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Determination of weakly squeezed vacuum states through photon statistics measurement

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ABSTRACT

Weakly squeezed vacuum light, especially when resonant with an atomic transition, plays an important role in quantum storage and the generation of various quantum sources. However, achieving a weak squeezing measurement with a precision better than 0.01 dB by means of typical homodyne detection (HD) is still very challenging due to the low signal-to-noise ratio and the limited resolution of HD systems. Here, we provide an alternative method based on photon statistics measurement to determine the weak squeezing of the squeezed vacuum light generated from an optical parametric oscillator (OPO) working far below the threshold, and we establish the relationship between the squeezing parameter and the second-order degree of coherence. The experimental results agree well with the theoretical analysis. The advantages of this method are that it provides a feasible and reliable experimental measure to determine weak squeezing with high precision and that the measurement is independent of the detection efficiency. This method can be used to measure other quantum features for various quantum states with extremely weak nonclassicality.

1. Introduction

As well-investigated nonclassical states of light, optical squeezed states are important sources for many applications related to quantum memory [1,2], quantum key distribution [3,4], precision measurement [5–7], quantum communication [8–10], and the interaction between light and atoms [11–13]. To date, considerable progress has been made in the generation, detection, and application of squeezed states, such as polarization squeezed states [14,15], photon number squeezed states [16], and higher-order squeezed states [17]. For different applications, researchers have generated squeezing in various wavebands, with wavelengths ranging from communication wavelengths to wavelengths corresponding to specific atomic transitions [18,19]. Currently, the highest squeezing that has been obtained is 15 dB, and it has significant applications in quantum metrology [20].

In contrast to strong squeezing generation via an OPO working near the threshold, weak squeezing can be generated when an OPO works far below the threshold. Such weakly squeezed vacuum light exhibits a strong photon bunching effect [21,22], which can be used to enhance multiphoton nonlinear light-matter interactions [23] and improve the visibility of ghost interference and imaging [24,25]. Meanwhile, weakly squeezed vacuum light plays a key role in the generation of various quantum sources [26], such as single-photon states [27], photon-pair states [28], and Schrödinger cat states [29]. Weak squeezing can also contribute to applications for quantum communication [30]. Moreover, a weak displaced-squeezed state exhibiting a photon antibunching effect has been prepared and measured, which is characterized by the nonclassical statistics of the weakly squeezed state [31]. In the abovementioned experiments, the squeezing parameter is a key factor affecting the performance of quantum state preparation and the nonclassicality, which are fundamental to quantum communication and precision measurement. It is thus very important to determine the squeezing parameter (i.e., squeezing degree) in the weak pumping regime.

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Squeezing is normally measured using an HD system [32]. However, achieving a weak squeezing measurement with a precision better than 0.01 dB by means of typical HD is still very challenging due to the low signal-to-noise ratio and the limited resolution of HD systems. On the other hand, the HD measurement is strongly affected by the total detection efficiency, and low efficiency can even cause the squeezing to deteriorate. Thus, the determination of weak squeezing is a problem that remains to be explored.

In this paper, we experimentally and theoretically study the determination of weak squeezing and establish a quantitative relationship between the squeezing parameter and the second-order degree of coherence. It is shown that if the second-order degree of coherence and the parameters of the OPO cavity have been measured, the squeezing parameter can then be determined with high precision. We have experimentally built an OPO system working far below the threshold and resonating with the waveband of the cesium D_2 line (852 nm) and have measured all related parameters. Weak squeezing of approximately -0.066 ± 0.001 dB is eventually determined. The experimental results can be well explained by the theory, and this method is independent of the detection efficiency.

2. Theoretical analysis

OPO is a workhorse for quantum source generation, and such devices has been investigated both theoretically and experimentally [32,33]. When an OPO works near the threshold, the optimum squeezed vacuum state is generated, and it shows an even photon number distribution. On the other hand, when the OPO works far below the threshold, the pump power of the OPO is generally less than 1% of the oscillation threshold [34–36], and a two-photon state can be prepared. The down-conversion rate of an OPO can be expressed as [35]

$$R = \varepsilon^2 \tau_F F^2 / \pi F_0, \tag{1}$$

where ε is the single-pass parametric amplitude gain, which is proportional to the pump amplitude and the nonlinear coefficient; $\tau_F = l/c$ is the round-trip time of the OPO cavity, with l being the cavity length and c being the speed of light; and $F = 2\pi/\tau_F(\gamma_1+\gamma_2)$ and $F_0 = 2\pi/\tau_F\gamma_1$ are the finesses of the cavity with and without the loss γ_2, where $\gamma_1 = T/\tau_F$, with T being the output coupler transmission of the OPO, and $\gamma_2 = L/\tau_F$, with L being the extra loss of the OPO. This indicates that the down-conversion rate is linearly proportional to the pump power since ε is proportional to the pump amplitude. The down-conversion rate can also be expressed as $R = kP$ [35], where P is the pump power of the OPO and k is a linear coefficient of the pump power. The down-conversion rate can be determined by measuring the number of photons generated from the OPO. The output light from an OPO working far below the threshold shows a photon superbunching effect. We employ the second-order degree of coherence at zero time delay, $g^{(2)}(0)$, to describe the photon statistical properties of the light field. $g^{(2)}(0)$ is equal to the normalized intensity correlation function at zero time delay, which can be expressed as [37]

$$g^{(2)}(0) = 2 + \frac{(\gamma_1+\gamma_2)^2}{\varepsilon^2}. \tag{2}$$

From Eqs. (1) and (2) and $R = kP$, we can obtain the relationship between $g^{(2)}(0)$ and the pump power of the OPO in the weak pumping regime, which is expressed as

$$g^{(2)}(0) = 2 + \frac{(\gamma_1+\gamma_2)^2}{\frac{4\pi F_0}{\tau_F F^2} kP}. \tag{3}$$

When an OPO works below the threshold, the output field of the OPO is generally described by a squeezed vacuum state, and the output squeezing level V_- and antisqueezing level V_+ are given by [38]

$$V_\pm = e^{\pm 2r} = 1 \pm \eta_{\rm esc} \frac{4\sqrt{P/P_{th}}}{(1 \mp \sqrt{P/P_{th}})^2 + 4\Omega^2}, \tag{4}$$

where r is the squeezing parameter and P_{th} is the oscillation threshold of the OPO. $P_{th} = \frac{(T+L)^2}{4E_{NL}}$, where E_{NL} is the single-pass nonlinear conversion efficiency. η_{esc} is the escape efficiency of the cavity, which is defined as $\eta_{esc} = T/(T+L)$, and $\Omega = 2\pi f/(\gamma_1+\gamma_2)$ is the normalized measurement frequency corresponding to the measurement frequency f. Therefore, from Eqs. (3) and (4), we can obtain the relationship between the squeezing parameter and the second-order degree of coherence in the weak pumping regime, which is expressed as

$$r = \frac{1}{2} \ln \left[1 + \frac{\frac{4\gamma_1 c}{(\gamma_1+\gamma_2)^2 l}\sqrt{\frac{2\gamma_1 E_{NL}}{k(g^{(2)}(0)-2)}}}{\left[1 - \frac{c}{(\gamma_1+\gamma_2)l}\sqrt{\frac{2\gamma_1 E_{NL}}{k(g^{(2)}(0)-2)}}\right]^2 + \left(\frac{2\pi f}{\gamma_1+\gamma_2}\right)^2} \right]. \tag{5}$$

From Eq. (5), we can see that the squeezing parameter r is related to the second-order degree of coherence $g^{(2)}(0)$. The squeezing can be determined when the experimental parameters γ_1, γ_2, l, E_{NL} and k are measured. In the weak pumping regime, the output of the OPO has a strong bunching effect and can easily be measured with high precision. Thus, the squeezing parameter can be determined.

3. Experimental setup and results

A schematic diagram of the experimental setup is shown in Fig. 1. We use an 852 nm tuneable CW Ti:sapphire solid laser produced by Msquare Co., and the laser frequency is locked to the D_2 line of the cesium atom using the polarization spectroscopy method. The periodically poled KTiOPO4 crystals used in the second harmonic generator (SHG) and OPO are type-I crystals produced by Raiol Co., and the sizes are 1 mm × 2 mm × 20 mm in the SHG and 1 mm × 2 mm × 10 mm in the OPO. The crystals are placed at the waist centres of the cavities, and the temperatures are precisely controlled to maintain optimum phase matching. Each cavity is composed of two planar mirrors and two concave mirrors. In the OPO cavity, the curvature radiuses of the concave mirrors are 50 mm, the distance between the concave mirrors is 59 mm, and the waist of the fundamental mode is 22.7 μm. The transmission of the output-coupling mirror is 11%, and a piezoelectric (PZT) element is bonded to one concave mirror to stabilize the cavity length. The E_{NL} of the crystal is 2% W^{-1}. The 426 nm pump light passes through the crystal once in the OPO cavity, and the mode-matching efficiency is 85%. The oscillation threshold of the OPO is 165.3 mW. A triangular ring cavity, with a fineness of 2000 and a bandwidth of 1.4 MHz, is used as a mode cleaner (MC) to reduce the noise of the Ti:sapphire laser. The 852 nm light passing through the MC is split into local oscillator light and probe light for the OPO. To lock the OPO cavity without importing the locking beam into the single photon counting module (SPCM) of the Hanbury Brown and Twiss (HBT) detection system, an 894 nm laser, made to resonate with the D_1 line of the caesium atom via the polarization spectroscopy method, is used as the locking beam, and this locking beam is blocked by an 852 nm narrow-bandpass interference filter. We use an avalanche photodiode (APD, C30659-900-R5B) to record the faint locking light signal. By tuning the modulation frequency, the sideband frequency of the

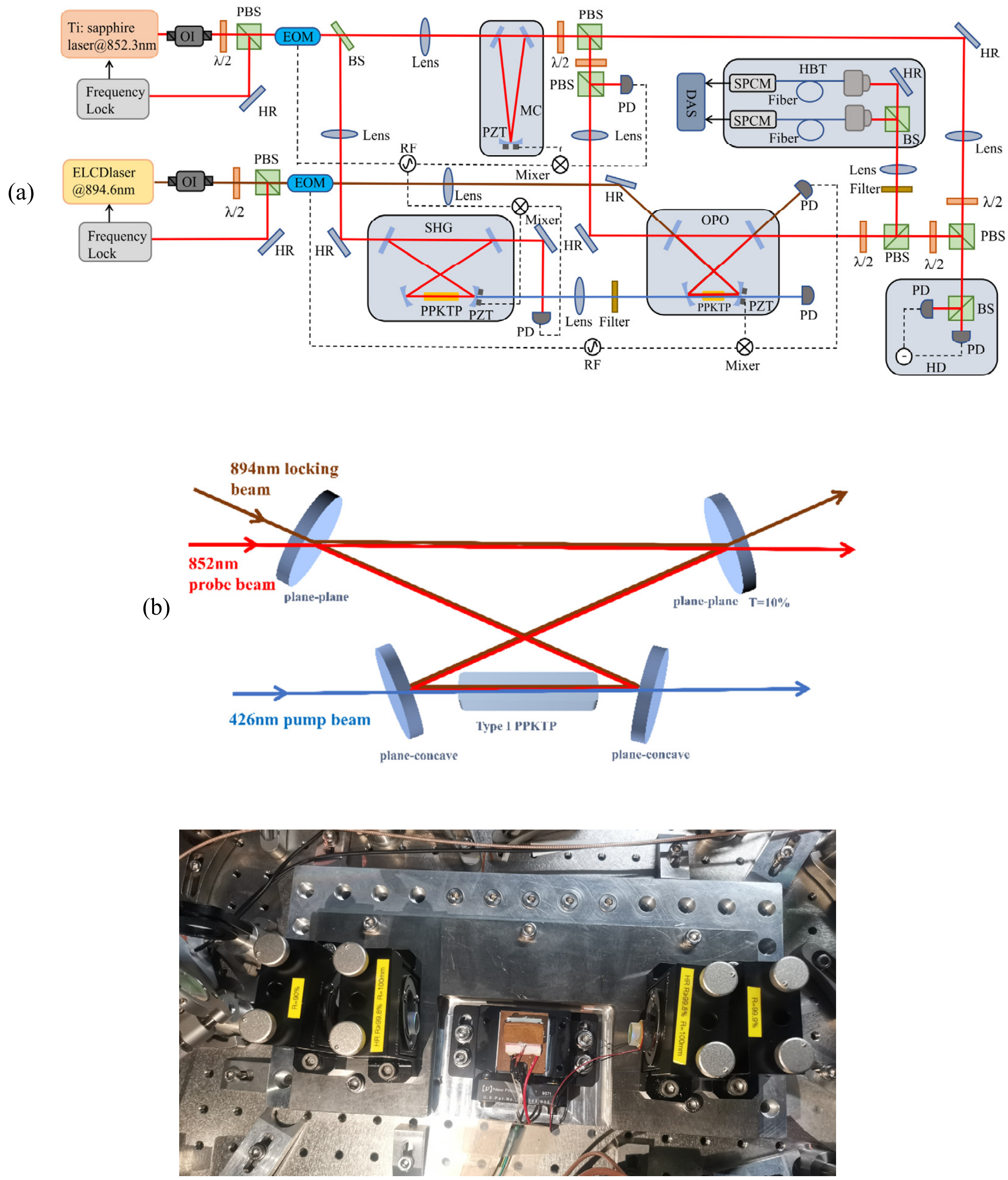

Fig. 1. (a) Schematic diagram of the experimental setup. OI: optical isolator; λ/2: half-wave plate; PBS: polarization beam splitter; BS: beam splitter; EOM: electro-optical modulator; HR: high-reflectivity mirror; DAS: data acquisition system. The dashed lines indicate the control electronics for the cavity length locking process. PD: photodetector; RF: radio-frequency source. (b) The configuration of the OPO and a photograph of the real system.

894 nm locking beam and the 852 nm probing beam are both simultaneously made to resonate with the OPO cavity and locked using the Pound-Drever-Hall technique [39].

The squeezed vacuum light generated from the OPO is divided into two parts: one is subjected to the HD scheme, and the other is subjected to the HBT scheme. We first study the squeezed light generated below the OPO threshold. Different from the output squeezing V_- and antisqueezing V_+ generated from the OPO, the observed squeezing level V'_- and antisqueezing level V'_+ by HD are given as follows [38]:

$$V'_{\pm} = \eta_{\text{det}} V_{\pm} + (1 - \eta_{\text{det}}) \tag{6}$$

where η_{det} is the total detection efficiency of HD, expressed as $\eta_{\text{det}} = \eta_{tr} \times \eta_{vis}^2 \times \eta_{qu}$, with the propagation efficiency $\eta_{tr} = 0.95$, the interference efficiency $\eta_{vis}^2 = 0.97^2$, and the photodiode quantum efficiency $\eta_{qu} = 0.99$. The escape efficiency of the cavity η_{esc} is 0.7. The detected normalized noise power in the experiment is shown as a function of the pump power in Fig. 2. The black squares indicate the experimental antisqueezed noise data, and the blue squares indicate the experimental squeezed noise data. The red curve is the theoretical result according to Eq. (6). The quantum noise limit reference was recorded using a local power of 2 mW with a blocked probe beam port. It should be noted that when the pump power is sufficiently weak, the corresponding squeezing is difficult to determine using this traditional HD method. As the pump power increases, the experimental results gradually deviate from the theoretical prediction due to the decrease in the escape efficiency of the OPO induced by the intracavity losses.

Now, let us investigate the photon statistics of the OPO output in the weak pumping regime, where the parameters γ_1, γ_2 and l are all determined from the comb-like structure of the second-order degree of coherence. The output of the OPO passes through an 852 nm narrow-bandpass interference filter and is divided into two paths by a 50/50 BS. The outputs are coupled into two SPCMs

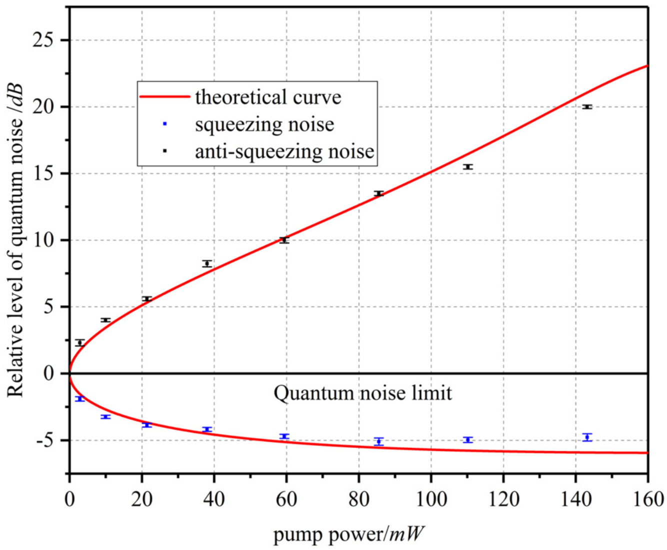

Fig. 2. Squeezing and antisqueezing versus the pump power. The solid curve represents the theoretical results, and the squares denote the experimental results. The analysis frequency is 800 kHz, with RBW = 100 kHz and VBW = 30 kHz. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

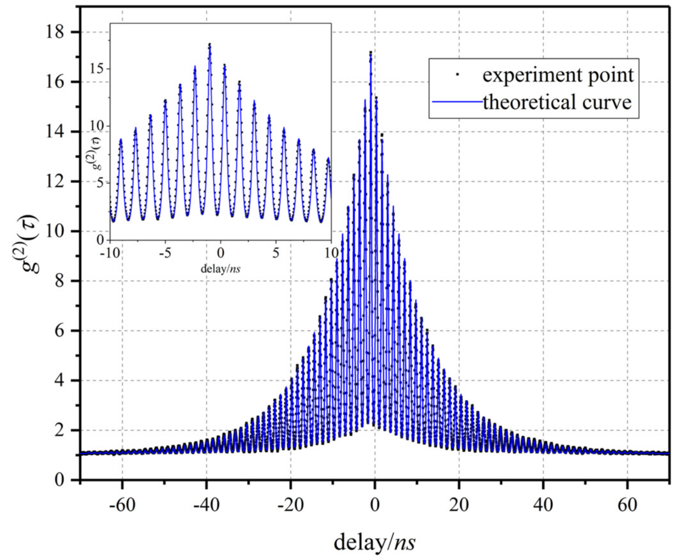

Fig. 3. Experimental results for the second-order degree of coherence. The solid blue line represents the theoretical results, and the black squares denote the experimental results. The inset shows the results for delay times from −10 ns to 10 ns. The pump power is 30 μW. The parameters are as follows: $N_1 = 16$, $N_2 = 0.064$, $\Omega_C/2\pi = 14.16$ MHz, $\tau_0 = -0.98$ ns, $\tau_R = 185$ ps, and $\tau_F = 1.34$ ns.

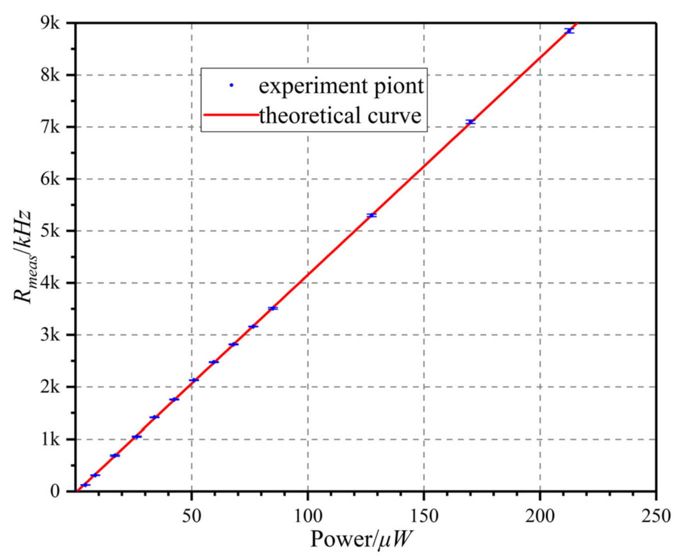

Fig. 4. Measured down-conversion rate R_{meas} versus pump power with a detection efficiency of $\eta = 0.4$. The solid red line represents the theoretical result, and the blue dots denote the experimental results. The error bars represent the statistical error from 5 measurements.

through an optical fibre. The maximum count rate of the SPCM is 25 Mcounts/s, and the quantum efficiency of the SPCM at 852 nm is approximately 50%. The dark count is less than 1 kcounts/s. The outputs of the SPCMs enter a data acquisition system (QuTag). The second-order degree of coherence in this case is expressed as [37]

$$g^{(2)}(\tau) = N_1 \left[N_2 + e^{-\Omega_c|\tau-\tau_0|} \sum_n \left(1 + \frac{2|\tau - n\tau_F - \tau_0| \ln 2}{\tau_R} \right) \times \exp\left(-\frac{2|\tau - n\tau_F - \tau_0| \ln 2}{\tau_R} \right) \right]. \quad (7)$$

Here, N_1 and N_2 are constants that are proportional to the pump power. τ_0 denotes the electronic delay, n is the number of nondegenerate modes, $\Omega_C/2\pi = (\gamma_1 + \gamma_2)/2\pi$ is the linewidth of the OPO, and τ_R is the resolution time of the detection system. It should be noted that the second-order degree of coherence shows a comb-like structure with a peak interval of $\tau_F = 2\pi/\Omega_F$. The measured experimental result for $g^{(2)}(\tau)$ is shown in Fig. 3. The pump light power is 30 μW. The resolution time of the DAS is 35 ps, and the bin count is 4000. The black squares indicate the experimental data, and the blue curve represents the theoretical result based on Eq. (7). According to the theoretical fit, we can determine the following parameters: $\gamma_1 = 82.1$ MHz, $\gamma_2 = 6.9$ MHz, and $l = 405$ mm. It should be noted that the important parameters of the OPO, such as the total loss corresponding to the linewidth, are determined by this measurement. We obtain a total loss of 11.5% for the OPO and a cavity bandwidth of 14.16 MHz with a cavity length of 405 mm.

To determine the value of k in Eq. (5), we measure the photon generation rate as the pump power varies. Fig. 4 shows how the measured down-conversion rate R_{meas} varies with the pump power. The solid line represents the theoretical result, and the blue dots denote the experimental results. The results indicate that R_{meas} increases linearly with the pump power. The generated rate of down-conversion by the OPO, $R = R_{meas}/\eta$, can be obtained from R_{meas} by considering the detection efficiency η, which is given by $\eta = tfd$. In the experimental system, the light transmittance from the OPO to the fibre is $t = 0.85$, and the fibre coupling efficiency is $f = 0.95$. The SPCM efficiency is $d = 0.5$. The background noise is also subtracted. We obtain $k = 104.5$ MHz/mW by analysing the experimental results.

As expected, $g^{(2)}(0)$ is inversely proportional to the pump power according to Eq. (3). We measure $g^{(2)}(0)$ versus the pump power for a certain detection efficiency $\eta = 0.4$. The photon statistics of the OPO working far below the threshold show a strong bunching effect, and $g^{(2)}(0)$ can be accurately measured via the HBT scheme. The results are shown in Fig. 5. The blue dots denote the experimental results, and the red curve is the theoretical result according to Eq. (3). The experimental data agree well with the theoretical curve. To determine weak squeezing, we must measure $g^{(2)}(0)$ as precisely as possible in the experiment. As shown in Fig. 5, the lower the pump power is, the larger the error bars for $g^{(2)}(0)$. When the pump power is less than 5 μW, the count rate of the SPCM is too low to obtain an adequately accurate

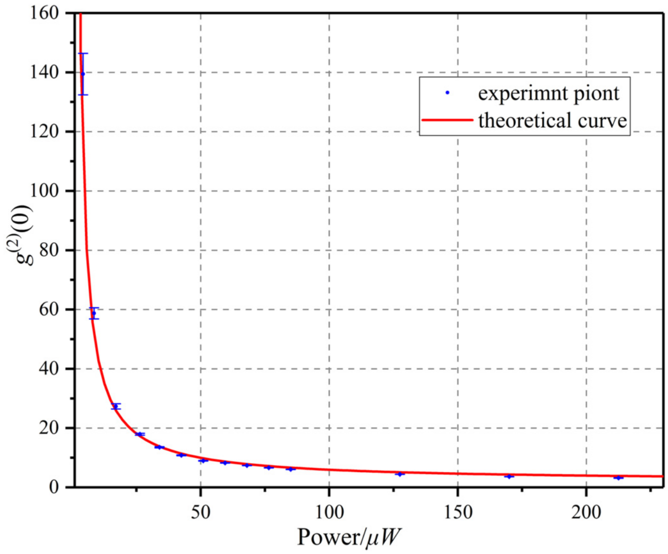

Fig. 5. Measured $g^{(2)}(0)$ versus pump power with a detection efficiency of $\eta = 0.4$. The red solid line represents the theoretical curve, and the blue dots denote the experimental results. The error bars represent the statistical error from 5 measurements.

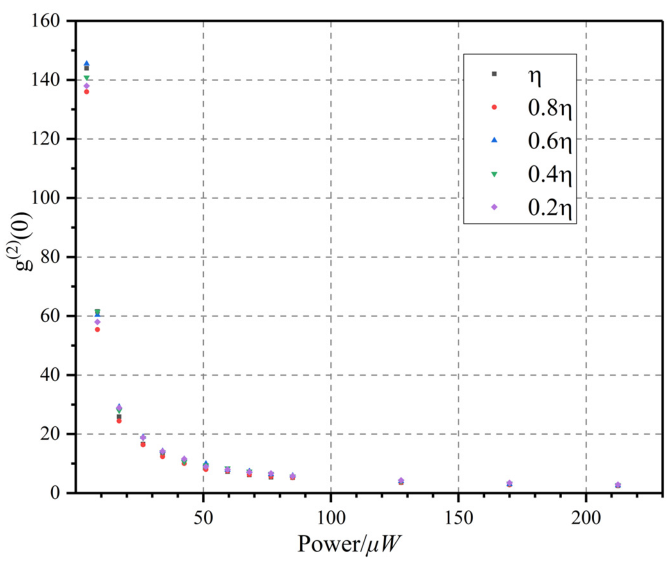

Fig. 6. Measured $g^{(2)}(0)$ versus pump power under different total efficiencies with a detection efficiency of $\eta = 0.4$. The coloured dots denote the experimental results.

$g^{(2)}(0)$ because of the inevitable background count rate. On the other hand, when the pump power is higher than 200 μW, the change in $g^{(2)}(0)$ as the pump power increases is not obvious, but the squeezing still gradually increases. Therefore, the method provided here to determine the squeezing parameter no longer works in this case. In summary, our detection scheme works effectively when the pump power is within the range of 5-200 μW. We also measure $g^{(2)}(0)$ versus the pump power under different detection efficiencies. The results, which are shown in Fig. 6, indicate that the measured $g^{(2)}(0)$ remains almost unchanged at a fixed pump power as the detection efficiency varies. Even if the total detection efficiency drops to 0.2η, the system still works for measuring $g^{(2)}(0)$.

Based on the above measurements, we eventually obtain the results for the squeezing parameter r in the case of working far below the OPO threshold, and the results when the pump power is in the range of 5 μW to 200 μW are shown in Fig. 7 (left side).

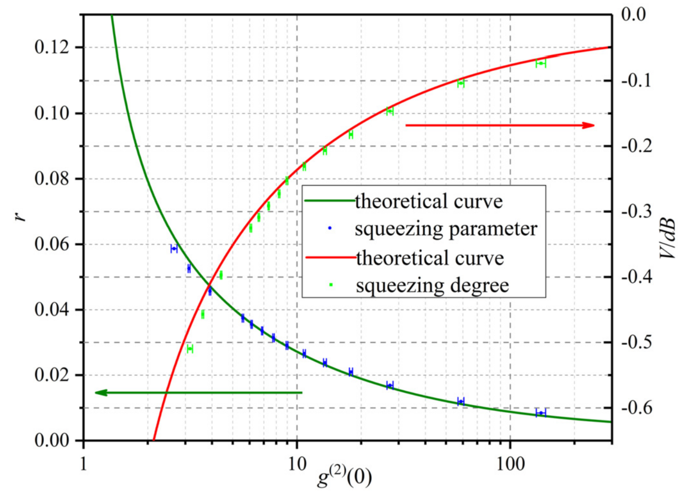

Fig. 7. Squeezing parameter versus the second-order degree of coherence with zero time delay, $g^{(2)}(0)$. The left vertical axis in the figure shows the squeezing parameter, and the right vertical axis shows the squeezing degree on a dB scale. The solid line represents the theoretical results, and the dots denote the experimental results, with error bars from 5 measurements. The corresponding parameters are $\gamma_1 = 82.1$ MHz, $\gamma_2 = 6.9$ MHz, $E_{NL} = 2\%$ W^{-1}, $l = 405$ mm, $k = 104.5$ MHz/mW and $f = 800$ kHz.

The solid line represents the theoretical results according to Eq. (5), and the dots are the experimental results. All parameters are determined from the experimental data, and the theoretical analysis is well consistent with the experiment. Since the photon statistics are very sensitive to the squeezing, which depends on the pump rate, a very small change in the pump power can result in a considerable change in $g^{(2)}(0)$. We can then infer the tiny change in the squeezing from the $g^{(2)}(0)$ measurement. The right side of Fig. 7 shows the squeezing on a dB scale. Weak squeezing of -0.066 ± 0.001 dB is eventually determined when the pump power is 5 μW. In the case of 200 μW of pump power, the squeezing is -0.54 ± 0.01 dB. Compared to general HD measurement, there are two advantages. First, the proposed method provides an alternative way to determine weak squeezing that is valid beyond the measurement limitations of typical HD detection. Second, in principle, this approach for determining the squeezing parameter is independent of the detection efficiency.

4. Conclusion

We have presented a feasible method for determining the weak squeezing parameter of an OPO based on photon statistics measurement. The relationship between the second-order degree of coherence and the squeezing parameter is established. An experiment has been performed by setting up an OPO system working far below the threshold and resonating with the waveband of the cesium D_2 line (852 nm). In cases of different pump rates and total detection efficiencies, we have measured the second-order degree of coherence of the squeezed vacuum light and proved that weak squeezing, along with strong bunching of the photon statistics, can be determined with high precision. This approach has advantages both for the verification of extremely weak nonclassicality and for the detection-efficiency-independent measurement of quantum light sources. This measurement approach based on photon statistics can be extended to correlations of even higher-order to reveal other quantum features of light fields [40,41].

CRediT authorship contribution statement

Guanhua Zuo: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Method-

ology, Investigation, Formal analysis, Data curation, Conceptualization. **Yuchi Zhang:** Methodology, Resources, Writing – review & editing. **Jing Li:** Writing – review & editing, Data curation, Software. **Shiyao Zhu:** Resources, Investigation, Conceptualization. **Yanqiang Guo:** Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing. **Tiancai Zhang:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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