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Squeezing level strengthened by a temperature dependent dispersion compensation methodology

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ABSTRACT

Doubly resonant optical parametric oscillator (DR-OPO) is a valuable resource for preparing squeezed state. Temperature dependent dispersion compensation technology has become a popular methodology for high degree squeezing generation with DR-OPO. Nevertheless, details for the realization of temperature dependent DR-OPO have not been demonstrated yet. Here, we have constructed a full experimental layout for charactering the doubly resonant temperatures and verifying the squeezing levels in the phase matching bandwidth of the crystal. Three co-resonance temperatures of 30.74 °C, 42.54 °C and 53.71 °C were directly measured, at which 11.7 dB, 12.3 dB and 11.5 dB squeezing were observed, respectively. The experimental and theoretical results both indicate that the temperature dependent frequency detuning contributes to the discrepancy of the squeezing levels for the three temperature conditions. Careful calibration of the temperature dependent frequency detuning should be tracked to strengthen the squeezing level with DR-OPO.

1. Introduction

Squeezed state is a potential resource to enhance precision measurement beyond the standard quantum limit (SQL), such as, gravitational wave detection [1–5], nonlinear microscopy [6], biological measurement [7], spin noise spectroscopy [8,9], magnetometry [10], quantum information [11–14], optical atomic clocks [15] and so on. Squeezed state generation with optical parametric oscillator (OPO) is an efficient way to eminently suppress the quantum noise below SQL. With this method, Vahlbruch et al. had demonstrated a 10 dB squeezed vacuum state at 1064 nm for the first time, with a single resonant OPO in 2008 [16]. The noise reduction was improved to 15 dB below SQL in 2016 [17]. Differing from the 10 dB squeezing observation, doubly resonant OPO was applied to enhance the nonlinear interaction of the second harmonic with the periodically poled potassium titanyl phosphate (PPKTP) crystal. Whereafter, Schönbeck had increased the squeezing factor to 13 dB at 1550 nm in the same way [18].

As contrasted with single resonant OPO (SR-OPO), doubly resonant one (DR-OPO) should simultaneously achieve co-resonance of the pump and squeezing beams, at phase matching temperature. DR-OPO provides a useful way in squeezing production, for its low threshold and stable cavity length locking properties, especially benefits to strength the squeezing level. It is hard to reach the optimal co-resonance condition for high degree squeezing generation. Initially, an adjustable dispersive component, such as a rotatable window [19] or gas pressure [20], is used to compensate for the dispersive between the two beams. However, excess vacuum noise introduced by additional optical loss decreases the squeezing degree, which is harmful to high degree squeezing generation. Furthermore, to meet the co-resonance with optimal phase matching, a wedge nonlinear crystal was designed to change the optical path length in a traveling wave cavity [21,22]. But this method is impractical for a half-monolithic resonator. Therefore, a temperature dependent dispersion compensation technology is proposed for optimal co-resonance realization in a half-monolithic cavity [17,18,23,24]. Nevertheless, only a short statement for dispersion compensation was present in these literatures, and no details of this technique had been described. In this paper, detailed analysis of the DR-OPO with temperature dependent dispersion compensation technology is theoretically and experimentally demonstrated. We had measured the co-resonance condition by injecting a fundamental wave in the DR-OPO, then the output power of the generated second harmonic wave was used to calibrate the co-resonance. By adjusting the temperature of the PPKTP crystal in the phase matching bandwidth, three co-resonance temperatures were confirmed. With the measured squeezing degree for each temperature, we found that the detuning of the fundamental wave contributes to the decreasing decrease of the squeezing level. And

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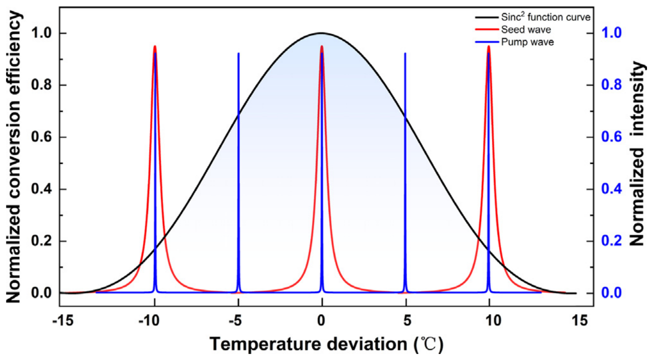

Fig. 1. The theoretical results for strict co-resonance of the fundamental and harmonic waves in the bandwidth of the nonlinear crystal.

we had obtained an optimal co-resonance condition near the phase matching temperature, and observed a 12.3 dB bright squeezed light.

2. Theoretical models of the co-resonance and squeezing preparation

The ideal co-resonance of the fundamental and second harmonic optical waves is expected to be realized at the phase matching temperature of the nonlinear crystal, as the center shown in Fig. 1. As the temperature tuning from the ideal co-resonance status, the different temperature dependent refractive index of the two waves makes their optical paths deviate from co-resonance, as well as the phase matching condition. The corresponding normalized transmission intensity of the DR-OPO depending upon the temperature of the nonlinear crystal can be deduced as [25],

$$t = \left| \frac{\sqrt{\left(1-(r_{in})^2\right) * \left(1-(r_{out})^2\right)} * e^{i*\frac{2\pi * T}{2*\Delta_{T,FSR}}}}{1 - r_{in} * r_{out} * e^{i*\frac{2\pi * T}{\Delta_{T,FSR}}}} \right|^2 \tag{1}$$

where r_{in} and r_{out} are the reflectivities of the optical input and output fields, and T is the crystal temperature. $FSR = c/(2 * L)$ is the free spectral range of the cavity, where c is the speed of light in vacuum, L is the total optical path. $L = L_{ag} + n_T * L_c$, where L_{ag} is the length of free space, L_c is the crystal length with a refractive index n_T, which is temperature dependent. $\Delta_{T,FSR}$ is the free spectral region corresponding to the crystal temperature, and can be expressed as [26]

$$\Delta_{T,FSR1} = \frac{\lambda_1}{2 * L_c} \times \frac{1}{\Delta_{nT1}} + \frac{\lambda_1}{2 * L_{ag}} \tag{2}$$

$$\Delta_{T,FSR2} = \frac{\lambda_2}{2 * L_c} \times \frac{1}{\Delta_{nT2}} + \frac{\lambda_2}{2 * L_{ag}} \tag{3}$$

where Δ_{nT} is the crystal's photorefractive constants and $\lambda_{1,2}$ is the wavelength of two beams.

With Eq. (1)–(3) and the parameters in our experiment (Table 1), the ideal co-resonance, in the temperature bandwidth of the nonlinear interaction in the crystal ($sinc^2$ function of the interaction), can be calculated as shown in Fig. 1. The red curve is the transmission peak of the seed beam, and the blue one is that of the pump beam. The overlapping region of the two transmission curves represents the co-resonance condition in the OPO cavity. It can be found that, three co-resonance peaks are theoretically predicted in the bandwidth of the phase matching temperature. However, only the central peak owns the perfect co-resonance, which has the lowest threshold of the OPO due to the largest enhanced nonlinear interaction.

In practice, the experimental parameters are really not ideal, which always induces a frequency deviation f_T from the co-resonance. When the pump wave is used to lock the length of the OPO below the threshold, f_T will make the internal fundamental wave off-resonate.

Table 1
Experiment parameter and loss budget for our squeezed light source.

Experiment parameter	Value
λ_1	1550.012 nm
λ_2	775.006 nm
n_{T1}	1.81584 [27]
n_{T2}	1.84607 [27]
Δ_{nT1}	3.13331×10^{-5} 1/K [28]
Δ_{nT2}	3.66942×10^{-5} 1/K [28]
$L_a g$	21 mm
L_c	10 mm
ν	110.4 MHz
Source of loss	**Value (%)**
OPO escape efficiency	98 ± 0.47
99.7% interference visibility	99.4 ± 0.2
Propagation efficiency	98 ± 0.2
Photodiode quantum efficiency	99 ± 0.2
Total efficiency	95 ± 0.15
Total phase fluctuation	4.4 ± 0.26

Then, a dispersion induced frequency detuning results in a measured squeezing degree deviation from the generated one. In this case, the squeezing or anti-squeezing noise variance is changed to [29–31]

$$V_{\pm} = 10\log_{10}\left[\left\{1 \pm \frac{4\eta \times \sqrt{\frac{P}{P_1}}}{\left(1 \mp \sqrt{\frac{P}{P_1}}\right)^2 + 4\left(\frac{f_0+f_T}{\nu}\right)^2}\right\}\cos^2\theta + \left\{1 \mp \frac{4\eta \times \sqrt{\frac{P}{P_1}}}{\left(1 \pm \sqrt{\frac{P}{P_1}}\right)^2 + 4\left(\frac{f_0+f_T}{\nu}\right)^2}\right\}\sin^2\theta\right] \tag{4}$$

where f_0 is the sideband frequency of the squeezed state. $f_T = -(\Delta_{n1T} * \Delta_T * L_c)/\lambda_1 \times c/(2 * L_1) + (\Delta_{n2T} * \Delta_T * L_c)/\lambda_2 \times c/(2 * L_2)$ is the temperature induced frequency detuning, $L_{1,2} = L_{ag} + L_c(n_{T1,2} + \Delta_{nT1,2} * \Delta_T)$ is the optical path length of the cavity, where $\Delta_{nT1,2}$ are the crystal's photorefractive constants for the fundamental and pump waves, Δ_T is the temperature difference between the two waves. η is the total optical transmission efficiency of the squeezer, and is determined by its escape efficiency and total optical losses l. The escape efficiency is the ratio of the output coupling transmittance of the OPO to the sum of the transmittance and the internal loss in the cavity. The total losses contain the internal loss of OPO, the propagation loss between OPO and the detection part, and the losses in squeezing detection. P is the pump power, and P_1 is the threshold pump power of the OPO. P/P_1 is the pump parameter. θ is the total fluctuation of the relative phases in the squeezing generation and detection processes. $\nu = FSR/F$ is the full width at half maximum (FWHM) linewidth of the OPO. Specific experimental parameters and device loss are shown in Table 1.

3. Experimental setup and results

The schematic of the experimental setup is shown in Fig. 2. A fiber laser with 2 W output power at 1550 nm (E15, NKT Photonics) is firstly injected into a mode cleaner (1550 MC), which is used to improve the fundamental spatial–temporal mode and reduce the intensity noise above MHz radio frequency (RF) region [32]. Then its output is divided into three parts. One passes through the other 1550MC to further improve the intensity noise for the preparation of local oscillator (LO) in the balanced homodyne detection (BHD). The second one serves as the seed beam for the OPO. And the third one is injected into the second harmonic generator (SHG) to produce an up-conversion lasing with 775 nm, applied as the pump wave of OPO. The OPO length is locked to the pump beam with Pound–Drever–Hall (PDH) technique [33].

The OPO is a half-monolithic cavity, which optical path is optimized doubly resonant for the pump and seed beams at phase matching temperature, and realizes a dispersion compensation with the temperature

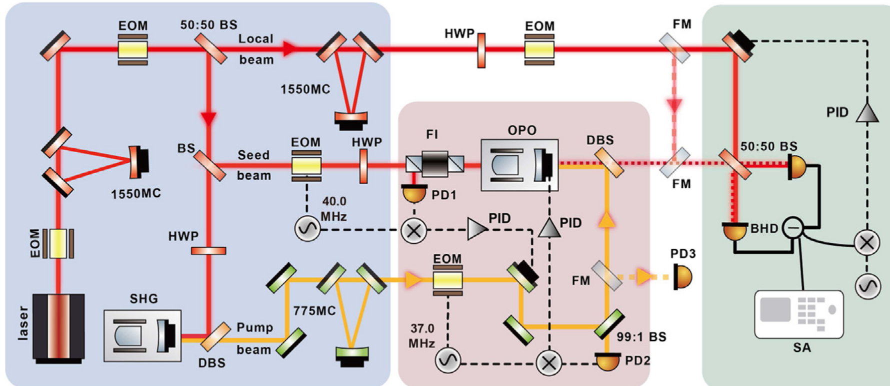

Fig. 2. The schematic of the experimental layout. EOM, electro-optical modulator; FI, Faraday isolator; FM, Flip mirror; SHG, second harmonic generator; MC, mode cleaner; OPO, optical parametric oscillator; DBS, dichroic beam splitter; BS, beam splitter; PD, photodetector; BHD, balanced homodyne detection; HWP, half wavelength plate and SA, spectrum analyzer.

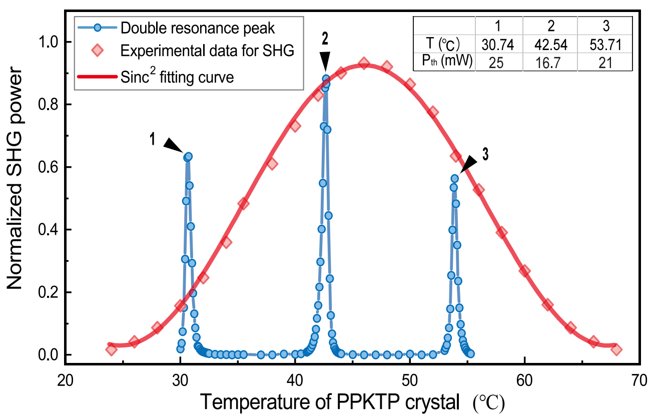

Fig. 3. The curve of normalized power of frequency doubling light with a temperature of the nonlinear crystal.

dependent refractive index of the PPKTP crystal [23,24]. The cavity is constituted of a concave mirror and a PPKTP crystal. The PPKTP is 10 mm long (L_c), and one end of the crystal is convex with a radius of 12 mm, which is high reflectivity (HR) coated with 1550 nm and 775 nm. The other surface is plane coated with antireflection (AR) for both wavelengths. The concave mirror serves as the output coupler of the OPO, with a curvature radius of 25 mm and reflectivities of 84.3% and 97.8% for 1550 nm and 775 nm, respectively. Therefore, the pump wave can be directly used to maintain the resonance condition for the two waves. The air gap between the PPKTP plane face and the output mirror is 21 mm. The fineness (linewidth) of the OPO is 34.7 (110.4 MHz) for the fundamental wave and 200 (19 MHz) for the harmonic wave. The interference visibility of LO and squeezing beam in BHD is better than 99.5% and the quantum efficiency is more than 99% (Laser Components).

To gain the accurate doubly resonant status of the OPO, we design a convenient method to characterize the temperatures for co-resonance. Before constructing the OPO, the uncoated PPKTP crystal is applied for single-pass measurement with a homemade temperature controller (precision ±0.01 °C). We scan the crystal temperature with a step of 2 °C to acquire the phase matching bandwidth as the red rhombus data shown in Fig. 3. After establishing the squeezing system, an auxiliary beam of the fundamental wave is reverse injected into the OPO, to generate a second harmonic wave in the cavity. Only under the co-resonance circumstance, the harmonic wave will export from the concave mirror, otherwise is stored in the cavity. Based on this rule, the SHG power becomes the beacon for co-resonance condition. Then, we can record the co-resonance point by scanning the temperature of the crystal with a step of 0.1 °C under the OPO length locking. Fig. 3 shows the measurement results, i.e., three temperature points 30.74°C, 42.54 °C, and 53.71 °C are observed under co-resonance condition. The results are consistent with the theoretical prediction in Fig. 1. The difference in the output power of SHG mainly attributes to the larger phase mismatching for both sides of the intermediate temperature. In fact, the crystal parameters are always accompanied by errors, which are difficult to calibrate. The inaccurate evaluation of the crystal parameters inevitably introduces a deviation between the co-resonance (highest squeezing point) and optimum phase matching temperature.

By removing the auxiliary beam, the SHG beam is gradually injected into the OPO to acquire the threshold pump power of the three co-resonance points, i.e., 25 mW (30.74 °C), 16.7 mW (42.54 °C), and 21 mW (53.71 °C), respectively. All the measurements are calibrated near the threshold pump power, by distinguishing the obvious bright down-conversion signal overflowing from the OPO, then the threshold pump power is defined as the down-conversion signal just appeared. The results confirm that the optimum co-resonance with the lowest threshold power appears at the temperature near the ideal phase matching point.

Subsequently, as shown in Fig. 2, the OPO is seeded with the fundamental wave, and locked to the pump beam below the threshold power. It operates on de-amplification with the relative phase between pump and seed waves locked to π. Then, by fine tuning the temperature of PPKTP crystal around the three co-resonance points, the optimized resonant cavity lengths are finally determined to generate the maximum degree of squeezed state. The squeezing and anti-squeezing for different pump powers are measured by the BHD and acquired with a spectrum analyzer (SA). All the experimental results are shown in Fig. 4. It can be found that the maximum quantum noise reduction of 12.3 dB is observed at the temperature of 42.54 °C with a pump power of 13.7 ± 0.5 mW. We fit the measured squeezing and anti-squeezing versus pump parameters with Eq. (4), a $5\% \pm 0.15\%$ total optical loss, a phase noise 4.4 ± 0.26 mrad, and also an extra frequency detuning f_T = 2 MHz. With the same method, the frequency detuning f_T = 6 MHz and 15 MHz for 30.74 °C and 53.71 °C are respectively figured out. The frequency detuning also can be obtained from the temperature dependent transmission peaks in Fig. 5, calculated with the theoretical model in Section 2. The detuning attributes to the temperature dependent dispersion of the crystal. However, after experiencing 11.8/11.17 °C temperature scanning, about 4.5 times FSR of the fundamental wave, the resonant peaks of the two waves meet again at the side temperatures. But the resonant peaks are not perfectly overlapped, a larger frequency detuning is observed. The corresponding squeezing degree for the two side co-resonance temperatures are 11.7 dB and 11.5 dB, respectively. In consequence, frequency detuning is one of the dominating limitations for the enhancement of squeezing level in doubly resonant OPO technical solution.

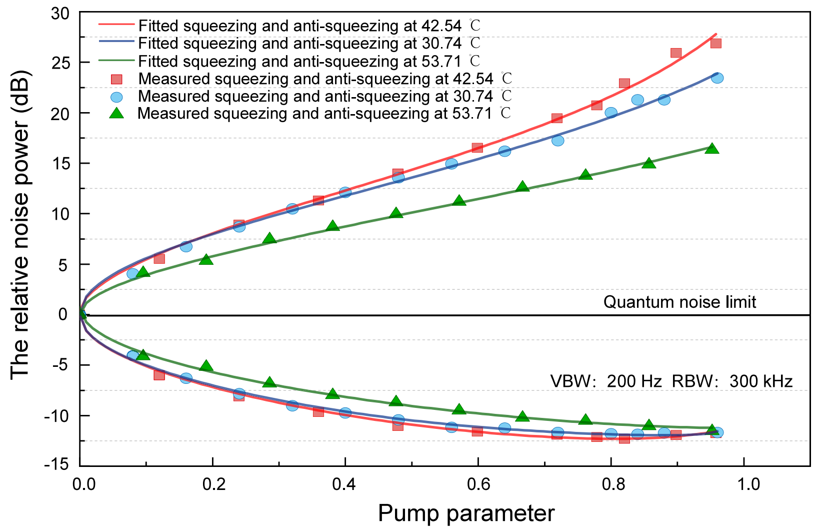

Fig. 4. Squeezing and anti-squeezing quadrature noise with experimental and theoretical results for the three co-resonance temperature points. The analysis frequency is 3 MHz, with a resolution bandwidth (RBW) of 300 kHz and a video bandwidth (VBW) of 200 Hz.

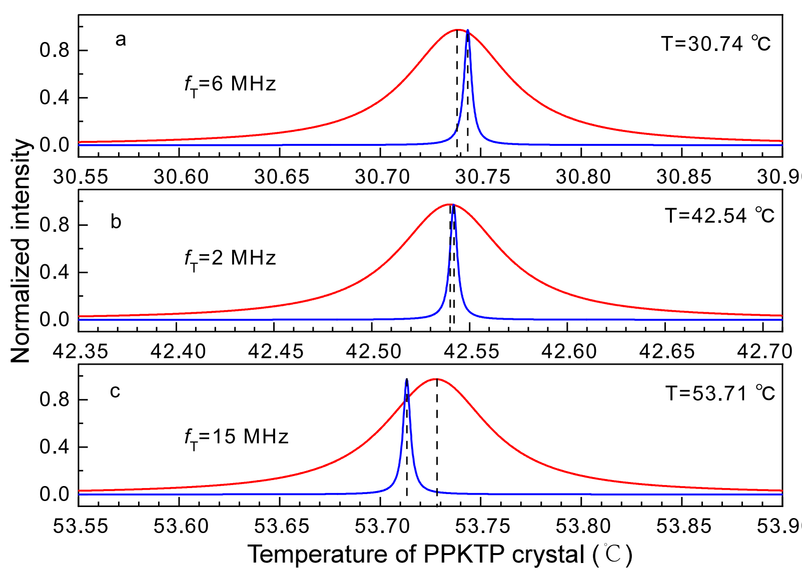

Fig. 5. The normalized intensity of the seed light and pump light at different co-resonance temperatures.

4. Conclusions

We theoretically and experimentally demonstrated a doubly resonant enhanced squeezing generation in an OPO. Three co-resonance temperatures in the phase matching bandwidth of PPKTP crystal were directly measured, and also applied to generate the squeezed state. The squeezing degree of 11.7 dB, 12.3 dB and 11.5 dB were directly observed at the co-resonance temperature of 30.74 °C, 42.54 °C and 53.71 °C. The temperature dependent dispersion induced frequency detuning ascribes to the discrepancy of the squeezing levels, which were confirmed by the pump-squeezing relationships and overlapping of resonant peaks around the co-resonance temperatures. Therefore, it should carefully calibrate the dispersion dependent frequency detuning to enhance the squeezing level with doubly resonant OPO.

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Declaration of competing interest

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Data availability

Data will be made available on request.

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