Electronic noise-free measurements of squeezed light

Leonid A. Krivitsky[1,2], Ulrik L. Andersen[2], Ruifang Dong[1],
Alexander Huck[2], Christoffer Wittmann[1], and Gerd Leuchs[1]
[1] *Institute of Optics, Information and Photonics, Max-Planck Research Group, University Erlangen-Nuremberg, G. Scharowsky street 1, 91058 Erlangen, Germany*
[2] *Technical University of Denmark, Department of Physics, Fisikvej 309, 2800 Lyngby, Denmark*

We study the implementation of a correlation measurement technique for the characterization of squeezed light. We show that the sign of the covariance coefficient revealed from the time resolved correlation data allow us to distinguish between squeezed, coherent and thermal states. In contrast to the traditional method of characterizing squeezed light, involving measurement of the variation of the difference photocurrent, the correlation measurement method allows to eliminate the contribution of the electronic noise, which becomes a crucial issue in experiments with dim sources of squeezed light.

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The pioneering experiments of Hanbury-Brown and Twiss [1] on the implementation of the intensity interferometer, based on correlation measurements, offered great potentials in modern optics. Nowadays, this technique plays an essential role in the *discrete variables quantum optics*, where correlated photons are generated in various nonlinear optical processes. The observation of the simultaneous detection events (coincidences) from spatially separated single-photon detectors reveals the nonclassical correlation properties of the system. Such a correlation measurement strategy is indispensable in many quantum optical experiment such as tests of the foundations of quantum mechanics [2], quantum cryptography [3], and quantum metrology [4].

In *continuous variables quantum optics*, associated with the manipulation and detection of a continuous degree of freedom, a different measurement technique is traditionally implemented. The most common method here is balanced homodyne detection (HD), where the squeezed light is mixed on a symmetric beamsplitter with an auxiliary beam, denoted the local oscillator (LO) and the difference photocurrent of two analogue photodetectors is recorded [5] (Fig.1). This method represents the basis of optical homodyne quantum tomography, thus facilitating a complete reconstruction of the Wigner function. In fact, the potential of the HD has been proven in many experiments with continuous variable systems [6] and also in experiments with their discrete variables counterparts [7, 8]. However, the realistic HD setup suffers from optical losses and electronic noise (EN) of the detectors. These factors mask the nonclassical properties of the detected light and therefore limits the performance of the HD. However, detailed knowledge of the statistics of the optical loss and the EN allows to account for these effects, using special mathematical algorithms [6, 9]. As an alternative to this inference method one can directly measure the optical variance free from the EN using a correlation measurement method, commonly used in discrete variable quantum optics. Such a detector noise suppression technique has been applied to other areas [10] and its application to continuous variable quantum optics was proposed in [11]. Therefore, the present paper reports its experimental demonstration.

Characterization of squeezed light by correlation measurements was first theoretically proposed in [12]. Later, the correlation function of the output of the optical parametric amplifier was experimentally measured [13], where direct access to the photon number correlations was obtained using single photon detectors. An alternative approach was developed in [14], where correlations between different quadratures in HD setup were used to study the photon statistics of the optical parametric oscillator.

Let us consider a standard HD setup as shown in Fig.1. We express the field operator as $a = \alpha + \delta a$, where α represents the "classical" bright component and δa is an operator with zero mean value, describing the quantum fluctuations of the field amplitude. It is useful to introduce also the amplitude and phase quadratures, which are given by $X = 1/2(a^\dagger + a)$ and $Y = i/2(a^\dagger - a)$, respectively. We consider the input state to be a *squeezed vacuum* state. Following the standard formalism [15], and accounting for the EN, we derive the photocurrents of two detectors in each port of the beamsplitter:

$$i_{1,2} = 1/2\alpha_{LO}^2 + \alpha_{LO}(\delta X_{LO} \pm \delta X_\phi) + \delta i_{el1,2} \quad (1)$$

where α_{LO} is a mean field amplitude of the LO, $\delta X_\phi \equiv \cos\phi\delta X + \sin\phi\delta Y$ is an operator representing the quantum fluctuations of the tilted quadrature of the input beam, δX_{LO} is the amplitude quadrature of the LO and $\delta i_{el1,2}$ are stochastic numbers associated with the EN. In order to reveal the squeezing properties of the input beam, the variance of the difference photocurrent is traditionally recorded (onwards referred to as *the substraction method*). One obtains the following expression:

$$\langle (i_1 - i_2)^2 \rangle = 4\alpha_{LO}^2 \langle \delta X_\phi^2 \rangle + \langle \delta i_{el1}^2 \rangle + \langle \delta i_{el2}^2 \rangle. \quad (2)$$

From (2) it is clear, that the contribution from the EN always affects the substraction method. Thus, in case if the EN is prevailing over the optical signal, the measurement data would mainly represent EN. We also note that

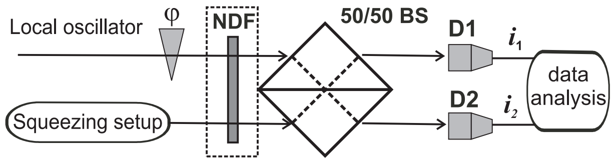

FIG. 1: The scheme of the HD setup. The beam from the squeezing setup is interfering with the LO on a 50/50 beam-splitter **BS**, ϕ is the phase of the LO, **D1** and **D2** are analogue photodetectors. Linear attenuation is introduced in both beams by the neutral density filter **NDF**. The produced photocurrents i_1 and i_2 are further analyzed by the computer.

the shot noise level (SNL) can be calibrated by blocking the input signal state, so that $\delta X_\phi \equiv \delta X_{vac}$ assuming $4\alpha_{LO}^2 >> \langle \delta i_{el1}^2 \rangle + \langle \delta i_{el2}^2 \rangle$.

As an alternative to the subtraction method we now investigate the correlation method. We obtain the following expression for the covariance coefficient of two photocurrents

$$\mathrm{cov}(i_1, i_2) \equiv \langle i_1 i_2 \rangle - \langle i_1 \rangle \langle i_2 \rangle = \alpha_{LO}^2 [\langle \delta X_{LO}^2 \rangle - \langle \delta X_\phi^2 \rangle], \tag{3}$$

where it is assumed that the EN of two detectors are not correlated, i.e. $\langle \delta i_{el1} \delta i_{el2} \rangle = \langle \delta i_{el1} \rangle \langle \delta i_{el2} \rangle$. As it is seen from (3) the covariance coefficient is completely independent on the EN due to the time averaging of the data and statistical independence of the noises of two photodetectors. For the sake of clarity, we now assume that the beam of the LO is shot noise limited, i.e. $\langle \delta X_{LO}^2 \rangle = \langle \delta X_{vac}^2 \rangle$. The analysis of the formula (3) suggests, that the sign of the covariance is determined by the statistics of the incoming light. Indeed, if the input state is squeezed, i.e. $\langle \delta X_\phi^2 \rangle < \langle \delta X_{vac}^2 \rangle$, then the covariance is positive. In contrast, if the input state is coherent, i.e. $\langle \delta X_\phi^2 \rangle = \langle \delta X_{vac}^2 \rangle$ then the covariance equals zero, and finally, if the input state exhibits classical excess noise, i.e. $\langle \delta X_\phi^2 \rangle > \langle \delta X_{vac}^2 \rangle$, the covariance is negative. Therefore, the sign of the covariance coefficient allows one to distinguish between different kinds of input states independently on the amount of EN, provided that one has information about the noise of the LO.

In our experiment we used a squeezing source based on the Kerr nonlinearity in an optical fiber, which is pumped by a femtosecond pulsed laser at the wavelength of $1.5\mu m$. Combining two orthogonally polarized quadrature squeezed beams with a fixed relative phase, we generated a special kind of two mode squeezed states (known as polarization squeezing) [16], where the squeezed beam and the beam of the LO have orthogonal polarizations and propagate in the same spatial mode. Therefore, the interference between the LO and the squeezed pulses is achieved by interfering them at the polarizing beam-splitter with a relative phase controlled by a half-wave plate. Schematically, our experimental setup is completely equivalent to the one shown in Fig.1, where the squeezed pulses and the LO propagate in different spatial modes and interfere on a symmetric beamsplitter. The two output beams of the beamsplitter are measured with PIN diodes. The phase of the local oscillator as well as the total attenuation of the two input beams were adjustable, as shown in the figure. In each experimental run we recorded the raw data from the two detectors by digitizing the AC components of the photocurrents. For this purpose we used a high-speed digitizer with a sampling rate of $20{*}10^6$samples/s whilst the bandwidth of the detected signal was restricted by the low-pass RF-filter with a full width at half maximum of 3MHz. We applied a simple Mathlab script to one and the same recorded data in order to calculate the covariance, and for comparison, the variance of the difference photocurrent.

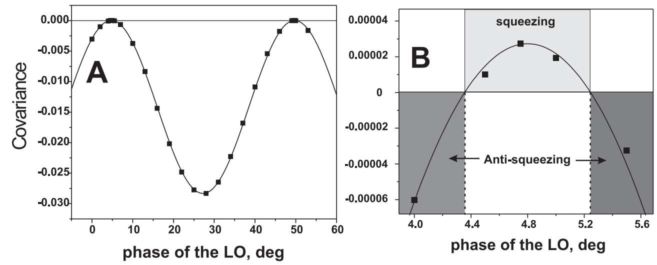

FIG. 2: Experimental dependence of the covariance versus the phase of the LO. (A) is the dependence on the full range of the phase variation and (B) is the magnified part of the dependence with the positive covariance. Light-gray shaded region corresponds to the measurement of the squeezed quadrature, whilst the dark-grey shaded region corresponds to the measurement of the quadrature exhibiting excess noise. The line represents the fit of experimental data.

We performed two series of measurements: the first one aimed at witnessing the squeezing and anti-squeezing by correlation measurements and the second one aimed at testing of the EN-free detection of the degree of squeezing.

Witnessing squeezing: The quadrature of the squeezed beam being observed by the detectors is controlled by the relative phase, ϕ, of the LO. Thus the phase of the LO determines whether correlation or anti-correlation between the detectors is measured. Measurements of the correlation coefficient through a scan of the LO is shown in Fig.2. In this measurement run the average power of the LO was set to 6mW, providing a 17dB clearance between the EN level and the SNL. The zero covariance was observed with the coherent beam of the same intensity. The positive covariance corresponds to the measurement of the squeezed quadrature, whilst the negative covariance corresponds to the measurement of the anti-squeezed quadrature. Note, that the modulus of the positive covariance values are much smaller than the negative ones, which suggests that the measured quantum state was not pure. The impurity arises from various linear and nonlinear effects in the optical fiber [17].

Electronic noise free detection: In the second series of measurements we investigate the influence of the measured degree of squeezing with attenuation of the signal

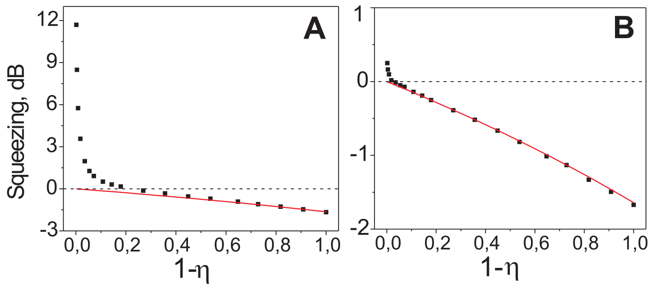

FIG. 3: Experimental dependence of the squeezing on the transmission $1-\eta$:(A) for the substraction method and (B) for the covariance method. Red solid line represents the theoretical dependence without accounting for the EN. Horizontal dashed line at zero defines a border between the squeezing and the classical access noise.

and LO by a neutral density filter (NDF). In case of a strong attenuation, the produced photocurrents carry a considerable amount of the EN relative to the optical noise. As mentioned above, this EN affects the subtraction method but it should not appear when the correlation coefficient is measured. We adjust the phase of the LO such as to minimize the detected noise variance (corresponding to a measurement of the squeezed quadrature). By using the standard subtraction method we obtain results of the degree of squeezing summarized in Fig.3A. The variances of the measured squeezed quadrature are normalized to the EN free SNL. To establish an EN free calibration of the SNL we perform noise measurements of a shot noise limited LO at very high powers where the optical shot noise dominates over the EN. Knowing the linear behavior of the shot noise, we subsequently extrapolated the data to yield a reliable (thus EN free) calibration of the SNL for all powers of the LO. From Fig.3A, we see that at maximum optical power, when the influence of the EN is negligible, we observed -1.65dB of squeezing. However, when the beams are strongly attenuated the EN starts to play a role and at a certain attenuation (about 80%), excess noise is observed thus indicating the dominance of the EN. For comparison, we also plot the expected squeezing of the state as it would be measured with an ideal EN-free detector as a function of the attenuation (solid traces in Fig.3).

We now use the correlation method to find the variance of the squeezed quadrature. After measuring the correlation coefficient, the variance is found from (3) with the shot noise calibration being identical to the one used above for the subtraction method. The results are presented in Fig.3B, where we also include the theoretically expected variances for noise-free detection (solid line). The theoretical curve is seen to fit the experimental data up to very low powers. Therefore, in contrast to the subtraction method, we see that the correlation method is less affected by the EN, even when the optical power is very low.

In the experiment we observe a small but non-zero background correlation coefficient stemming from the EN of the detectors, which turned out to be slightly correlated. Such a background correlation limits the ability to resolve squeezing at very low powers as seen from the discrepancy at high attenuations in Fig.3B. The correlation of the EN can be reduced by using completely independent acquisition systems for the two detectors unless the reason for this correlation is common pick-up of external electromagnetic signals.

In conclusion, we have experimentally realized a correlation measurement strategy that yields results that are free of EN of the detector. Using this method, we have witnessed the presence of squeezed noise and excess noise, and more importantly we have performed an EN free detection of squeezed light. The method is therefore a very interesting alternative to standard homodyne detector where EN may affect the measurements.

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[1] R. Hanbury Brown and R. Q. Twiss Nature 178, 1046-1048 (1956).

[2] M.A. Nielsen and I.L. Chuang, "Quantum Computation and Quantum Information", Cambridge Univ. press (Cambridge, 2000). D. Bouwmeester et al., "The physics of Quantum Information", Springer Verlag (Berlin, 2000).

[3] N. Gisin et al. *Rev. Mod. Phys* **74**, 145 (2002).

[4] A. Migdall, Phys. Today **52**, 41-46 (1999).

[5] Rodney Loudon *The Quantum Theory of Light* (Oxford University Press, 2000).

[6] M. Raymer and M. Beck, in "Quantum state estimation", edited by M.G.A. Paris and J. Rehacek (Springer-Verlag, Berlin, 2004) p. 235-295.

[7] A. Lvovsky et al., Phys. Rev. Lett. **87**, 050402 (2001).

[8] A. Zavatta, S. Viciani, M. Bellini, Phys. Rev. A **70**, 053821 (2004); V. Parigi et al., Science **317**, 1890 (2007).

[9] J. Appel, et al., Phys. Rev. A **75**, 035802 (2007).

[10] A. Van der Ziel, Noise in Solid State Devices and Circuits (Wiley, New York, 1986), p. 53.

[11] U. Andersen and G. Leuchs, Laser Physics **15**, 129 (2005).

[12] Z. Y. Ou, C.K. Hong and L. Mandel, Phys. Rev. A **36**, 192 (1987).

[13] M. Koashi et al., Phys. Rev. Lett. **71**, 1164 (1993).

[14] N. B. Grosse et al., Phys. Rev. Lett. **98**, 153603 (2007).

[15] H. Bachor and T. Ralph, "A Guide to Experiments in Quantum Optics" (2nd edition, Wiley, New York, 2004).

[16] J. Heersink, et al., Optics Letters, **30**, 1192 (2005).

[17] J. Corney et al., Phys. Rev. Lett. **97**, 023606 (2006).