High-Precision Spectroscopy Enhanced with Squeezed Light

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Abstract

Highly-sensitivity measurements require low intrinsic noise within the apparatus. While technical noise often can be actively controlled and thereby reduced, relative shot noise can be reduced by increasing the laser power. Here, we demonstrate a novel alternative approach that circumvents technical noise sources and improves the signal-to-shot-noise ratio without increasing the laser power. To benefit from the high-frequency squeezing in our lab, we shift the signal of interest at kHz frequencies to the high MHz range. This approach is relevant for applications in spectroscopy, e.g. trace gas detection where the gas may set a limit for the laser power used.

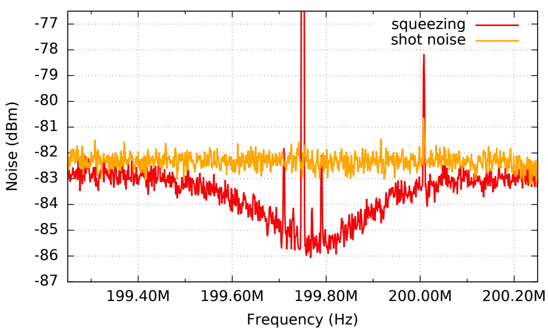
In high-precision metrology, experiments rely on a sufficiently high signal-to-noise ratio. The tiny signals of gravitational waves can only be detected because of the large effort in noise suppression beforehand and the high laser power used in the interferometer to reduce the shot noise level. However, some applications set a limit on laser power and those significantly benefit from noise reduction. Technical noise can generally be suppressed, while the fundamental quantum shot noise can only be reduced by manipulating the quantum properties of light. We report on a new method to increase the signal-to-noise ratio in spectroscopic experiments sensing small kHz signals without increasing the laser power by using squeezed light.

In our experiment we built an optic parametric oscillator (OPO) operating below threshold at 1064 nm that has a free spectral range (FSR) of 199.75 MHz. The OPO is held on resonance for the laser frequency and is seeded with light phase modulated (PM) at 199.75 MHz. Equation 1 shows that the output variance in one quadrature is reduced at every FSR of the OPO cavity [1]. The phase between seed and pump field can be locked in order to generate phase or amplitude quadrature squeezed states. Particularly, we do not need a coherent frequency shifted local oscillator for this lock [2].

The squeezed light is then sent to a high finesse Fabry-Pérot (FP) cavity that has the same FSR as the OPO to sense tiny cavity length modulations simulating our signal of interest. This signal does not only appear at the carrier frequency where technical noise sources might be present, but also at the PM sidebands around 199.75 MHz. The high-frequency quadrature spectrum can be measured with a local oscillator on a homodyne detector installed behind the FP cavity.

$$V_{\mathrm{out}}^{\pm}(\omega) = \left| \frac{(\kappa \pm \chi)^2 - (\frac{1-e^{i\omega\tau}}{\tau})^2}{(\kappa - \frac{1-e^{i\omega\tau}}{\tau})^2 - \chi^2} \right|^2 . \qquad (1)$$

The graph depicted in the figure shows the PM peak at 199.75 MHz and in addition the resolved cavity length modulation signal at ±40 kHz. This signal was originally masked by shot noise, shown by the measurement in yellow. With our method the signal becomes visible and can now be resolved in the 3 dB reduced noise floor depicted by the red graph.



We use a phase modulated beam to frequency shift our signal of interest to the high frequency regime, where we are not affected by technical noise and still reach sub-shot-noise sensitivity because of the applied squeezing. We conclude that high-precision laser spectroscopy applications like cavity ring-down spectroscopy or frequency-modulation spectroscopy can benefit from our method. In particular, it appears to be very promising for applications such as explosive trace gas detection where the specific gas sets a limit for the used laser power.

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[2] H. Vahlbruch, S. Chelkowski, B. Hage, A. Franzen, K. Danzmann, and R. Schnabel, "Coherent control of vacuum squeezing in the gravitational-wave detection band," Physical Review Letters, vol. 97, no. 1, 2006.