Letters

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Letter

Quantum enhanced kHz gravitational wave detector with internal squeezing

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Abstract

We propose adding a nonlinear element to a long signal recycling cavity to enhance the high-frequency sensitivity (900 Hz–5 kHz) of a kilometer-scale interferometric gravitational wave detector. Using numbers for absorption and scattering losses in the detector consistent with advanced LIGO+, we demonstrate a factor of 3.5 improvement in quantum noise limited strain sensitivity in the kHz regime. Such a configuration is robust to internal losses and reduces the requirement on the amount of circulating power in the detector to achieve sensitivity comparable to future gravitational wave detectors. This proposed configuration is compatible with the existing gravitational wave detector vacuum infrastructure and could enable exploration of exotic science, such as observing the merger phase of binary neutron stars, which in turn may provide constraints on the neutron star equation of state.

Keywords: gravitational wave detectors, coupled cavities, nonlinear optics, long signal recycling cavity, gravitational waves

1. Introduction

Observing gravitational waves (GWs) from mergers of compact objects such as binary neutron stars (BNS) should further constrain the neutron star equation of state (EoS) at supranuclear densities [1] and could explain potential exotic matter at the core of a neutron star such as quarks, hyperons and meson condensates. Neutron stars are invaluable sources for studying

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nuclear physics and quantum chromodynamics due to their extreme densities and low temperatures. Gravitational wave detectors (GWDs) provide access to these astrophysical laboratories as they look at the extremely high density regime which cannot be produced in terrestrial particle colliders [2]. Furthermore, measurements of the spin and mass distribution of binary black holes using GW astronomy would allow us to distinguish the quasi-normal modes of gravstars, axion stars, boson stars from Kerr black holes [3], and also allow us to explore the concepts of ultralight bosons, quasi-normal modes, gravitational modes, and excited matter modes of extremely compact objects [4].

Multi-messenger follow-up of the BNS inspiral GW170817 [5] was enabled by the current generation of GWDs, advanced LIGO (aLIGO) [6] and advanced Virgo (AdV) [7]. It placed constraints on the neutron star EoS [8], jet formation and topology and r-process nucleosynthesis. In addition, the emission of short gamma ray bursts was also observed. Although the GWDs observed this BNS inspiral, the GWs in the merger and post-merger phases went undetected as the frequencies of the emitted waves (0.9–5 kHz) were above the sensitive band of the GWDs. Thus, potentially important information about the event was not obtained. However, by altering the signal recycling cavity (SRC) [9] parameters in a GWD, the frequency response to GWs can be reshaped to make the merger and post-merger phases observable.

Although the high frequency sensitivity of a GWD increases the circulating power in the interferometer, the power cannot be increased indefinitely due to technical challenges as observed in aLIGO currently [10]. Injecting squeezed states of light has the same effect, and this is actively used in the current generation GWDs [11–13].

Several other techniques such as the use of long coupled cavities to obtain narrow band sensitivity have been proposed in literature to shape the frequency response of the GWD to improve the high frequency sensitivity [14–16]. The prospect of building a high frequency (HF) focussed detector in Australia to join the network of third generation GWDs using a combination of long SRC and increased arm cavity power has been investigated in [17]. The science presented in both [16, 17] relies on large circulating powers in the arms of the interferometer, however such techniques also face technical difficulties such as parametric instabilities [10, 18]. Other exotic techniques like white-light cavities [19, 20] have also been proposed in literature to increase the overall bandwidth of terrestrial GWDs without violating the fundamental limit set by the Cramér-Rao bound [21, 22].

In this paper we propose combining a long signal recycling cavity with a technique known as internal squeezing [23–25] to obtain high frequency sensitivity without increasing the total circulating power in the interferometer. This *combination* has not been proposed to date and is superior compared to the individual techniques. This could be a potential upgrade for any of the existing or future GWDs, including aLIGO, AdV, Kagra [26], and LIGO-India [27] before the era of third generation GWDs [28]. Other applications of such a coupled cavity system are in experiments involving optomechanics like optomechanically induced transparency [29], negative mass systems [30] and precision metrology experiments [31–33].

1.1. Signal recycling cavities

In a conventional Dual-Recycled Fabry–Perot Michelson Interferometer (DRFPMI) configuration, such as the one used in aLIGO, the length of the SRC is small compared to the interferometer arms. By changing the length of (macroscopic) and/or detuning the SRC (microscopic), the frequency response of the interferometer can be tuned around a certain frequency, and therefore also to increase the overall sensitivity to certain GW sources [34].

Several theoretical investigation of SRC modification techniques for aLIGO have been performed by previously and one such technique [15], detuned SRC was utilised by GEO 600 [35] between 2005 and 2009 [36, 37]. While this configuration allows for improved high frequency sensitivity, it comes with technical challenges regarding the control of the interferometer [16]. When used in conjunction with external squeezing, a detuned interferometer requires two filter cavities as opposed to one the non-detuned interferometer which requires one filter cavity to achieve optimal frequency-dependent rotation of the squeeze ellipse [38].

To circumvent the challenges of a detuned SRC but still obtain the targeted high-frequency sensitivity, the concept of a DRFPMI with a long signal recycling cavity (LDRFPMI) was proposed [14, 15]. In this case, the length of the SRC is comparable to the arm length and the phase accumulated by the GW signal sidebands in the SRC cannot be ignored. As with coupled oscillator systems, the LDRFPMI displays a characteristic splitting of the frequency where the signals are resonantly enhanced, improving the sensitivity. This splitting frequency ($f_{\rm sp}$) and the bandwidth of the coupled cavity system (γ) is given by [39]

$$f_{\rm sp} = \frac{c\sqrt{T_{\rm ITM}}}{4\pi\sqrt{L_{\rm arm}L_{\rm src}}} \quad \text{and} \tag{1}$$

$$\gamma = \frac{cT_{\rm SRM}}{4L_{\rm src}}, \tag{2}$$

where c is the speed of light; $T_{\rm ITM}$ and $T_{\rm SRM}$ are the transmissivities of the input test mass and SRM respectively; $L_{\rm arm}$ and $L_{\rm src}$ are the lengths of the arm cavities and the SRC respectively. The bandwidth of this coupled cavity system depends on the transmission of the signal recycling mirror (SRM) as well as the length of the SRC.

1.2. Internal squeezing

As quantum fluctuations limit current-generation GWDs at high frequencies, the injection of squeezed states of light can improve their sensitivity. This technique, *external squeezing* was first proposed by Caves [40] and has since been demonstrated many times, including at the aLIGO sites [11–13]. Future upgrades to aLIGO and AdV will include a high-finesse filter cavity to rotate the squeezed states and thereby reduce quantum noise across the sensitivity bandwidth of the detector [41]. Novel techniques have been proposed in literature to rotate the squeezed states without a filter cavity [42] and to reduce the quantum noise at low frequencies [43].

A related technique, known as *internal squeezing*, uses squeezed states of light generated *inside* the SRC by means of an optical parametric amplifier (OPA) [23–25]. Internal squeezing uses a nonlinear crystal integrated into the SRC as shown in figure 1a. The crystal is pumped below threshold in a degenerate fashion such that the phase fluctuations are squeezed at the expense of uncertainity in the amplitude quadrature. Both the quantum noise and the GW signal are affected by internal squeezing, however, as the noise is squeezed more than the signal is deamplified, the overall bandwidth of the detector is broadened [23]. The total improvement in sensitivity with this technique is still bound by a fundamental quantum limit which depends on the circulating optical power in the interferometer [44]. Reduction of quantum noise combined with signal deamplification through a linear Fabry–Perot cavity with a nonlinear element has been experimentally demonstrated in [23].

Internal squeezing affects the sensitivity of the GWD only within the linewidth of the coupled cavity system formed by the arm cavity and the SRC (figure 1b). Figure 2 shows the effect of internal squeezing in an LDRFPMI system. The signal which originates in the arm cavities is deamplified as it passes through the nonlinear crystal. However, the noise which enters the interferometer from the output port in the form of vacuum fluctuations is squeezed more than

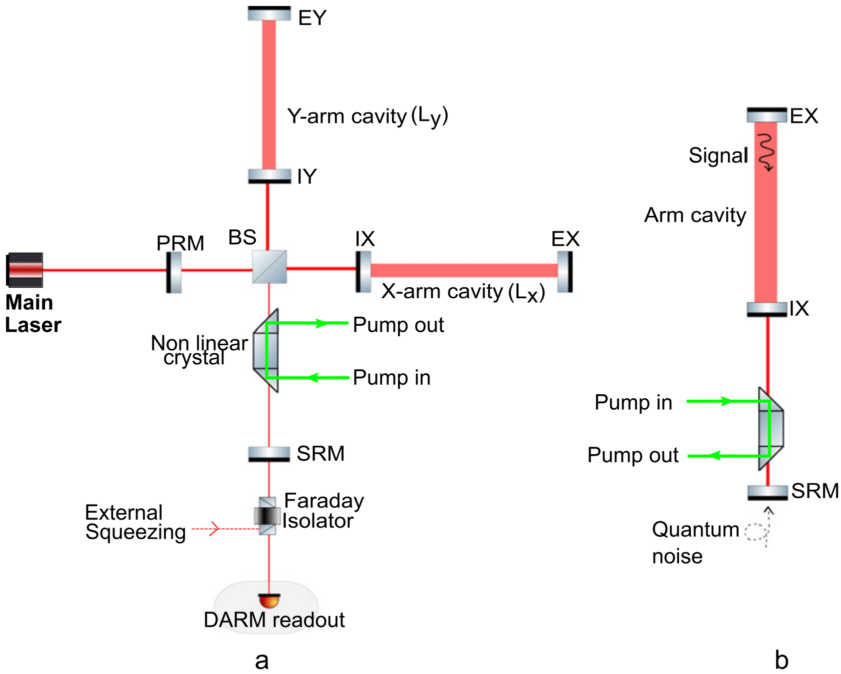

Figure 1. A simplified layout of a GWD with internal squeezing and a long signal recycling cavity is shown in figure a. The power recycling mirror (PRM), signal recycling mirror (SRM), input test masses (IX and IY) together with the beam splitter (BS) and the end test masses (EX and EY) form the LDRFPMI. The entire interferometer however can be reduced to a three mirror coupled cavity system where the origin of the GW signal and quantum noise is shown in figure b.

the signal is deamplified, as the noise sees the entire coupled cavity system as a squeezer. Internal squeezing can thus be viewed as an optical filter that modifies both the signal and noise transfer functions. This technology is compatible with external squeezing and the combination has been proposed by Korobko *et al* to broaden the bandwidth of GWDs [24].

2. The optical model

A DRFPMI/LDRFPMI can be modelled as a simpler three mirror coupled cavity system as shown in the figure 1b. We have used the mathematical framework in [24, 25]. Asymmetries like dark fringe offset, Schnupp asymmetry are not accounted for in this model. Using this formalism, the quantum noise spectral density of a GWD normalised to GW strain (S_h) with a squeezer in the SRC [equation (9), [24]] can be written as,

$$S_\mathrm{h} = \frac{\hbar c}{8\omega_0 L_\mathrm{arm} P_\mathrm{circ}} \frac{(\Omega^2 - {\omega_s}^2)^2 + (\gamma - \chi)^2\Omega^2}{\gamma {\omega_s}^2}, \tag{3}$$

where, P_circ is the circulating power in the arm cavity, χ is the internal squeezing factor (also known as effective parametric gain of the OPA), ω_0 is the laser carrier frequency, ω_s is the angular splitting frequency and Ω is the GW sideband frequency.

In our model, losses in the interferometer are modelled using a beamsplitter inside the signal recycling cavity after the crystal. This overall loss (in our case 35 ppm single-pass, or 408

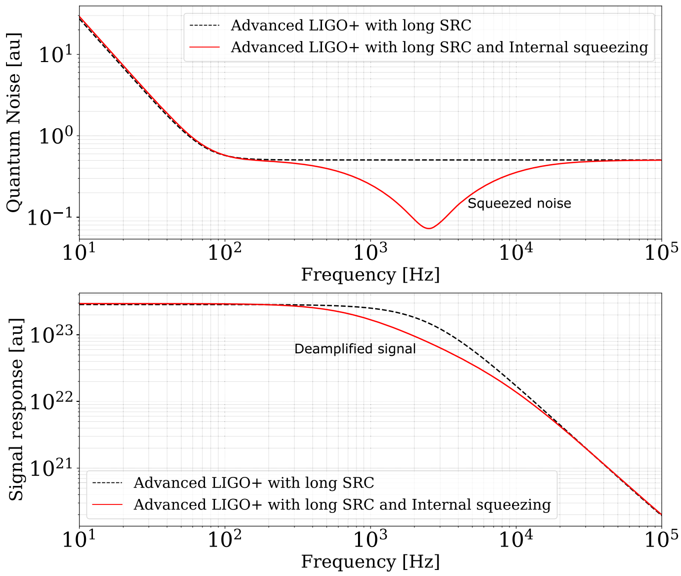

Figure 2. Behaviour of signal and noise with and without internal squeezing using the parameters for aLIGO-HF listed in table 1.

Table 1. Parameters of aLIGO versus aLIGO-HF.

Parameter	aLIGO	aLIGO-HF
Arm length (m)	4000	4000
SRC length (m)	53	319
Power on beam-splitter (kW)	5.3	5.3
SRM power transmission	0.325	0.12
Injected external squeezing level (dB)	6	6
Internal squeezing factor	0	0.065
SRC internal loss (single pass)	35	35
Detector losses (%)	99.5	99.5 [48]
Number of filter cavities	1	1
Splitting frequency (kHz)	6.13	2.5
Strain at 2.5 kHz $\left(1/\sqrt{Hz}\right)$	1×10^{-23}	9×10^{-25}

ppm total) encompasses all individual losses such as mode-matching, vacuum fluctuations etc. The loss values assumed here are consistent with those used in the advanced LIGO+ model [45]. Additional information and equations pertaining to loss calculations can be found in the supplementary sections S5 and S1.2 of [24] and sections B and C of [16]. Using equations (1) and (3) and the aLIGO parameters from table 1, the length of the SRC corresponding to a splitting frequency of 2.5 kHz is 319 m.

The LDRFPMI is inherently more robust to losses in the SRC compared to a DRFPMI as the effect of the cavity losses is reduced with a longer cavity [46, 47]. Our model introduced in this work, aLIGO-HF, combines a long SRC with internal squeezing, in addition to the 6 dB of frequency dependent external squeezing included in the advanced LIGO+ design. In the case of external and internal squeezing, the nonlinear crystal is pumped degenerately. The internal

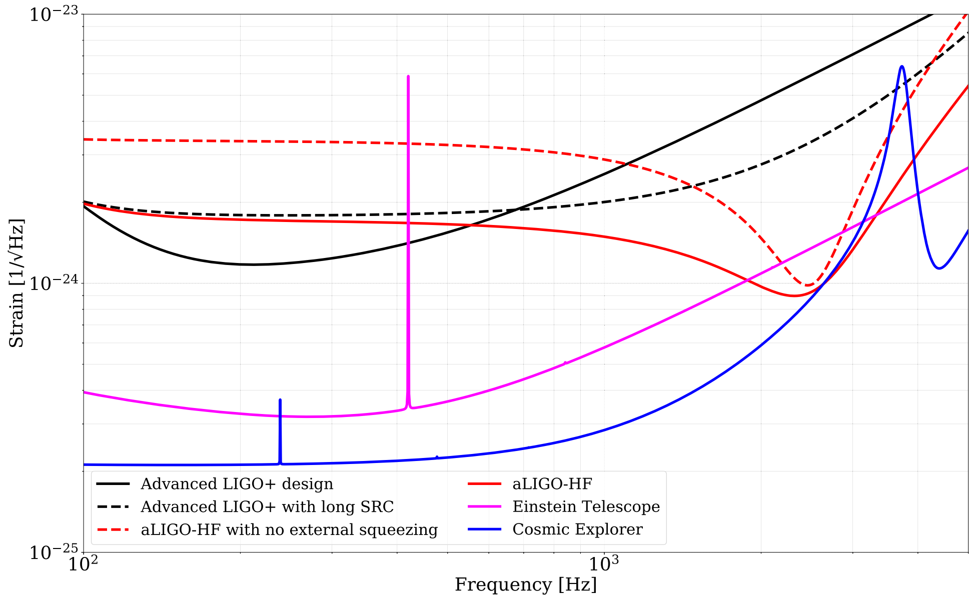

Figure 3. Comparison of the quantum noise limited sensitivity of aLIGO-HF with internal and external squeezing (solid red) to third generation GWDs such as Einstein telescope (magenta) and cosmic explorer (blue). Also shown is the sensitivity of aLIGO-HF with only internal squeezing (dashed red line) which shows the enhancement of the coupled cavity pole at high frequencies.

squeezing factor was chosen such that the sensitivity was maximised but under the condition that the internal squeezer stays below threshold.

The difference in parameters between advanced LIGO+ design parameters and our aLIGO-HF model which we define here to include internal squeezing, external squeezing and a long SRC are listed in table 1.

3. Results and discussion

With a moderately reflective SRM and a short SRC, internal squeezing in combination with external squeezing offers a broadband improvement of quantum noise limited strain (QNLS) sensitivity. If the reflectivity of the SRM is increased, then within the bandwidth of the coupled cavity system, the combination of internal and external squeezing offers a substantial increase in the QNLS around the coupled cavity pole [which is calculated from equations (1) and (3)] as shown in figure 2. The sensitivity of our model of the long SRC combined with internal squeezing, aLIGO-HF is shown as the solid red line in figure 3. At the coupled cavity pole (2.5 kHz) , the quantum noise limited strain sensitivity of aLIGO-HF in solid red in figure 3—with the same circulating power as the advanced LIGO+ design (black, figure 3)—is comparable to that of third generation detectors such as the Einstein telescope (magenta) and Cosmic Explorer (blue). This cavity pole was chosen to maximise the sensitivity of aLIGO-HF at a frequency relevant to GW sources such as neutron stars and supernovae.

The advanced LIGO+ design which has a short SRC and 6 dB of frequency-dependent external squeezing to reduce quantum noise across the sensitive frequency band has limited sensitivity in the kHz regime, and is therefore not well suited to studying the physics of neutron

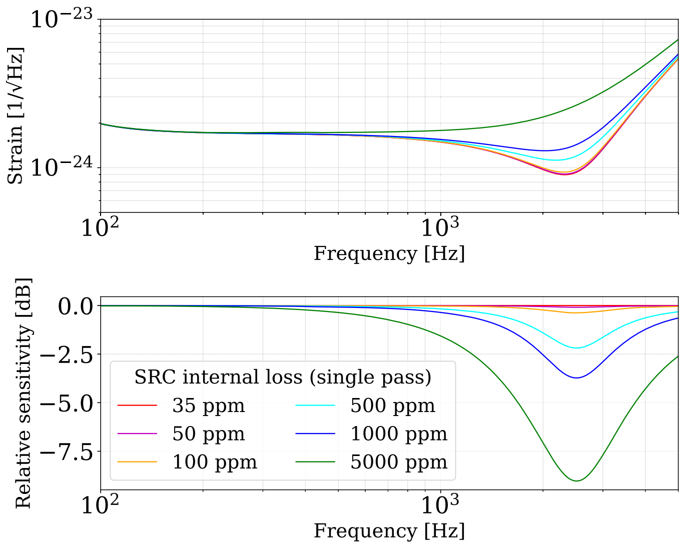

Figure 4. Effect of internal losses in the long SRC on internal squeezing. Also shown is the relative decrease in sensitivity with respect to the aLIGO-HF assumed SRC losses of 35 ppm and an internal squeezing factor of 0.065.

star mergers. By modifying this configuration to incorporate a long SRC (black dashed line), the high frequency performance is improved, but this compromises the sensitivity below 1 kHz due to the change in linewidth of the coupled cavity system.

An improvement of 9 dB around the coupled cavity pole at 2.5 kHz is evident compared to the advanced LIGO+ design. In order to obtain the same sensitivity at 2.5 kHz as aLIGO-HF with the advanced LIGO+ design, the circulating power in the arm cavities would need to be increased by two orders of magnitude, from 800 kW to 110 MW. The overall sensitivity of the aLIGO-HF design also scales with the circulating power in the arms [see equation (3)], i.e. the addition of internal squeezing does not change the fact that increased arm cavity power increases sensitivity.

The overall sensitivity of any GW detector is limited by the optical losses in the interferometer and in the readout. As with all configurations involving squeezed light, the aLIGO-HF model is sensitive to readout losses. Any detector configuration with internal squeezing is also sensitive to readout losses since it behaves like a filter that modifies both the GW signal and the noise. External squeezing which modifies only the noise entering the interferometer leaving the signal unchanged is also sensitive to readout losses [49]. The addition of the internal squeezer to the SRC also increases the total loss in the interferometer, which reduces the sensitivity to GW signals. However, a long SRC is more robust to internal losses than a short SRC as discussed in section 2. This effect is examined in figure 4, which shows the effect of varying levels of internal loss on the aLIGO-HF model for a fixed internal squeezing factor, in our case 0.065 as explained in section 2. The degradation in sensitivity of aLIGO-HF with respect to currently assumed losses of 35 ppm (solid red line) SRC loss is shown in the relative sensitivity plot. Only losses greater than or equal to 500 ppm show significant degradation in sensitivity.

The technical challenges pertaining to the addition of a squeezing element to an interferometer are detailed in appendix S1.2 of [24] however, the increased sensitivity at high frequencies allows for study of merger and post merger epochs from binary neutron star collisions [50], gravitational modes and excited matter modes of extremely compact objects [4] and makes for a compelling science case for neutron star physics.

4. Conclusions

This paper shows that the additional of a combination of a long SRC and internal squeezing to the advanced LIGO+ design, has the potential to significantly increase the high-frequency sensitivity. We also show that such a configuration is robust to internal losses. Such a GWD could potentially come online before third generation detectors (ca 2045). This proposed upgrade would be extremely relevant for study of high energy astrophysical objects such as neutron stars and their equation of state. Future work includes studying the effects of mode mismatches between the optical cavities and asymmetries.

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