Detection of 13.8 dB squeezed vacuum states by optimizing the interference efficiency and gain of balanced homodyne detection

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Squeezed states belong to the most prominent non-classical resources. They have compelling applications in precise measurement, quantum computation, and detection. Here, we report on the direct measurement of 13.8 dB squeezed vacuum states by improving the interference efficiency and gain of balanced homodyne detection. By employing an auxiliary laser beam, the homodyne visibility is increased to 99.8%. The equivalent loss of the electronic noise is reduced to 0.05% by integrating a junction field-effect transistor (JFET) buffering input and another JFET bootstrap structure in the balanced homodyne detector.

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Squeezed states, which have fewer fluctuations in one quadrature than vacuum noise at the expense of increased fluctuations in the other quadrature[1], can be used to enhance the measurement precision[2–8], increase the detection sensitivity[9–12], and improve the fault tolerance performance for quantum information and quantum computation[13,14]. A pair of single-mode squeezed states can be used to generate a cluster state, which can be applied for greater information capacity and measurement-based quantum computation[14,15]. Moreover, the squeezed states have been used to increase the sensitivity of the gravitational wave detector by reducing the quantum noise[2,16]. All of these performance improvements strongly depend on the measured squeezing level. In terms of large amounts of quantum noise suppression, the optical parametric process has been proved to be the most successful one[17–23], which has continually held the highest squeezing strength record. Although the first experimental demonstration of squeezed states based on the optical parametric oscillator (OPO) succeeded in 1986[24], in the following two decades, the dedicated research could only achieve modest strengths of squeezing[23–27]. Until 2007, researchers at the University of Tokyo took a giant step forward and obtained a factor of 9 dB quantum noise reduction at 860 nm[22]. Under the motivation of gravitational waves detection, a 10 dB squeezed vacuum state was detected for the first time, to the best of our knowledge, at the University of Hanover[17]. Subsequently, the squeezing strength was gradually increased[18,19], reaching the maximum value of 15 dB at 1064 nm based on periodically poled $KTiOPO_4$ (PPKTP)[20]. With stronger squeezing, the applications of squeezed states will become more momentous. In ideal conditions, an infinite squeezing factor can be generated and detected at the threshold. However, the measured squeezing level is usually limited by photon loss during squeezed states generation, propagation, and detection[12,28–30]. The loss that occurs during the generation of the squeezed state is dependent of the escape efficiency of the OPO. The escape efficiency can be increased by reducing the reflectivity of the OPO output coupler. However, this is at the expense of a much larger OPO threshold, which is usually limited by the pump power of the laser source. The propagation loss is determined by the optical components losses from the OPO output to the photodetector (PD). The detection efficiency consists of the quantum efficiency of the photodiode, the equivalent loss of the electronic noise, and the interference efficiency of balanced homodyne detection (BHD). Quantum efficiency is the intrinsic parameter of the photodiode, which cannot be improved by optimizing the experiment parameters. Therefore, the interference efficiency and gain of the BHD become the crucial factors for stronger squeezing factor improvement. In this Letter, the visibility is increased to 99.8% by using an auxiliary laser beam technique, where the loss coming from the interference efficiency is reduced to 0.4%. The electronic noise of the PD is significantly reduced by a junction field-effect transistor (JFET) buffering input and another JFET bootstrap structure. The gain is increased to 33.5 dB at the local oscillator (LO) of 10.88 mW, where the equivalent loss of the electronic noise corresponds to 0.05%. As a result, a squeezed vacuum state with non-classical noise reduction of 13.8 ± 0.2 dB is directly observed.

The experimental setup is shown in Fig. 1. The laser is a home-made single-frequency laser at 1064 nm. Three mode cleaners (MCs) are used to improve the properties

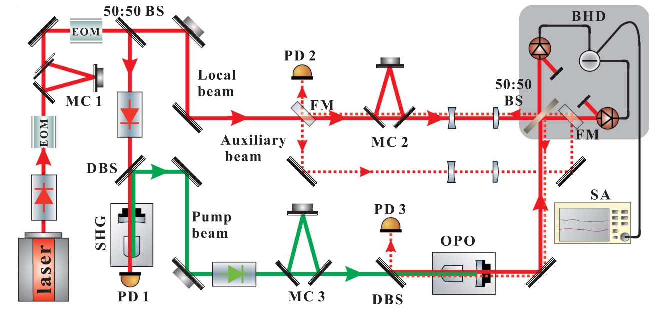

Fig. 1. Schematic of the experiment setup. Laser, home-made Nd:YVO_4 ring laser with 2.5 W continuous-wave single-frequency output power at the wavelength of 1064 nm; MC, mode cleaner; EOM, electro-optical modulator; FM, flip mirror; OPO, optical parametric oscillator; DBS, dichroic beam splitter; SHG, second harmonic generation; PZT, piezoelectric transducer; PD, photodetector; BHD, balanced homodyne detection.

of the laser beams, including the intensity noise and spatial distribution. The OPO is a semi-monolithic cavity consisting of a piezo-actuated concave mirror and a PPKTP crystal. The crystal end face used as the input coupler is coated with high reflectivity (HR) for the fundamental and harmonic fields. The concave mirror used as the output coupler has a transmissivity of 12%, which not only increases the escape efficiency of the OPO, but also confirms a modest threshold of 163 mW. The squeezed vacuum states are interfered with by an LO on a 50:50 beam splitter. The 50:50 beam splitter is placed in a 16 position indexing mount that can rotate all around the center with a step of 22.5°. The two output beams are directed toward a BHD to detect the noise level[30–32].

The mode overlap between the squeezed state and LO has to be perfectly matched to minimize the optical losses, which would decrease the squeezing performance[33,34]. During the process of the mode matching, the amount of optical components in the path of the squeezed field is minimized to reduce the propagation loss. Therefore, the mode matching of the two beams is only adjusted by the LO beam.

To adjust the interference efficiency, a bright beam transmitting from the OPO is usually needed. However, the OPO is an extreme impedance mismatch cavity that has very low transmittance, which is disadvantageous to achieve a high-efficiency homodyne visibility. Here, an auxiliary laser beam is employed and guided via the 50:50 beam splitter toward the output coupler of the OPO, whose transmission spectrum is monitored by PD3. Firstly, a lens assembly is positioned in the path between the 50:50 beam splitter and the auxiliary beam to meet the mode matching between the reflected auxiliary beam and the fundamental mode of the OPO. A mode-matching efficiency of 99.9% is experimentally obtained. Secondly, the transmitted auxiliary beam from the 50:50 beam splitter is aligned to match the fundamental mode of MC2 and obtain an efficiency of 99.9%. PD2 is used to measure the mode-matching efficiency. High-efficiency mode matching is achieved by the lens assembly positioned in the path between the 50:50 beam splitter and MC2. As a result, an interference visibility as high as 99.8% in the BHD is experimentally achieved.

The electronic noise of the PD can be equivalent to an additional optical attenuator with a transmission equal to η_e. The equivalent loss $1-\eta_e$ is dependent on the clearance between the shot noise of the laser beam and electronic noise of the BHD [signal to noise ratio (SNR)]. In order to reduce the influence of the electronic noise on the measured squeezed factor, the electronic noise should be decreased as far as possible. For a general PD, the transimpedance amplifier (TIA) has been widely used to convert the photodiode's current signal to a voltage one. However, the input voltage noise of the operational amplifier (op amp) in the TIA would affect the noise performance of the PD. To reduce the noise gain, it is necessary to keep the photodiode capacitance as small as possible[35,36]. Here, we adopt a JFET buffering input and another JFET bootstrap structure together to reduce the electronic noise. The scheme is shown in Fig. 2, in which a JFET buffering input is introduced to boost the input impedance of the op amp and reduce the input noise effectively. In addition, a JFET bootstrap structure replaces the junction capacitance of the photodiode to meet a smaller buffer amplifier. To confirm the observed squeezed strength, we check the linearity and SNR of the homodyne detection system by measuring the shot noise levels versus LO power at the analysis frequency of 2 MHz, which is shown in Fig. 3. LO powers changed by a factor of two entail a 3 dB shift of the corresponding shot noise trace, and it confirms that the detector is quantum noise limited and operates linearly in the measurement region. When the power of the LO is 10.88 mW, the clearance between the shot noise and electronic noise is 33.5 dB, corresponding to the equivalent loss of 0.05%. At this point, the influence of the electronic noise on the measured squeezed degree can be neglected.

Figure 4 shows the quantum noise levels of the squeezed state at the pump power of 133 mW as the LO phase is being scanned. The noise level is measured with a spectrum analyzer (Agilent Signal Analyzer N9020 A with electronic noise of −117 dBm) at the Fourier frequency

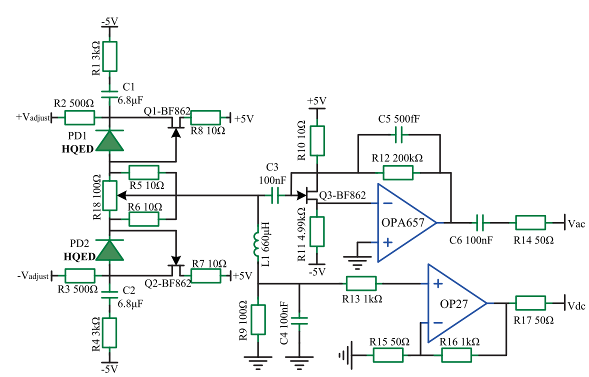

Fig. 2. BHD scheme based on a JFET buffering input and another JFET bootstrap structure. HQED, high quantum efficiency photodiode from Laser Components.

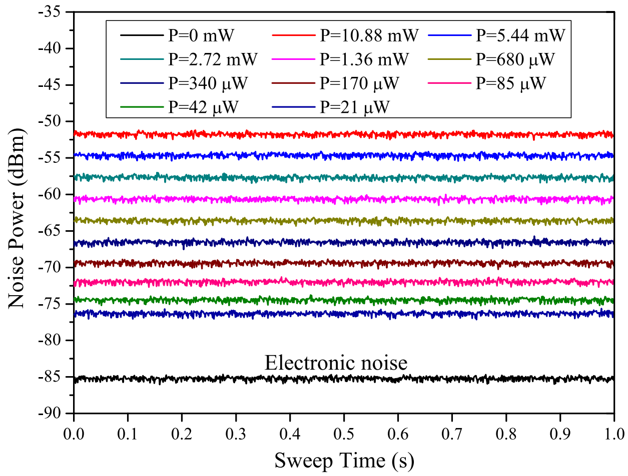

Fig. 3. Shot noise limit measurement with ten different LO powers.

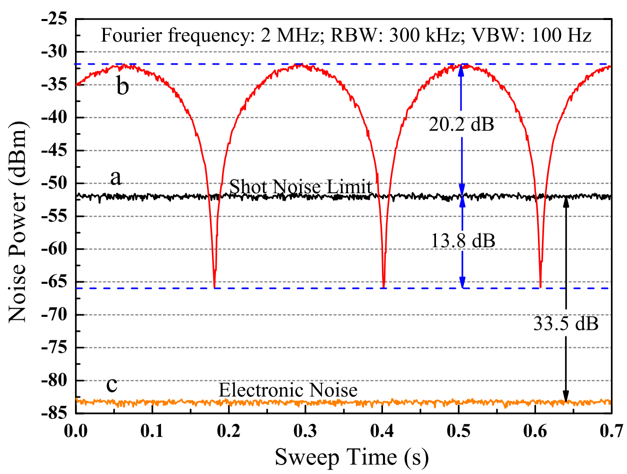

Fig. 4. Quantum noise levels of the squeezed and anti-squeezed state at the pump power of 133 mW as the LO phase is being scanned.

of 2 MHz, with a resolution bandwidth of 300 kHz, and a video bandwidth of 100 Hz. Trace a corresponds to the shot noise limit (SNL) of 10.88 mW LO power and is measured with the squeezed light input blocked, which corresponds to the quantum mechanical ground state of the light. Trace b shows the quantum fluctuations depending on the relative phase between the LO and squeezing beam, when the squeezed vacuum is injected. Trace c is the electronic noise, which is 33.5 dB below the SNL at the LO power of 10.88 mW. The measured squeezed noise level is 13.8 dB $\pm$ 0.2 dB below the SNL, and the anti-squeezed noise level is 20.2 dB $\pm$ 0.2 dB above the SNL. Increasing the pump power further cannot enhance the quality of the squeezed noise. However, if a higher escape efficiency with a higher transmissivity of the output mirror of the OPO is used, the quality of the squeezed noise can be further reduced at the expense of high power consumption.

We succeed in directly observing 13.8 dB $\pm$ 0.2 dB of squeezing and 20.2 dB $\pm$ 0.2 dB of anti-squeezing by using a home-made all-solid-state single-frequency laser as the pump source. At the low squeezed level, the squeezing factor is insensitive to optical and detection losses. The loss dependence becomes acute as the squeezing factor increases. Because the total loss is proportional to the square of the homodyne visibility, the homodyne visibility is a crucial factor for the strong squeezing level. We improve the homodyne visibility to 99.8% by employing an ingenious experiment, which is a very important process for accurately measuring the quantum noise suppression. At the same time, a JFET bootstrap structure is integrated into a JFET buffered TIA to effectively suppress the electronic noise of the PD, which is another key point of measuring high-level squeezing in our experiment. The generation of the high squeezing factor is of high relevance for the application in gravitational wave detection and quantum metrology.

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