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Noise transfer of pump field noise with analysis frequency in a broadband parametric downconversion process

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Our previous work had proved pump field noise coupling in the seed field injected optical parametric amplifier (OPA) at a certain analysis frequency. Inspired by this noise coupling mechanism, the frequency dependent squeezing factor due to excess pump noise was experimentally demonstrated. Apart from a reduced squeezing level with an increased noise, the results also prove that a broadband squeezing noise spectrum is not frequency dependent on the amplitude modulated pump field, but limited by the bandwidth of the amplitude modulator and OPA resonator, and the effective measurement is carried out in the frequency range of 2–10 MHz. It provides a guidance to design a broader-bandwidth, higher-level bright squeezed light.

Keywords: quantum optics; nonlinear optics; parametric processes; squeezed states.

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1. Introduction

Squeezed states can be used to construct quantum entanglement as a resource of continuous-variable (CV) quantum information processing schemes like quantum teleportation[1], quantum key distribution (QKD)[2–4], and quantum computation[5–8]. In measurement-based quantum computation[6,7], broadband squeezed states can shorten the temporal length of virtual wave-packets and accelerate the processing rate, which makes it easy to construct the entanglement state with more spatial mode numbers. In CV quantum teleportation and QKD with frequency-domain multiplexing, a broadband entanglement state is essential to realize fast quantum processing and high key rate. Taking advantage of the reduced fluctuation of the squeezed state, the detection sensitivity of LIDAR can be enhanced by an assisted receiving technique in combination with the squeezed state[9]. The bandwidth of the squeezed states is the upper limit of the detection speed.

An optical parametric oscillator (OPO) can enhance the nonlinear effect by longitudinal confinement, which was demonstrated to be the most successful technology for high-level squeezed state generation[10–12]. To meet a high-level squeezing requirement, the optical loss should be reduced as much as possible[10,11], and stable control loops for the locking of the resonator length and relative phases should be constructed[12–14]. The bandwidth of squeezed vacuum states is dependent of the linewidth of the OPO, which is confirmed by the transmissivity of the output coupler and resonance length of the OPO. The cavity length should be shortened enough to broaden the linewidth, while the transmissivity should be a determined value to make a compromise between the bandwidth and threshold. A high-bandwidth squeezed vacuum has been experimentally obtained by adopting a monolithic or semi-monolithic cavity with a simple structure, which enables us to shorten the cavity length of the OPO to the fullest extent[15,16]. Subsequently, a triangle-shaped ring OPO was demonstrated to generate a broadband squeezed vacuum, which conveniently controls the relative phases and the resonance length.

Distinguished from the squeezed vacuum state generation, the presence of a coherent seed beam results in a squeezing degradation at low frequency in comparison with a case without a seeding because of technical noise coupling[17]. Further researches show that the squeezing factor is dependent of the noise of the pump beam and the power of the seed beam at a certain analysis frequency. Although the pump beam noise reaches the shot noise limit (SNL), the squeezing level degrades with the increase of the seed power with an enhanced noise coupling[18]. According to the motion equation of the OPO, the transfer coefficient of the pump noise coupling with the Fourier frequency is theoretically implied as $V^{\pm}_{\rm sqz}(\Omega) \sim a^2 C_p(\Omega) V^{\mp}_p(\Omega)/C(\Omega)$, where a is the amplitude of the seed beam, $V^{\mp}_p(\Omega)$ is the noise variance of the pump field, $C(\Omega)$ is directly related to the analysis frequency Ω, and $C_p(\Omega)$ is related

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to the nonlinear interaction process, linewidth (full width at half-maximum, FWHM) of the OPO (relating to the decay rates of the output and input coupler), and independent of Ω[18]. However, until now, no literature mentions the frequency dependence of the squeezing level on the pump beam noise with the presence of the seed beam, which is a major difference between the bright squeezed states and squeezed vacuum state.

In this Letter, we report on the dependence of the noise transfer of the pump beam noise on the analysis frequency in the generation process of bright amplitude squeezed states. By imposing an additional noise on the pump beam, the dependence of the squeezing factor in a certain frequency range is experimentally evaluated. Limited by the bandwidth of the actuator driven by a white noise source and the linewidth of the OPA, the effective measurement range is limited to 2–10 MHz. The result confirms that the influence of the pump beam noise on squeezing factor is insensible with the analysis frequency, where the frequency dependent noise coupling effect can be neglected in the actual squeezer, which provides a helpful reference for developing broadband, higher-level bright squeezed states.

2. Experiment Setup

Figure 1 is the configuration for the broadband squeezed state generation and noise coupling demonstration. A home-made single frequency laser is used as the pump source of the optical parametric amplifier (OPA), and its output power is 2 W at the wavelength of 1064 nm. The three mode cleaners (MCs) are used as a low pass filter for the laser intensity noise and the spatial fundamental mode, also purifying the laser polarization and assisting to complete a high-efficiency mode-matching for the downstream experiment. Three electro-optical modulators (EOMs) are inserted in the optical path before MCs and OPA, which are used to modulate the phase sideband frequencies as reference for locking the cavities to resonance with the injected laser beams. An electro-optic amplitude modulator (EOAM, Thorlabs, EO-AM-NR-C4) is installed in the light path between the 532MC and OPA, to manipulate the intensity noise of the pump beam. After the MCs, both the seed and pump beams' amplitude noise overlaps with SNL beyond the analysis frequency of 1.5 MHz. The results make sure that the noise floor of the laser has no disturbance on the frequency dependent squeezing measurement. A function generator is connected with the EOAM placed in the optical path of the pump beam to manipulate the intensity noise of the pump beam. A Faraday isolator (FI) isolates the OPA cavity from the backscatter of the photodetectors. The squeezed light is injected into balanced homodyne detection (BHD) to diagnose its quadrature noise level. A folding mirror (Newport, 1EA) is fixed after the EOAM to switch the pump beam injected into the OPA and the amplitude noise measurement for the pump beam (10 mW).

The OPA is composed of a periodically poled titanyl phosphate (PPKTP) crystal and a piezo actuated concave mirror, whose parameters are identical to those in Refs. [11,12], with a linewidth of 67 MHz, and the pump power (144 mW) is fixed to 80% of the threshold power (180 mW). The seed beam power is 25 mW. During the experiment for noise coupling measurement, no experimental parameters except for the pump beam intensity noise are varied by introducing white amplitude noise. A dichroic beam splitter is used to separate the squeezed light from the pump beam, and the squeezing one is injected into the BHD for quadrature noise detection. The common mode rejection ratio of the BHD is 75 dB[19,20], which guarantees no contamination of the amplitude noise of the local beam to the squeezed quadrature.

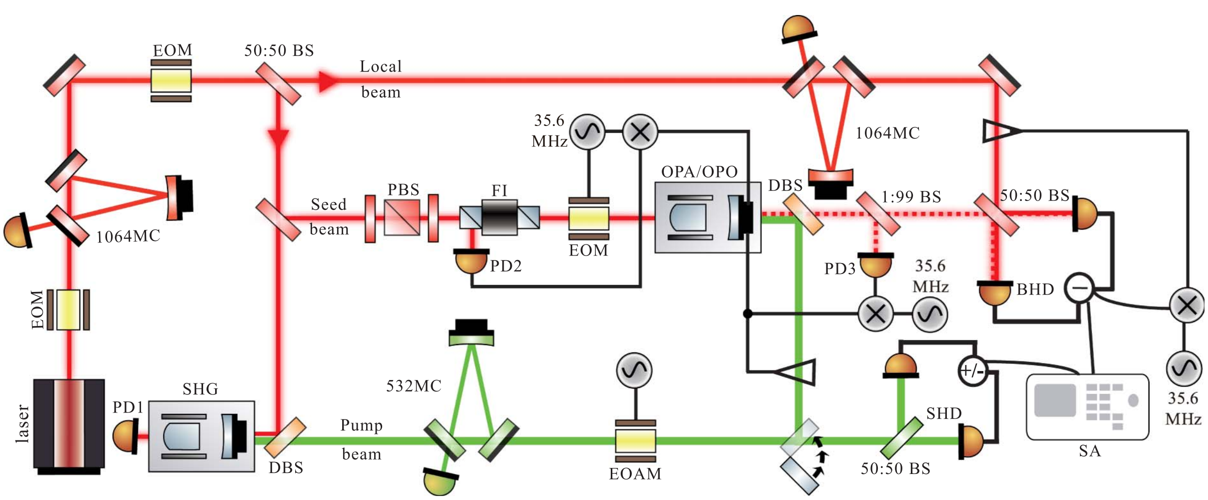

Fig. 1. Configuration of the squeezed state generation. FI, Faraday isolator; MC, mode cleaner; SHG, second harmonic generation; OPO, optical parametric oscillator; OPA, optical parametric amplifier; PBS, polarization beam splitter; DBS, dichroic beam splitter; EOM, electro-optical modulator; EOAM, electro-optic amplitude modulator; PZT, piezoelectric transducer; PD, photodetector; BHD, balanced homodyne detection; SHD: self-homodyne detection.

3. Experiment Results

The frequency dependent squeezing factor actuated by the EOAM in the pump field was measured and analyzed experimentally. To simulate broadband excess noise with constant amplitude on the pump beam, a white noise function generator (RIGOL, DG4202, bandwidth of 100 MHz) is introduced to drive the EOAM. Firstly, the direct output of the generator was measured, whose noise spectrum is shown in Fig. 2-I, and presented a flat noise distribution for each of the four cases (a)–(d). Secondly, the function generator is used to actuate the EOAM, but the bandwidth of the modulated optical field is localized to 10 MHz, as shown in Fig. 2-II. Self-homodyne detection[21] is used to fabricate the noise variance of the pump beam, which consists of a 50:50 beam splitter and two low noise detectors[20]. The two detectors must have the same bandwidth and electronic gain. The subtraction of the outputs of the two detectors corresponds to the SNL of the injected beam, and the sum of the two is its amplitude noise. Case (a) corresponds to no amplitude modulation measurement for a 10 mW pump beam, and its amplitude noise variance is shot noise limited, which is attributed to the two MCs in the fundamental and second harmonic optical paths. For cases (b)–(d), the modulated optical noise is flat within 10 MHz for a certain modulated amplitude, but decays quickly above 10 MHz, which forms the upper limit for the frequency dependent squeezing measurement on the amplitude noise of the pump beam. The possible cause is that the EOAM only responds to a broadband modulation (100 MHz) for the sinusoidal waves, while a white noise source only contains a small portion of sinusoidal waves in its outputs, which limits the bandwidth of the modulated optical field. Meanwhile, due to the higher amplitude noise of the seed beam at lower frequencies and the finite linewidth of the OPA, a constant squeezing level is limited to 2–10 MHz, as shown in Fig. 3 case (a). Therefore, for certain modulated amplitudes, to prevent the variation of the squeezing factor or modulated optical amplitude noise from influencing the frequency dependent quadrature noise measurement, all of the squeezing data are compared in the Fourier frequency range of 2–10 MHz.

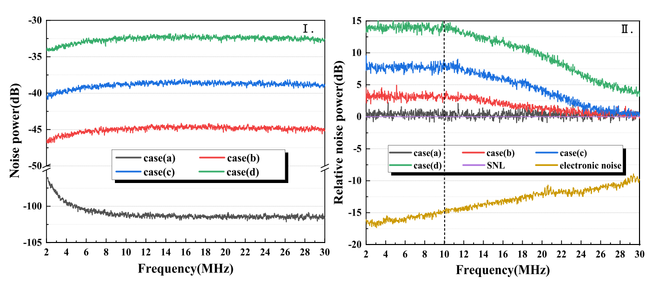

Fig. 2. Experimental results of the white noise direct output from the function generator and quadrature amplitude variances, with frequency for different pump beam noises, which are measured with the self-homodyne method. Case (a), without amplitude modulation; an amplitude modulation of 400 mV for case (b), 800 mV for case (c), and 1600 mV for case (d). RBW: 300 kHz and VBW: 200 Hz.

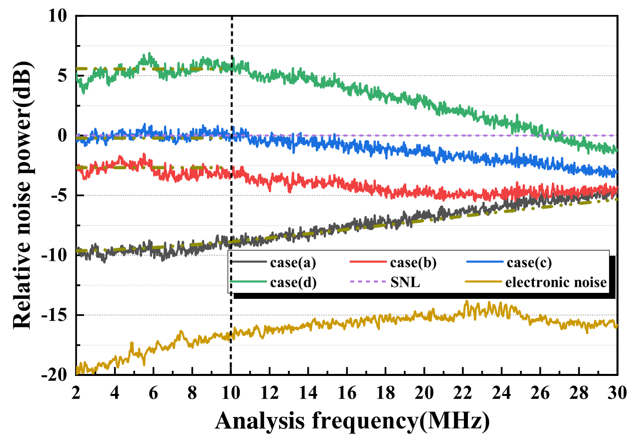

Fig. 3. Experimental results of the amplitude squeezed quadrature noise with the variation of pump intensity noise at the Fourier frequency from 2 MHz to 30 MHz. RBW: 300 kHz and VBW: 200 Hz.

Under the squeezing generation, 25 mW of the seed beam is injected into the OPA for stable locking of the relative phase between the seed and pump beams and the cavity length. The relative phase is locked to out of phase for the generation of amplitude squeezed states. In order to analyze the frequency dependent noise coupling effect, the initial squeezing factor should be a constant value in the measured sideband frequency range and the white noise modulated optical amplitude is also constant. Otherwise, it cannot separate the frequency dependent squeezing factor from the modulated excess noise. Figure 3 presents the measurements of the squeezing noise in the Fourier frequency of 2–30 MHz with BHD technology, and all the noise spectra are also normalized to the SNL of a 10 mW local beam. With the increase of the modulated amplitude of the EOAM, the quadrature amplitude squeezing decreases gradually, on account of the noise coupling between the pump field and seed one. When the excess noise is large enough, the noise reduction disappears and tops the SNL. The results show that the squeezing factor stays constant for certain modulated amplitudes in the frequency range of 2–10 MHz. But, the noise variance changes from −10 dB below SNL to about 5 dB above SNL when the output amplitude of the actuator increases from case (a) to case (d). That is to say, the squeezing level is independent of the frequency for a constant excess noise. However, the noise spectrum shows a frequency dependent feature above 10 MHz. In this frequency range, the modulated amplitude of the pump beam decays quickly due to a limited bandwidth of a white noise modulation process. Therefore, a non-normal variation trend for the noise spectra [cases (b)–(d)] was observed. In case (a), the frequency dependent noise spectrum ($>$ 10 MHz) is due to a larger detuning noise coupling at higher sideband frequency, in which a smaller number of photons at higher frequency escaped from the OPA[15,16]. The finite bandwidth of the OPA is responsible for this frequency dependent broadband noise spectrum [case (a) in Fig. 3]. The theoretical model in Refs. [17,18] was used to fit the experimental data in Fig. 3 (the dash dot line). Case (a) was well fitted with the experimental results. Cases (b)–(d) were fitted in the frequency range of 2–10 MHz because of the nonlinear modulated noise spectrum above 10 MHz. These results also confirmed a frequency independent noise coupling effect at a certain modulated amplitude noise of the pump beam.

Incorporation with the results of Fig. 3 cases (a)–(d), it can be concluded that the amplitude squeezing factor degrades significantly due to the noise coupling effect of the pump field to the seed one, i.e., the squeezing noise level is sensitive to the pump noise. However, the noise coupling effect is insensitive to the Fourier frequency for a certain excess pump noise, and the frequency dependent amplitude noise reduction is only attributed to the bandwidths of the squeezed state generation, white noise modulated bandwidth, and detection (not the limitation of our case) processes. It provides guidance for the design of high-bandwidth and high-level bright amplitude squeezed light.

4. Conclusion

We demonstrate the dependence of the amplitude squeezing factor of bright squeezed states on the pump beam intensity noise in a broad sideband frequency range. The results indicate that the squeezing factor is sensitive to the amplitude noise coupling between the pump and seed fields with an increased modulated amplitude noise from −10 dB below SNL to 5 dB above SNL for a modulated optical noise from case (a) to case (d). But, for a certain modulated amplitude noise, the noise coupling of the pump field to the squeezing one is independent of the analysis frequency if the initial squeezing factor is not frequency dependent, i.e., the frequency dependent pump noise coupling implied by the theory model can be neglected in an actual squeezing generation. The frequency dependent amplitude noise reduction is only related to the frequency bandwidth of the OPA, the modulated white noise, and BHD, which will provide guidance for designing broader band, higher-level bright amplitude squeezed light.

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