Experimental demonstration of a squeezing enhanced power detector

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FIG. 1: Schematic of the experiment. Squeezed light can be injected into the output port of the interferometer via the Faraday rotator or interrogated using homodyne detection. The control servos for the interferometer are shown schematically by the dashed lines. BS=beam-splitter, CL=power cavity locking detector FL=flipper mirror, OL=offset locking detector, PM=phase modulator (75MHz), PZT=piezo-electric transducer and SQK=squeezed state generation system.

FR 1060/5] to give spatial degeneracy between the injected squeezing and the output beam of the interferometer, as required in a long baseline GW detector. The fringe visibility between the squeezing and the interferometer output beam was 99%. The squeezed beam could also be measured directly by the homodyne system via a flipper mirror. The interferometer had a power cavity of length 1m and power mirror of 90% reflectivity. The input beam to the interferometer had a power of 20mW, of which 3mW exited at the dark port where it was measured by the homodyne system. The homodyne detectors were built around ETX 500 photodiodes with 93% quantum efficiency. A GW signal was simulated by modulating one of the Michelson arm lengths using a piezo-electric transducer (PZT) at a frequency outside the power cavity bandwidth. In our case this was 5.46MHz [16]. The signal readout was obtained from the sum output of the homodyne detectors.

A vital feature of our setup is that the control scheme is compatible with future GW detectors and squeezed light. For squeezing to be of any use, the squeezed quadrature must be in phase with the interferometer output. The 15.8MHz phase modulation of the squeezed beam allowed us to use the Pound-Drever-Hall (PDH) [17] method to gather an error signal for the squeezed beam phase. This was fed-back to a PZT in the squeezed beam path. The power cavity error signal was also derived using the PDH technique (using the 75MHz phase modulation) and was fed-back to the length of the power cavity, via PZTs on the Michelson mirrors. The relative length of the Michelson arms was controlled with offset locking. This error signal was derived by subtracting an offset voltage, obtained via the detector OL, from the sum voltage of the homodyne detectors [18]. The error signal was fed-back to PZTs on the Michelson mirrors. Offset locking is being used in Advanced LIGO prototypes [19] and is highly compatible with squeezing. It requires no modulation, so that unlike Schnupp/frontal modulation [20], the signal readout does not require demodulation. This is a benefit as the squeezing is only required at the GW signal frequencies. If modulation techniques are used, squeezing is required at the signal frequency and twice the modulation frequency ± the signal frequency [21]. This simplification of the requirements for squeezing in a GW detector is valuable.

Squeezed states of light may also be used to suppress radiation pressure noise in GW detectors by tuning the angle of the squeezed quadrature [2, 22]. Our experimental setup can, in principle, be used to suppress radiation pressure noise, however our experiment does not operate in a regime where radiation pressure is significant. Suppression of radiation pressure noise is, therefore, not considered in this letter.

Shot noise arises as the electromagnetic vacuum mode enters the dark port of the beam-splitter. The vacuum mode interferes with the input beam passing on its noise characteristics. The smallest phase a SNL interferometer can measure is:

\[ \Delta \phi \geq 1/\sqrt{n}, \]  

(1)

where \( n \) is the number of photons incident on the beamsplitter. Sub-shot noise sensitivity can be achieved if the vacuum mode is filled by a squeezed state. The noise suppression can be characterised by the intensity variance of the light at the interferometer output, \( V_{pd} \) (where the
variance is normalised to the SNL). When optimised, this variance is a function of the input beam intensity noise, \( V_{\text{LO}} \); the squeezed state noise, \( V_{\text{sc}} \), and the losses in the interferometer, modelled by adding vacuum noise with variance \( V_{v} = 1 \). The normalised transfer functions for each noise input to the photodetector for our system are \( T_{\text{LO}}(\omega), T_{\text{sc}}(\omega) \) and \( T_{v}(\omega) \), so that the detected variance \( V_{\text{pd}} \) is given by

\[
V_{\text{pd}} = |T_{\text{LO}}(\omega)|^2 V_{\text{LO}} + |T_{\text{sc}}(\omega)|^2 V_{\text{sc}} + |T_{v}(\omega)|^2 V_{v}.
\]  

(2)

These transfer functions are frequency independent for a simple Michelson. If a power recycling mirror is present, they are functions of the power recycling cavity linewidth. When the interferometer is locked close to a dark fringe, the intensity fluctuations on the input beam couple weakly to the interferometer output, i.e. \( T_{\text{LO}} \) is very small. The amount of squeezing that couples to the output, however, is large as \( T_{\text{sc}}(\omega) \) is close to 1. This is the dominant term in equation (2). To model our experiment we consider 3dB of input squeezing over the detected frequency range. Theoretical plots of the frequency spectrum of the detected output variance for a simple Michelson and a power recycled Michelson (PRM) are shown in Fig. 2. The results show improved performance of the PRM compared to the simple Michelson. This difference is a result of two effects. Firstly, to keep the same power at the homodyne photodetector, the position of the Michelson fringe shifts, such that the effective Michelson reflectivity increases. In our experiment the reflectivity for the simple Michelson is \( \approx 0.92 \), whereas it is \( \approx 0.99 \) for the PRM. The result is an increase in \( T_{\text{sc}}(\omega) \) and a decrease in \( T_{\text{LO}}(\omega) \), so that more squeezing is transferred to the interferometer output. In the presence of a power recycling mirror, therefore, less squeezing is wasted in the interferometer. Secondly, the power mirror introduces a frequency dependence to the squeezing transfer function, \( T_{\text{sc}} \). Outside the power cavity linewidth, the interferometer becomes highly reflective so that transfer of the

squeezing becomes close to ideal.

Figure 3 shows the noise of our squeezed beam prior to entering the interferometer. The noise suppression is 3.5dB below the SNL. When the squeezing was injected into the interferometer, our Faraday rotator gave 15% loss (double pass). This was the dominant source of loss in our experiment. It reduced the amount of squeezing coupled into the interferometer to 2.8 dB (measured).

A signal at 5.46 MHz was used to characterise our Michelson interferometer. Fig. 4 trace (a) shows the result for a simple Michelson. The noise floor is at the SNL. When squeezing was introduced (trace (b)) we observed noise suppression of 1.8 \( \pm 0.2 \) dB below the SNL. Traces (c) and (d) show the response of the PRM with and without the squeezed input. The signal power is proportional to the circulating power. Our power recycling factor of \( \approx 4 \) therefore gives the PRM a signal \( \approx 4 \) times larger than the simple Michelson. The noise floor of trace (d) is 2.3 \( \pm 0.2 \) dB lower than SNL. The predicted improvement of the squeezing performance with power recycling is evident in the different noise floors of traces (b) and (d). If the electronic noise is subtracted from trace (d), the squeezed noise floor is found to be 3.0 \( \pm 0.2 \) dB below SNL. Our experiment maintained lock for periods longer than 15 minutes, and was limited only by the temperature stability of our laboratory.

These results confirm that squeezing is compatible with power recycling, however the practicality of using squeezed light in existing and future GW detectors depends on the compatibility with current designs and the amount of squeezing that will be actually available. We will briefly look at these two issues.

In terms of compatibility to proposed GW detectors, there are three outstanding considerations: the requirement of arm cavities; signal recycling and the generation
of squeezing in the GW signal band. The arm cavities introduce fractionally higher loss into the interferometer (~1% [2]), and require additional locking servos. The extra loss will result in only ~0.1dB reduction of the squeezing, while the locking of the arm cavities will be independent of the squeezing.

With regard to signal recycling, modelling of a system with long signal storage times [21] has shown that the squeezing will suffer an imprinted matched cavity and therefore be transmitted through the interferometer at the signal frequency. Squeezing is nonetheless disadvantageous as it will broaden the bandwidth of the signal recycling. With resonant sideband extraction (RSE) [23], the injected squeezing will sense a reflective cavity. In this case we do not expect significant degradation of squeezing due to signal recycling. Employing squeezing and signal recycling together, while feasible, might not be a worthwhile exercise. Squeezing is only helpful if quantum noise sources are limiting the interferometer performance. A combination of RSE and squeezing is likely to reach a regime where other noise sources, particularly thermal noise, will be dominant at low frequencies [1]. In this case, squeezing will only be of benefit at higher frequencies, outside the thermal noise bandwidth [13]. Instead, one may imagine a squeezed, power recycled interferometer with arm cavities as an alternative to RSE [2, 24].

With respect to the squeezing bandwidth, our experiment shows squeezing at MHz, rather than the ~100Hz range required for GW detection. The major impediment to bench-top low frequency squeezing is laser technical noise. The lowest squeezing frequency in a continuous wave beam reported to date is 200kHz, which was achieved by the use of two OPAs, enabling common-mode rejection of the classical noise [25]. Fortunately, GW detection facilities provide the ideal environment for low frequency squeezed state generation. In particular, there will be a ready supply of laser light shot noise limited to frequencies as low as 10Hz [19], suitable for generation of squeezing inside the GW detection bandwidth.

The key issue governing the amount of squeezing that can be realistically injected into a GW detector is the availability of low loss optics, both for squeezing generation and application to the interferometer. The dominant loss in our interferometer was the 15% double pass transmission of the rotator. Given the low absorption of the materials used in rotators (such as TGG with an absorption of 0.55% cm⁻¹), careful tuning of the magnetic fields around the crystal should provide rotators with < 5% double pass loss. The amount of squeezing generated is limited by material losses in the OPA crystal. The high laser powers available in GW facilities will allow squeezing generation in regimes not possible in bench-top systems. High laser powers may be used to pump OPA cavities with much lower finesse, thereby reducing the loss of the squeezing that occurs inside the OPA cavity. Given that bench-top squeezing experiments currently measure 7 dB of quantum noise suppression [7, 8], over 10dB of squeezing is a realistic target in a GW facility.

In summary, the technology of high precision interferometry and squeezed state generation, have now reached a stage where their fusion presents a genuine alternative configuration for future gravitational wave detectors. Our results, which show the compatibility of advanced interferometer design and squeezed light, represent the first step toward this goal.

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[16] A bench-top interferometer is limited to MHz signals due to the short laser cavity. The power cavity linewidth of a long laser-line interferometer will be of order 100 Hz.