Quantum Nondemolition Measurements Improved by a Squeezed Meter Input

Robert Bruckmeier,* Klaus Schneider, Stephan Schiller, and Jürgen Mlynek
Fakultät für Physik, Universität Konstanz, 78434 Konstanz, Germany
(Received 23 July 1996)

Continuous quantum nondemolition (QND) measurements of the amplitude quadrature of a 1064 nm wave are performed with a monolithic dual-port degenerate optical parametric amplifier (OPA). The quality of the measurement is limited in part by the quantum fluctuations carried by the vacuum meter input wave. Improved QND measurements are realized by injecting 3.4 dB amplitude-squeezed light into the meter input port of the OPA. This achieves increased squeezing and correlation of the output signal and meter waves, and both improved operation as a quantum optical tap and as a quantum state preparator. The all-solid-state system was operated for 5 h with high stability. [S0031-9007(97)02339-9]

PACS numbers: 42.50.Dv

Quantum nondemolition (QND) measurements [1] seek to measure a quantum mechanical observable precisely without disturbing its evolution. An example is a measurement of a photon number without absorbing a single photon. QND measurement strategies are of importance since they allow one to circumvent quantum mechanical limits inherent to standard measurement techniques. They are indirect measurements: The signal system to be measured is coupled to a meter system for a finite time. The interaction is chosen such that it couples an observable of the meter to the signal observable of interest, but does not influence its evolution. Subsequently, a (destructive) measurement on the meter system provides the desired information on the signal system observable without disturbing it.

During the search for appropriate coupling schemes, nonlinear optical systems attracted interest [2], because the necessary technology was better developed than for mechanical systems such as gravitational bar antennas. Since 1986, a variety of experiments on QND-type measurements has been realized. Initial experiments employed a $\chi^{(3)}$ coupling of pulses in an optical fiber [3]. Following experiments used $\chi^{(2)}$ nonlinearities in crystals [4], $\chi^{(3)}$ effects in sodium atomic beams [5] and in fibers for solitons [6], and electromechanical coupling to a nonlinear mechanical resonator [7]. Recently, the long-standing challenge for repeated QND measurements was successfully mastered both for pulsed [8] and continuous-wave measurements [9]. The latter approach is based in part on the system discussed here.

In this Letter, we show that the performance of a QND system is limited by quantum fluctuations of the meter input state, and demonstrate that a squeezed meter input can break this restriction and permit improved QND performance.

QND systems can be described by a linear input-output formalism [10], relating the output to the input fluctuation operators via the internal dynamics of the coupling system. For the present discussion, amplitude and phase quadrature operators are the appropriate choice, since they decouple. For the frequency domain amplitude quadratures X_s, X_m, and X_l of signal, meter, and vacuum (due to loss) modes, respectively, we write

$$\begin{pmatrix} X_s^{\text{out}} \\ X_m^{\text{out}} \end{pmatrix} = \begin{pmatrix} a & b & c \\ d & e & f \end{pmatrix} \begin{pmatrix} X_s^{\text{in}} \\ X_m^{\text{in}} \\ X_l^{\text{in}} \end{pmatrix}, \tag{1}$$

where a through f are complex coefficients. A QND measurement of X_s^{in} aims at both back action evasion, i.e., $X_s^{\text{out}} \to X_s^{\text{in}}$, which guarantees a nondestructive measurement, and at a precise measurement, i.e., X_m^{out} is dominated by X_s^{in}. As a quantum mechanical consequence, there is strong back action on and low measurement precision of the phase quadrature.

QND may be achieved by following two strategies to implement the necessary phase sensitivity that discriminates amplitude and phase. The first is to devise a *phase sensitive system* with an input-output matrix with $a \to 1$, $b \to 0$, and $c \to 0$ to ensure back action evasion, and $|d| \gg |e|, |f|$ to guarantee high measurement precision. This approach has been followed by all previous QND experiments.

In contrast, the second strategy is based on injecting the meter in a *squeezed state* with reduced quantum uncertainty $\mathrm{Var}X_m^{\text{in}} \to 0$ rather than the vacuum state with $\mathrm{Var}X_m^{\text{in}} = 1$ into a coupling system with $a \to 1$ and small losses, $|c|, |f| \ll 1$. The prototype realization of this approach [11], which was recently demonstrated [12], is a high transmittance beam splitter with squeezed light injected into its usually dark port. The use of squeezed light for noise reduction in nonlinear optical systems has so far only been demonstrated in optical amplification with a nondegenerate optical parametric amplifier (OPA) [13]. Here we present the first demonstration of the combined use of both strategies to perform QND measurements.

Our QND system is based on a proposal by Smith *et al.* [14] using a degenerate dual-port OPA [15]. Referring to the lower right of Fig. 1, signal and meter input waves are resonantly injected into the cavity through partially

0031-9007/97/78(7)/1243(4)$10.00

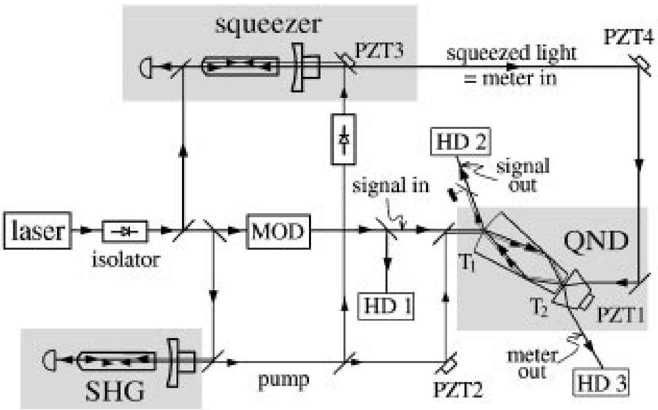

FIG. 1. Experimental setup. HD: homodyne detector; MOD: modulation system; PZT: piezoelectric translator. SHG: second harmonic generator.

transmitting mirrors (power transmissions T_1, T_2). The waves emitted therefrom are the output waves. The wave inside the OPA resonator experiences a parametric deamplification d due to $\chi^{(2)}$ interaction with the injected pump and a passive loss A per round trip.

Qualitatively, good QND measurements of the amplitude quadrature require the condition

$$A \ll T_1 \ll T_2 \approx d \,. \tag{2}$$

Then the meter-in wave is near impedance matched, and consequently the meter-out wave is dominated by the part of the signal-in wave that is transmitted through the cavity. Thus, a precise measurement is possible. In addition, the measurement back-action is small since the cavity is impedance mismatched for the signal-in wave and most of it is reflected, while perturbations from the cavity are small. As relation (2) is difficult to implement experimentally and can only be approximated, fluctuations from the meter input are transferred to both signal and meter output, reducing the QND performance. Injection of a squeezed meter input state then reduces this added noise and results in improved QND measurements.

Quantitatively, this QND system can be described by a single figure of merit r^{-1} which compares parametric interaction and losses: $r \equiv \sqrt{A/d}$. The overall QND performance can be considered optimal if the port transmissions are chosen as $T_1 = rd$ and $T_2 = d + T_1$, which leads to operation close to, but below threshold. QND measurements become perfect as $r \rightarrow 0$, which can be seen from the leading terms of the input-output matrix for relation (1) at low measurement frequencies:

$$\begin{pmatrix} 1 - r & -\sqrt{r} & -r^{3/2} \\ \sqrt{r} & -r^2/2 & r \end{pmatrix}. \tag{3}$$

The dual port OPA has been implemented as a miniature (6 mm long) monolithic MgO:LiNbO$_3$ ring resonator, allowing a large operation bandwidth of $\approx$50 MHz. A ring cavity is used so that the input and output waves are spatially separated. The port for signal input and output is a dielectric mirror with transmission $T_1 = 1.45\%$ at 1064 nm. The second port for the meter is realized by a frustrated total internal reflection mirror with variable transmission T_2, which is stabilized by actively controlling the distance (PZT1) between the coupling prism and the resonator.

A continuous-wave Nd:YAG laser (500 mW, 1064 nm) serves both as the source of the signal wave and as the fundamental wave to be resonantly frequency doubled for the pump waves of the QND (113 mW) and squeezing (77 mW) parametric amplifiers. The pump wave for the ring OPA is injected single pass and achieves a parametric deamplification of $d = 2.4\%$ per round trip.

The signal wave is imparted an amplitude modulation at 14.0 MHz and is power stabilized to 1.05 mW by a modulation system before being resonantly injected into the ring OPA. The important optical properties T_1, A and the signal input beam mode match $M_s = 89.3\%$ are characterized by measuring the power reflectance and transmittance of the ring OPA as a function of prism position without pumping. Optical efficiencies for the propagation of the signal-in beam to the crystal, and the signal-out and meter-out beams from the crystal to the detectors are 99.4%, 97.5%, and 99.0%, respectively.

The accurate measurement of the 14.0 MHz modulation on the signal-in, signal-out, and meter-out waves is one central task of the setup; the other is to measure the quantum noise of the output beams and their correlation. To this end three self-homodyne detectors are used, one (HD1) for the characterization of the input modulation and the other two (HD2, HD3) to detect the two output beams. The detectors use InGaAs photodiodes with 97% quantum efficiency. Each homodyne detector generates a current that is proportional to the amplitude quadrature of the detected beam and a calibrated reference for the shot noise level. All output signals are measured by spectrum analyzers (HP 8591A, detection bandwidth 100 kHz, zero span time 0.5 s) and evaluated by a computer.

The source of the squeezed meter input wave is a standing-wave parametric amplifier, injection seeded by a weak beam for its stabilization [16]. The squeezed light (30 μW power) exhibits 3.4 ± 0.3 dB quantum noise reduction around 14 MHz, which is stable for many hours. The meter input mode match is $M_m = 74\%$. To operate the entire system stably, the doubling cavity, the squeezing OPA cavity, and the laser frequency are locked on resonance with the resonance frequency of the ring OPA cavity. Each pump wave is phase locked for maximum deamplification (PZT2, PZT3). In addition, the squeezed meter-in wave is phase-locked (PZT4) with respect to the signal-in wave so that its squeezed quadrature enters the ring OPA as X_m^{in}.

The first nonclassical effects considered are the squeezings $S_{s,m} \equiv (\mathrm{Var}\, X_{s,m}^{\text{out}})^{-1}$ of the signal-out and the meter-out beam, respectively. The results at 14.6 MHz as a

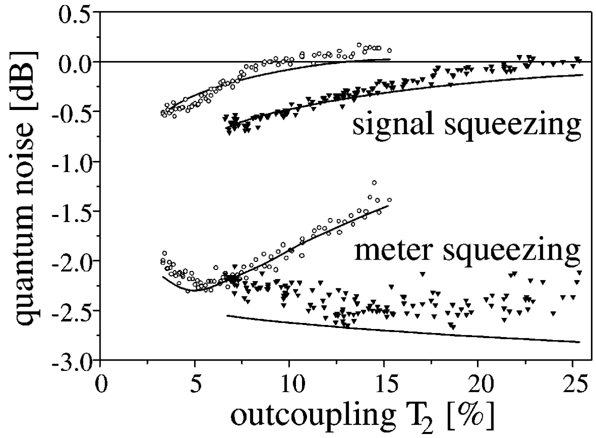

FIG. 2. Relative quantum noise Var $X_{s,m}^{\text{out}}$ of the signal and meter output beams as a function of outcoupling T_2. Circles: vacuum meter input, triangles: squeezed meter input, and lines: theory.

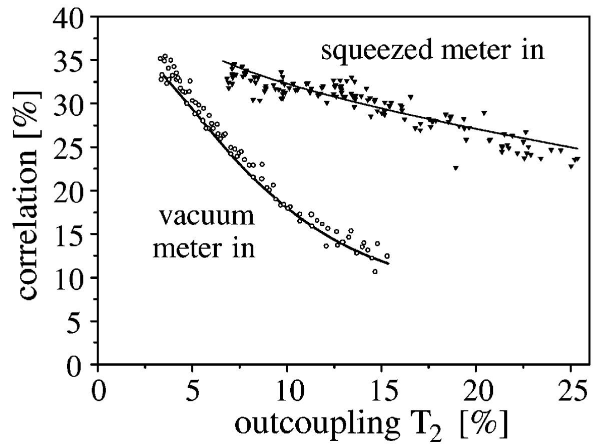

FIG. 3. Optical correlation vs T_2 for vacuum (circles) and squeezed meter input (triangles). Lines: theory.

function of T_2 are shown in Fig. 2. It can be seen clearly that the fluctuations of both output beams are further reduced upon injection of the squeezed meter input wave [17]. The antisqueezing of the signal-out beam at large T_2 reflects the 0.16 dB excess noise of the signal-in beam.

The functional dependences of $S_{s,m}(T_2)$ can be understood qualitatively for the case of a vacuum meter input: The squeezing of the signal output beam is degraded for higher T_2 since the outcoupling efficiency decreases and the optical parametric oscillator (OPO) threshold increases. The meter-out squeezing exhibits an optimum, since for low T_2 the outcoupling efficiency for the meter-out beam limits the squeezing, while for increasing T_2 the OPO threshold grows compared to the pump power. The quantum noise reduction in the meter output is larger than that of the signal because $T_2 > T_1$.

To provide a satisfactory theoretical description of the experiment, the theory given in Ref. [14] must be extended to include the imperfect mode matchings M_s and M_m, optical propagation losses, detector quantum efficiencies, and a large outcoupling T_2 beyond the good cavity approximation together with measurement frequencies comparable to the cavity linewidth [9]. Good agreement between theory and experiment is obtained by assuming increased losses of $A = 1.1\%$ when the ring OPA is pumped, compared to the cavity losses of 0.57% for no pump, which may indicate the presence of green induced infrared absorption. All other parameters of the theory are determined by measurements.

For a QND device the meter output reading must be correlated to the signal output reading: "the needles move together" [2]. The optical correlation C_o of the amplitude fluctuations of the output beams leads to a detector current correlation C_c, which is measured by interfering the currents and measuring the noise at 14.6 MHz. C_c is reduced as compared to C_o by electronic noise of the photodetectors. As shown in Fig. 3C_o is improved when the vacuum is replaced by the squeezed meter input.

This QND scheme has the particular property of permitting quantum state preparation for both output beams: measuring one beam will lead to a state reduction of the entangled state and therefore to a state preparation of the other beam. This will reduce the variance of the second beam by the factor $1 - C_c^2$, leading to the conditional variances $V_{s|m} = (1 - C_c^2)/S_s$ and $V_{m|s} = (1 - C_c^2)/S_m$ of the signal-out and the meter-out beams, respectively. They are both below unity and therefore fulfill the quantum state preparation condition. When using squeezed light, $V_{m|s}$ for optimal T_2 is improved from -2.5 to -2.8 dB. Like squeezing, the state preparation ability can be applied to extend the measurement precision beyond the standard quantum limit.

Besides the quantum state preparation ability, the transfer coefficients T_s and T_m characterize the quality of a QND system [18]. They are defined as the fraction of the signal-to-noise ratio (SNR) of the signal input beam that is transferred to the signal and meter output beams,

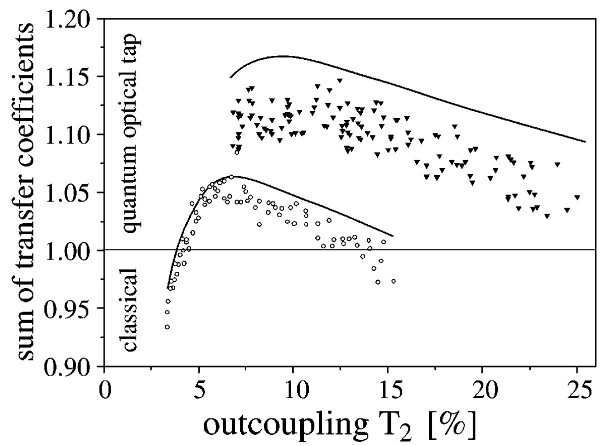

FIG. 4. $T_s + T_m$ vs the meter outcoupling for vacuum (circles) and squeezed meter input (triangles). Lines: theory.

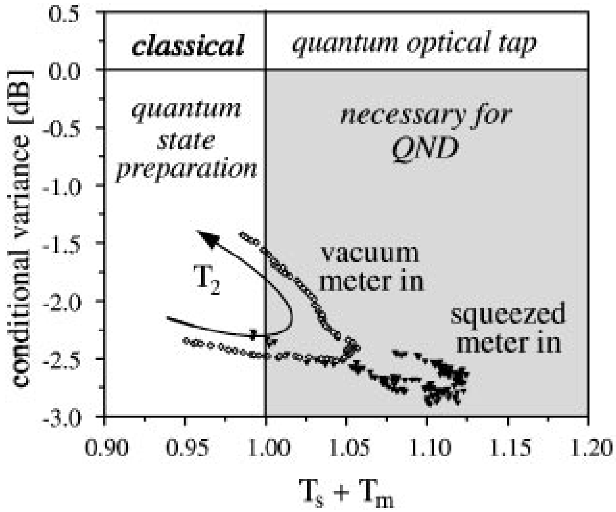

FIG. 5. Summary diagram: $V_{m|s}$ vs $T_s + T_m$ when varying T_2 for vacuum (open triangles) and squeezed meter input (closed triangles).

respectively. For any phase-insensitive device, the sum of both transfer coefficients is at most unity if the input beams are shot noise limited: $T_s + T_m \leq 1$. However, a quantum optical tap succeeds in breaking this barrier and offers improved optical information transmission by operating phase sensitively, ideally transferring the full SNR from the input to both outputs: $T_s + T_m = 2$. Figure 4 shows the measurement results as T_2 is varied. It can be seen clearly that the signal transfer is improved when the vacuum meter input is replaced by a squeezed beam, where $T_s + T_m$ reaches its optimum at $T_2 = 7.6\%$, resulting in $T_s = 0.69$ and $T_m = 0.43$. Much care was taken to operate the experiment at rf frequencies where the input beam was almost perfectly shot noise limited, as technical noise causes an overestimation of the transfer coefficients.

In summary, the two independent nonclassical properties of the OPA, i.e., operation as a state preparator and as a quantum optical tap, are shown in Fig. 5, slightly averaged for clarity. Both are improved by the injection of squeezed light into the meter port, demonstrating the value of squeezed light to overcome limitations of QND measurement systems. At present, the available crystal quality is the critical limitation of the experiment: bulk losses lead to both reduced normal QND performance and generated squeezing, and inhomogeneities cause phase front distortions and imperfect M_s and M_m. Reducing the losses to 0.06% appears possible for both OPAs and would then allow, at otherwise unchanged conditions, a 7.3 dB squeezed meter input and QND performance of $T_s + T_m = 1.49$ and $V_{m|s} = -7.0$ dB.

Aside from the proof of principle of improved QND measurements, this system was designed for long-time operation. Five hours of continuous and reliable operation were obtained using 13 servo loops. Reliability is a crucial feature for bringing QND measurements to the arena of applications, e.g., precision experiments requiring very long integration times or resolution beyond the standard quantum limit.

It is a pleasure to thank H. Hansen, J.-Ph. Poizat, R. Paschotta, G. Breitenbach, and H. J. Kimble for stimulating discussions and helpful suggestions. Financial support has been provided by ESPRIT projects BRA 6934 QUINTEC, LTR 20029 ACQUIRE, and the Optik-Zentrum Konstanz. R. B. was supported by a fellowship of the Studienstiftung des deutschen Volkes.

*Electronic address: http://quantum-optics.physik.uni-konstanz.de

[1] K. S. Thorne *et al.*, Phys. Rev. Lett. **40**, 667 (1978); V. B. Braginsky *et al.*, Science **209**, 547 (1980); C. M. Caves *et al.*, Rev. Mod. Phys. **52**, 341 (1980); special issue on QND measurements, Appl. Phys. B **64** (1997).
[2] B. Yurke, J. Opt. Soc. Am. B **2**, 732 (1985).
[3] M. D. Levenson *et al.*, Phys. Rev. Lett. **57**, 2473 (1986).
[4] A. La Porta *et al.*, Phys. Rev. Lett. **62**, 28 (1989); S. F. Pereira *et al.*, Phys. Rev. Lett. **72**, 214 (1994).
[5] P. Grangier *et al.*, Phys. Rev. Lett. **66**, 1418 (1991); J.-Ph. Poizat and P. Grangier, Phys. Rev. Lett. **70**, 271 (1993).
[6] S. R. Friberg *et al.*, Phys. Rev. Lett. **69**, 3165 (1992).
[7] D. S. Greywall *et al.*, Phys. Rev. Lett. **72**, 2992 (1994).
[8] K. Bencheikh *et al.*, Phys. Rev. Lett. **75**, 3422 (1995).
[9] R. Bruckmeier *et al.* (to be published).
[10] M. J. Collett and C. W. Gardiner, Phys. Rev. A **30**, 1386 (1984).
[11] J. H. Shapiro, Opt. Lett. **5**, 351 (1980).
[12] R. Bruckmeier *et al.*, (to be published).
[13] Z. Y. Ou *et al.*, Phys. Rev. Lett. **70**, 3239 (1993).
[14] P. Smith *et al.*, Opt. Commun. **102**, 105 (1993); Opt. Commun. **106**, 288 (1994).
[15] S. Schiller *et al.*, Europhys. Lett. **36**, 281 (1996).
[16] K. Schneider *et al.*, Opt. Lett. **21**, 1396 (1996).
[17] At a lower meter input squeezing level of 1.5 dB, the maximum meter output squeezing was 2.4 dB. This net noise reduction represents the first observation of sequential squeezing, achieved by operating two OPAs in series.
[18] M. J. Holland *et al.*, Phys. Rev. A **42**, 2995 (1990); J.-Ph. Poizat *et al.*, Ann. Phys. (Paris) **19**, 265 (1994).