Quantum correlation between fundamental and second-harmonic fields via second-harmonic generation

Yongmin Li, Sujing Zhang, Jianli Liu, and Kuanshou Zhang

State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China

Received August 15, 2006; accepted October 16, 2006;
posted October 20, 2006 (Doc. ID 73938); published February 15, 2007

We experimentally demonstrated the quantum anticorrelation between fundamental (1064 nm) and second-harmonic (532 nm) fields in an external cavity-enhanced singly resonant periodically poled KTP (PPKTP) frequency doubler. Fundamental amplitude squeezing of 0.5 dB and second-harmonic amplitude squeezing of 0.3 dB were generated simultaneously at a pump power of 6.1 mW. Meanwhile, quantum anticorrelation of 0.64 dB between the squeezed fundamental and the second-harmonic fields was observed. © 2007 Optical Society of America

OCIS codes: 190.4410, 270.6570.

1. INTRODUCTION

Parametric processes with a second-order susceptibility have proved to be one of the most successful ways to generate nonclassical states of light. In particular, second-harmonic generation (SHG) is very attractive for its capability of generating nonclassical states with short wavelength regions that are not readily accessible by parametric downconversion. It is well known that quadrature squeezing of both the fundamental and second-harmonic (SH) fields occurs in SHG.[1–3] The existence of quantum correlation between the fundamental and the SH fields was also predicted in theory for a singly resonant SHG.[4] The quantum correlations indicate that the squeezing of either mode does not give a complete measure of the nonclassicality of the source, and it was shown that these correlations can be used to enhance the squeezing in either beam by constructing a feedback loop.[4] The generation of quantum correlation between optical fields at vastly different frequencies would be very useful in the field of quantum information. For example, it can be used in any situation where a nonclassical link is required between two systems at different optical frequencies.[5] Such a "two-color" source is also an ideal candidate for long-distance quantum communication, because the wavelength of the fundamental and SH fields can be readily chosen to be around 1560 nm (which lies in the low-loss transmission window of optical fibers) and 780 nm (which is compatible with the absorption lines of alkaline atoms and can be used for storage and processing of quantum information).[6–9]

In this paper, we present the first measurement (to our knowledge) of quantum correlation between fundamental and SH fields with a vast wavelength difference of 532 nm. Our experimental results clearly verify the theoretical predictions[4] and take a key step toward the generation of a two-color nonclassical state at vastly different frequencies.

2. THEORY

A. Squeezing and Quantum Correlation Spectra

For a singly resonant frequency doubler in which only the fundamental wave is resonantly enhanced, the output amplitude fluctuations can be written as[3]

$$\delta X_{1out}(\nu)=\frac{(\gamma_0-\gamma_1-3\mu|\alpha|^2+i2\pi\nu)\delta X_{1in}(\nu)+2\sqrt{2\gamma_0\mu|\alpha|^2}\delta X_{2in}(\nu)+2\sqrt{\gamma_0\gamma_1}\delta X_{loss}(\nu)}{\gamma+3\mu|\alpha|^2-i2\pi\nu}, \tag{1}$$

$$\delta X_{2out}(\nu)=\frac{(-\gamma+\mu|\alpha|^2+i2\pi\nu)\delta X_{2in}(\nu)+2\sqrt{\mu|\alpha|^2}[\sqrt{2\gamma_0}\delta X_{1in}(\nu)+\sqrt{2\gamma_1}\delta X_{loss}(\nu)]}{\gamma+3\mu|\alpha|^2-i2\pi\nu}, \tag{2}$$

where $\delta X_{1out}(\nu)$ and $\delta X_{2out}(\nu)$ are the fundamental and SH fields' output amplitude fluctuations, respectively; $\delta X_{1in}(\nu)$ and $\delta X_{2in}(\nu)$ are the fundamental and SH fields' input amplitude fluctuations entering the cavity through

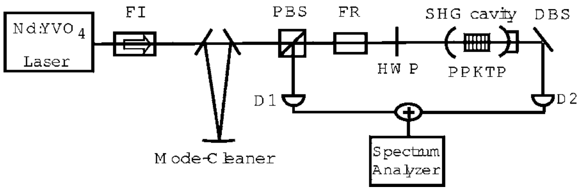

Fig. 1. Schematic diagram of the experimental setup. FI, Faraday isolator; PBS, polarizing beam splitter; FR, Faraday rotator; HWP, half-wave plate; DBS, dichroic beam splitter; D1, D2, photodetectors.

the coupling mirrors, respectively; $\delta X_{loss}(\nu)$ is vacuum amplitude fluctuations, μ is the two-photon damping rate; α is the average amplitude of the fundamental beam inside the cavity; γ_0, γ_1 are the input coupling and the intracavity loss rate for the fundamental field, respectively; and ν is the frequency in hertz.

By using Eqs. (1) and (2), the noise spectra can be given by

$$V_1 = \langle \delta X_{1out}(\nu)^\dagger \delta X_{1out}(\nu)\rangle = 1 - \frac{4\gamma_0\mu|\alpha|^2}{(\gamma_0+\gamma_1+3\mu|\alpha|^2)^2+(2\pi\nu)^2}, \tag{3}$$

$$V_2 = \langle \delta X_{2out}(\nu)^\dagger \delta X_{2out}(\nu)\rangle = 1 - \frac{8\mu^2|\alpha|^4}{(\gamma_0+\gamma_1+3\mu|\alpha|^2)^2+(2\pi\nu)^2}. \tag{4}$$

To derive Eqs. (3) and (4), we use the usual assumption $\langle \delta X_{1in}(\nu)^\dagger \delta X_{1in}(\nu)\rangle = \langle \delta X_{2in}(\nu)^\dagger \delta X_{2in}(\nu)\rangle = \langle \delta X_{loss}(\nu)^\dagger \delta X_{loss}(\nu)\rangle = 1$.

The normalized quantum correlation spectrum between the SH and the fundamental fields can be given by[4]

$$\begin{aligned} C &= \frac{\langle \delta[X_{1out}(\nu)+X_{2out}(\nu)]^\dagger \delta[X_{1out}(\nu)+X_{2out}(\nu)]\rangle}{\langle \delta X_{1out}(\nu)^\dagger \delta X_{1out}(\nu)\rangle + \langle \delta X_{2out}(\nu)^\dagger \delta X_{2out}(\nu)\rangle} \\ &= 1 + \frac{\langle \delta X_{1out}(\nu)^\dagger \delta X_{2out}(\nu)\rangle + \langle \delta X_{2out}(\nu)^\dagger \delta X_{1out}(\nu)\rangle}{\langle \delta X_{1out}(\nu)^\dagger \delta X_{1out}(\nu)\rangle + \langle \delta X_{2out}(\nu)^\dagger \delta X_{2out}(\nu)\rangle}, \end{aligned} \tag{5}$$

where

$$\begin{aligned} \langle \delta X_{1out}(\nu)^\dagger \delta X_{2out}(\nu)\rangle &= \langle \delta X_{2out}(\nu)^\dagger \delta X_{1out}(\nu)\rangle \\ &= -\frac{4\mu|\alpha|^2\sqrt{2\gamma_0\mu|\alpha|^2}}{(\gamma_0+\gamma_1+3\mu|\alpha|^2)^2+(2\pi\nu)^2}. \end{aligned} \tag{6}$$

B. Detection of Quantum Correlation

The schematic arrangement for detection of quantum correlation is shown in Fig. 1. The signals directly measured by the two photodetectors are determined by the operators

$$n_1' = g_1 a_1'^\dagger a_1', \quad n_2' = g_2 a_2'^\dagger a_2', \tag{7}$$

with

$$a_1' = \sqrt{\eta_1}a_1 + \sqrt{1-\eta_1}c_v, \quad a_2' = \sqrt{\eta_2}a_2 + \sqrt{1-\eta_2}d_v, \tag{8}$$

where a_1, a_2 are the fundamental and SH fields' output annihilation operators, respectively, and a_1', a_2' are the corresponding annihilation operators reaching the two detectors; η_1 and η_2 are the detection efficiencies; g_1 and g_2 are electronic gain factors; and c_v and d_v are vacuum mode operators.

The amplitude quadrature operators are defined by

$$\begin{aligned} X_1' &= a_1' + a_1'^\dagger, \quad X_2' = a_2' + a_2'^\dagger, \quad X_1 = a_1 + a_1^\dagger, \\ X_2 &= a_2 + a_2^\dagger, \quad X_c = c_v + c_v^\dagger, \quad X_d = d_v + d_v^\dagger. \end{aligned} \tag{9}$$

Using Eqs. (7)–(9), we can get the equations for fluctuations in the frequency domain,

$$\delta n_1'(\nu) = g_1\sqrt{I_1}\delta X_1'(\nu) = g_1\sqrt{I_1}[\sqrt{\eta_1}\delta X_1(\nu) + \sqrt{1-\eta_1}\delta X_c(\nu)], \tag{10}$$

$$\delta n_2'(\nu) = g_2\sqrt{I_2}\delta X_2'(\nu) = g_2\sqrt{I_2}[\sqrt{\eta_2}\delta X_2(\nu) + \sqrt{1-\eta_2}\delta X_d(\nu)], \tag{11}$$

where $I_1 = \langle X_1'\rangle^2/4$, $I_2 = \langle X_2'\rangle^2/4$ are measured intensities of the fundamental and SH fields, respectively. The normalized spectrum of fluctuations measured by the spectrum analyzer is given by

$$\begin{aligned} \frac{\langle \delta[n_1'(\nu)+n_2'(\nu)]^\dagger \delta[n_1'(\nu)+n_2'(\nu)]\rangle}{\langle \delta n_1'(\nu)^\dagger \delta n_1'(\nu)\rangle + \langle \delta n_2'(\nu)^\dagger \delta n_2'(\nu)\rangle} &= 1 \\ + \frac{g_1 g_2\sqrt{\eta_1\eta_2 I_1 I_2}[\langle \delta X_1(\nu)^\dagger \delta X_2(\nu)\rangle + \langle \delta X_2(\nu)^\dagger \delta X_1(\nu)\rangle]}{\langle \delta n_1'(\nu)^\dagger \delta n_1'(\nu)\rangle + \langle \delta n_2'(\nu)^\dagger \delta n_2'(\nu)\rangle}&, \end{aligned} \tag{12}$$

with

$$\begin{aligned} &\langle \delta n_1'(\nu)^\dagger \delta n_1'(\nu)\rangle + \langle \delta n_2'(\nu)^\dagger \delta n_2'(\nu)\rangle \\ &= g_1^2\eta_1 I_1\langle \delta X_1(\nu)^\dagger \delta X_1(\nu)\rangle + g_1^2(1-\eta_1)I_1 \\ &\quad + g_2^2\eta_2 I_2\langle \delta X_2(\nu)^\dagger \delta X_2(\nu)\rangle + g_2^2(1-\eta_2)I_2. \end{aligned} \tag{13}$$

To see clearly how Eq. (5) is connected with Eq. (12), we assume $\eta_1 = \eta_2 = 1$ and set $g_1^2 I_1 = g_2^2 I_2$. The right-hand side of the Eq. (12) can then be simplified to

$$1 + \frac{\langle \delta X_1(\nu)^\dagger \delta X_2(\nu)\rangle + \langle \delta X_2(\nu)^\dagger \delta X_1(\nu)\rangle}{\langle \delta X_1(\nu)^\dagger \delta X_1(\nu)\rangle + \langle \delta X_2(\nu)^\dagger \delta X_2(\nu)\rangle}, \tag{14}$$

which is consistent with Eq. (5).

The equations given above will be used to determine all the theoretical values of the following experimental data.

3. EXPERIMENT

The experimental setup is depicted in Fig. 1. A homemade all-solid-state single-frequency $Nd:YVO_4$ laser delivers 700 mW of infrared power at 1064 nm. A narrow linewidth empty cavity (mode cleaner) was used to filter spatially and temporally the 1064 nm laser. After the mode cleaner, the intensity noise of the laser reaches the quantum noise limit (QNL) at 5 MHz, and the ellipticity of the Gaussian beam profile is reduced to less than 1%. The SHG cavity was formed by two cavity mirrors with 20 mm radii of curvature, which are separated by 40 mm. The beam waist of the fundamental is about 46 μm inside the cavity. The input coupler was coated for partial transmission of 2% at 1064 nm and high reflectivity at 532 nm. The output coupler was coated for high reflectivity at 1064 nm and high transmission at 532 nm. A periodically poled KTP (PPKTP) crystal was chosen as the nonlinear crystal for its relatively high nonlinear coefficient and room temperature operation. The PPKTP crystal was positioned at the center of the cavity, and its dimension is 1 mm $\times$ 2 mm $\times$ 10 mm (thickness $\times$ width $\times$ length). Both end faces of the PPKTP crystal were antireflection coated at 1064 and 532 nm. The intracavity loss was determined to be 1% by measuring the finesse of the cavity.

Before measuring the quantum correlation between fundamental and SH fields, we first investigated the amplitude noise of the fundamental and SH fields individually. The green light was separated from the infrared by using a dichroic beam splitter, and its amplitude noise was directly measured by a photodetector (FND-100Q). At a pump power of 6.1 mW, 3.2 mW green light was generated; Fig. 2 shows the amplitude noise of the green light and the corresponding QNL (calibrated by a thermal white-light source). Noise reduction of 0.3 dB is observed for the green light. (Considering the detection efficiency of 60%, the real squeezing is 0.5 dB.) The reflected pump beam with power of 0.62 mW, after the interaction with the SHG cavity, is reflected by a polarizing beam splitter after double passage through the Faraday rotator. A photodetector based on an ETX-300 photondiode was used to

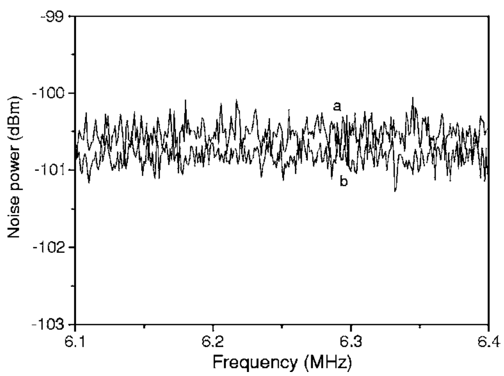

Fig. 2. Green-light amplitude-squeezed spectrum at a pump power of 6.1 mW. Curve a is the QNL, and curve b is the green-light amplitude noise. The resolution bandwidth and the video bandwidth are 30 kHz and 100 Hz, respectively.

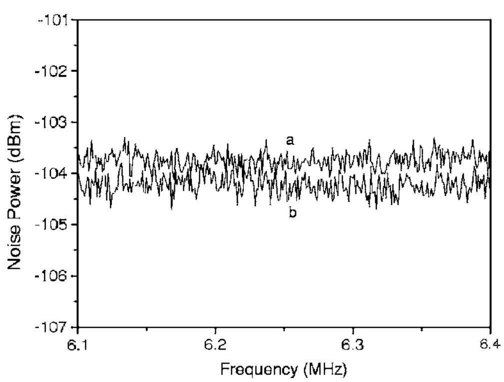

Fig. 3. Fundamental-light amplitude-squeezed spectrum at a pump power of 6.1 mW. Curve a is the QNL, and curve b is the fundamental-light amplitude noise. The parameters of the spectrum analyzer are the same as in Fig. 2.

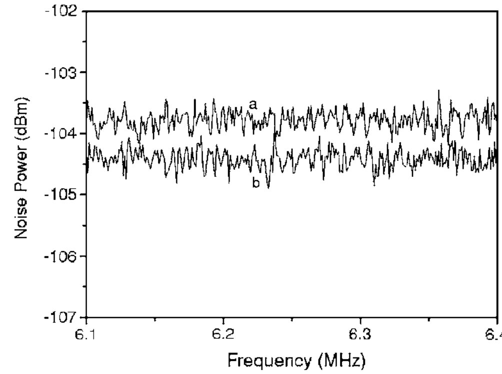

Fig. 4. Observation of quantum anticorrelation between fundamental and SH fields. Curve a is the sum of individual amplitude quadrature noise power of the SH and fundamental fields. Curve b is the noise power of the amplitude quadrature sum of SH field and fundamental fields. The parameters of the spectrum analyzer are the same as in Fig. 2.

directly detect the amplitude noise of the fundamental field (its noise spectrum is shown in Fig. 3; the QNL was also calibrated by a thermal white-light source), and squeezing of 0.5 dB can be observed. (Considering the detection efficiency of 79%, the real squeezing is 0.64 dB.) The measured results in Figs. 2 and 3 indicated that both beams are amplitude squeezed.

To measure the quantum correlation between the fundamental and the SH fields, the photodetectors of the SH and fundamental fields were well balanced with a thermal white-light source that provided a dc photocurrent equal to that given by the corresponding squeezed light. The measured quantum correlation result is shown in Fig. 4, where curve a is the sum of the individual amplitude quadrature noise power of the SH and fundamental fields corresponding to the case of no quantum correlation; curve b is the noise power of the amplitude quadrature sum of the SH and fundamental fields. It can be seen that curve b is 0.6 dB below curve a, which clearly verifies that the amplitude quadrature of the SH and fundamental fields are quantum anticorrelated.

By using our experimental parameters in the above equations ($\mu = 0.029\ \mathrm{s}^{-1}$, $\gamma_0 = 3.1 \times 10^7\ \mathrm{s}^{-1}$, $\gamma_1 = 1.57 \times 10^7\ \mathrm{s}^{-1}$, $\nu = 6.2$ MHz, and $|\alpha|^2 = 5.3 \times 10^8$), we can get (the detection efficiencies have been considered) $V_{1,Theo} = 0.7$ dB, $V_{2,Theo} = 0.5$ dB, and $C_{Theo} = 0.7$ dB. These theoretical values agree well with our experimental results: $V_{1,Expe} = 0.5$ dB, $V_{2,Expe} = 0.3$ dB, and $C_{Expe} = 0.6$ dB.

In conclusion, amplitude quadrature squeezing of both the fundamental and SH fields was generated with degrees of squeezing of 0.5 and 0.3 dB, respectively, in an external cavity-enhanced singly resonant PPKTP frequency doubler. At the same time, the quantum anticorrelation of 0.6 dB between these squeezed fundamental and SH fields was also observed experimentally.

ACKNOWLEDGMENTS

This research is supported by the National Natural Science Foundation of China (grants 60478007 and 60527003), the Shanxi Province Young Science Foundation (grant 2006021003), and the Shanxi Province Foundation for Returned Overseas Chinese Scholar.

Kuanshou Zhang's e-mail address is kuanshou@sxu.edu.cn.

REFERENCES

1. S. F. Pereira, M. Xiao, H. J. Kimble, and J. L. Hall, "Generation of squeezed light by intracavity frequency doubling," Phys. Rev. A **38**, 4931–4934 (1988).
2. A. Sizmann, R. J. Horowicz, G. Wagner, and G. Leuchs, "Observation of amplitude squeezing of the up-converted mode in second harmonic generation," Opt. Commun. **80**, 138–142 (1990).
3. R. Paschotta, M. Collett, P. Kürz, K. Feidler, H. A. Bachor, and J. Mlynek, "Bright squeezed light from a singly resonant frequency doubler," Phys. Rev. Lett. **72**, 3807–3810 (1994).
4. H. M. Wisman, M. S. Taubman, and H.-A. Bachor, "Feedback-enhanced squeezing in second-harmonic generation," Phys. Rev. A **51**, 3227–3233 (1995).
5. N. B. Grosse, W. P. Bowen, K. Mckenzie, and P. K. Lam, "Harmonic entanglement with second-order nonlinearity," Phys. Rev. Lett. **96**, 063601 (2006).
6. B. Julsgaard, J. Sherson, J. I. Cirac, J. Fiurášek, and E. S. Polzik, "Experimental demonstration of quantum memory for light," Nature **432**, 482–486 (2004).
7. T. Chanelière, D. N. Matsukevich, S. D. Jenkins, S.-Y. Lan, T. A. B. Kennedy, and A. Kuzmich, "Storage and retrieval of single photons transmitted between remote quantum memories," Nature **438**, 833–836 (2005).
8. M. D. Eisaman, A. André, F. Massou, M. Fleischhauer, A. S. Zibrov, and M. D. Lukin, "Electromagnetically induced transparency with tunable single-photon pulses," Nature **438**, 837–841 (2005).
9. C. W. Chou, H. de Riedmatten, D. Felinto, S. V. Polyakov, S. J. van Enk, and H. J. Kimble, "Measurement-induced entanglement for excitation stored in remote atomic ensembles," Nature **438**, 828–832 (2005).