

Quadrature-witness readout for backscatter mitigation in gravitational-wave detectors dominated by backaction

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Disturbances in gravitational wave (GW) observational data are often caused by nonstationary noise in the detector itself, such as backscattering of laser stray light into the signal field. Unlike GW signals, nonstationary noise can appear in both the GW-signal quadrature and the orthogonal quadrature, which is usually not measured. Simultaneous sensing of this orthogonal quadrature provides a witness channel that can be used to reconstruct the disturbance in the signal quadrature enabling subtraction of nonstationary noise. Here, we present the concept of quadrature witness that is compatible with frequency-dependent squeezing, which is already used to simultaneously reduce photon shot noise and photon radiation-pressure noise. We demonstrate that implementing this approach in a GW detector could reduce noise caused by loud backscatter events, thereby improving the overall sensitivity and robustness of GW observatories.

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I. INTRODUCTION

Since the first observation of a gravitational wave (GW) in 2015 by the two LIGO detectors [1], over 200 GW events from binary mergers have been observed. While the current generation of GW detectors observes new events every few days [2–6], future detectors, such as the Einstein Telescope [7] and the Cosmic Explorer [8], will bring this rate to several events per minute. Such an improvement in the detection capabilities will bring unprecedented progress in scientific understanding of the Universe [9], but it will require significant technological advancement. The sensitivity of the current observatories, Advanced LIGO [10], Advanced Virgo [11], and KAGRA [12], is limited by various sources of noise. One of the most fundamental noises is quantum: it originates from the ground state fluctuations of the quantum vacuum field entering the output port of the interferometer. These fluctuations couple to the amplitude and phase of the light field inside the detector, leading to quantum radiation-pressure noise (QRPN) on the mirrors and photon shot noise (SN) upon detection. SN is the main limitation of detector sensitivity at midfrequencies and above ($\gtrsim 100$ Hz), while QRPN is one of the limiting noises at lower frequencies ($\lesssim 30$ Hz).

Modern detectors employ quantum squeezed light to suppress quantum noise [13–15]. Since its first implementation in the GEO600 GW detector in 2011 [16,17], squeezed light has been brought to continuous operation in both Advanced LIGO and Advanced Virgo [18,19], culminating in the simultaneous reduction of both SN and QRPN in Advanced LIGO [20] using a frequency-dependent squeezing approach [21–24]. Future detectors will reach even higher quantum enhancement employing advanced quantum technology [25–27].

Quantum noise is not the only factor limiting the detector sensitivity. Backscattered laser light is a dominant, nonstationary noise source: tiny fractions of laser light from the arm cavities of the detectors scatter out of the main beam, reflect off moving surfaces and then reenter the main beam, imprinting surface motion as a parasitic phase/amplitude modulation that can mask the genuine GW signal [28–31]. Backscatter noise is commonly mitigated by using higher-quality optical surfaces to reduce scattering, blackening potential backscatter surfaces, reducing the motion of the backscatter surfaces relative to the mirrors of the arm resonators [30], precise modeling of the effects [32], and baffles to intercept and absorb scattered light [33]. These measures remain imperfect and further suppression is required.

Quantum technology provides a complementary path by enabling direct readout of these disturbances and their coupling to GW signals. Quantum-dense metrology (QDM) uses two-mode squeezed light to simultaneously read out two noncommuting field quadratures with a precision better than photon SN [34]. Because the backscattered disturbance couples both into the signal

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quadrature and in the orthogonal quadrature (which contains no GW signal), simultaneously detecting both allows the orthogonal quadrature to serve as a witness for subtracting the disturbance from the signal. QDM enables this approach enhanced with squeezed-light injection [35]. However, neither this quantum approach nor similar non-squeezed techniques [36–39] have been extended to interferometers operating in the backaction-dominated regime at low frequencies—precisely where both backscattered light and QRPN are most significant.

Here, we provide that extension. We present a new quantum-enhanced readout that preserves frequency-dependent squeezing of the signal quadrature while extracting the backscatter witness from the orthogonal quadrature. This scheme employs two squeeze lasers to enable the witness readout without sacrificing the high level of frequency-dependent quantum enhancement for the signal quadrature. We perform a statistical analysis of random scattering events and show that already in the near-term upgrades of existing detectors, a noninvasive implementation can remove the loudest scatter events with only minimal loss of GW sensitivity—making it a promising approach for detectors affected by the backscatter noise.

II. QUADRATURE-WITNESS READOUT

The main idea of the dual readout is to split the signal that comes out of the detector onto two independent balanced homodyne detectors, one of which measures the GW signal (together with backscatter disturbance) and the other one, only the backscatter contribution. However, this split creates a loss channel for the squeezed light, where a quantum vacuum state couples into the squeezed state and leads to severe decoherence [15]. Quantum-dense metrology suggests to replace this quantum vacuum state by an Einstein-Podolsky-Rosen-entangled state, negating the detrimental effects of loss. However, combining it with frequency-dependent squeezing requires employing a sophisticated quantum system, as we show in the follow-up work [40]. Instead, in this work, we propose replacing this vacuum field with another squeezed field, which we will call readout squeezing. This also negates the detrimental effects of splitting the signal, but prevents achieving quantum enhancement on witness quadrature, as done in QDM.

In this section, we start by presenting the general concept of our dual readout approach and its theoretical foundation. We demonstrate its compatibility with frequency-dependent squeezing, provide an intuitive theoretical description that exemplifies the resulting quadrature sensitivities, and outline the optimization procedure that allows us to achieve high sensitivity in a realistic setting. The computation of the sensitivities, which were used to produce the sensitivity curves in this paper, can be found in Supplemental Material [41].

A. Setup and sensitivities

The detector setup, shown in Fig. 1, consists of three core components: a Michelson interferometer with arm, power recycling, and signal extraction cavities; the injection of frequency-dependent squeezed light; and the dual readout. Frequency-dependent squeezing is achieved by reflecting squeezed light off a detuned filter cavity. This creates a frequency-dependent rotation of the squeezed state of light [23]. The reflected squeezed light is then coupled into the detector through a Faraday isolator. Dual readout is realized by a readout beam splitter, which sends the signal onto two balanced homodyne detectors. One of them measures the signal quadrature and the other one, orthogonal witness quadrature. As a novelty of this work, we inject squeezed light into the detector through the open port of the readout beam splitter. The purpose of doing this is to avoid vacuum entering the detector through this port, which would reduce the amount of detected squeezing. In this subsection, we consider the simple case of a balanced readout beam splitter. Equal splitting leads to the loss of 50% of the signal in both quadratures, resulting in 3 dB penalty to the sensitivity at high frequencies. In the next sections, we relax this condition to further optimize the sensitivity.

Figure 2 shows the signal and witness quadrature sensitivities of our approach. The parameters of the detector and the filter cavity were chosen such that we achieve optimal frequency-dependent squeezing and get approximately the same signal quadrature sensitivity as A+ [46] for the single readout (see Table I). At low frequencies, QRPN dominates the sensitivity of the signal quadrature, which is almost identical for single readout and for quadrature witness with readout squeezing. In the latter case, both QRPN and signal are reduced by the readout beam splitter, and their noise-to-signal ratio remains almost unchanged. At high frequencies, the sensitivity is limited by SN, which is not affected by the readout beam splitter (without squeezing), since the noise lost is compensated by the added vacuum field. Half of the signal is still lost, and thus noise-to-signal ratio is reduced by 50%. In this case, replacing the vacuum field entering the readout beam splitter with squeezed vacuum significantly increases the signal quadrature sensitivity compared to dual readout.

The witness quadrature sensitivity has more complex frequency-dependent behavior. In a single readout, the witness quadrature is only accessible if the readout quadrature is switched away from the signal, but it is useful to compute its sensitivity as a reference. In this case, the quadrature of the squeezed state is optimized in a frequency-dependent way to suppress QRPN at low frequencies and SN at high frequencies. Therefore, the witness quadrature is highly squeezed at low frequencies and antisqueezed at high frequencies. For the quadrature-witness readout,

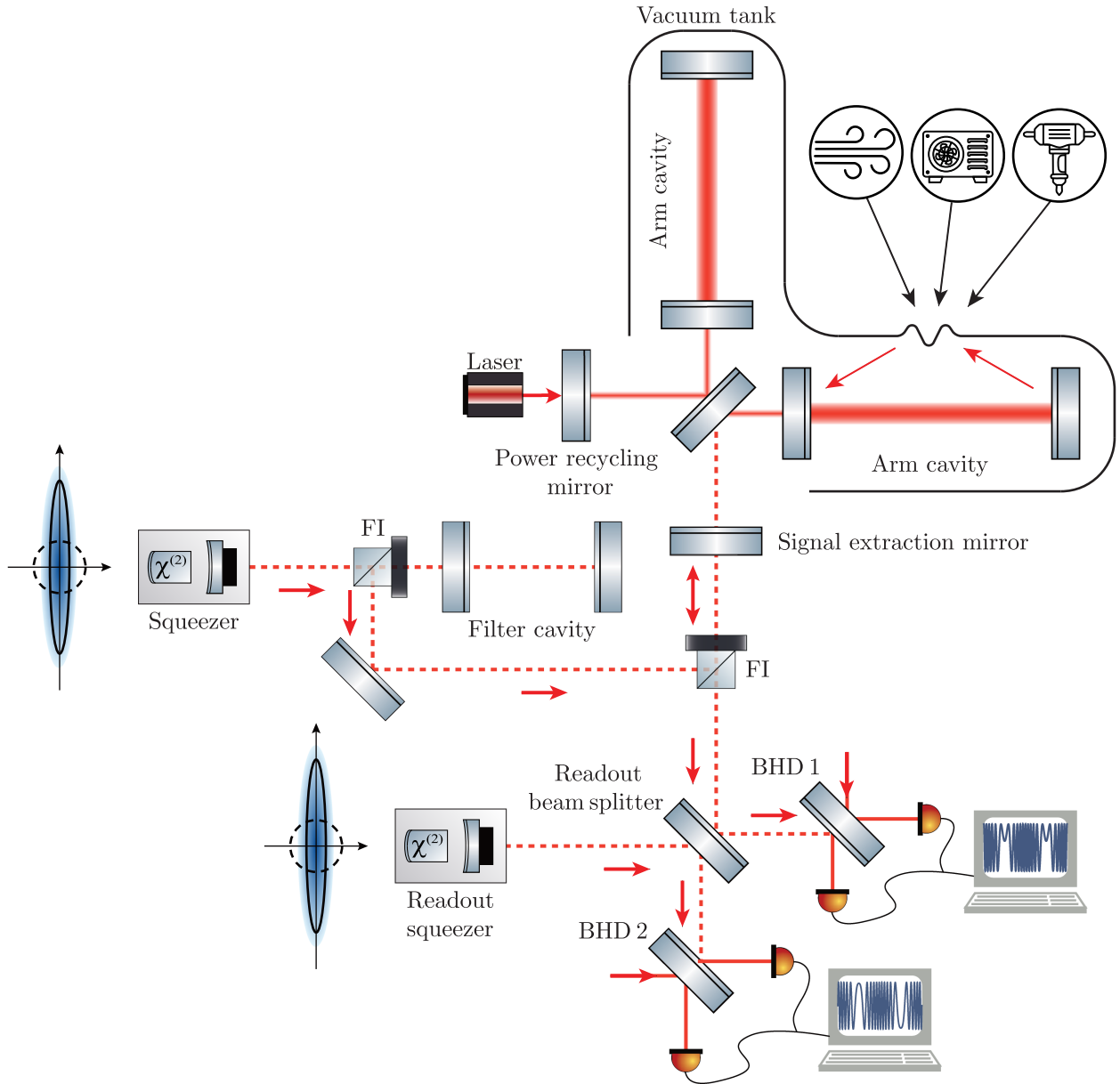


FIG. 1. Conceptual setup of our approach in a GW detector. The walls of the vacuum tanks are excited by microseisms and anthropogenic sources. Dual readout is implemented by the readout beam splitter and two balanced homodyne detectors (BHDs) in the output of the interferometer. One BHD measures the signal quadrature, while the other one measures the witness quadrature. A second squeezed state is injected through the open port of the readout beam splitter. Frequency-dependent squeezing is realized by a filter cavity and injected into the detector through a Faraday isolator (FI).

the phase of the readout squeezing is aligned with squeezing in the signal quadrature. Thus, the witness quadrature has two contributions: squeezed from the main squeezing and antisqueezed from the readout squeezing. At high frequency, main squeezing turns to antisqueezed quadrature due to frequency-dependent squeezing, which further increases noise in the witness quadrature. Similar to the case above, the loss of 50% of the signal leads to the 3 dB reduction in the sensitivity at high frequency. Despite increased noise for the witness quadrature, its measurement

still allows one to subtract a significant fraction of backscatter light. Moreover, the witness quadrature provides high sensitivity down to very low frequencies, due to not being limited by other fundamental noises that couple to the signal quadrature. Measurement at those frequencies can allow one to predict the nonlinear up-conversion of the scattered photons to the signal band. As a consequence, the subtraction of these events from the signal quadrature would allow one to reach quantum-noise-limited sensitivity.

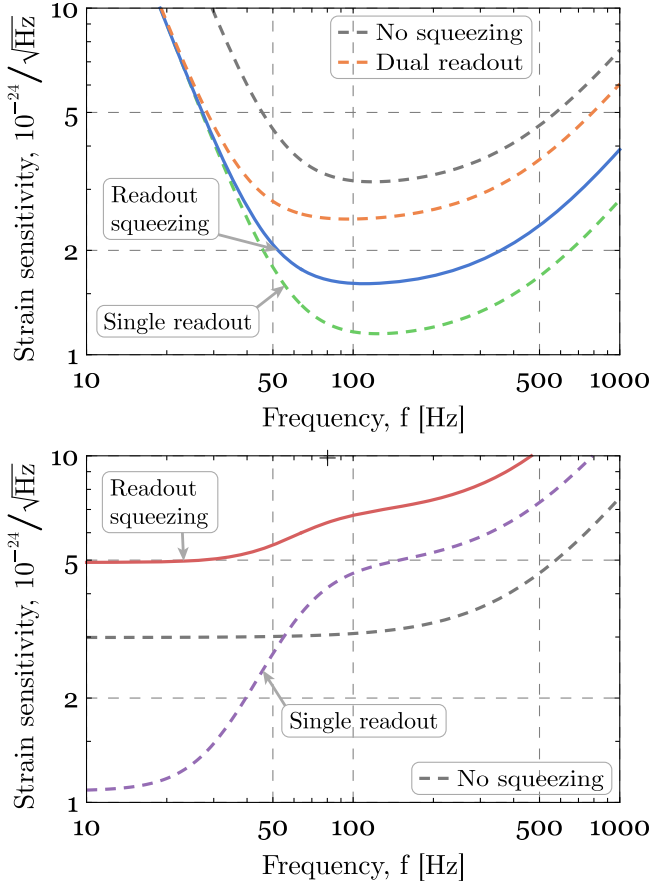


FIG. 2. Strain sensitivity of the signal quadrature (top) demonstrates that frequency-dependent squeezing is compatible with dual readout. Quadrature witness with readout squeezing (solid blue) maintains quantum enhancement at all frequencies compared to the case without squeezing (dashed gray), only suffering a 3 dB penalty for dual readout at high frequency. Readout squeezing allows one to restore a significant portion of sensitivity compared to the dual readout without readout squeezing (orange dashed). The witness quadrature sensitivity (bottom) is sufficient to allow effective backscatter subtraction. The detector parameters are chosen such that we achieve optimal frequency-dependent squeezing and reach approximately the same signal quadrature sensitivity as A+ for single readout (see Table I).

B. Theory

In this section, we present the physical intuition for the quadrature-witness readout, considering a simplified scenario of a detector without the signal-recycling cavity and any losses, while Supplemental Material contains the full derivation [41]. We follow the formalism of Ref. [25] to derive simplified expressions for the signal and witness quadrature sensitivities. Here, we consider the case that a scattering event inside the interferometer produces a signal field in both quadratures, denoted by

TABLE I. Parameters used to get the sensitivity close to the one of A+ [46].

Parameter	Value
Laser wavelength	1064 nm
Arm circulating power	750 kW
Test mass weight	40 kg
Input test mass power transmission	1.4%
End test mass power transmission	5 ppm
Signal extraction mirror power transmission	32.5%
Arm cavity length	3995 m
Signal extraction cavity length	55 m
Single pass loss inside the signal extraction cavity	1000 ppm
Total detection efficiency	90%
Squeezer: injected external squeezing	7.5 dB
Readout squeezer: injected external squeezing	7.5 dB
Readout beam splitter power reflectivity	50%

n^w and n^s for the witness and signal quadratures correspondingly [47],

$$n^w = \sqrt{f_r \frac{P_{\text{out}}}{P_{\text{in}}}} \mathcal{F}[\cos(\phi_{\text{sc},0} + \phi_r(t))], \quad (1a)$$

$$n^s = \sqrt{f_r \frac{P_{\text{out}}}{P_{\text{in}}}} \mathcal{F}[\sin(\phi_{\text{sc},0} + \phi_r(t))], \quad (1b)$$

where f_r is the fraction of scattered light that is coupled back into the main beam, P_{out} is the light power of the scattered light, P_{in} is the light power inside the interferometer, $\mathcal{F}$ indicates the Fourier transform, $\phi_{\text{sc},0}$ is a constant phase that depends on the position of the scattering event, and $\phi_r(t)$ is the phase caused by the motion of the backscatter surface. These contributions appear at the output weighted by the interferometer transfer functions G^w and G^s . The exact form of these functions depends on the particular detector configuration and how the recoupling of the backscattered light is treated. In a simplest case, considering a tuned arm cavity with a perfectly reflective end mirror where backaction effects can be neglected, assuming the recoupling to happen at the end mirror results in the following transfer functions:

$$G^w = G^s = \frac{\sqrt{\gamma}}{\sqrt{\tau}(\gamma - i\Omega)}, \quad (2)$$

where γ and τ are the cavity bandwidth and single trip time, respectively. Since this example is not representative of all possible coupling mechanisms, we will keep the general form of the transfer functions in the rest of this section.

The two output quadratures of a Michelson interferometer without a signal-recycling cavity are given by the

input-output relations,

$$\begin{pmatrix} b^w \\ b^s \end{pmatrix} = e^{2i\phi} \mathbb{M} a_{\text{in}} + \begin{pmatrix} G^w n^w \\ G^s n^s \end{pmatrix} \quad (3)$$

with

$$\mathbb{M} = \begin{pmatrix} 1 & 0 \\ -\mathcal{K}(\Omega) & 1 \end{pmatrix}, \quad (4)$$

and input

$$a_{\text{in}} = \begin{pmatrix} a_{\text{in}}^w \\ a_{\text{in}}^s \end{pmatrix}. \quad (5)$$

Here, b^w is the output in the witness quadrature; b^s is the output in the signal quadrature; $\mathcal{K}(\Omega)$ is the Kimble factor [23]; $\phi = \phi(\Omega)$ is the single trip phase of the interferometer. Frequency-dependent squeezing is achieved by reflecting the input off a filter cavity before it is injected into the interferometer. In the lossless case, the reflection off a filter cavity is described by

$$\mathbb{F} = \mathbb{P}[\theta(\Omega)] e^{i\beta}, \quad (6)$$

with the rotation matrix

$$\mathbb{P}[\theta(\Omega)] = \begin{pmatrix} \cos \theta(\Omega) & -\sin \theta(\Omega) \\ \sin \theta(\Omega) & \cos \theta(\Omega) \end{pmatrix}. \quad (7)$$

The filter cavity rotates the input state by the frequency-dependent rotation angle $\theta(\Omega)$ and adds a phase $\beta = \beta(\Omega)$. After adding frequency-dependent squeezing, we obtain

$$\begin{pmatrix} b^w \\ b^s \end{pmatrix} = e^{i(2\phi+\beta)} \mathbb{M} \mathbb{P}[\theta(\Omega)] a_{\text{in}} + \begin{pmatrix} G^w n^w \\ G^s n^s \end{pmatrix}. \quad (8)$$

From this equation, we can compute the signal quadrature output for a standard detector with single readout,

$$b^s = e^{i(2\phi+\beta)} \sqrt{1 + \mathcal{K}^2(\Omega)} a_{\text{in}}^s + G^s n^s, \quad (9)$$

where we set the rotation angle to $\theta(\Omega) = \arctan \mathcal{K}(\Omega)$. In this case, the noise-to-signal ratio is given by

$$S_h^s = \frac{1 + \mathcal{K}^2(\Omega)}{|G^s n^s|^2} S_{\text{in}}^s \quad (10)$$

with the signal quadrature spectral density of the input state S_{in}^s .

To readout both quadratures simultaneously, we need to place a beam splitter in the output port of the interferometer.

Here, we consider the simple case of a balanced beam splitter. In the case of dual readout, Eq. (9) changes to

$$\begin{pmatrix} b^w \\ b^s \end{pmatrix} = \frac{1}{\sqrt{2}} \left[e^{i(2\phi+\beta)} \mathbb{M} \mathbb{P}[\theta(\Omega)] a_{\text{in}} + \begin{pmatrix} G^w n^w \\ G^s n^s \end{pmatrix} \right] + \frac{1}{\sqrt{2}} v_{\text{BS}} \quad (11)$$

with vacuum

$$v_{\text{BS}} = \begin{pmatrix} v^w \\ v^s \end{pmatrix} \quad (12)$$

that couples into the detector through the open port of the beam splitter. This vacuum limits the sensitivity of the detector. Therefore, we replaced it with a second input

$$a_{\text{BS}} = \begin{pmatrix} a_{\text{BS}}^w \\ a_{\text{BS}}^s \end{pmatrix}, \quad (13)$$

which could have a squeezed signal or witness quadrature,

$$\begin{pmatrix} b^w \\ b^s \end{pmatrix} = \frac{1}{\sqrt{2}} \left[e^{i(2\phi+\beta)} \mathbb{M} \mathbb{P}[\theta(\Omega)] a_{\text{in}} + \begin{pmatrix} G^w n^w \\ G^s n^s \end{pmatrix} \right] + \frac{1}{\sqrt{2}} a_{\text{BS}}. \quad (14)$$

As before, we compute signal quadrature output

$$b^s = \frac{1}{\sqrt{2}} \left[e^{i(2\phi+\beta)} \sqrt{1 + \mathcal{K}^2(\Omega)} a_{\text{in}}^s + G^s n^s + a_{\text{BS}}^s \right] \quad (15)$$

and the spectral density of the output

$$S_{\text{out}}^s = \frac{1}{2} [(1 + \mathcal{K}^2(\Omega)) S_{\text{in}}^s + |G^s n^s|^2 + S_{\text{BS}}^s], \quad (16)$$

where S_{BS}^s is the signal quadrature spectral density of the second input state a_{BS} .

If we consider the case where a_{in} and a_{BS} both have squeezed signal quadratures with identical spectral densities S_{SQZ} , we obtain the following noise-to-signal ratio:

$$S_h^s = \frac{2 + \mathcal{K}^2(\Omega)}{|G^s n^s|^2} S_{\text{SQZ}}^s. \quad (17)$$

At low frequencies, the $\mathcal{K}^2(\Omega)$ term dominates and we obtain the same sensitivity as for single readout [see Eq. (10)]. At higher frequencies, the $\mathcal{K}^2(\Omega)$ term becomes negligible and the sensitivity is reduced by a factor of 2 compared to single readout.

In the same way, we can compute the witness quadrature output,

$$b^w = \frac{1}{\sqrt{2}} \left[\frac{e^{i(2\phi+\beta)}}{\sqrt{1+\mathcal{K}^2(\Omega)}} (a_{\text{in}}^w - \mathcal{K}(\Omega)a_{\text{in}}^s) + G^w n^w - a_{\text{BS}}^w \right] \quad (18)$$

and the corresponding spectral density

$$S_{\text{out}}^w = \frac{1}{2} \left[\frac{S_{\text{in}}^w}{1+\mathcal{K}^2(\Omega)} + \frac{\mathcal{K}^2(\Omega)S_{\text{in}}^s}{1+\mathcal{K}^2(\Omega)} + |G^w n^w|^2 + S_{\text{BS}}^w \right], \quad (19)$$

where S_{in}^w and S_{BS}^w are the witness quadrature spectral densities of the input states a_{in} and a_{BS} , respectively.

As before, we assume that a_{in} and a_{BS} both have squeezed signal quadratures with identical spectral densities S_{SQZ} . The noise-to-signal ratio is as follows:

$$S_h^w = \frac{2 + \mathcal{K}^2(\Omega)}{(1 + \mathcal{K}^2(\Omega))|G^w n^w|^2} S_{\text{SQZ}}^w + \frac{\mathcal{K}^2(\Omega)}{(1 + \mathcal{K}^2(\Omega))|G^w n^w|^2} S_{\text{SQZ}}^s. \quad (20)$$

At low frequencies, $\mathcal{K}(\Omega)$ is very large and Eq. (20) simplifies to

$$S_h^w \approx \frac{S_{\text{SQZ}}^w + S_{\text{SQZ}}^s}{|G^w n^w|^2} \approx \frac{S_{\text{SQZ}}^w}{|G^w n^w|^2}. \quad (21)$$

Since we consider squeezed states in signal quadrature, the witness quadrature component of the input states is anti-squeezed and so the sensitivity is decreased compared to the case without squeezing.

At high frequencies, $\mathcal{K}(\Omega)$ becomes very small and the sensitivity is given by

$$S_h^w \approx \frac{2S_{\text{SQZ}}^w}{|G^w n^w|^2}. \quad (22)$$

Again, we can see the reduction in sensitivity by a factor of 2 due to dual readout.

C. Optimization

The two main parameters introduced by the quadrature-witness readout are the level of readout squeezing and the transmission of the readout beam splitter. In the previous section, we assumed both to be fixed: beam splitter to be 50/50 and the squeeze value to match that of the main squeezing. They can be optimized for better performance. In particular, the main squeeze value is defined by the total loss in the GW detector and is limited

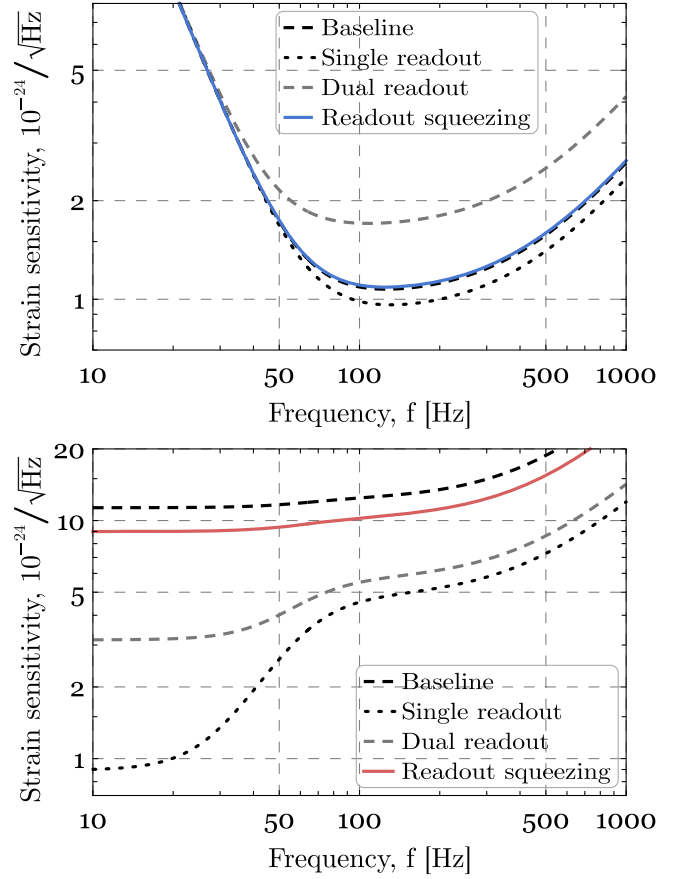


FIG. 3. Optimized signal (top) and witness (bottom) quadrature sensitivities. The baseline curves show the sensitivities for a detector with readout losses of 2% after the readout beam splitter and 15 dB of readout squeezing. The solid curves show the sensitivities for the optimized readout beam splitter power reflectivity of 69% and amount of readout squeezing of 9.5 dB. For comparison, we plotted the sensitivity of the single readout and dual readout without readout squeezing for the same reflectivity.

to a moderate value to reduce the impact on the QRPN [27]. Readout squeezing only suffers the readout loss (typically, the inefficiency of the photodiodes and the imperfect mode overlap at the homodyne detector), which is comparatively small. Therefore, a much higher readout squeeze value can be used. Balancing between the signal lost at the readout beam splitter, antisqueezing introduced in the witness quadrature, and squeezing restored to the signal quadrature, we find an optimal configuration that preserves high signal quadrature and increases the sensitivity in the witness quadrature.

In Fig. 3 we show an example of such optimization, considering 2% of the readout loss after the readout beam splitter. The signal quadrature remains unaffected by the changes to the beam splitter ratio from 50/50 (baseline) to 69/31 (detecting more signal quadrature) and by the

reduction of the readout squeeze value from 15 to 9.5 dB. Further optimization can be performed for more detailed loss budget for each specific detector design.

III. BACKSCATTER LIGHT SIGNAL AND STATISTIC

In this section, we present the details of the model that we use to generate scattering events. We also describe how we use this model to simulate a set of scattering events with a statistic that corresponds to those observed in GW detectors. We consider the sensitivity of the signal and witness quadratures as presented in Sec. II A without further optimization.

A. Model

The projections of a scattering signal in the signal quadrature $p_{\text{sig}}(t)$ and witness quadrature $q_{\text{wit}}(t)$ in time domain are given by [35,48]

$$p_{\text{sig}}(t) = A \cos[\varphi_0 + m \sin(2\pi f_m t + \phi_m)], \quad (23)$$

$$q_{\text{wit}}(t) = A \sin[\varphi_0 + m \sin(2\pi f_m t + \phi_m)]. \quad (24)$$

A is the amplitude of the scattering signal, m is the modulation depth, f_m is the modulation frequency, ϕ_m is the initial phase shift of the modulation, and φ_0 is the initial phase shift of the projection in the two quadratures. This model describes fast scattering events, which produce so-called scatter shoulders. Frequency up-conversion of a low-frequency motion leads to a signal at higher frequencies. The maximum frequency component of a scatter shoulder scales linearly with the frequency and modulation depth of the scatter source and can be in the frequency range where detectors are most sensitive. Figure 4(a) shows the normalized projections of a scattering signal in both quadratures in the time domain for the model parameters: $A = 2.13 \times 10^{-22}$, $f_m = 5$ Hz, $m = 32.7$, $\phi_m = 0$, and $\varphi_0 = 0$. To estimate the amplitude spectral density of these signals, we used Welch's method and applied a Savitzky-Golay filter to smooth the resulting curves. The resulting spectral density of the scatter shoulder with a peak around 150 Hz is shown in Fig. 4(b). The plot also highlights that scattering signals can be so strong that they can be detected in both quadratures.

B. Statistic

The SNRs of fast scattering events span a wide range. As a practical reference, we adopt the SNR distribution of all events (fast and slow) reported in [49] and treat them as if they were all fast events with large modulation depths. This choice is motivated by three assumptions: (i) we lack a reliable model for slow scattering; (ii) scattering events with small modulation depth that affect the detector

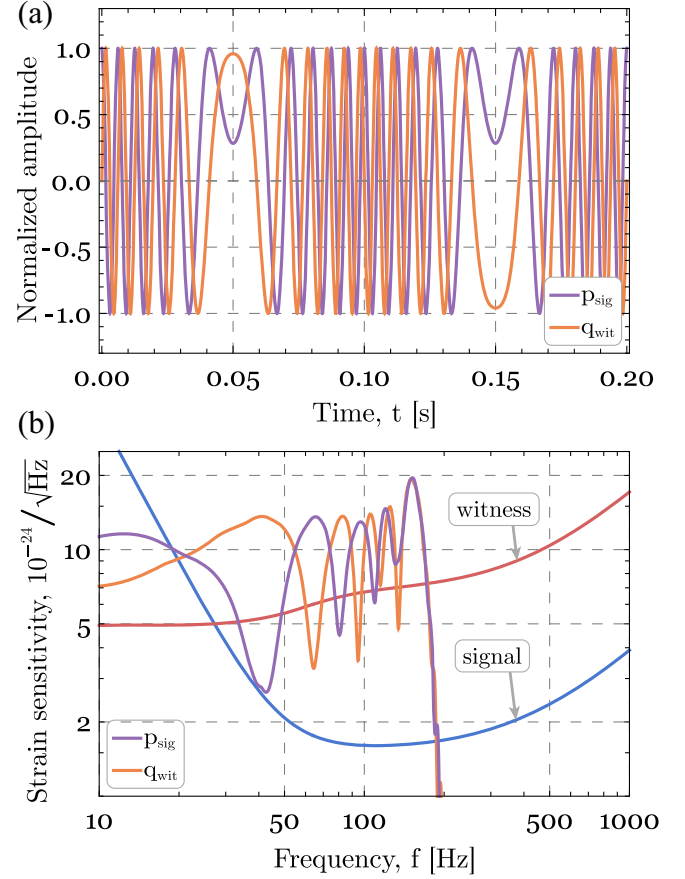


FIG. 4. Scattering signal from a fast scattering event. (a) Normalized projections in the signal p_{sig} and witness quadrature q_{wit} of a scattering signal in time domain. (b) Amplitude spectral density of the same scattering signal compared to the signal and witness quadrature sensitivities. Here, we can see the characteristic scatter shoulder produced by a fast scattering event.

sensitivity are rare; (iii) using the full catalog significantly increases the sample size and yields more realistic SNR distributions to test our approach. Moreover, slow scattering events are typically louder and produce signals at frequencies lower than fast scattering events. Since the witness quadrature is most sensitive at low frequencies, slow events should be at least as detectable as the fast ones in our scheme. In principle, scattering events with small modulation depths are also detectable in our scheme. In most cases, these events appear as monochromatic peaks in the spectrum of both quadratures. In rare events, the signal can randomly couple to the witness quadrature with a very small amplitude, whereas the signal in the other quadrature would couple strongly enough to contaminate the GW signal. Such events cannot be subtracted using our approach. Because of the rarity of such events, we do not include these events in our statistics, but depending on the specific instrument they may need to be considered. This makes our simulation conservative: we do not make

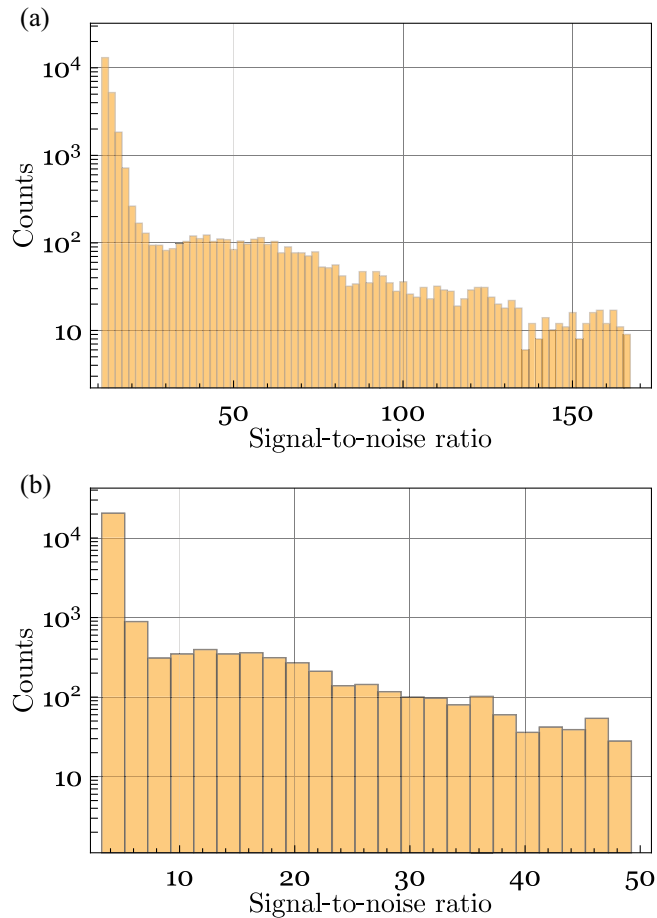


FIG. 5. Histograms of our set of random scattering events. (a) Histogram of signal-to-noise ratios for the signal quadrature. (b) Histogram of signal-to-noise ratios for the witness quadrature.

statements about the true composition of data statistics, but only demonstrate the potential of our approach to reduce the residual scattering.

Our reference set, provided by Gravity Spy [50,51], contains all LIGO Livingston O3a events classified as slow or fast scattering with $10 \leq \text{SNR} \leq 120$ and machine learning confidence > 0.95 . Our scattering waveform depends on multiple parameters whose marginal distributions are unknown. We therefore incorporate the reference SNR distribution only via the distribution of scattering amplitudes, keeping the other parameters fixed at $f_m = 5$ Hz, $m = 32.7$, $\phi_m = 0$, and $\varphi_0 = 0$. We chose a relatively high modulation frequency f_m to avoid biasing the study toward the witness quadrature: increasing f_m shifts more power to higher-frequency sidebands where the witness quadrature is less sensitive, resulting in a less favorable detectability (thus a harder test). In addition, we compute the spectral densities over multiple oscillations of the scattering signals, which averages out the impact of the initial phase and prevents accidental preference of one quadrature over another.

Since our modeled sensitivity differed from the one used in a reference set for Advanced LIGO, we used the following protocol to ensure a realistic statistical distribution. From the reference data, we approximated the probability density function of the SNR distribution and used it to generate a set of random scattering amplitudes. This provided us with a realistic set of random scattering events, whose statistic would match the reference statistic if we had the sensitivity of Advanced LIGO for which the reference set was collected.

Figure 5 shows the distribution of SNRs for our detector concept. We generated a set of 25000 random scattering events, each with an SNR of at least 8 for the sensitivity of Advanced LIGO. Afterward, we computed the SNRs in both quadratures for each event. In Fig. 5(a), we present the distribution of SNRs for the signal quadrature. Since the sensitivity of the detector we consider here is higher than that of Advanced LIGO, corresponding SNRs are also higher compared to the reference. Figure 5(b) shows the distribution of SNRs for the witness quadrature. As expected, they are smaller compared to those of the signal quadrature since the witness quadrature is less sensitive for most frequencies.

IV. RESULTS

In this section, we analyze the potential of our detector concept to filter out scattering events. The general idea is to detect the scattering signal in the witness quadrature. This information can then be used to reconstruct the scattering signal in the signal quadrature. Afterward, the reconstructed scattering signal is subtracted from the signal quadrature data. This would increase the sensitivity to GW signals. On top of that, the witness quadrature channel makes it possible to veto scattering events. This method depends strongly on how well the scattering signal can be reconstructed. While we do not commit to a specific reconstruction method here, the witness SNR provides a generic proxy for the achievable subtraction accuracy. For any unbiased estimator in additive Gaussian noise, parameter uncertainties scale approximately inversely with SNR (e.g. Fisher-information scaling). We considered two cases with different SNR thresholds: a conservative case with a threshold of 8 (error of 12.5%) and a moderate case with a threshold of 5 (error of 20%). Further in the text we apply a binary categorization: all events with SNRs above the threshold are considered subtractable under an assumed model, and all with SNRs below not meeting the criteria for subtractability. We note that our study is intended to illustrate qualitative scaling and feasibility, in principle. It is not a detector-specific technology study and does not yield a performance forecast for any particular observing run.

In Fig. 6 we show the statistic of our simulated scattering events before and after subtraction. In the case where we set

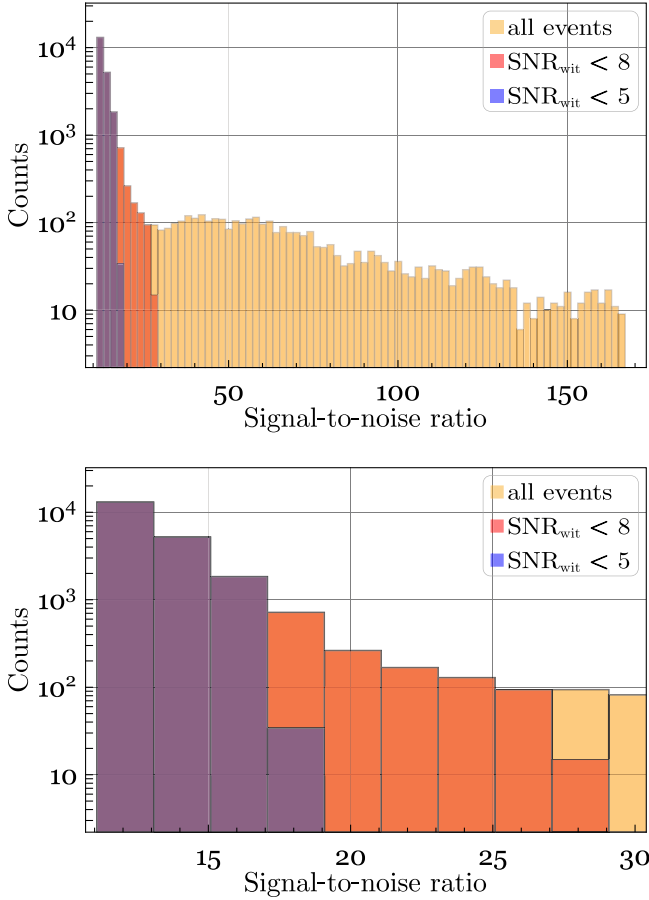


FIG. 6. Histogram of signal-to-noise ratios for the signal quadrature. The histograms show the remaining scattering events after subtraction. The red events are the events that cannot be subtracted if the witness quadrature threshold is set to 8. Blue are the remaining events for which the signal-to-noise ratio in the witness quadrature is smaller than the threshold 5. Top: whole signal-to-noise ratio range. Bottom: focus on the remaining scattering events.

the subtraction threshold to 8, we can reduce the number of scattering events by 13.9%. In the other case, we can subtract 19.3% of the scattering events. In both cases, we are able to subtract all loud events, but the sensitivity is dominated by multiple quiet events, which we do not have sufficient sensitivity to.

As mentioned previously, the potential to subtract scattering events depends on the choice of the signal-to-noise ratio threshold in the witness quadrature. Here, we considered rather high thresholds. As shown in Fig. 7, lowering the required signal-to-noise ratio in the witness quadrature could significantly improve the percentage of subtracted events. For a threshold of 4, we could subtract 39.1% of the events and even all events for a threshold of 3.2.

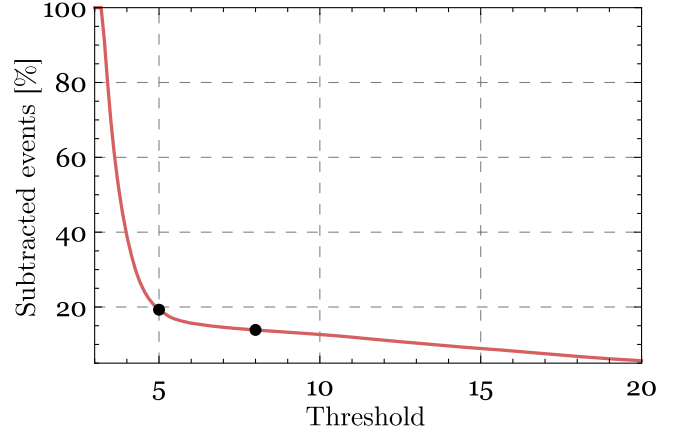


FIG. 7. Percentage of subtracted scattering events versus required signal-to-noise ratio in the witness quadrature used as an illustrative proxy for subtractability. The black points indicate our choice of thresholds. The plot highlights that the performance of our approach strongly depends on the minimal signal-to-noise ratio required for the reconstruction of the scattering signal. Especially, below a threshold of 5 we can see that the percentage of subtractable events increases drastically with decreasing threshold.

V. SUMMARY AND CONCLUSION

Previous research has shown that quantum-dense sensor technology is suitable for simultaneously reading out precise information in two noncommuting quadratures of the electromagnetic output field of an interferometer [34,35,52]. This quantum technology approach is highly relevant for GW detectors. While the GW signal appears exclusively in the signal quadrature of the output beam, nonstationary disturbances caused by backscattered laser light appear correlated in both quadratures. The principle has been successfully demonstrated in tabletop experiments in the quantum measurement noise-dominated range. However, it is particularly relevant for GW detectors because the quantum technology approach can also be used at frequencies where quantum backaction noise rotates the optimal GW readout quadrature depending on the frequency. In this work, we propose for the first time, to the best of our knowledge, an approach that is inspired by the quantum-dense metrology and allows one to achieve frequency-dependent quantum enhancement simultaneously with reading out the orthogonal witness quadrature. While it does not take full advantage of quantum-dense metrology features, it has the advantage that it could be implemented in current GW detectors without increased quality requirements.

To evaluate the potential of our approach in the back-action regime, we generated a set of random scattering events and analyzed how many of these events can be

subtracted. We find that we can filter the very loud scattering events out. The actual performance strongly depends on the signal-to-noise ratio needed in the witness quadrature to reconstruct the signal. Using tools such as machine learning could lower the requirement and significantly improve the performance of our approach.

The additional quadrature-witness readout comes at a price of a reduced signal quadrature sensitivity at high frequencies. In the case of equally strong quadrature detection, this corresponds to a loss in GW sensitivity of approximately 3 dB. This loss can be minimized by optimizing the properties of the readout beam splitter and the second squeezer. A more detailed optimization requires further insight into the reconstruction procedure of the scattering signals. Alternatively, a filter cavity could be used to separate the signals so that low-frequency components are measured by dual readout, while high frequencies are measured by a traditional single readout [36]. Further studies on the impact of our approach on the scientific case will need to be performed, including tradeoffs between low-frequency sensitivity gain and high-frequency

sensitivity loss. This will enable an educated optimization of the quadrature-witness readout.

Our concept allows one to mitigate loud backscattering events without modification of the core layout of the detector. Crucially, this approach is not limited to backscatter noise: other noise that produces a signal in the orthogonal quadrature, e.g., technical noise, could be reduced in the same way. This remains a subject of future studies.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [53].

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