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Investigation of residual amplitude modulation in squeezed state generation system

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Abstract: We present an analysis on how the optical parametric oscillator (OPO) detuning and the relative phase drift deteriorate the stability of the squeezed states, including the output power and the squeezed degree, and investigate the influence of RAM on the cavity detuning and the relative phase drift under different cases. Subsequently, the RAM is experimentally measured. In term of the measurement results, we perform a comparative study about RAM's influence on the cavity and phase locking in two cases. As a result, with the error signal extracted from the transmission of the OPO, the output power stability of the squeezed light is greatly improved. With the phase modulation imposed on the signal beam, the long-term stability of the squeezed degree is significantly enhanced.

1. Introduction

Squeezed states of light with a smaller variance in squeezed quadrature and a larger variance in anti-squeezed quadrature are an important resource for reducing the quantum noise. The high level of squeezed states can not only increase the sensitivity of laser interferometer measurement [1-3], but also improve the fidelity of quantum information processing [4,5]. There are a few methods for the generation of squeezed states [6-8], but the optical parametric oscillation (OPO) has been proved to be the most efficient path for generating the squeezed light [9-12]. Since the squeezed state was firstly generated based on the OPO, the experiments have been further optimized and the squeezing level upto 15 dB has been achieved [13]. Currently, interest has been moved away from the proof of principle experiments to the construction of robust squeezing sources with long term stability. Many researches show that the main challenge of improving the stability is the phase noise in low frequency band [14,15].

In the practical implementation of squeezing generation, servo-control loops are required to lock the OPO cavity length, the relative phase between the pump and signal beams, and the relative phase between the local oscillator (LO) and the signal beam. The Pound-Drever-Hall (PDH) locking technique is an essential method for carrying out the servo-control [16]. In PDH locking loops, an electro-optic modulator (EOM) is usually used to perform the phase modulation in which a residual amplitude modulation (RAM) is inevitably generated, resulting in locking point drift with external environment. The locking point drift can be equivalent to the phase noise. The impact of phase noise becomes acute as the optical loss is reduced, so the RAM will make the squeezed degree fluctuate acutely with time under the circumstance of highly squeezing level [17].

The RAM originates from the inevitable axis misalignment between the incident polarized and the principal axes of the electro-optic crystal, each polarization component experiences different phase shift, which will fluctuate with temperature and stress of the modulator crystal. Polarizing optical components downstream will thus convert the polarization misalignment into RAM [18]. Some passive and active RAM suppressions have been presented to improve

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the system performance in the spectroscopic technique and the laser frequency stabilization [19-25]. However, the squeezed state generation system is distinguished from the laser frequency stabilization in two aspects: (1) OPO is a severe impedance mismatch and large-linewidth cavity; (2) The relative phase between two beams with large amplitude difference is required to stabilize. The influences of the RAM on the cavity detuning and the phase drift present some new phenomena compared with the laser frequency stability. A comprehensive understanding of the influences of the RAM on the cavity detuning and phase drift can provide guidance on the analysis of the related systematic effects, and will be beneficial to the optimization of experimental parameters for a maximum amount of RAM suppression, in squeezed state generation with high squeezed degree as well as with long-term stability. Furthermore, such analysis will aid the development of alternative RAM-reducing approaches for squeezed state generation with long term stability.

In this paper, we systematically analyze the influences of the OPO cavity detuning and the relative phase drift on the long-term stability of the squeezed degree. In terms of the features of the OPO, we quantitatively evaluate the OPO cavity detuning difference, while extracting the error signal from the reflection and transmission of the OPO, respectively. Due to the large amplitude difference between the LO and the signal beam, we investigate the difference of the relative phase drift, when the phase modulation is imposed on the two beams, respectively. Combining with the experimental results of the RAM, the OPO detuning and the relative phase drift, originating from the RAM, are inferred. When the error signal is read from the transmission of the OPO, the detuning is about 1/640 of that from the reflected. When the phase modulation is imposed on the signal beam, the phase drift is far less than that of phase-modulated LO, the scaling factor depends on the power ratio between the two beams. As a result, the stability of the squeezed states, including the output power and the squeezed degree, can be greatly improved by these RAM-reducing approaches, which is benefit for the generation of long-term stable squeezed state.

2. Influence of the phase noise on squeezed degree

In this section, a theoretical description of the phase noise induced by the OPO cavity detuning and the relative phase drift is given. The discussion is divided into two parts: one is the effect of OPO cavity detuning on the squeezing angle fluctuation, which can be equivalent to the phase noise, the other concerns the phase noise due to the relative phase drift. The stability of measured squeezing will fluctuate with these factors described above.

2.1. Squeezing angle fluctuation produced by the OPO cavity detuning

In the process of squeezed state generation, the signal and pump fields need to be injected into the OPO cavity, simultaneously. For a single resonant OPO cavity with a detuning Δ for the signal field, we can use the Hamiltonian of the cavity to obtain the quantum Langevin equations of motion for the signal and pump fields:

$$\frac{d}{dt}\hat{a}_s = -\gamma_s^{tot}\hat{a}_s + i\Delta\hat{a}_s + \varepsilon\hat{a}_p\hat{a}_s^{\dagger} + \sqrt{2\gamma_s^{in}}\hat{a}_s^{in} + \sqrt{2\gamma_s^{out}}\hat{a}_s^{out} + \sqrt{2\gamma_s^{l}}\hat{a}_s^{l} \tag{1}$$

$$\frac{d}{dt}\hat{a}_p = -\gamma_p^{tot}\hat{a}_p + \sqrt{2\gamma_p^{in}}\hat{a}_p^{in} \tag{2}$$

where $\hat{a}_s$ and $\hat{a}_s^{\dagger}$ are annihilation and creation operators for the signal field; $\hat{a}_p$ and $\hat{a}_p^{\dagger}$ are annihilation and creation operators for the pump field; $\hat{a}_{s,p}^{in}$, $\hat{a}_s^{out}$ and $\hat{a}_s^{l}$ are annihilation operators for the vacuum fluctuations that leak into the cavity through the input coupler, the output coupler and the intra-cavity losses, the subscripts s and p stand for the signal and pump fields, respectively; $\gamma_{s,p}^{in}$, γ_s^{out} and γ_s^{l} are the decay rates for the input coupler, the output coupler and the intra-cavity loss, $\gamma = \gamma_s^{tot} = \gamma_s^{in} + \gamma_s^{out} + \gamma_s^{l}$ and $\gamma_p^{tot} = \gamma_p^{in}$ are the total cavity field decay rates for the signal

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and pump fields, respectively; ε is the nonlinear coupling parameter; Δ is the detuning of the signal field from the cavity resonance.

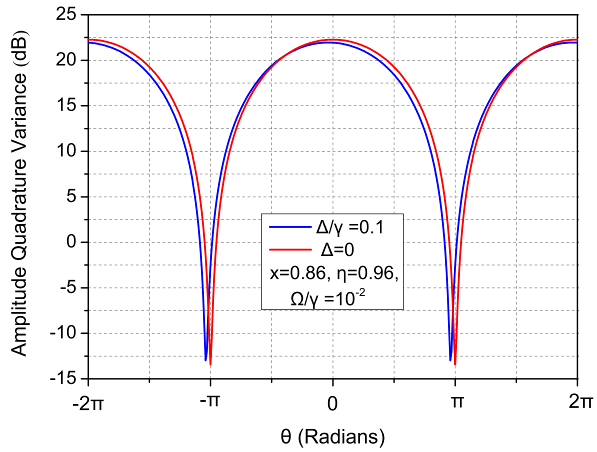

Fig. 1. Amplitude quadrature variance of the OPO cavity output field as a function of the relative phase between the siganl and pump fields θ for the cavity on resonance (red) and slightly detuning (blue).

Using the aforesaid equations of motion, we can calculate the variance of amplitude quadrature at the output of the OPO cavity. With the cavity detuning, the measured quantum noise variance is:

$$V = 1 + \frac{4x\eta\left[\left(x^2+1-\left(\frac{\Delta}{\gamma}\right)^2+\left(\frac{\Omega}{\gamma}\right)^2\right)\cos\theta + 2x + 2\left(\frac{\Delta}{\gamma}\right)\sin\theta\right]}{x^4-2x^2+1-2x^2\left(\frac{\Delta}{\gamma}\right)^2+2\left(\frac{\Delta}{\gamma}\right)^2+\left(\frac{\Delta}{\gamma}\right)^4+2x^2\left(\frac{\Omega}{\gamma}\right)^2+2\left(\frac{\Omega}{\gamma}\right)^2-2\left(\frac{\Delta}{\gamma}\right)^2\left(\frac{\Omega}{\gamma}\right)^2+\left(\frac{\Omega}{\gamma}\right)^4} \tag{3}$$

where x is the normalized nonlinear interaction strength; η is the escape efficiency; Ω is the measurement frequency; θ is the relative phase between the signal and pump fields. For an OPO cavity that is on resonance, $\Delta = 0$, the phase θ determines which quadrature will be squeezed, the squeezing angle can be expressed as $\theta_{sqz} = \theta/2$. As illustrated by the red trace in Fig. 1, the minimum variance of the amplitude quadrature occurs at the relative phase $\theta = \pi$, and the squeezing angle is $\theta_{sqz} = \pi/2$. If the OPO cavity length is away from resonance due to the RAM, the squeezing angle will be shifted relative to the phase θ, as illustrated by the blue trace in Fig. 1. As can be seen, the maximum squeezing level is almost unchanged by compensating the squeezing angle [26]. However, the OPO cavity detuning can induce the fluctuation of the output power of the squeezed light, which should be avoided as much as possible.

To estimate the relationship between the squeezing angle shift and the OPO cavity detuning, we take the derivatives at the point where the variance has a linear dependence on the relative phase $\theta = \pi/2$. The first order squeezing angle shift caused by the OPO cavity detuning can be expressed:

$$\frac{d\theta_{sqz}}{d\Delta} = \frac{1}{2}\frac{\frac{dV}{d\Delta}|\Delta = 0, \theta = \pi/2}{\frac{dV}{d\theta}|\Delta\theta = \pi/2, \Delta = 0} = \frac{1}{\gamma\left(1+x^2\right)} \tag{4}$$

From Eq. (4) we can find that the effect of the OPO cavity detuning on the squeezing angle fluctuation is an approximate linear coupling. Using the equation, we can quantitatively analyze the rotation of the squeezing angle with the OPO cavity detuning.

2.2. Phase noise produced by the relative phase drift

To measure the squeezed degree from the output of the OPO cavity, the generated squeezed light interferes with a strong LO on a 50/50 beamsplitter. By locking the relative phase between the LO and the signal beam to 0, the amplitude squeezed quadrature is measured. The relative phase drift makes the anti-squeezed quadrature contaminates the observed squeezing level, which is the limiting mechanism deteriorating the measured squeezed degree and stability [27].

When the OPO cavity on resonance and the pump and signal fields have a well defined relative phase π, the ideal amplitude squeezing is obtained. The OPO cavity detuning causes the rotation of the squeezed ellipse with the characteristic angle $\theta/2$. If we lock the relative phase between the LO and the signal beam to $\theta/2$, the minimum quadrature can be observed. However, the relative phase drift between the LO and the signal beam, coming from the RAM, makes the measured quadrature fluctuates around the most squeezing quadrature. So it needs to take countermeasures to minimize the influence of the RAM and ultimately improves the long-term stability of the squeezed degree.

3. Investigation of the cavity detuning and the phase drift from RAM

In this section, we investigate the OPO cavity detuning and the relative phase drift originating from the RAM that arises from the birefringence of the EOM under different cases.

3.1. Investigation of the RAM-induced cavity detuning

Distinguishing from the cavity applied to the frequency stabilization, which is a high-finesse and impedance matching cavity, the OPO cavity is a low-finesse and under-coupled cavity. We use the two-mirror linear cavity as an example for all the analysis and discussions. The input mirror is coated as high reflectivity (HR) for the signal field and high transmission for the pump field. The output mirror has a transmissivity of 12% for the signal field and HR for the pump field [28]. The distance between the two mirrors is 34 mm. In order to simplify the analysis, we suppose that the nonlinear crystal has no absorption loss. The setup corresponds to the cavity fineness of 49, the cavity linewidth of 90 MHz. The amplitude reflection and transmission coefficients of the OPO are given by:

$$F(\omega) = \frac{-r_1 + r_2 \exp\left(i\omega/\Delta\upsilon_{fsr}\right)}{1 - r_1 r_2 \exp\left(i\omega/\Delta\upsilon_{fsr}\right)} \tag{5}$$

$$T(\omega) = \frac{\sqrt{\left(1-r_1^2\right)\left(1-r_2^2\right)}\exp\left(i\omega/2\Delta\upsilon_{fsr}\right)}{1 - r_1 r_2 \exp\left(i\omega/\Delta\upsilon_{fsr}\right)} \tag{6}$$

where r_1 and r_2 are, respectively, the amplitude reflection coefficient of the input and output mirrors; $\Delta\upsilon_{fsr}$ is the free spectral range of the OPO for the signal field.

When the polarization direction of the incident beam has an inevitable misalignment with the principal axes of the EOM, the phase-modulated field is [19]:

$$E = E_0 e^{i\omega t}\left[a e^{i(\varphi_o + \delta_o \sin\Omega t)} + b e^{i(\varphi_e + \delta_e \sin\Omega t)}\right] \tag{7}$$

where E_0 is the amplitude of the incident field; $a = \sin\alpha\sin\beta$ and $b = \cos\alpha\cos\beta$ are alignment factors, where α and β are the angles between the direction of z axis of EO crystal and the allowed polarization of the input and output polarizers, respectively; ω and Ω are the optical carrier and phase modulation frequencies, respectively; $\delta_{o,e}$ and $\varphi_{o,e}$ are the modulation index and the phase shifts of the polarized lights, the subscripts o and e represent the ordinary and extraordinary lights, respectively.

The phase-modulated birefringence light described by Eq. (7) impinges upon the OPO cavity, and the outgoing optical field is detected to produce the PDH error signal to lock the cavity. In general, the error signal with the birefringence of the EO crystal incorporated can be expressed [29]:

$$V_{err-cavity} = E_0^2 K\{\mathrm{Re}\,[AG(\omega)\,G^*(\omega+\Omega) - A^* G^*(\omega)\,G(\omega-\Omega)]\cos\Phi \\ - \mathrm{Im}\,[AG(\omega)\,G^*(\omega+\Omega) - A^* G^*(\omega)\,G(\omega-\Omega)]\sin\Phi\} \tag{8}$$

where

$$A = a^2 J_0(\delta_o)\,J_1(\delta_o) + b^2 J_0(\delta_e)\,J_1(\delta_e) + ab\,[J_0(\delta_o)\,J_1(\delta_e) + J_0(\delta_e)\,J_1(\delta_o)]\cos\Delta\varphi \\ -iab\,[J_0(\delta_o)\,J_1(\delta_e) - J_0(\delta_e)\,J_1(\delta_o)]\sin\Delta\varphi \tag{9}$$

$J_n(\delta_{o,e})$ is the Bessel function of order n; $\Delta\varphi = \varphi_e - \varphi_o$ is the phase difference between the extraordinary and ordinary lights due to the natural birefringence of the crystal; Φ is the demodulation phase, by adjusting the phase Φ, the absorption ($\cos\Phi$) and dispersion ($\sin\Phi$) terms in Eq. (8) can be selectively detected; K is the joint gain of the photodetection and the demodulation process; $G(\omega)$ represents the reflection or transmission coefficient of the OPO cavity interrogated by the modulated beam. When the laser beam is reflected by an optical cavity at an off-resonance condition, the reflection coefficient is $F(\omega) = 1$, the error signal from the reflection of the optical cavity can be simplified to a birefringence-induced RAM:

$$V_{RAM-A} = 2E_0^2 KabJ_1(M)\sin\Delta\varphi = 2E_0^2 KR(\varepsilon) \tag{10}$$

where $R(\varepsilon)$ is RAM factor, which depends on the alignment factors, modulation depth, and phase difference $\Delta\varphi$. In experiment, the parameter can be measured by performing directly the detection after the EOM.

Due to the broad linewidth of the OPO cavity, there is impossible to use the modulation frequency, which is much larger than the linewidth of the OPO, to modulate the laser beam. The optimal modulation frequency is firstly investigated. The servo-loop performance depends sensitively on the discrimination slope of the error signal D, and we would like to have an abrupt slope D to improve the locking performance. So the dependence of the slope of the error signal on modulation frequency is analyzed, which is shown in the Fig. 2. These results indicate that the maximum discrimination slope of the dispersion term is larger than that of the absorption term, and it is contingent on the modulation frequency. Thus, one chooses the dispersion term as the error signal of cavity-locking by adjusting the modulation phase. As a result, the cavity-locking result depends on the discrimination slope of the dispersion term. The larger the discrimination slope is, the better the cavity-locking performance is. When the ratio between the modulation frequency and the cavity linewidth Ω/γ is more than 0.5, the dispersion terms from both the reflection and transmission of the OPO have an abrupt slope. According to the analysis results, we choose the modulation frequency and make Ω/γ equal to 0.5 in experiment.

An absolute impedance matching cavity is immune to the birefringence-induced RAM when we extract the error signal from the reflection of the cavity [29]. However, in order to obtain high-level squeezed state, the OPO is an extreme impedance mismatch cavity, we cannot evaluate the influence of the RAM with the similar results with the laser frequency stabilization. Based on the actually experimental system of the squeezed state generation, the frequency offset is evaluated to provide valuable observations that are beneficial to the RAM suppression of the servo loop.

Because the modulation frequency is less than the linewidth of the OPO, the error signals can be extracted from the reflection or transmission of the OPO according to the requirements of the experiment. On the basis of the optimal modulation frequency, we investigate the frequency offsets as a function of the impedance matching efficiency, while extracting the error signal from the reflection and transmission of the OPO, respectively. When the laser beam resonates with

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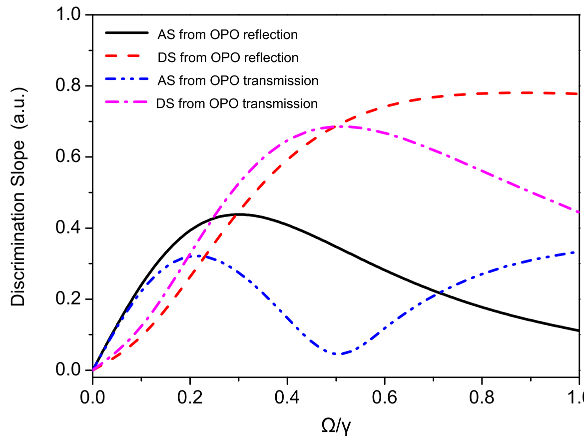

Fig. 2. The discrimination slopes of the absorption signal (AS) and the dispersion signal (DS), which are extracted from the reflection and transmission of the OPO, respectively.

the OPO, the dispersion term of the Eq. (8), extracted from the reflection of the OPO, can be simplified to a birefringence-induced RAM of:

$$V_{RAM-R} = 2E_0^2 K R(\varepsilon) F(0) \left(\frac{F(0)-1}{2}\right) = F(0)\left(\frac{F(0)-1}{2}\right) V_{RAM-A} \tag{11}$$

The dispersion term of the Eq. (8), extracted from the transmission of the OPO, can be simplified to a birefringence-induced RAM of:

$$V_{RAM-T} = 2E_0^2 K R(\varepsilon) \frac{T^2(0)}{2} = \frac{T^2(0)}{2} V_{RAM-A} \tag{12}$$

For the central portion of a typical error signal, close to the zero crossing, the signal can be well approximated by a straight line. The resultant frequency shift resulting from the RAM is:

$$\Delta\upsilon = \frac{V_{RAM}}{D} \tag{13}$$

By using Eqs. (5)-(13), the locking frequency offset is investigated in terms of the alignment factors and the phase difference, which is shown in Fig. 3. When the impedance matching efficiency is rather small, the frequency offset by using the error signal extracted from the reflection of the OPO is far greater than that of the transmission. With the increase of the impedance matching efficiency, the frequency offset from the RAM with the error signal extracted from the reflection, is sharp reduced. While extracting the error signal from the transmission, the frequency offset remains a small value over the entire range of the impedance matching efficiency. In squeezed state generation system, the OPO is an under-coupled cavity, which has an extremely low impedance matching efficiency (about 0.3%). A phase modulated light impinges upon the OPO, most of the power is directly reflected from the input mirror of the OPO, which does not obtain the error signal for cavity locking but include the RAM. A small fraction of the power can be coupled into the OPO to obtain the error signal for cavity locking, the discrimination slope of the error signal D is extremely small. According to the Eq. (13), there is no doubt that the frequency offset resulting from the RAM is large. While extracting the error signal from the transmission, there is no reactive light power into the photodetector, which can extremely reduce the frequency offset. Based on the above analysis, the error signal extracted from the

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transmission of the OPO can reduce the influence of the RAM on the frequency offset of the OPO in our setup. It is worth of noting that one can avoid the addition loss by extracting the error signal from the leaking of the signal beam on the dichroic beam splitter (DBS). The DBS is an inherent component that is used to separate the squeezed light from the residual pump beam.

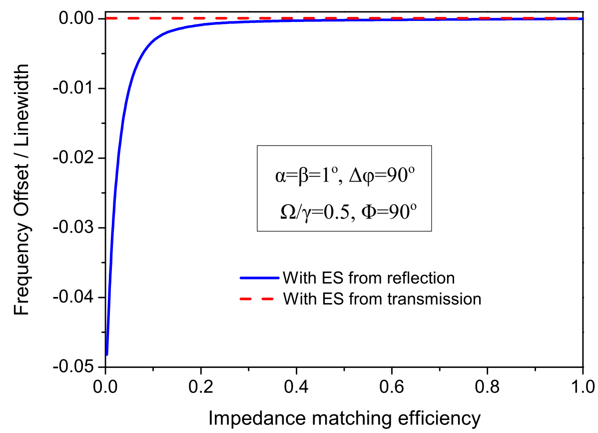

Fig. 3. The ratio between the frequency offset and the linewidth as a function of the impedance matching efficiency with the error signals (ES) extracted from the reflection and transmission of the cavity, respectively. Under the circumstances, the polarization angles α and β is fixed to 1°, the birefringence phase shift $\Delta\varphi$ is 90°, the proportion of modulation frequency and cavity linewidth Ω/γ is 0.5, and the demodulation phase Φ is 90°.

3.2. *Investigation of the RAM-induced phase drift*

Let us consider the experimental scheme of the relative phase locking by adopting the EOM. The phase-modulated birefringence beam described by Eq. (7) interferes with a beam $E_2 = E_{20}e^{i\omega t}$ on the 50/50 splitter, and the optical field after the subtracter is detected, then demodulated to produce the error signal to lock the relative phase between the two beams. The error signal after demodulation can be expressed in a generalized form of:

$$V_{err-phase} = E_0 E_{20} bKJ_1(M)\sin\Psi + E_0^2 KabJ_1(M)\sin\Delta\varphi = E_0 E_{20} bKJ_1(M)\sin\Psi + \frac{1}{2}V_{RAM-A} \quad (14)$$

It is obvious that the error signal in Eq. (14) is the sum of a bias term due to RAM and an error term that is proportional to the relative phase deviation from lock point. The scaling factor is the discrimination slope of the error signal, which depends linearly on the amplitude product of the two interference beams. The RAM can be measured by performing directly the detection after the EOM, which scales with the amplitude of the phase-modulated beam. Considering the above analysis, the EOM should be imposed on the beam with the lower power to reduce the influence of RAM on the phase drift.

For the generation system of squeezed state, the power of the LO should far more than that of the signal beam in order to reduce the measurement error [28]. So there can obtain the lower phase drift when the phase modulation is imposed on the signal beam, instead of the LO, which is conducive to improving the stability of the squeezed degree. However, the modulation signal is imposed on the squeezed beam (after the OPO) to lock the relative phase, partial carrier signal will be transferred to the sidebands, which leads to inevitable loss. In practical experimental system, one can impose the modulation signal on the signal beam (before the OPO) to overcome

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the problem. The lower modulation frequency relative to the OPO linewidth can confirm that the sideband signal can effectively transmit through the OPO.

4. Experimental results and analysis

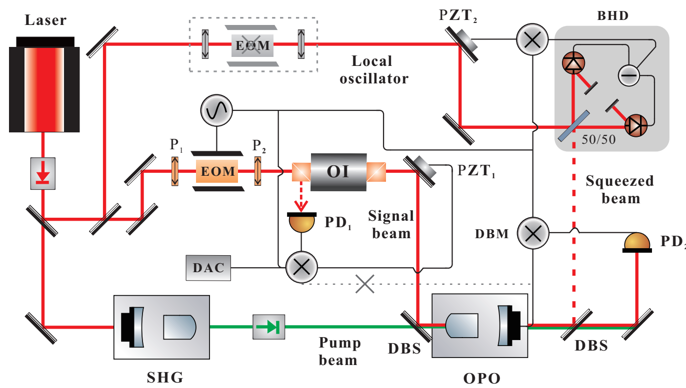

Fig. 4. The experimental setup for measuring the RAM and the scheme for cavity and phase locking. EOM: electro-optical modulator; OI: optical isolator; OPO: optical parametric oscillator; P: polarizer; PD: photodetector; DBM: doubly balanced mixer; DAC: data acquisition card; SHG: second harmonic generation; DBS: dichroic beam splitter; BHD: balanced homodyne detection; PZT: piezoelectric transducer.

Figure 4 shows the experimental setup for measuring the RAM and the scheme for cavity and phase locking. A homemade single-frequency Nd:YVO_4 laser at 1064 nm is used [30]. The EOM is placed in the optical path to provide the phase modulation signal for the downstream experiment. When the laser frequency is tuned far from the cavity resonance, the PD_1 reads the reflected signal of the OPO, the mixer output corresponds to the baseline of the error signal, which fluctuates with temperature and stress of the modulator crystal, that is RAM. In order to reduce the influence of the RAM on the output power of bright squeezed light, the error signal for the OPO length locking is extracted from the transmission of the OPO, instead of from the reflection. For the relative phase locking between the LO and the signal beam, the phase-modulation signal is derived from the EOM placed on the optical path of the signal beam (before the OPO), instead of imposing an additional EOM on the LO. Order to evaluate the influence of RAM on the long-term stability of squeezed state, we perform an 8 h measurement of RAM recorded by a data acquisition card (DAC) [23]. Figure 5 shows the time-related RAM V_{RAM-A} in 8 h with the modulation index of around 0.1. The peak-to-peak value of the RAM V_{RAM-A} is about +/-1.6 mV in 8 h, its drift-line presents like sinusoidal curve, which indicates that the birefringence-induced RAM is the major factor of generating the RAM in our setup. Of course, the laser power fluctuation does also affect the RAM. However, the laser power fluctuation is usually 1%, which is very weak comparing with the birefringence-induced RAM with the range from -1 to 1. So the influence of the laser power is usually neglected.

The RAM can be converted into a relative fluctuation divided by the discrimination slope of the error signal, which results in the OPO frequency detuning and the relative phase drift between the two beams in the vicinity of the resonance point and desired value. The detuning and drift drive the squeezing noise fluctuation with time. For the OPO in our setup, the input coupler has the reflectivity of 99.99% for the signal beam, the output coupler is coated with the reflectivity of 88%, corresponding to the amplitude reflectivity of 0.9984 on resonance. When the OPO is on resonance, the peak-to-peak value of the RAM with the error signal extracted from the reflection of the OPO is +/-1.6 mV in 8 h. While the error signal is extracted from the transmission of the

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OPO, the maximum RAM V_{RAM-T} is only +/-0.0025 mV. The discrimination slope of the error signal is approximate 10^{-9} V/Hz. According to the Eq. (13), the frequency detuning with the error signal extracted from the transmission of the OPO is +/-0.0025 MHz, which is roughly 1/640 of that from the reflected. It is obvious that the frequency detuning coming from the RAM decreases dramatically if we extract the error signal of the OPO locking from the transmission of the OPO (as shown in Fig. 4), instead of from the reflection.

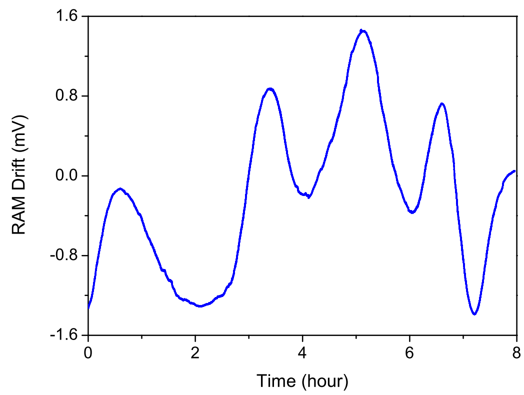

Fig. 5. Residual amplitude modulation (RAM) drift with time.

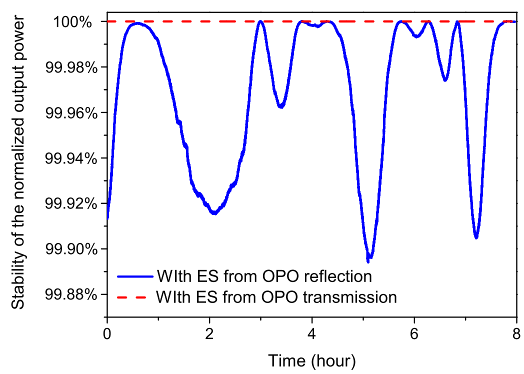

Fig. 6. Stability of the normalized output power in 8 h with the error signals (ES) extracted from the reflection and transmission of the OPO, respectively.

The OPO frequency detuning does not only cause the squeezing angle rotation, but also induce the instability of the output power of the bright squeezed light. The squeezing angle rotation can be compensated by the deviation of the relative phase between the pump and signal beams. The instability of the output power can be inferred from the measurement results about the RAM. Here, we compare the stability of the output power in the same RAM when extracting the error signal from the reflection and transmission of the OPO. The result can provide a guidance to reduce the influence of the RAM. The laser power fluctuation has the same effect on the output power stability in two cases. Therefore, we do not consider the laser power fluctuation during the analysis process. The analysis results is shown in Fig. 6, when the error signal is detected from the transmission of the OPO, the instability of the output power originating from the RAM can be neglected, which is greatly improved comparing with that from the reflection.

The dependence of the relative phase on the RAM is investigated in section 3.2. According to the analysis results, the phase-modulated signal should be imposed on the signal beam to reduce the relative phase drift between the LO and the signal beam. For the usual experiment system, the power of LO is 100 times more than that of the signal beam. If the EOM is placed in the path of the signal beam, the relative phase drift is about +/-0.1 mrad, which is far less than that of phase-modulated LO, the scaling factor depends on the power ratio between the two beams.

Here we suppose there is a squeezed state generation system with the theoretical squeezing level of -13 dB. The quantum noise fluctuation is compared in two cases: phase modulation imposed on the LO, phase modulation imposed on the squeezed beam. The comparison is performed in the same experiment condition with the modulation index of 0.1. As shown in Fig. 7, when the LO is modulated to produce the error signal, the observed squeezing is only -12 dB at worst, which shows that the fluctuation of the squeezing level is more than 1 dB in 8 h. However, if the EOM is placed in the path of the signal beam, instead of the LO, the measured squeezing is -12.9999 dB at worst, the fluctuation of the squeezing level is less than 0.0001 dB in 8 h, without noticeable drift. Obviously, by imposing the phase modulation on the signal beam in our experimental system (as shown in Fig. 4), it can effectively improve the long-term stability performance of the squeezed state generation system.

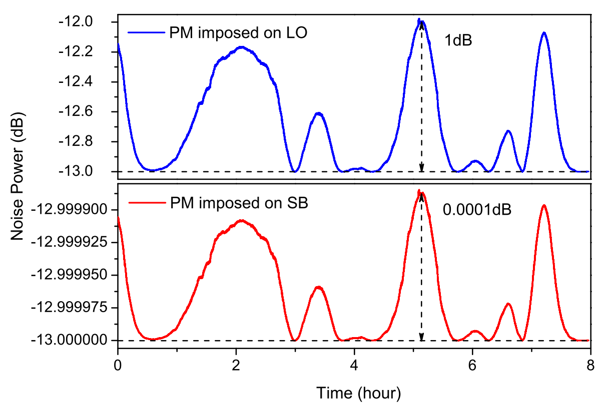

Fig. 7. Quantum noise fluctuation originating from RAM in 8 h with the phase modualtion (PM) imposed on the local oscillator (LO) and the signal beam (SB), respectively.

5. Conclusion

In conclusion, we present an analysis on how the OPO cavity detuning and the relative phase drift deteriorate the stability of the squeezed states, including the output power and the squeezed degree, and investigate the influence of RAM on the OPO cavity detuning and the relative phase drift under different cases. Due to the severe impedance mismatch and large-linewidth, the influence of RAM on the OPO cavity locking presents some new phenomena comparing with the laser frequency stability. When the error signal is extracted from the reflection of the OPO, most of the power is directly reflected from the input mirror of the under-coupled cavity, which does not obtain the error signal for cavity locking but include the RAM. The cavity detuning coming from the RAM is very large, which is about 640 times of that from the transmitted for our experimental system. For the relative phase locking between the LO and the signal beam, the two beams have a considerable difference in power. The discrimination slope of the error signal depends linearly on the amplitude product of the two interference beams. The RAM is proportional to the power of the beam, which is phase modulated. When the phase modulation is imposed on the signal light, instead of the LO, the phase fluctuation can be reduced, the scaling factor depends on the power ratio between the two beams. As a result, the stability of the squeezed states, including

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the output power and the squeezed degree, can be greatly improved by these RAM-reducing approaches, which is benefit for the generation of long-term stable squeezed state.

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