunnong Zhao[1]

[1]Australian Research Council Center of Excellence for Gravitational Wave Discovery, University of Western Australia, 35 Stirling Highway, Perth, Western Australia 6009, Australia

[2] Australian Research Council Center of Excellence for Engineered Quantum Systems, University of Western Australia, 35 Stirling Highway, Perth, Western Australia 6009, Australia

[3] Astrophysics and Space Research Group, University of Birmingham, Birmingham B15 2TT, United Kingdom

[4] Theoretical Astrophysics, California Institute of Technology, 1200 E California Blvd, Pasadena, California 91125, United States

[5] Center for Gravitational Experiment, School of Physics, Huazhong University of Science and Technology, Wuhan, 430074, China

[6] Yale Quantum Institute, Yale University, 17 Hillhouse Ave, New Haven, Connecticut 06511, United States and

[7] Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark

CHANGES REGARDING REVIEWER COMMENTS

The following changes are related to the comment of Reviewer 1 regarding the optomechanics of the quartz Bulk Acoustic Wave (BAW) resonator. Thermal noise limitations restrict the range of mechanical modes that we can use in optomechanical filters for gravitational wave detectors. The mechanical mode selected in our manuscript has extremely high quality factor but requires high optical pumping to achieve white light signal recycling. The reviewer has stated that they believe the BAW optomechanical filter design parameters to be too challenging, and that we should consider only publishing the design using the phononic crystal (PNC) resonator. As outlined in our response letter, we wish to add additional support for the idea that the power requirements in the BAW optomechanical filter cavity are not in principle unfeasible, and we believe the BAW resonator should remain in the paper as a viable technology, especially for future long arm gravitational wave detectors. We have added the following changes to indicate our justification for including the BAW resonator in the paper:

- Line 237 - We specifically state the power density of 17 MW/cm^2 which is required to produce the curve "BAW" of figure 1. This respective curve has also been recalculated from the previous version - the specific change is reducing the filter cavity input transmission from 250 ppm to 100 ppm (table S2), which proportionally decreases the power requirement as per equation 3, at a slight penalty to sensitivity enhancement. The maximum intensity in the optomechanical filter cavity is well below the cited threshold for quartz on line 239.
- Line 241 - Added a citation stating that AlGaAs crystalline dielectric coatings planned for use in GW detector optics can withstand 64 MW/cm^2, more than the maximum intensity inside the filter cavity. This maximum intensity is located at the BAW resonator, so the intensity at the cavity mirrors is lower.
- Line 244 - Pointed to the estimate undertaken in the Supplementary Material which indicates that a quartz BAW could maintain less than 1 K temperature increase from a 4 K environment given 10 mK absorbed power.
- Line 256, Supplementary Line 190 - Rephrased sentences to indicate that BAW optomechanical technology will be more promising for longer interferometers, which require less filter cavity power for white light signal recycling as per equation 3. Previously, these sentences did not emphasise the importance of this power scaling for the BAW scheme.
- Line 356 - Added sentence stating that the BAW resonator's larger beam size requirement makes it advantageous versus the PNC resonator with regards to possible mode matching loss.
- Supplementary Line 254 - Clarified that the absorption heating calculation is based on the size of contacts that have been used on the BAW resonator at $Q_m = 8 \times 10^9$, with citation to Galliou, *et al.*

Reviewer 1 also asked for clarification regarding the quantum noise introduced by the proposed control system for the unstable filter cavity. In the original text it is stated that local control of the unstable filter is possible, but introduces readout noise, with citation to J. Bentley *et al. Physical Review D* **99**, 102001 (2019). We have two responses to this point, which make reference to manuscripts in preparation by LIGO Scientific Collaboration members:

- Line 338 - Figure 6 of J. Bentley's text (citation 24) illustrates the control scheme of the unstable filter and the discussion contains citation of a manuscript in preparation that has proposed a solution to the readout noise of the local control. We indicate the presence of the idea discussed in Bentley's text that by optimal postprocessing combination of the filter cavity and main interferometer readouts, it is possible to cancel the introduced readout noise. Reference is given to a manuscript in preparation by D. Martynov.

- Line 339 - We mention an idea from the Caltech GW group including one of our authors Y. Chen, which proposes coherent quantum feedback control of the filter cavity and can eliminate the stability issue on a fundamental level. This has been discussed within LIGO working groups i.e. with reference to X. Li's presentation (citation 45).

Reviewer 3 offered the following minor changes:

- Line 32 - Added sentence to the second paragraph of the introduction indicating that the sensitivity of current GW detectors is insufficient for properly characterising the binary neutron star postmerger remnant. Here, a reference is made to the paper *Physical Review X* **9**, 011001 (2019). These additions were suggested by Reviewer 3 to strengthen the motivation of the paper.
- Line 26, 30 - Fixed error to "newborn black holes", and line 115 of the original supplementary material.
- Line 381 - It is clarified that the University is investigating both types of proposed resonator technologies for the purpose of GW detection.
- Supplementary Line 115 - Fixed error to "corresponding to a 1064 nm wavelength"

MISCELLANEOUS CHANGES

- Abstract - modified wording to fit within 200 word limit. No changes to key results.
- Figures 1, S6 - Orientation of the SRM was drawn incorrectly - fixed so that the beam from the interferometer dark port promptly reflects into the filter cavity.
- Supplementary Line 135 - Clarified that the beam size of 260 μm is the beam radius.
- Supplementary Line 144 - The statement regarding 12 MW/cm^2 beam intensity is incorrect. Using 2.5 kW power and beam radius 260 μm results in power density 1.2 MW/cm^2.

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I have read carefully the response to the comments of all three reviewers, including me, as well as the revised manuscript.

I believe the authors have, in their rebuttal and the modification of the manuscript, addressed well the concerns expressed by the reviewers.

As such, I am happy to recommend publication of this paper.

Dear editors and reviewers,

We thank you for your consideration of our manuscript regarding gravitational wave detectors with broadband high frequency sensitivity using the method of white light signal recycling, and would like to reiterate our revisions regarding the following comments brought forth by the reviewers:

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4) On line 213-214 of the supplementary material “corresponding 1064 nm wavelength” should be changed to “corresponding to a 1064 nm wavelength”.>

The following is our original response to the reviewers’ comments:

Author response to reviewers:

<The first reviewer has recommended publication on the grounds that our manuscript is of *“of great interest to the community of scientists interested in gravitational wave astronomy”*, but have asked us to address two critical items related to the optomechanical design in our proposal.

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The third reviewer agrees that the supplementary items in the original submission were sufficient to justify the inclusion of the BAW resonator in the manuscript, stating that *"The supplementary material provides sufficient detail to back up the design choices and describes how the design choices made for the next generation of interferometers will influence the improvements that are possible with WLSR"*. The third reviewer also identifies our argument that BAW resonator technology is *"a more suitable technology for the longer arms and higher powers planned for the next generation of interferometric detectors"*. We thus conclude that BAW optomechanics should remain in the manuscript as a viable technology, especially for longer arm gravitational wave detectors such as Einstein Telescope and Cosmic Explorer.

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The third reviewer recommended publication and did not offer any major revisions. Their judgement has been presented in our response to the arguments of the first two reviewers. We thank them for their comments that have helped us strengthen the manuscript.>

After the resubmission of the paper with the above response, the paper was accepted for publication on 10 November. The reviewer offered the following comment:

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I believe the authors have, in their rebuttal and the modification of the manuscript, addressed well the concerns expressed by the reviewers.

As such, I am happy to recommend publication of this paper. >

There are no more issues from the reviewers to address, and we once again thank Communications Physics for accepting our publication.

Yours sincerely,

Dr Michael A. Page, on behalf of the authors

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