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Detection of stably bright squeezed light with the quantum noise reduction of 12.6 dB by mutually compensating the phase fluctuations

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We present a mutual compensation scheme of three phase fluctuations, originating from the residual amplitude modulation (RAM) in the phase modulation process, in the bright squeezed light generation system. The influence of the RAM on each locking loop is harmonized by using one electro-optic modulator (EOM), and the direction of the phase fluctuation is manipulated by positioning the photodetector (PD) that extracts the error signal before or after the optical parametric amplifier (OPA). Therefore a bright squeezed light with non-classical noise reduction of π is obtained. By fitting the squeezing and antisqueezing measurement results, we confirm that the total phase fluctuation of the system is around 3.1 mrad. The fluctuation of the noise suppression is 0.2 dB for 3 h.

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Squeezed light is an important resource for gravitational wave detection [1,2] and quantum information technology particularly with continuous variables [3,4]. To increase the sensitivity and fidelity of these applications as much as possible, it is extremely important to have the ability to detect a high-level squeezed light.

Optical parametric oscillation (OPO) belongs to the most successful approaches of squeezed light generation [5–10]. Squeezed vacuum states have a good non-classical noise reduction at the low-frequency band [11,12]. However a squeezed vacuum has no coherent amplitude, there is no direct way to extract the error signals of locking the OPO cavity length and the relative phase, but additionally require another two coherent but frequency-shifted auxiliary beams to control [11]. On the contrary, it is simple to implement the control of the cavity length and relative phase in the generation system of bright squeezed light [13,14]. Which type of squeezed light is desirable is dependent on its applications. For example, bright squeezed light is necessary for the improvement of the sensitivities of spectroscopic measurement [15,16], velocimetry [17], LIDAR [18], and quantum key distribution [19,20].

As we know that optical losses can reduce the level of squeezing, the phase fluctuations further deteriorate the level of measured squeezing. Moreover, the impact of phase noise becomes acute as the optical losses are reduced [21,22]. In order to increase the measurable squeezing level, we should reduce the total loss as much as possible [8,9], as well as improve the performance of the control loops [23–25].

The modulation and demodulation method [9,23] is an option for locking the OPO cavity length and the relative phase. However, the modulation frequency is generally of the order of tens of kilohertz, which will produce a modulation noise in the squeezed light. The Pound–Drever–Hall (PDH) technique is another option of the frequency looking. An electro-optic modulator (EOM) is an essential component of the PDH technique. In practice, it is inevitable to have a small axis misalignment between the incident polarized and the principal axes of the electro-optic crystal. Each polarization component experiences different phase shifts, which can fluctuate with temperature and stress of the modulator crystal. Polarizing optical components downstream will thus convert the polarization misalignment into residual amplitude modulation (RAM) [26,27]. Due to the RAM, the drift of the locking point is inherent in each control loop, which can give rise to phase fluctuation. These fluctuations will shift the quadrature at the locking point relative to the squeezed quadrature and result in a reduction of the level of measured squeezing. The RAM in each loop can be independently reduced by employing an active servo control [28], a wedged electro-optic crystal [29], or a rhomboid-shaped crystal [30]. However, the squeezing level is limited not by the phase fluctuation of each loop, but the total phase fluctuation of the system.

In this Letter, we propose and report on a mutual compensation scheme of the phase fluctuations originating from RAM in a squeezed generation system. The influence of the RAM, from these locking loops, is harmonized by using one EOM, and the position of the photodetector (PD) relative to the optical parametric amplifier (OPA) is chosen to compensate mutually the phase fluctuations. As a result, a bright squeezed light with non-classical noise reduction of 12.6 ± 0.2 dB is directly observed. By fitting the squeezing and antisqueezing measurement results, the total phase fluctuation of 3.1 mrad is obtained. The fluctuation of the noise suppression is 0.2 dB for 3 h.

A schematic of our experimental setup is illustrated in Fig. 1. The laser source of our experiment is a home-made Nd:YVO_4 ring laser with 2.5 W continuous-wave single-frequency output power at 1064 nm. The laser transmits through a mode cleaner that provides spatial-temporal filtering, polarization purifying for the downstream experiment. Approximately 100 mW (30 mW) of the transmitted light is reserved to be used as the signal beam (local oscillator). The remaining light is used for second-harmonic generation to provide the pump field at 532 nm for our OPA. Another two mode cleaners are positioned in the beam paths of both the local oscillator (LO) and pump field to serve as an optical filter for phase noise, and the mode matching efficiency of these two fields at the downstream experiment can be kept to a high level by using an auxiliary cavity technique [31,32].

Our OPA is a semi-monolithic cavity consisting of a piezo-actuated concave mirror and a PPKTP crystal with the dimensions of 10 mm × 2 mm × 10 mm. The crystal end face with a radius of curvature of 12 mm is coated as high reflectivity (HR) for the fundamental field and high transmission for the pump field, thus serving as the cavity end mirror. The plane front face of the crystal is coated as antireflectivity (AR) for both wavelengths. An air gap of 27 mm length is realized between the AR-coated side of the crystal and the coupling mirror. The concave mirror with a radius of curvature of 30 mm has a transmissivity of 12% ± 1.5% for 1064 nm and HR for 532 nm, which is used as the output coupler.

The squeezed light, emitting out from the concave mirror, is separated from the pump light by a dichroic beam splitter and

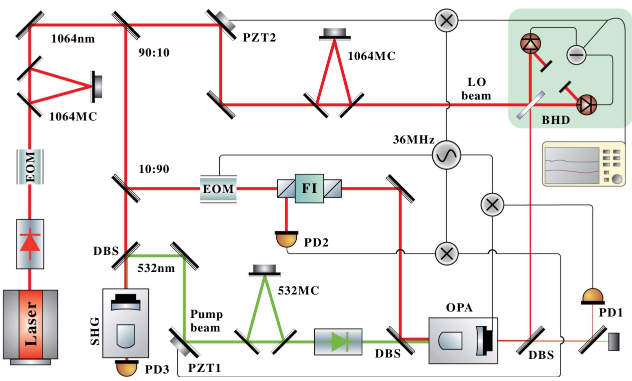

Fig. 1. Schematic of the experimental setup. SHG, second-harmonic generation; OPA, optical parametric amplifier; EOM, electro-optical modulator; MC, mode cleaner; DBS, dichroic beam splitter; FI, faraday isolator; PZT, piezoelectric transducer; PD, photodetector; BHD, balanced homodyne detection.

directed toward a balanced homodyne detection (BHD) to detect the noise level. The BHD, with the common mode rejection ratio of 75 dB [33], is built from a pair of p-i-n photodiodes (from Laser Components) with quantum efficiency of more than 99%. To recycle the residual reflection from photodiode surfaces, two concave mirrors with the curvature radius of 50 mm are used as retroreflectors.

On the basis of reducing the total loss of the system, the phase fluctuations should be as small as possible. In order to observe high-level amplitude squeezing, we need to lock the OPA cavity on resonance, lock the relative phase θ_{ps} between the pump and signal lights at π, and lock the relative phase θ_{ls} between the LO and the signal light at 0, respectively, by employing three servo-control loops. The lock point drifts from both the resonance points of the OPA and π phase of the θ_{ps} induces the rotation of the squeezing angle. If the deviation of the θ_{ls} from 0 has the same angle as the squeezing angle rotation, the total phase fluctuations can be mutually compensated, and therefore the most squeezing quadrature can be detected. If the deviation of the θ_{ls} from 0 has the opposite angle as the squeezing angle rotation, the total phase fluctuations are amplified, and the most squeezing quadrature cannot be detected. Although the squeezing angle rotation can be compensated by the θ_{ls} deviation, the fluctuation of the OPA does also induce the instability of the output power of the bright squeezed light. So it is also important to make efforts to cancel the fluctuation of the OPA.

For the previous squeezed generation system, each control loop has independent modulation to generate the error signal [9,14,15]. The inherent lock point drifts of these control loops are random; it is not enough to reduce the total phase fluctuation by considering separately each control loop. The fluctuation of the squeezed quadrature angle $\delta\theta_{\text{squ}}$ in detuning for a single resonant OPA is given below [22]:

$$\delta\theta_{\text{squ}} = \frac{\varepsilon \times \gamma_r}{\gamma_r \times (1 + x^2)}, \tag{1}$$

where γ_r is the cavity linewidth, x is the pump factor $\sqrt{P/P_{\text{th}}}$, ε is the parameter dependent of the RAM. The relative phase fluctuation $\delta\theta_{\text{ls}}$ is related to the amplitude ratio between the signal beam and the local oscillator, which can be expressed as

$$\delta\theta_{\text{ls}} = c \times \frac{E_s}{E_l} \times \varepsilon \times \pi, \tag{2}$$

where E_s and E_l are the amplitude of the signal beam and the local oscillator, respectively. c is a constant, dependent of the modulation depth and the intensity of the signal light in the generation system. Here, the c value is 10.7.

The relative phase fluctuation $\delta\theta_{\text{ps}}$ is dependent of the RAM and the parametric gain factor g, which can be expressed as

$$\delta\theta_{\text{ps}} = \pm c \times \frac{\varepsilon \times \pi}{\sqrt{g}}. \tag{3}$$

The $\delta\theta_{\text{ps}}$ fluctuation direction depends on the position of the PD relative to the OPA. When the PD is placed after the OPA, the right-hand side of the expression (3) is a minus sign. When the error signal is extracted from the light before the OPA, the expression (3) is a plus sign. If we adopt one EOM to generate the error signal of all of these locking loops, the fluctuation parameter ε originating from the RAM is consistent for these loops. However, for $\delta\theta_{\text{ps}}$, its fluctuation direction can be adjusted by changing the position of the PD relative to the OPA.

Based on the above analysis, we design the control scheme shown in Fig. 1, aiming to make the θ_{ls} follow the squeezed angle rotation coming from the lock point drift. The phase modulation signal, with the frequency of 36 MHz, is imprinted on the signal beam to generate an error signal for all three control loops, and as the only reference of the squeezed generation system. The signal beam is injected into the OPA through the crystal's back surface. The transmitted beam is separated (100 nW) by a dichroic mirror. The leaking of the fundamental wave from the dichroic mirror is detected by a resonant PD1, whose output is demodulated to generate an error signal for stabilizing the OPA cavity length on resonance. The backreflected light is separated from the incoming light by a Faraday rotator and a polarizing beam splitter and is detected by a resonant PD2 [34]. The generated ac photocurrent is mixed with the modulation signal to yield an error signal to lock the relative phase between the pump and the signal beams. By controlling the PZT1 on the optical path of pump beam, we make the signal beam intensity minimum, and the parametric process is locked at the most de-amplified phase. We lock a relative phase between the LO beam and the signal beam by demodulating the output signal of the homodyne detector with the modulation signal, to get an error signal for controlling the PZT2 on the optical path of the LO beam.

Based on the results on the RAM in [29], we can infer that the phase fluctuation originating from cavity detuning is approximately ±1.7 mrad for the gain factor of 0.9. The phase fluctuation between the pump and the signal beams is ±11.5 mrad or so when the parametric gain is 100. In our experiment, the power of the LO is 116 times as powerful as that of the signal light, and the phase fluctuation between the LO beam and the signal beam is about ±10.7 mrad. Adopting the compensation scheme presented here, in theory, the total phase fluctuation of the squeezed light generation system is about 0.8 mrad. However, without the compensation scheme, the total phase fluctuation may reach 22.2 mrad at worst.

Figure 2 presents the measured results of bright squeezed light at the pump power of 175 mW. All traces are measured by a spectrum analyzer (Agilent N9020A with the uncertainty of 0.2 dB). The power of the output squeezed light is 45 μW. Trace (a) corresponds to the shot noise of 5.5 mW LO power and is measured with the squeezed light blocked. Trace (b) shows the quantum noise reduction when squeezed states are injected. The directly observed squeezing level is 12.6 ± 0.2 dB. Trace (c) is a noise level with the LO phase scanned. The electronic noise of the homodyne detector is 28 dB below the shot noise and is not subtracted from the data.

We repeat the above measurement for several pump powers. The observed squeezing and antisqueezing levels are shown in Fig. 3. The measurements are performed at the pump power of from 25 mW to 195 mW with the step of 10 mW. Here, the contribution of the electronic noise is subtracted, corresponding to a maximum squeezing level of 12.8 dB. With the pump power of 65 mW, 8.7 dB squeezing with 9.7 dB antisqueezing are measured, which is close to the lower bound by Heisenberg's uncertainty relation. The generation of the pure state is of high relevance for the application in the generation of Schrodinger cat state. The absolute error of a given pump power is ±3% due to the measurement uncertainty of the power meter. More than 10 squeezing and antisqueezing factors are measured at each pump power, and the vertical error bars

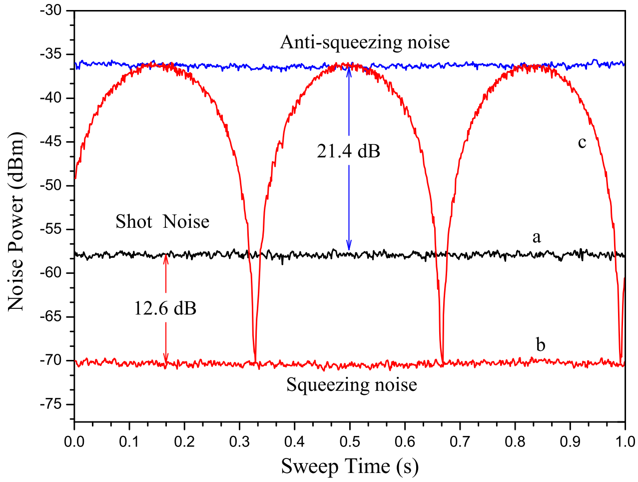

Fig. 2. Balance homodyne measurements of the quadrature noise variances. The measurement is recorded at a Fourier frequency of 3 MHz, with a RBW of 300 kHz and a VBW of 200 Hz. The data still include electronic noise, and represent direct observations.

are obtained by calculating the standard deviation of these results. Taking into account the OPA length $l = 37$ mm, the measurement frequency $f = 3$ MHz, the OPA (FWHM) linewidth $\kappa = 94$ MHz, and the threshold power $P_{th} = 220$ mW. We can fit for the total loss l_{tot} and the total phase fluctuation θ_{tot} using the expression (4):

$$V_{a/s} = \left[1 \pm \frac{4(1-l_{tot})\sqrt{P/P_{th}}}{\left(1 \mp \sqrt{P/P_{th}}\right)^2 + 4(f/\kappa)^2}\right]\cos^2\theta_{tot} + \left[1 \mp \frac{4(1-l_{tot})\sqrt{P/P_{th}}}{\left(1 \pm \sqrt{P/P_{th}}\right)^2 + 4(f/\kappa)^2}\right]\sin^2\theta_{tot}. \quad (4)$$

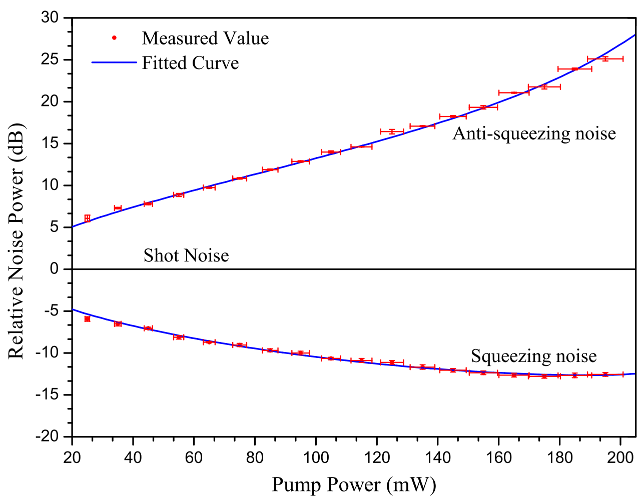

Fig. 3. Pump power dependence of antisqueezed and squeezed quadrature variances. All values are obtained from zero-span measurements at 3 MHz. In order to fit the numerical model, all the data are dark-noise corrected and subsequently normalized to the vacuum reference.

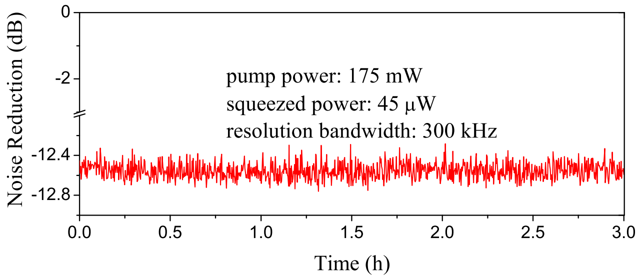

Fig. 4. Long-term stability of the bright squeezed light recorded continuously for 3 h, with a RBW of 300 kHz and a VBW of 27 Hz.

This obtains the following values: $l_{tot} = 0.049$, $\theta_{tot} = 3.1$ mrad. The result shows that the total phase fluctuation θ_{tot} in our squeezed generation system is only 3.1 mrad, which confirms that the compensating scheme is effective to reduce the total phase fluctuation. On the basis of available data [7,9,23], a squeezed vacuum state with non-classical noise reduction of 7 dB, 9 dB, and 12.3 dB is obtained, respectively, corresponding to the phase fluctuation of 68 mrad, 26.2 mrad, and 6.9 mrad. Limited by actual experiment parameters, the phase fluctuation is not thoroughly compensated. Assuming zero phase fluctuation, the squeezing level would theoretically approach 13.1 dB.

In order to evaluate more the compensation scheme, we record the long-term stability of noise suppression, and the noise of the bright squeezed light at a pump power of 175 mW is recorded continuously for 3 h. As shown in Fig. 4, the fluctuation of the noise suppression is 0.2 dB. According to the results of the squeezing and antisqueezing degree, we can calculate that the noise fluctuation is about 3 dB at worst without compensation. The results confirm that the compensation scheme is effective to reduce the phase fluctuation.

In conclusion, we have reported on a compensating scheme of the phase fluctuation of these control loops in the bright squeezed generation by using one EOM. The scheme harmonizes the variation of the phase difference between the slow and fast axes of the EOM of control loops compared with the independent modulation scheme. In combination with the position of the PD that extracts the error signal, we realize a bright squeezed light generation with a low phase fluctuation. A bright squeezed light with non-classical noise reduction of 12.6 ± 0.2 dB is directly observed. Taking the contribution of the electronic noise into consideration, this corresponds to a maximum squeezing level of 12.8 dB. By fitting the squeezing and antisqueezing measurement results, we confirm that the total phase fluctuation of the system θ_{tot} equals to 3.1 mrad. The fluctuation of the noise suppression is 0.2 dB in 3 h. Due to the complexity of the locking scheme for the squeezed vacuum generation, we did not analyze the feasibility of the scheme to generate the squeezed vacuum. In the future, we hope to propose a compensation scheme for the squeezed vacuum generation.

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