Squeezing more from a quantum nondemolition measurement

Buchler, B.C.; Lam, P.K.; Bachor, H.A.; Andersen, Ulrik Lund; Ralph, T.C.

Published in:
Physical Review A

Link to article, DOI:
10.1103/PhysRevA.65.011803

Publication date:
2002

Document Version
Publisher's PDF, also known as Version of record

PHYSICAL REVIEW A, VOLUME 65, 011803(R)

Squeezing more from a quantum nondemolition measurement

Ben C. Buchler,* Ping Koy Lam, and Hans-A. Bachor
Department of Physics, Faculty of Science, Australian National University, Canberra, ACT 0200, Australia

Ulrik L. Andersen
Department of Physics, Faculty of Science, Australian National University, Canberra, ACT 0200, Australia and Department of Physics, Technical University of Denmark, DK-2800 Lyngby, Denmark

Timothy C. Ralph
Department of Physics, University of Queensland, Queensland 4072, Australia

(Received 29 August 2001; published 13 December 2001)

We use a stable, 5 dB, amplitude squeezed source for a quantum nondemolition (QND) experiment. The performance of our QND system is enhanced by an electro-optic feedforward loop which improves the signal transfer efficiency. At best, we measure a total signal transfer of 1.81 and conditional variance of 0.55.

DOI: 10.1103/PhysRevA.65.011803 PACS number(s): 42.50.Lc, 03.67.Hk, 42.50.Dv

Quantum nondemolition (QND) devices allow the perfect readout of information on a quantum variable while the Heisenberg measurement noise is placed on the conjugate variable. As well as their original application to quantum limited measurement [1], QND is now recognized as an important tool in quantum information research. For example, the use of QND devices has been suggested in entanglement purification [2], state preparation [3], and even quantum computation [4]. Unsurprisingly real QND devices are never perfect. In this paper, we demonstrate a method that enhances a nonideal QND system. Our technique is based on electro-optic control. Electro-optic control of QND measurement was modeled in feedback configurations [5,6], where the information on the meter readout of the QND system is assumed to act on the input beam(s) to the QND system. Our experiment is based on feedforward [7], where the meter information is used to modify the signal output of the QND system. Feedforward has many other uses, including generation of squeezed states [8], noiseless amplification [9], quantum teleportation [10], and optical quantum computing [11]. Our QND device is based around a strong, stable source of amplitude squeezing from an optical parametric amplifier (OPA). We begin our discussion by describing the experiment that generates the squeezed light. We then show how squeezing may be used to make a QND measurement with a beam splitter. Last, results showing feedforward enhancement of QND are presented.

Figure 1 shows the design of our experiment. A 700 mW Nd:YAG laser at 1064 nm is used to pump a second-harmonic generator (SHG), which is cavity containing a MgO:LiNbO$_3$ crystal. The 532 nm green light from the SHG (dashed line) is used to pump the OPA cavity. Some of the 1064 nm laser output is tapped off to be used as the local oscillator beam for the eventual homodyne detection of the squeezing, and also as a seed beam for the parametric amplification. This beam is sent through a mode cleaning cavity of 1.5 MHz linewidth. The mode cleaner improves the spatial profile of the beam, thereby improving the homodyne efficiency. It also filters excess laser noise so that our seed beam is at the quantum noise limit (QNL) for frequencies outside the cavity linewidth. The laser was locked to the mode cleaner cavity via the tilt locking method [12]. The green SHG output and the seed beam from the mode cleaner are passed to the OPA cavity which is a monolithic MgO:LiNbO$_3$ crystal. A 15.8 MHz electric field applied to the OPA generates phase modulation on the reflected and transmitted infrared fields. The signal on the reflected beam is used to lock the frequency of the mode cleaner to the OPA. The laser frequency is locked to the mode cleaner so that, indirectly, the laser is locked to the OPA resonance. The amplitude squeezed output of the OPA (dotted line) has only 10 μW of optical power. This dim squeezed state is homodyned with a 3 mW local oscillator beam (LO) and observed with detectors $H1$ and $H2$. These were built around ETX500 photodiodes with quantum efficiency $93 \pm 2\%$. For stable squeezing, the phase of the green pump must be locked to the infrared seed beam and the phase of the local oscillator must be locked to the phase of the squeezed output. Error signals for both these locking loops may be derived from the 15.8 MHz sidebands of the squeezed beam. The amplitude modulators $A1$ and $A2$ are used for the QND measurements. The components inside the shaded box were only present during the QND enhancement experiments.

The amplitude squeezing spectrum of our OPA is shown in Fig. 2(i). It shows best squeezing of 5.5 dB below the QNL at frequencies near 4 MHz. The peaks on this spectrum

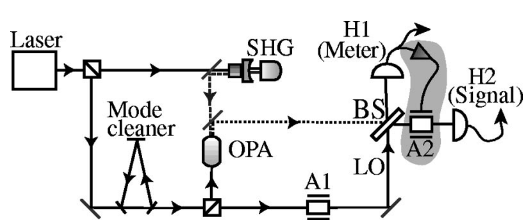

FIG. 1. Layout of our squeezing/QND experiment. $A(1,2)$ are amplitude modulators, LO is the local oscillator beam, BS is the homodyne beam splitter, and $H(1,2)$ are the homodyne detectors.

*Electronic address: ben.buchler@anu.edu.au

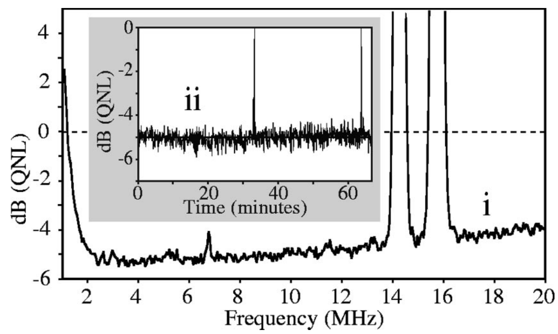

FIG. 2. Main figure (i) the squeezing spectrum of the locked OPA system. Resolution bandwidth (RBW) = 100 kHz, video bandwidth (VBW) = 30 Hz. Inset (ii) squeezing at 4.5 MHz as a function of time. RBW = 30 kHz, VBW = 30 Hz.

are due to the modulation signals used for cavity locking. The stability of our squeezing generation is shown in Fig. 2(ii). The spikes correspond to occasions where the servos controlling the locking of the green or homodyne phase ran out of range. The system immediately relocked to an adjacent fringe.

Another way of visualising the effect of amplitude squeezing is shown in Fig. 3. This measurement of the amplitude quadrature was made by individually mixing down the outputs from $H1$ and $H2$ at 4.5 MHz, passing these signals through 100 kHz low-pass filters and then plotting the signals against one another. Figure 3 is therefore a direct representation of the quantum correlation between the field intensities at $H1$ and $H2$. It also contains the entire probability distribution function of the amplitude quadratures of these fields. The data (i) was collected when no squeezing is incident on the homodyne beamsplitter, and shows no correlation $[C^2_{(H2,H1)} = 0.007 \pm 0.01]$. The data (ii) was collected when amplitude squeezing replaced the quantum vacuum. The correlation is now strong with $C^2_{(H2,H1)} = 0.17 \pm 0.01$. From the data (ii) we may infer 3.8 dB of amplitude squeezing entering the beam splitter. This is less than shown in Fig. 2 because we are able to subtract electronic noise from the spectrum analyzer measurements. A useful question is

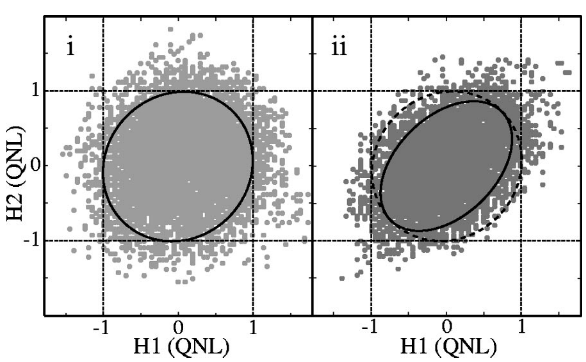

FIG. 3. Correlation between the photocurrents of $H1$ and $H2$ at 4.5 MHz for (i) vacuum noise and (ii) amplitude squeezing incident on the beam splitter. The quantum noise is shown for reference. The ellipses are the square root of the conditional variance, normalized to the QNL. The data is not to scale with the radii of the curves.

"given the information measured by detector $H1$, with what error may we infer the signal in $H2$?" The answer is the conditional variance $V_{H2|H1}$ defined as

$$V_{H2|H1} = V_{H2}[1 - C^2_{(H2,H1)}], \tag{1}$$

where V_{H2} is the variance of the noise at $H2$. From the experimental data, we may calculate contours of conditional variance. We do this by applying Eq. (0.1), then rotating the experimental data by 1° and repeating. The result of this calculation is shown by the ellipses of Fig. 3, which show the square root of the conditional variance as a function of angle. The radii have been normalized to the QNL, so that for the vacuum input to the beamsplitter (i) we see a near circle of radius 1. (It is not exactly circular because $C^2_{(H2,H1)} = 0.007 \pm 0.01$ is not exactly zero.) The squeezed input (ii) gives an ellipse that lies inside the quantum noise (dashed line). The conditional variance calculated in this way, for the data at 0 and 90° is 0.62 ± 0.03.

The quantum correlations and conditional variance shown in Fig. 3 hint at the QND nature of a squeezed beam incident on a beamsplitter [13,14]. In the setup of Fig. 1, the local oscillator becomes the "signal input beam," the squeezing is the "meter input beam," while $H1$ and $H2$ are now the meter and signal detectors, respectively. Meter squeezing is known to enhance QND measurement [15]. In this case, the squeezed meter input enables a beam splitter to fulfil the QND criteria. A small test signal, applied using the modulator A1, is used to measure the signal transfer efficiencies T_s and T_m. The sum of these transfer coefficients, T_{s+m}, is one of the criteria commonly used to quantify QND systems [16]. For an ideal QND device, $T_{s+m} = 2$, while the quantum limit for a measurement device is 1. The signal (meter) transfer $T_{s(m)}$ is defined as

$$T_{s(m)} = \mathcal{R}_{s(m)} / \mathcal{R}_{\text{in}}, \tag{2}$$

where $\mathcal{R}_{s(m)}$ is the signal-to-noise ratio of the signal (meter) output beam and $\mathcal{R}_{\text{in}}$ is the signal-to-noise ratio of the signal input beam. Trace **a** of Fig. 4(i) is a measurement of the signal input beam and therefore shows $\mathcal{R}_{\text{in}}$. With no squeezing incident on the beam splitter, we measure the spectrum **b** for the signal output. This trace therefore shows $\mathcal{R}_s$. Comparing $\mathcal{R}_{\text{in}}$ to $\mathcal{R}_s$ we find $T_s = 0.50 \pm 0.02$ as predicted for a 50/50 beam splitter and a vacuum state at the empty port. Trace **c** shows the signal output beam with the injection of the squeezed state. The improvement of $\mathcal{R}_s$ compared to the vacuum input is clearly evident. With the injected squeezing, we find $T_s = 0.72 \pm 0.02$. Similar data can be collected for T_m, which we measured as 0.50 ± 0.02 with no squeezed input, and 0.75 ± 0.02 with the addition of squeezing. The total signal transfer, T_{s+m} is therefore increased from 1 ± 0.03 to 1.47 ± 0.03 by the addition of squeezing. It is worth noting that there is something about these results that is not quite QND. The output signal noise background lies below the QNL (trace **c**), whereas the input signal noise floor is the QNL (trace **a**). Systems that exhibit such (de)amplification of

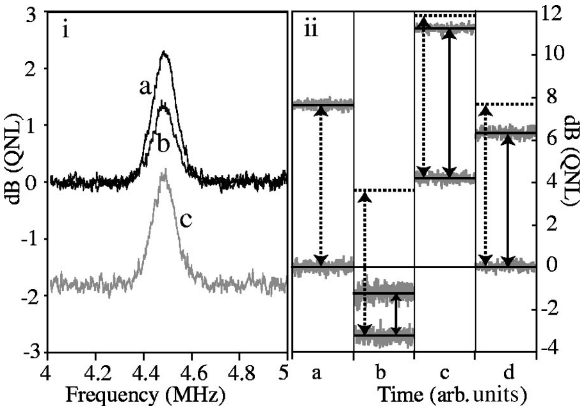

FIG. 4. Part (i) data used to calculate T_s for a 50/50 beam splitter with no feedforward. (a) Input signal level; (b) output signal without squeezing; (c) output signal with squeezing. Part (ii) data used to calculate the value of T_s for the 92/8 beam splitter. (a) The input signal level, (b) the output signal with no feedforward, (c) the output signal with feedforward to maximize T_s and (d) the output signal with unity signal gain feedforward. The dashed lines and arrows indicate the input signal level. All results taken at 4.5 MHz with RBW=30 kHz, VBW=30 Hz.

the signal are often referred to as "quantum taps" or "quantum repeaters" [17] rather than QND. We present a solution to this problem below.

The second criterion used to measure QND is the conditional variance. In the context of QND, $V_{s|m}$ says how well we may infer the signal beam information given a measurement of the meter beam. It is therefore also a measure of how far below the QNL the signal beam may be suppressed by using the information of the meter beam. A QND device requires $V_{s|m}<1$ and ideal QND has $V_{s|m}=0$. The conditional variance is given by

$$V_{s|m}=V_s[1-C^2_{(s,m)}]=V_s-|\langle \delta X_s \delta X_m\rangle|^2/V_m, \qquad (3)$$

where $\delta X_{s(m)}$ are the fluctuations of signal (meter) output quadratures, $V_{s(m)}$ are their corresponding variances and $C_{(s,m)}$ is the correlation between the signal and meter output beams. The correlation may be measured experimentally as shown in Fig. 3, however we cannot account for the effect of electronic noise with this technique. When measuring QND results we used one of two methods. (1) The "cross term" may be evaluated using $2\langle \delta X_m \delta X_s\rangle = \frac{1}{2}\langle(\delta X_m+\delta X_s)^2\rangle - \frac{1}{2}\langle(\delta X_m-\delta X_s)^2\rangle = V_{\text{sum}}-V_{\text{diff}}$ where $V_{\text{sum(diff)}}$ is the variance of the sum (difference) of the meter and signal photocurrents. These are the same sum and difference photocurrents used in the homodyne measurement of squeezing. (2) The conditional variance says how far below the QNL the signal noise may be suppressed using the meter information. This definition may be applied by subtracting (with variable gain) the meter photocurrent from the signal, and comparing the output to the QNL of the signal. Both methods (1) and (2) were used to measure $V_{s|m}$. For the 50/50 beam splitter, we found $V_{s|m}=0.51\pm0.04$.

In the limit of infinite squeezing, a beam splitter is predicted to give ideal QND behavior. This is, of course, unphysical due to the infinite energy of a perfectly squeezed beam. The QND performance of a beam splitter with finite squeezing may be improved by using the information of the meter photocurrent to modulate the signal output beam. In this way, the beamsplitter noise introduced onto the signal output may be canceled resulting in improved T_s [9]. Although our discussion here is limited to the beam-splitter, this feedforward technique will work for a range of QND systems [7]. The limit to improving T_s is imposed by the detector efficiency (η), the detector dark noise, and the noise of the feedforward amplifiers. All these nonideal electronic properties will add noise to the voltage applied to the modulator in the signal beam, therefore degrading the quality of the feedforward. With negligible electronic noise, $T_s\sim\eta$ is theoretically achievable. The additional equipment used for feedforward is shown in the shaded area of Fig. 1. The resultant value of T_s was measured as 0.90 ± 0.02. The value of T_m was unchanged at 0.76 ± 0.02, so that the total T_{s+m} was found to be 1.66 ± 0.03. The value of the conditional variance was reduced by the loss introduced by the amplitude modulator and the electronic noise of the feedforward electronics. With feedforward $V_{s|m}$ was found to be 0.55 ± 0.04.

These results may be extended by changing the beamsplitter ratio used in the experiment. By directing the majority of the signal input beam into the meter detector, the value of T_m can be made very large. The meter photocurrent drives the signal output beam so that $T_s\approx T_m$. As more of the input is directed into the meter beam, more of the squeezing is directed into the signal output beam. The noise background of the signal output beam is therefore reduced, leading to an improvement in the value of $V_{s|m}$. Ideally, we would like to detect 100% of the input signal and then write this information onto a squeezed beam. This would provide excellent QND performance and the output beam would be coherently related to the input because all our beams originate from the same laser. However, our squeezed beam is too dim to detect directly, so a strongly asymmetric beam splitter, with 92% of the light directed to the meter detector, was chosen instead. The measurement of T_s with this beam-splitter ratio is shown in Fig. 4(ii). Subplot **a** shows the input signal level. The output signal with no feedforward (**b**) is now very poor because only 8% of the input signal is sent to the signal detector. T_s was measured as 0.16 ± 0.03. The noise-floor of the signal, as for the case of the 50/50 beam splitter, is sub-QNL due to the ~4.5 dB of squeezing added at the beam splitter. The feedforward may now be turned on to maximize the value of T_s as shown in **c**. In this case, we find $T_s=0.85\pm0.02$.

Although the results of trace **c** show good T_s, the signal and noise levels are amplified by some 4 dB compared to the input signal. (This was also true of the 50/50 beam splitter which had 3 dB of amplification with feedforward.) This may be of practical advantage, since the signal is more resistant to loss, however, the QND nature of the system, similar to the case of the deamplified signal without feedforward, is questionable. Such amplification is not a problem in QND experiments [15,18–20]. Fortunately, feedforward provides a solution. The gain used to generate trace **c** was chosen to maximize the value of T_s. Instead, we may use less gain,

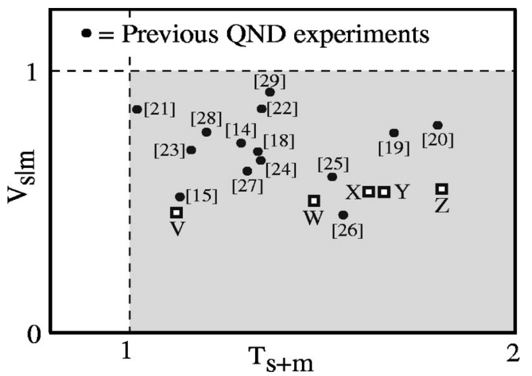

FIG. 5. Summary of QND points. V, 92/8 beam splitter no feedforward; W, 50/50 beam splitter no feedforward; X, 92/8 beam splitter feedforward with unity signal gain; Y, 50/50 beam splitter with maximized T_s; and Z, 92/8 beam splitter with maximized T_s. Points • are previous experiments as referenced.

and set the output noise floor equal to the QNL. This is possible because the output noise background without feedforward is below the QNL. The results of this ''unity-gain'' QND scheme are shown in trace **d**. The amplification brings the noise floor back to the QNL and $T_s = 0.66 \pm 0.02$. In all cases for the 92/8 beamsplitter, the value of the meter transfer T_m was measured as 0.96 ± 0.02. The conditional variance was found to be 0.46 ± 0.03 with no feedforward, which as expected, is better than the 50/50 case. With feedforward, the conditional variance was measured as 0.55 ± 0.03 in the case of feedforward with maximum T_s and 0.54 ± 0.03 in the case of feedforward with unity signal gain. Figure 5 shows a summary of our results in the context of other published QND experiments [14,15,17,21–29].

Unity-gain feedforward gives the correct signal strength, but the intensity of the output beam will, in general, be different to the input due to the attenuation of the beam splitter. This detail may be addressed by using a bright squeezed meter input with variable intensity. The output power could then be controlled independent of the quantum properties of the beam. Brighter squeezing may be generated by using a more powerful seed beam in our OPA. In the present experiment, the seed power is limited by the available laser power.

In conclusion, we have shown that feedforward greatly improves the signal transfer efficiency of QND measurements. Furthermore, the method is found to be compatible with QND enhancement via meter squeezing. Feedforward and meter squeezing are both general techniques. Together, they provide a two-stage system for improving the performance of a wide range of QND experiments.

The authors are grateful for numerous discussions with Friedrich König and Malcolm Gray, as well as the financial support of the Australian Research Council.

[1] V. B. Braginsky *et al.*, Science **209**, 547 (1980).
[2] L.-M. Duan *et al.*, Phys. Rev. Lett. **84**, 4002 (2000).
[3] M. Dakna *et al.*, Phys. Rev. A **55**, 3184 (1997).
[4] J. C. Howell and J. A. Yeazell, Phys. Rev. Lett. **85**, 198 (2000).
[5] H. M. Wiseman, Phys. Rev. A **51**, 2459 (1995).
[6] P. Tombesi and D. Vitali, Phys. Rev. A **51**, 4913 (1995).
[7] B. C. Buchler *et al.*, Phys. Rev. A **60**, 4943 (1999).
[8] J. Mertz *et al.*, Phys. Rev. Lett. **64**, 2897 (1990).
[9] P. K. Lam *et al.*, Phys. Rev. Lett. **79**, 1471 (1997).
[10] A. Furusawa *et al.*, Science **282**, 706 (1998); T. C. Ralph and P. K. Lam Phys. Rev. Lett. **81**, 5668 (1998).
[11] E. Knill *et al.*, Nature (London) **409**, 46 (2001).
[12] D. Shaddock *et al.*, Opt. Lett. **24**, 1499 (1999).
[13] J. Shapiro, Opt. Lett. **5**, 351 (1980).
[14] R. Bruckmeier *et al.*, Phys. Rev. Lett. **79**, 43 (1997).
[15] R. Bruckmeier *et al.*, Phys. Rev. Lett. **78**, 1243 (1997).
[16] M. J. Holland *et al.*, Phys. Rev. A **42**, 2995 (1990); J.-Ph. Poizat *et al.*, Ann. Phys. (Paris) **19**, 265 (1994).
[17] P. Grangier *et al.*, Nature (London) **396**, 537 (1998).
[18] J. A. Levenson *et al.*, Phys. Rev. Lett. **70**, 267 (1993).
[19] E. Goobar *et al.*, Phys. Rev. Lett. **71**, 2002 (1993).
[20] J. F. Roch *et al.*, Phys. Rev. Lett. **71**, 2006 (1993).
[21] J. F. Roch *et al.*, Appl. Phys. B: Lasers Opt. **55**, 291 (1992).
[22] J. P. Poizat *et al.*, Phys. Rev. Lett. **70**, 271 (1993).
[23] S. F. Pereira *et al.*, Phys. Rev. Lett. **72**, 214 (1994).
[24] K. Bencheikh *et al.*, Phys. Rev. Lett. **75**, 3422 (1995).
[25] K. Bencheikh *et al.*, Phys. Rev. Lett. **78**, 34 (1997).
[26] J. F. Roch *et al.*, Phys. Rev. Lett. **78**, 634 (1997).
[27] H. Wang *et al.*, Phys. Rev. Lett. **82**, 1414 (1999).
[28] S. Friberg *et al.*, Phys. Rev. Lett. **84**, 59 (2000).
[29] F. König *et al.*, in Fifteenth International Conference on Lasers and Electro-optics in Europe, CLEO/Europe-EQEC, Munich, 2001 [OSA Tech. Digest, 296 (2001)].