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Noise Sources in Gravitational Wave Detectors

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Abstract: The current Advanced LIGO interferometer is limited by coating thermal noise at frequencies between 40 and 200 Hz and quantum noises at most of the sensitivity band (above 10 Hz). However, the future Einstein Telescope observatory is expected to improve the sensitivity by a factor of 10. This will be accomplished by operating at cryogenic temperature with using a low loss material such as silicon to reduce the coating Brownian thermal noise contribution. Further improvement will be made by utilizing a higher laser power and heavy mirrors to mitigate shot noise and radiation pressure noise respectively. Further studies on mitigating coating Brownian noise and quantum noise are essential as they are expected to be the main noises affecting future detectors.

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1. Introduction

The prediction of gravitational waves (GWs) has fascinated physicists for more than a century and has attracted considerable attention after the first observation was made in 2015. Since the early 1960s, interferometers have been utilized as gravitational-wave detectors. These observatories aim to detect GWs produced by different sources such as supernova, compact binary coalescence and even any unknown astrophysical sources [1]. These sources produce unique gravitational-wave signals, which could open a new observational window to the universe. Over the past decades, the ground-based interferometers have gradually been improved with the aim of reaching better sensitivity. However, the sensitivity of such observatories is limited by noises of different origins, which can be divided into fundamental noises such as quantum noise and thermal noise and environmental noises that can be attributed to the seismic motion [2]. This report aims to discuss the impact of the limiting noises on current and future gravitational-wave detectors as well as the approaches to mitigate them.

2. Noise Sources

Noise sources can have a significant impact on the sensitivity of any gravitational-wave detector and impose limits on their performance. In principle, gravitational-wave detectors are a modified Michelson interferometer, in which the laser beam is split by a beam splitter into two orthogonal arms that have identical arm length (L). At the end of each arm, a mirror reflects each beam back and the two reflected beams are then made to interfere each other, creating interference detected in the photodiode. Therefore, a passing GW is expected to displace the end mirrors on the two arms, stretching one arm while squeezing the other, which then alerts the arm lengths. This differential length variation (ΔL) changes the strain ($\Delta L/L$) and generates a phase shift between the interfering light beams in the output photodetector [3]. This indicates that gravitational-wave signals appear in the phase quadrature. Consequently, the displacement in the mirrors due to any type of noises, can disrupt the detection of the gravitational-wave signals. Among the various noise sources entering the sensitivity band of gravitational-wave interferometers, thermal noises and quantum noises are the most dominate limiting noises at the most frequency range [4].

2.1. Thermal Noise

The most important thermal noise affecting gravitational-wave detectors is coating Brownian thermal noise which imposes limits on their sensitivity between 40 and 200Hz [5]. This noise arises from the intrinsic mechanical loss (internal friction) of the multilayers coatings due to the fluctuation in thermal energy (k_BT) [6]. Such noise is also proportional to the thickness of the coating layer (d), whereas it decreases with the increase in the laser radius (r). The coating Brownian noise can be determined by the power spectral density Sx(f) of coating material as follows:

$$S_x(f) = \frac{4k_B T}{\pi^2 f Y}\frac{d}{r_0^2}\left(\frac{Y'}{Y}\phi_{\parallel} + \frac{Y}{Y'}\phi_{\perp}\right) \qquad (1)$$

Where, Y and Y' are the Young's modulus of mirror substrate and coating respectively, whereas $\phi_{\parallel}$ and $\phi_{\perp}$ are the coatings mechanical loss angle. As previously mentioned, this noise could contribute to the displacement of the surface of the mirrors which therefore changing the phase of the reflected laser beam and affecting the measurement of the gravitational-wave signals [7].

2.2. Quantum Noise

Quantum noise is comprised of two fundamental mechanisms: radiation pressure noise (amplitude fluctuations) at low frequencies and shot noise (phase fluctuations) at high frequencies. Radiation pressure noise (RPN) arises from the uncertainty in the position of the mirror due to the fluctuations from the back action of the reflected photons exerting fluctuating radiation pressure on the suspended mirrors. Therefore, such displacement of the mirrors could be detected as a phase shift in the interference fringe at the photodiode. Shot noise (SN) stems from uncertainty due to statistical fluctuations in the number of photons (signal carriers) detected in the photodiode [8]. The SN contribution decreases with the increase in the laser power, however RPN contribution increases (follow Heisenberg's uncertainty principle). The minimum sum of these noises is represented by the standard quantum limit (SQL) which originates from Heisenberg's uncertainty principle. Quantum noise is approximately dominant for all frequencies above 10Hz of the detection band [9].

3. Current Gravitational Waves Detectors

The present gravitational-wave observatories are an enhanced version of their first generation and one of the most prominent detectors among these interferometers is the Advanced LIGO.

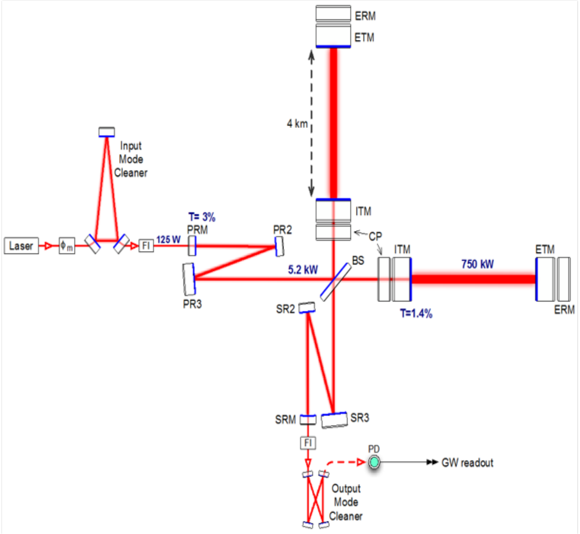

Figure 1. The Advanced LIGO interferometer optical configuration. The input and end of both arms mirrors are labeled ETM and ITM. The induced change in the length of the interferometer arms caused by a gravitational wave can be directly measured by measuring the change in output power [10].

This detector utilizes a basic Michelson interferometer whose mirrors are suspended with two widely 4 km long Fabray Perot cavities between them to boost the sensitivity. Such a detector was predesigned by using 40 kg fused silica mirrors (heavy mirrors) that are low-mechanical-loss materials to reduce radiation pressure noise and Brownian thermal noise [11]. However, RPN is still dominant between 10 and 100 Hz. The mirrors are coated with a dielectric multilayer of silica and titania-doped tantala. However, due to the loss of titania-doped-tantala layers (ϕ =2.4×10−4rad), coating Brownian noise is still dominant at intermediate frequencies between 40 and 200 Hz. Moreover, the Advanced LIGO is not operating with an optimum laser power required to reduce the SN. This is because the increase in the incident laser power is proportional to RPN and can also cause thermal noise. Thus, SN is a prime noise above 100Hz in the detection band as presented in Figure 1[12].

However, instead of increasing laser power, squeezed light has been injected. This method is based on the cancellation of the noise contribution of the amplitude quadrature(E_1) that is converted into fluctuations in the phase quadrature (E_{RP}). This contribution will be added to the gravitational-wave signals (E_{GW}) appearing in the phase quadrature (E_2), which is represented by quadrature picture. Therefore, the variational homodyne readout is implemented in the interferometer which chooses the best angle, depending on a single frequency to cancel the radiation pressure contribution E₁ as presented in Figure 2. The sensitivity due to phase squeezing (SN) increases at high frequencies whereas it decreases at low frequency due to $1/f^2$ [13]. These limiting noises indicate that further improved strain sensitivity is required to fully explore the potential of gravitational-wave astrophysics.

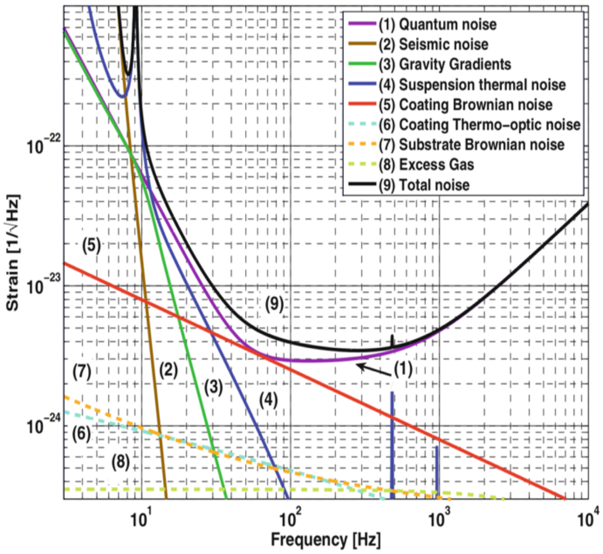

Figure 2. Shows the strain sensitivity of the Advanced LIGO GW detectors. The colored lines (1,5) represent the main limiting noises which are coating Brownian noises at mid frequencies and quantum noise at most of the sensitivity band [13].

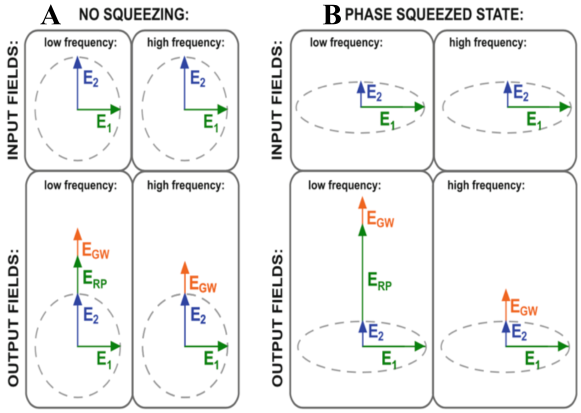

Figure 3. Shows quadrature picture of the interferometer with phase squeezing (B) and without squeezing (A) [13].

4. Future Detectors

Future gravitational-wave observatories such as the Einstein Telescope are expected to operate at better sensitivity ranges. The Einstein Telescope will use a dual operating scheme. Thus, it will utilize a high-power, high-frequency detector at room temperature with fused silica mirrors and a cryogenic low-power, low-frequency interferometer with crystalline mirrors. Furthermore, each detector will have heavy mirrors of approximately 200kg. The purpose of operating with higher laser power and heavy mirrors is to reduce both SN and RPN, respectively. However, the sensitivity of the high-frequency interferometer will be limited by Brownian coating noise between 40 and 200Hz due to the thermal noise that stems from the use of high laser power. At cryogenic temperatures fused silica is not a suitable material because it has a high mechanical loss. Therefore, this material will be replaced by crystalline materials such as silicon for both mirror substrate and coatings that have a low loss at cryogenic temperatures [14]. Therefore, a reduction in coating Brownian noise will be obtained as such noise decreases with low temperatures together with low loss materials. Furthermore, large radius laser beams will be utilized which can improve coating Brownian noise by distributing the power as well as averaging the thermal energy over the mirror surface [15]. Further improvement will be achieved by using the frequency dependent squeezing angle to squeeze RPN at low frequencies and SN at high frequencies. Consequently, the SQL can be surpassed. Altogether, these enhancements that utilize a dual operating scheme will improve the sensitivity at intermediate (around 100Hz) and high frequencies by a factor of 10 compared to the current detectors [16].

5. Conclusion

The current Advanced LIGO detector is not operating in optimal sensitivity. The sensitivity of such a detector is limited by coating thermal noise and quantum noise in most frequencies band. However, the future Einstein Telescope detector is aiming to significantly improve the sensitivity of at least factor 10, which is better than current observatories. This will be achieved by operating at cryogenic temperature using crystalline materials for mirrors substrate and coatings. Thus, a significant reduction will be obtained in coating Brownian thermal noise. Furthermore, a high-power laser together with heavy mirrors will be employed to reduce both SN and RPN. Moreover, SN and RPN will also be eliminated at all frequencies through the frequency dependent squeezing. Further investigation on reducing coating Brownian noise and quantum noises is required as they are dominant in both current and future detector.

References

[1] Abbott BP, Abbott R, Adhikari R, Ajith P, Allen B, Allen G, Amin RS, Anderson SB, Anderson WG, Arain MA, Araya M. LIGO: the laser interferometer gravitational-wave observatory. Reports on Progress in Physics. 2009 Jun 30;72(7):076901.

[2] Martynov DV, Hall ED, Abbott BP, Abbott R, Abbott TD, Adams C, Adhikari RX, Anderson RA, Anderson SB, Arai K, Arain MA. Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy. Physical Review D. 2016 Jun 2;93(11):112004.

[3] Bond C, Brown D, Freise A, Strain KA. Interferometer techniques for gravitational-wave detection. Living reviews in relativity. 2016 Dec 1;19(1):3.

[4] Abbott BP, Abbott R, Abbott TD, Abernathy MR, Acernese F, Ackley K, Adams C, Adams T, Addesso P, Adhikari RX, Adya VB. Observation of gravitational waves from a binary black hole merger. Physical review letters. 2016 Feb 11;116(6):061102.

[5] Brown DD. *Interactions of light and mirrors: advanced techniques for modelling future gravitational wave detectors*(Doctoral dissertation, University of Birmingham).

[6] Kroker S, Dickmann J, Hurtado CR, Heinert D, Nawrodt R, Levin Y, Vyatchanin SP. Brownian thermal noise in functional optical surfaces. Physical Review D. 2017 Jul 10;96(2):022002.

[7] Harms J, Mow-Lowry CM. Suspension-thermal noise in spring–antispring systems for future gravitational-wave detectors. Classical and Quantum Gravity. 2017 Dec 19;35(2):025008.

[8] Heurs M. Gravitational wave detection using laser interferometry beyond the standard quantum limit. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2018 Apr 16;376(2120):20170289.

[9] Singh R. Quantum Radiation Pressure Noise: Exposing the Quantum Mechanics of Optomechanical Interactions.2016

[10] Sanders JR. *Advanced Gravitational Wave Detectors and Detection: Arm Length Stabilization and Directed Searches for Isolated Neutron Stars* (Doctoral dissertation).

[11] Ballmer S, Mandic V. New Technologies in Gravitational-Wave Detection. Annual Review of Nuclear and Particle Science. 2015 Oct 19;65:555-77.

[12] LIGO Scientific Collaboration. The Sensitivity of the Advanced LIGO Detectors at the Beginning of Gravitational Wave Astronomy. arXiv preprint arXiv:1604.00439. 2016.

[13] Hild S. A Basic Introduction to Quantum Noise and Quantum-Non-Demolition Techniques. InAdvanced Interferometers and the Search for Gravitational Waves 2014 (pp. 291-314). Springer, Cham.

[14] Abbott BP, Abbott R, Abbott TD, Abernathy MR, Ackley K, Adams C, Addesso P, Adhikari RX, Adya VB, Affeldt C, Aggarwal N. Exploring the sensitivity of next generation gravitational wave detectors. Classical and Quantum Gravity. 2017 Jan 24;34(4):044001.

[15] Hammond G, Hild S, Pitkin M. Advanced technologies for future ground-based, laser-interferometric gravitational wave detectors. Journal of modern optics. 2014 Dec 12;61(sup1):S10-45.

[16] Hild S, Abernathy M, Acernese F, Amaro-Seoane P, Andersson N, Arun K, Barone F, Barr B, Barsuglia M, Beker M, Beveridge N. Sensitivity studies for third-generation gravitational wave observatories. Classical and Quantum Gravity. 2011 Apr 18;28(9):094013.

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