Electronic noise-free measurements of squeezed light

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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\textsuperscript{1,2} 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 non-classical 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\textsuperscript{2}, quantum cryptography\textsuperscript{3}, and quantum metrology\textsuperscript{2}.

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\textsuperscript{2} (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\textsuperscript{2} and also in experiments with their discrete variables counterparts\textsuperscript{2,8}. 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\textsuperscript{2,8}. 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\textsuperscript{10} and its application to continuous variable quantum optics was proposed in\textsuperscript{11}. Therefore, the present paper reports its experimental demonstration.

Characterization of squeezed light by correlation measurements was first theoretically proposed in\textsuperscript{12}. Later, the correlation function of the output of the optical parametric amplifier was experimentally measured\textsuperscript{13}, where direct access to the photon number correlations was obtained using single photon detectors. An alternative approach was developed in\textsuperscript{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 \[ \hat{a} = \hat{\alpha} + \delta \hat{a} \], where \( \alpha \) represents the "classical" bright component and \( \delta \hat{a} \) 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 \[ X = \frac{1}{2}(\hat{a}^\dagger + \hat{a}) \] and \[ Y = \frac{i}{2}(\hat{a}^\dagger - \hat{a}) \], respectively. We consider the input state to be a squeezed vacuum state. Following the standard formalism\textsuperscript{13}, and accounting for the EN, we derive the photocurrents of two detectors in each port of the beamsplitter:

\[ i_{1,2} = 1/2 \alpha_{LO}^2 + \alpha_{LO} (\delta X_{LO} \pm \delta \phi) + \delta i_{1,2} \] (1)

where \( \alpha_{LO} \) is a mean field amplitude of the LO, \( \delta X_{\phi} = \cos \phi X + \sin \phi Y \) is an operator representing the quantum fluctuations of the tilted quadrature of the input beam, \( \delta X_{LO} \) is the amplitude quadrature of the LO and \( \delta i_{1,2} \) 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 (outwards referred to as the substraction method). One obtains the following expression:

\[ \langle (i_1 - i_2)^2 \rangle = 4 \alpha_{LO}^2 \delta X_{\phi}^2 + (\delta i_{11}^2 + \delta i_{12}^2). \] (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
the shot noise level (SNL) can be calibrated by blocking the input signal state, so that $\delta X_\phi \equiv \delta X_{\text{vac}}$ assuming $4\alpha^2_{\text{LO}} \gg \langle \delta i_\text{el}^2 \rangle + \langle \delta i_\text{el}^2 \rangle$.

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

$$\text{cov}(i_1, i_2) \equiv \langle i_1 i_2 \rangle - \langle i_1 \rangle \langle i_2 \rangle = \alpha^2_{\text{LO}} \langle \delta X_{\text{LO}}^2 \rangle - \langle \delta X_{\text{vac}}^2 \rangle,$$

where it is assumed that the EN of two detectors are not correlated, i.e. $\langle \delta i_\text{el} \delta i_\text{el} \rangle = \langle \delta i_\text{el} \rangle \langle \delta i_\text{el} \rangle$. 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. $\langle \delta X_{\text{LO}}^2 \rangle = \langle \delta X_{\text{vac}}^2 \rangle$. 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. $\langle \delta X_{\phi}^2 \rangle < \langle \delta X_{\text{vac}}^2 \rangle$, then the covariance is negative. In contrast, if the input state is coherent, i.e. $\langle \delta X_{\phi}^2 \rangle = \langle \delta X_{\text{vac}}^2 \rangle$, then the covariance equals zero, and finally, if the input state exhibits classical excess noise, i.e. $\langle \delta X_{\phi}^2 \rangle > \langle \delta X_{\text{vac}}^2 \rangle$, the covariance is positive. 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 1.5μm. 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) [14], 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 beamsplitter 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*10^9 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 Matlab script to one and the same recorded data in order to calculate the covariance, and for comparison, the variance of the difference photocurrent.

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, $\phi$, 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 correlation 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
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, the EN free detection of squeezed light. The method is therefore a very interesting alternative to standard homodyne detector where EN may affect the measurements.

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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