*Note: Underlined components emphasize importance (not formatting recommendations)

Lumiere Research Scholar Program – Squeezed Light to Reduce Noise Floor in Laser-Interferometric Gravitational Wave Detectors

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***Abstract* – This paper shall discuss the application of squeezed light to reduce the noise floor associated with photoconductive photodiodes in laser-interferometric gravitational wave detectors. To fulfil the needs of the research question, the paper presents a literature review of the need for reducing the noise floor, the scientific principles behind squeezed light and its applications in gravitational wave detection. The working principle of semiconductors, photodiodes and interferometers are addressed in the first section of the paper while the effects of quantum noise on gravitational wave strains are delineated in the second part. Following this, the paper provides a simple, quantum mechanical explanation of squeezed light, why it's suitable for our interferometric purposes, and its applications in squeezed light detection. Suggestions for future research on reducing the noise floor are included based on the learnings from the literature review.**

Index Terms – Laser-Interferometric Gravitational Wave Detectors, Noise Floor, Photodetectors, Quantum Noise, Squeezed Light.

I. Introduction

Scientific Context

Gravitational waves are ripples in spacetime generated due to astronomically cataclysmic events such as black hole and neutron star mergers [1]. Regarded merely as a theoretical phenomenon predicted by Einstein's theory of general relativity, the existence of gravitational waves was first confirmed in 1974 and first recorded in 2015 by the Laser-Interferometric Gravitational Observatory (LIGO) [1]. Not only did this confirm Einstein's theory of gravitation, but also the detection of so-called gravitational-wave strain signals opened the door to a more in-depth study of astrophysical phenomena to an extent considered unreachable previously.

Yet, despite the violent nature of phenomena that generate gravitational waves, gravitational wave signals weaken significantly upon reaching the gravitational wave detectors on Earth. As a matter of fact, the strain sensitivity required for the optimal functioning of gravitational wave detectors (i.e., to differentiate noise signal from gravitational-wave signal) is10^{-21}[2]. There are various sources of noise as well, such as quantum noise, thermal noise and dark current noise, which have a negative impact on the precision of gravitational wave detectors by causing an increase in the noise floor [2][3]. Of these, since the quantum noise is inherent to the laser light utilized in the interferometer, a noise floor called the Standard Quantum Limit is created beyond which greater sensitivity is not possible [2]. The utilization of squeezed light however, could lead to precision beyond the SQL in GW strain signal measurements. While the paper is limited to the discussion of quantum noise, it can still be said that a lower noise floor shall lead to a more precise study of gravitational waves specific and astronomical events in general.

In this regard, the utilization of squeezed light in interferometric gravitational-wave detectors has potential in reducing the quantum noise associated with detection at the photodetector. A special state of light with unconventional uncertainty characteristics [4], it has been used in the GEO 600 [5] and has garnered results by reducing noise signal by 6 dB [6], its application in gravitational-wave detection can reduce the noise floor and make photodetectors ever more precise.

Research Question

The research question this paper shall address is: “To what extent can squeezed light be utilized to reduce the noise floor associated with photoconductive photodiodes in laser-interferometric gravitational wave detectors?”

Through this literature review, I aim to familiarize the reader with photodiodes, quantum noise and squeezed light, following which I aim to infer that squeezed light is a pragmatic method to reduce the noise floor in photoconductive photodiodes. This shall include a discussion of not only the positive effects on noise floor, but also an investigation to ensure squeezed light leads to no unwanted difficulties in the detection process.

II. LITERATURE REVIEW

Working Principle of Photoconductive Photodiodes

A photovoltaic photodiode is an integral component of interferometric gravitational wave detectors. The generation of photocurrents due to subtle changes in incoming light intensity owing to gravitational wave strains is the core principle based on which photodetectors are able to detect GWs [7].

The photodiode consists of a semiconductor material connected to an external circuit [8]. A semiconductor is a material that allows current flow in only one direction, and is the basis for the PN junction that photodiodes use. This is achieved by doping, or adding impurities of a particular kind, to each to alter their conduction properties. For example, one end of a silicon semiconductor would be doped with a fifth period element to create an excess of electrons that could transfer to the conduction band. Here, electrons would be the majority carriers and this would be the N junction. Conversely, the other end is doped with a period 3 element that creates holes as majority carriers and electrons as minority carriers.
[8]. The doping is uniform, so an even concentration gradient due to the excess of holes in the P-type bulk substrate and excess of electrons in the N-type bulk substrate is created [8]. Around the PN junction, a depletion region is created with an absence of free ions which imparts an inherent resistance to the photodiode [9]. Therefore, the photodiode has an inherent ‘built-in voltage’ beyond which current flow will be permitted through the semiconductor [9]. This occurs as the absorption of photons among the ions in the depletion region excites electrons from the valence band to the conduction band across the band energy gap [13], creating an electron-hole pair [8]. The electrons and holes move through the depletion region through diffusion current (under the influence of the concentration gradient) and in the non-depletion region as drift current, resulting in the measured current [14]. It is thus of special interest to us to maximize the depletion region space, which is achieved through a reverse bias voltage being applied to the semiconductor [15]. Care must be taken to keep the bias voltage below the breakdown voltage for the semiconductor [9]. The antisymmetric port must also have an anti-reflective coating and the material must have a large absorption coefficient [12], so that the photocurrent is easily distinguishable from noise sources by being over the noise floor. The load resistance in the external circuit must also be low to achieve the same aforementioned purpose [16].

In the absence of a passing gravitational wave, the destructive interference of interacting waves in the Fabry-Perot cavities create a null intensity on the photodiode’s antisymmetric port [10][11]. However, the minute phase change due to the changing lengths of the interferometer arms (GW strain) results in a recorded light intensity at the antisymmetric port. This occurs as destructive interference which originally occurred fails due to the minute phase change. [12].

There are some sources of noise in the photodiode as well during operation, one of which is dark current [17]. This is the reverse leakage current in the absence of light due to the increased motion of minority carriers because of the enlarged depletion region in the reverse bias mode [14]. There is also the thermal noise which occurs due to the thermal excitation of charge carriers (electrons in our case), which is recorded by the photodetector and is noise as it may be mistaken for a FW strain signal [18]; the thermal energy causes excitation and the creation of electron hole pairs without the influence of externally incident light [18]. These, in addition to the shot noise, contribute to an additional intensity called the noise equivalent power (NEP) that skews photocurrent readings [10].

Therefore, it is in our interest to reduce the noise floor and increase the signal to noise ratio. This literature review shall explore the ways to achieve the same.

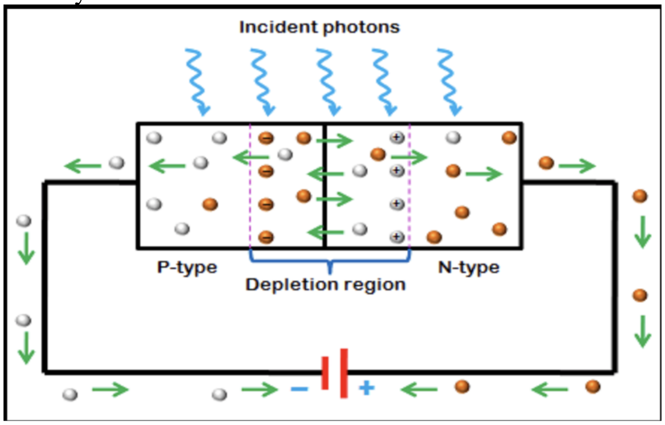

Figure 1: The PN-junction based photoconductive photodiode

Laser-Interferometric Gravitational Wave Detectors

Laser Interferometry is the preeminent methodology utilized in gravitational wave detection. As the name suggests, it utilizes aberrations in the interference of 2 laser beams as a signifier of a passing gravitational wave [12].

The general construction involves two long arms (possibly kilometres long) perpendicular to one another [12]. A high-frequency laser beam is projected toward a beam-splitting mirror, with each laser beam propagating into each of the arms [13]. The signal strength increases with the distance the wave travels, and having a maximum signal strength is critical in the detection of gravitational wave strains (the GW strain-induced current occurs in microamperes).

Therefore, the test masses in each arm (which also act as the reflecting mirrors) lead into Fabry Perot cavities which make it possible for the laser beam to traverse the long arms of the LIGO detector multiple times, which amplifies the signal strength [11]. This occurs due to a vacuum being maintained within the arms to ensure a zero resistance path to the beam, with low chances of additional noise [19].

Eventually, the laser beams are made to interfere at the beam-splitter, where due to the exact same path length and phase of the two beams, destructive interference should produce a null signal. Yet, in the presence of a passing gravitational wave, a strain is established which alters the difference in length of the two arms. This breaks down the destructive interference case and produces a signal at the dark port of the photodiode, signifying a gravitational wave.

Of course, we have discounted 'noise' or unwanted signals in this section. This is the subject of the next section.

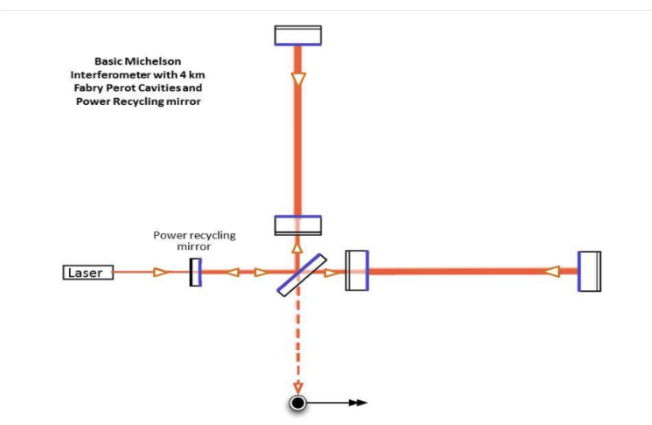

Figure 2:Basic Michelson Interferometer with 4 km long Fabry-Perot cavities and power recycling mirror

Quantum Noise and its Effect on the Noise Floor

One of the most perpetual issues in gravitational wave detection has been the sensitivity of the photodetector itself [20]. This is because of the relatively small gravitational wave signals and the large presence of noise (unwanted signals which skew the gravitational wave signals upwards or downwards) [2]. There are many different kinds of noise affecting gravitational wave signals: thermal noise, dark current noise, quantum noise, etc. The scope of this paper encompasses solely the quantum noise, and this section shall qualitatively analyse the effects quantum noise has on gravitational wave signal detection.

Quantum noise, generally speaking, originates from the inherent quantum uncertainties associated with electromagnetic radiation [21]. The paper shall cover two kinds of quantum noise: photon shot noise and radiation pressure noise. Both have a negative impact on the signal to noise ratio (SNR) of the photoconductive photodiode [2], and so a way to reduce one or more of these noise sources would definitely reduce the noise floor and improve GW strain sensitivity.

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The photon shot noise is due to fluctuations in the arrival of photons from the laser light source [2]. Photons do not flow from the laser at a constant rate, rather their arrival follows a Poisson process [2]. This irregular arrival of photons manifests itself in an irregular phase for the light beam, and is a result of the inherent uncertainty in the phase quadrature in the coherent state. Due to this phase uncertainty, the ideal scenario of uniform photon counting statistics breaks down and there is a photon shot noise signal created at the dark port due to the resultant change in photon flux [22]. This occurs in place of total destructive interference that would have occurred if not for the non zero phase difference, producing a signal that is challenging to differentiate from an actual GW strain signal [22]. This phenomenon may cause errors in identification of GW strain signals, and thus constitutes noise, 'shot noise' specifically.

Applying the Poisson statistics, we find that the standard deviation of photon flow rate varies as the square-root of expected value of photon arrival rate R [2]. Since photon shot noise is an inherent property associated with propagating photons, it is a frequency-independent form of noise [23]. So, as signal strength increases at higher frequency, shot noise shall remain constant. So, the signal to noise ratio shall increase with increased frequency. This is precisely why a higher laser frequency is favoured in laser-interferometers, due to their higher precision.

While photon shot noise was due to phase fluctuations, the radiation pressure noise is due to the zero point (i.e. the ground state) amplitude quadrature fluctuations in the electromagnetic wave [24]. In the general sense, the fluctuations cause the waves in the Fabry-Perot cavities to transfer their momentum to the test masses (thus the radiation pressure) [25], which alters the true length difference between the test masses due to a passing gravitational strain and causes aberrations in the ideal destructive interference case at the beam-splitter [26]. Thus, the pressure exerted by the amplitude fluctuations of laser light affects the displacement of mirrors (hence this noise is a subset of displacement noise) and skews GW strain signal readings [2].

The effect of this radiation pressure noise increases with laser intensity [2]. So, in short, there is an optimal low level of noise to be attained through the standard quantum limit.

It must be noted that while on average the phase fluctuations in photon shot noise and the amplitude fluctuations may return to the expected value due to the law of large numbers, in the short time scale these fluctuations severely impact photodiode sensitivity [4]. Therefore, reducing the noise floor is an important priority that this paper addresses [27].

Quantum Mechanical Explanation of squeezed light and its application in reducing the noise floor in laser interferometric GW detection

In general, a quadrature is any measurable quantity associated with a system [29]. The uncertainty principle uses position (p) and momentum (q) as its quadrature operators to determine a relation between them [30]. Typically, the uncertainty in position is depicted on the vertical axis and gives the phase quadrature. The uncertainty in momentum is depicted in the horizontal axis, and gives the amplitude quadrature.

Both quadratures have an associated quantum uncertainty at any given state [31][32], which can be represented in a phase-space diagram as shown in Figure 3.

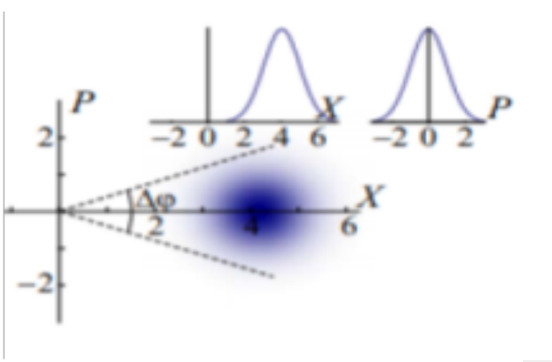

Figure 3:Phase space diagram showing both quadratures with spherical(uniform) uncertainty for both quadratures. This depicts the coherent state of light.

In figure 3, the horizontal axis represents the amplitude state and the vertical axis represents the wave phase state. The uncertainty is spherical and thus evenly distributed between both quadratures. This is a typical representation of the un-squeezed coherent state that was being used typically in GW detection interferometers. To represent this in terms of the uncertainty principle, this is a state where,

$\Delta X \Delta Y = 1/4$ (*by uncertainty principle*) [2]

$\Delta X = ½$; $\Delta Y = ½$;

Where X represents the amplitude quadrature and Y represents the phase quadrature.

Furthermore, in the coherent state, as mentioned in previous sections, the probability versus photon number graph follows Poisson statistics. The effects, of the uncertainty in either the amplitude or phase quadratures, can be visualized as in Figure 4:

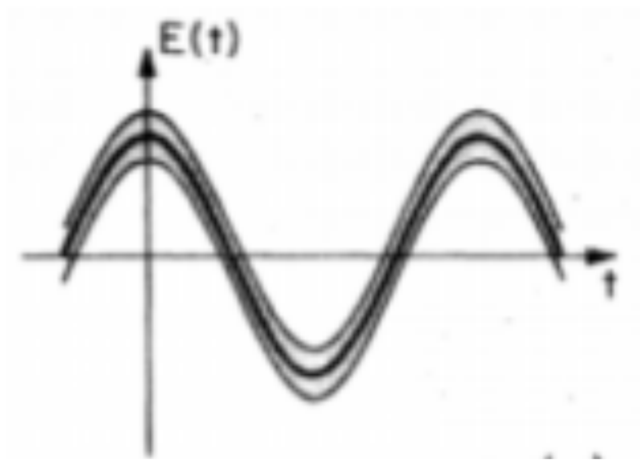

Figure 4:The thick line indicates an electric field oscillation with time. However, a visible uncertainty is visualized in the electric field oscillation, in both amplitude and phase

The consequences of the uncertainty are what lead to quantum noise . To summarize from the previous section, phase uncertainty fluctuations cause shot noise, while the amplitude uncertainty fluctuations cause radiation pressure noise.

Quantum squeezing is a process utilized to generate non-classical, squeezed-states of light [33]. They are ‘squeezed’ in the sense that the quantum uncertainty associated with one of the quadratures is reduced, while for the other it is enlarged [13][33]. Thus, while the uncertainty relation is maintained, one quadrature is squeezed while the other is anti-squeezed [34].

Amplitude squeezed light occurs when the amplitude has a smaller quantum uncertainty associated with it [30], while the opposite is true for phase-squeezed light. This is shown in figure 5.

The effect of amplitude squeezing is evident through the diagrammatic representation in Figure 4.

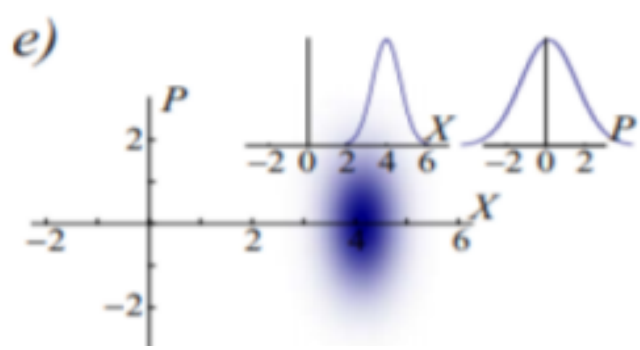

Figure 5:Amplitude squeezed light. It is clearly seen that the phase quadrature is anti-squeezed

Similarly, the phase squeezed state occurs when the wave phase has a smaller quantum uncertainty associated with it, while the opposite is true for the light amplitude quadrature [30]. This basic property of phase squeezed light is extremely useful in our application to reduce quantum shot noise [35]. The phase-space diagram for phase squeezed light is seen is figure 7, while its effects are seen in figure 8.

Note that the diagrams 3, 4, and 5 in the section pertain to squeezed coherent states and not vacuum states, which is what is normally used in GW detection interferometers. For the vacuum state, we must consider solely light in its ground remain exactly the same [36].

The vacuum state of squeezed light is very similar to coherent states, except that the average amplitude and frequency of the wave is zero [14][35]. As such, the differences are manifested in the phase space diagrams of all the states associated with vacuum state squeezed light.

Application of squeezed state in laser-interferometers:

Carrying forward from the previous section’s section of vacuum squeezed state light, I shall explain theoretically in this section how exactly vacuum squeezed light is used to reduce the noise floor associated with GW detection. First and foremost, it is important to understand the additional set-up required to introduce the squeezed vacuum state in our interferometric system.

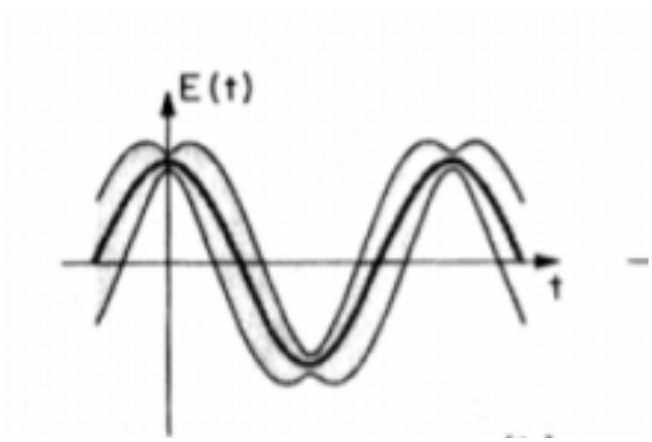

Figure 6: In amplitude-squeezed light, the reduced quantum uncertainty in the expected electric field oscillation (dark line) is evident.

As can be seen, the addition to the setup is the optical isolator and the squeezing source. The working principles of the latter shall be discussed in the next section. The general principle involved for this section is the fact that vacuum squeezed states of light are directed to the beam-splitter from the dark port such that it perfectly modulates the coherent state light at the beam-splitter [37].

For modulation, both the interacting light beams must be of the same mode, i.e. they must have the same frequency, phase, amplitude, direction, polarization [38]. This is done by ensuring that the generated squeezed light is in the detection band of frequency, amplitude and phase, with the optical isolator ensuring that interacting beams have the same polarization [38].

An optical isolator ensures that the squeezed light travels in only one direction. It consists of a Faraday rotator which changes the polarization to match the coherent state light [39]. At the beam-splitter, since the vacuum state squeezed light has, on average, zero energy and amplitude, the modulation of the 2 interacting beams has no effect on any of the modulated wave's characteristics [30]. Only the uncertainty associated with either amplitude or phase is changed, which ensures a positive effect on the signal to noise ratio [30].

Now, we summarize from the previous section: photon shot noise is due to fluctuations in the phase quadrature. So, phase squeezed vacuum state light must be injected from the dark-port to reduce the quantum uncertainty associated with phase in the modulated beam [40]. This has the effect of reducing photon shot noise.

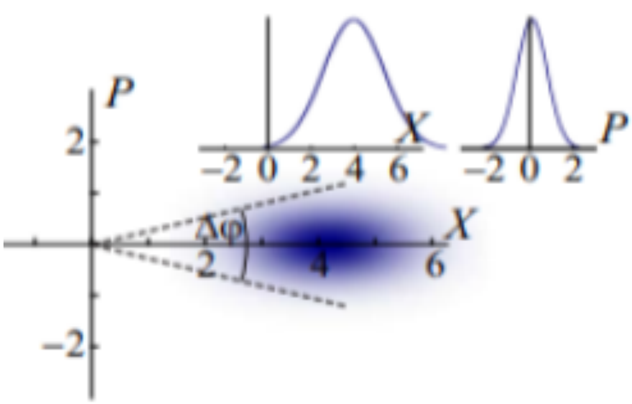

Figure 7:Phase squeezed light, with the amplitude quadrature antisqueezed

The way to account for the reduced shot noise is by employing the balanced homodyne detection method. We assume the case where a GW strain signal is detected and there is a non-zero light intensity at the beam-splitter. The injection of the phase-squeezed vacuum state from an optical parametric oscillator shall produce no change in signal intensity, but shall reduce the shot noise associated with the light beam, which shall be reflected at the laser interferometer's antisymmetric port.

The effects of squeezed states on the noise levels witnessed can be visualized.

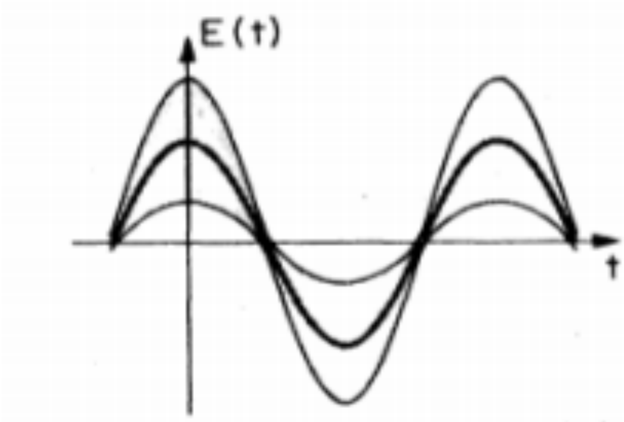

Figure 8:Phase squeezed light shows a clear reduction in uncertainty at the phase, although uncertainty in amplitude quadrature is increased.

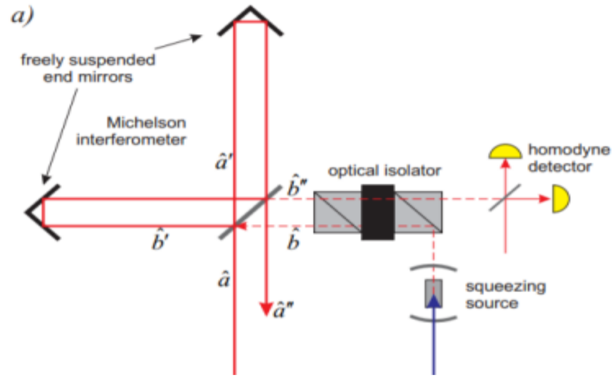

Figure 9: Application of squeezed light in GW detection laser-interferometers.

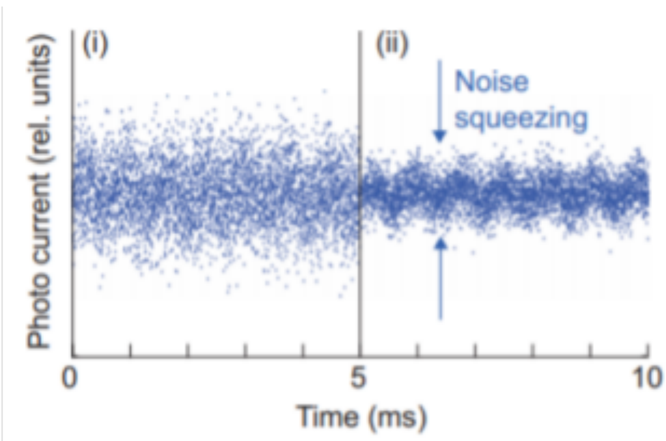

Figure 10: Left, coherent state. Right, noise when beam is modulated with the vacuum squeezed state

To better understand the effects of squeezing on the noise floor levels, and how exactly a 6 dB noise floor reduction was achieved in the GEO 600, we need to consider the frequencies we are working with during gravitational wave detection.

The degree of squeezing can also be expressed in terms of squeezing angle. When the squeezing angle is 45 degrees for vacuum squeezed light, both the phase and amplitude quadratures have the same uncertainty. As such, the effects of both the radiation pressure noise and the shot noise are uniform on the noise equivalent power [34]. The total uncertainty for both quadratures in this condition gives us our standard quantum limit.

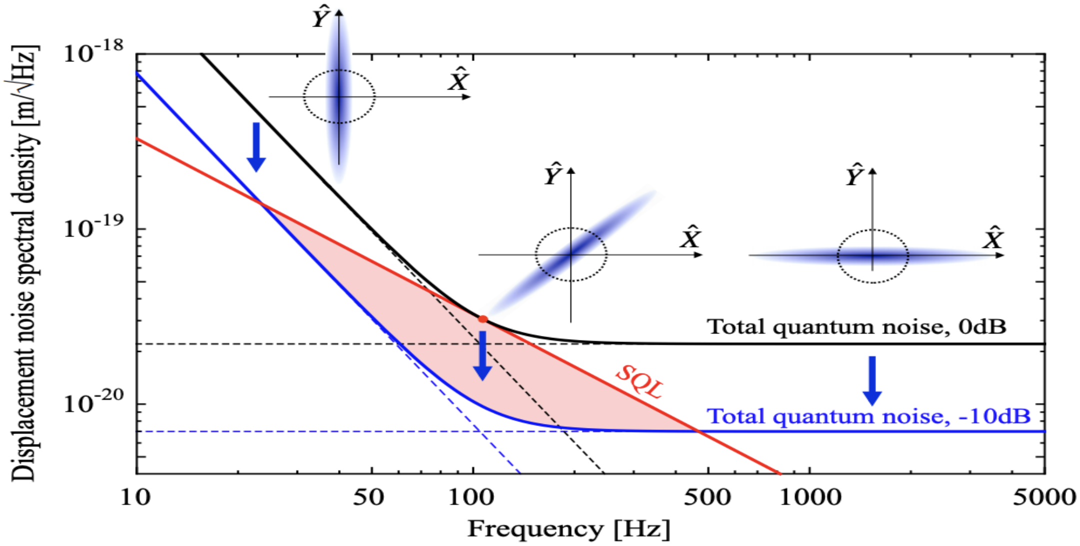

Figure 11

Now, it has been experimentally found that higher frequencies are shot-noise limiting, in the sense that radiation pressure affects the noise floor greater than the shot noise [41]. Meanwhile, the lower frequencies that are utilized in gravitational wave detectors are radiation pressure limiting, in the sense that shot noise affects the noise floor greater than radiation pressure [41].

Furthermore, the correlation between shot noise and radiation pressure noise based on quadratures can be explained as follows. Consider that light is x degrees vacuum squeezed, such that the amplitude quadrature uncertainty is higher than average (the 45 degree squeezing case). As such, a greater amplitude uncertainty would translate to a greater optical path length, which would lead to a reduction in the phase uncertainty. This light would be phase-squeezed. The point here is that the correlation between shot noise and radiation pressure noise can be utilized to obtain an optimal squeezing level at radiation pressure limiting frequencies for reducing the noise floor [34].

We can now explore the effects of reduced shot noise on the signal to noise ratio and noise floor.

In figures 12 and 13, the vertical axis represents the phase quadrature component, and the horizontal axis shows frequency.

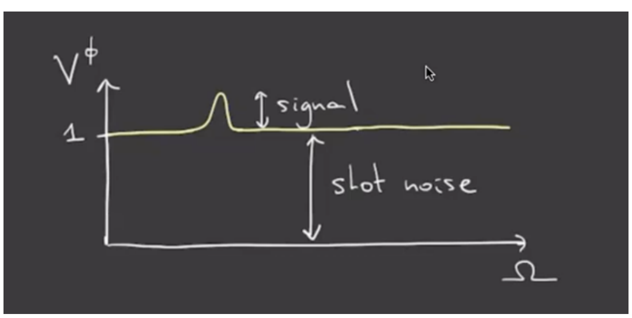

Figure 12

The effect of vacuum squeezed states on the noise floor can be studied by mapping shot noise and the GW strain signal for different frequencies of light. We know that strain signal occurs in the first place since the phase change caused by the GW strain that destructive interference at the beam-splitter breaks down and a non-zero intensity is achieved at the dark port. Thus, we can generalize our learning to conclude that the GW strain signal as a fluctuation in the phase quadrature component of light. In the absence of a GW signal, the threshold signal recorded is dictated by the shot noise and is represented by the flat line in figure 12. When a GW passes, the frequency and phase of incoming laser light at the beam-splitter is manipulated so as to produce a non-zero light intensity and a photocurrent at the photodetector. These are represented as peaks in the spectrum.

Furthermore, we must consider that for the coherent state of light, the uncertainty associated with the phase quadrature is 1 for any light frequency. This holds true with the principle that $\Delta V^{\Phi} \Delta V^{\Phi+\frac{\pi}{2}} \geq 1$ as defined previously for any 2 quadrature operators defining a system. Therefore, in figures 12 and 13, the uncertainty in the phase quadrature is shown to be normalized to 1, where the uncertainty is at its least value for coherent states.

At this relatively high level for shot noise, the noise floor is high, and the SNR is low. This is because it is challenging to resolve the weak GW signals from the shot noise, with some signals being weaker than the shot noise equivalent power not even being recorded.

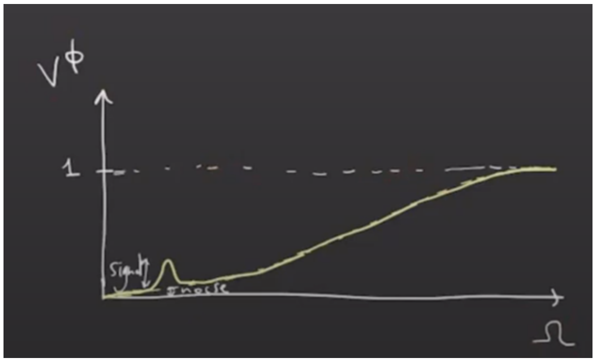

Figure 13

It was shown previously how vacuum squeezed light reduces the uncertainty associated with the phase quadrature of light, and here we shall see how this precisely affects the signal-to-noise ratio. We know that reduced uncertainty in the phase quadrature leads to reduced shot noise at any frequency of laser light, since shot noise is frequency independent.

Now, in figure 13, we see a GW strain signal comparable in intensity to the signal in figure 12. Yet, at low detection frequencies the shot noise shall reduce and since low-frequencies are radiation-pressure limiting as stated earlier, the total noise the system experiences shall reduce [43].

As seen, the shot noise is significantly lower when quadrature uncertainty is lowered in one-direction (i.e., for the phase quadrature) for the output field of light from the beam-splitter. The signal can be easily resolved from the shot noise, and thus the SNR improves as a result of application of squeezed states in laser-interferometric GW detectors [44]. Moreover, GW strain measurements can be made with a larger frequency since weak GW strain signals can now be differentiated from shot noise [45][46].

As shown in figure 11, phase-squeezed light does in fact lead to a reduced overall level of noise below the standard quantum limit. The improvement of 10 dB in this case can also be clearly seen, considering the blue line indicates the presence of vacuum squeezed light and the black line indicates use of solely coherent states. The results discussed at GEO600 previously, which showed a drastic improvement in SNR through squeezed state utilization, confirms the theoretical explanation behind the utilization of squeezed states in GW detection.

Conversely, one would assume that at shot noise limiting frequencies, amplitude squeezed light would reduce radiation pressure noise. While true in some cases, the reduction in the level of radiation pressure will depend on the construction and geometry of our setup [42]. In order to address radiation pressure noise using squeezed states, ponderomotive squeezed states will have to be utilized, using sideband modulated frequencies that is outside the scope of this paper.

IV. CONCLUSION

From the paper, we recognize that theoretically, vacuum squeezed light is an effective method to reduce the noise floor associated with photoconductive photodiodes in laser-interferometric gravitational wave detectors. Considering the previously held belief that precision beyond the standard quantum limit was impossible, the application of squeezed light is surely an innovative breakthrough in the detection of astronomical phenomena light years away. It effectively reduces quantum noise and shall allow more precision and more frequent detections of gravitational waves.

However, squeezed light has been shown to be challenging to generate and can only reduce quantum noise to an extent. Furthermore, squeezing angles allowing for negligible phase quadrature uncertainty are challenging to produce as well. To put it shortly, there is much scope for research into optimizing the use of squeezed light in such a way that quantum noise can be reduced to ever lower degrees. Research must also continue in altering the laser-interferometric system to reduce other sources of noise not covered here in detail (i.e. thermal noise, dark current noise, etc.) as much as possible.

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*Note: Underlined components emphasize importance (not formatting recommendations)

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