INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS

J. Phys. B: At. Mol. Opt. Phys. **39** (2006) 4163–4168 doi:10.1088/0953-4075/39/20/014

Investigation of fundamental and second harmonic squeezed lights from a singly resonant PPKTP frequency doubler

Sujing Zhang, Yongmin Li, Jianli Liu and Kuanshou Zhang

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

E-mail: kuanshou@sxu.edu.cn

Received 25 April 2006, in final form 24 July 2006
Published 10 October 2006
Online at stacks.iop.org/JPhysB/39/4163

Abstract

Both fundamental and second harmonic amplitude squeezed lights were generated from an external cavity-enhanced singly resonant PPKTP frequency doubler. The effect of input coupling and fundamental power on the squeezing was experimentally investigated. It was shown that the optimal conditions (input coupling and fundamental power) are different for the squeezing of the fundamental and second harmonic lights. An agreement between experiment and theoretical prediction was found.

1. Introduction

The squeezed lights can improve precision measurements below the standard quantum noise limit (QNL) for optical detection [1] and can also be utilized to generate continuous variable entangled states that are essential resources for the field of quantum information science, such as teleportation [2], cryptography [3], quantum computing [4] and error correction [5]. Second harmonic generation (SHG) is not only a method to extend the spectrum of a laser to a short wavelength, but also has been proved to be an effective means of generating bright amplitude squeezed light [6–8]. Recently, some experiments have utilized quasi-phase-matched (QPM) crystals to achieve efficient SHG [10] and to generate continuous-wave amplitude squeezing light [11, 12] by SHG. For generation of squeezed light by SHG, QPM is very attractive because the largest nonlinear coefficient can be used and any nonlinear interaction within the transparency range of the material can be noncritically phase matched at a specific temperature, even interactions for which birefringent phase matching is impossible [13]. PPKTP has a relatively large optical nonlinearity and good power-handling capability in UV and visible spectra and can be used at room temperature. A further advantage of PPKTP is the high quality and homogeneity of the QPM structures generated by a cryogenic poling technique [14]. In this paper, we present experimental observations of both fundamental and second harmonic (SH)

0953-4075/06/204163+06$30.00

bright amplitude squeezed lights from an external cavity-enhanced singly resonant PPKTP frequency doubler. The system presented here can be used for high efficiency and simultaneous generation of squeezing lights with two different wavelengths. Such a 'two-colour' source is useful for long distance quantum communication, the wavelengths of the fundamental and SH fields can be readily chosen to be around 1560 nm which lies in a low-loss transmission window of optical fibres and 780 nm which is compatible with the absorption lines of alkaline atoms and can be used for storage and processing of quantum information.

2. Theory

For a singly resonant frequency doubler in which only the fundamental wave is resonantly enhanced, two methods have been used to analyse such a system: the mean-field approximation [8] which neglects the variation of the fundamental field in the nonlinear crytal (NLC) and a self-consistent method which considers the fundamental field depletion in the NLC [9]. Under our experimental conditions, the fundamental input is low and the dimensionless single-pass interaction length [9] satisfies $\xi < 0.06$; so the mean-field approximation method is enough to model our experiment. The amplitude quadrature noise spectra of the SH and the fundamental modes are given by [8]

$$V_{\mathrm{SH}} = 1 - \frac{8\mu^2|\alpha|^4}{(\gamma + 3\mu|\alpha|^2)^2 + (2\pi\nu)^2}, \tag{1}$$

$$V_{\mathrm{fu}} = 1 - \frac{4\gamma_0\mu|\alpha|^2}{(\gamma + 3\mu|\alpha|^2)^2 + (2\pi\nu)^2}, \tag{2}$$

with

$$|\alpha|^2 = \frac{\left(-\gamma\mu + \left(\mu^3(\gamma^3 + 27\alpha_{\mathrm{in}}\gamma_0\mu) + 3\sqrt{3}\sqrt{\alpha_{\mathrm{in}}\gamma_0\mu^7(2\gamma^3 + 27\alpha_{\mathrm{in}}\gamma_0\mu)}\right)^{1/3}\right)^2}{3\mu^2\left(\mu^3(\gamma^3 + 27\alpha_{\mathrm{in}}\gamma_0\mu) + 3\sqrt{3}\sqrt{\alpha_{\mathrm{in}}\gamma_0\mu^7(2\gamma^3 + 27\alpha_{\mathrm{in}}\gamma_0\mu)}\right)^{1/3}}, \tag{3}$$

where V_{fu} and V_{SH} are fundamental mode amplitude quadrature noise spectrum and SH amplitude quadrature noise spectrum, respectively. $|\alpha|^2$ is the average intensity of the fundamental mode inside the cavity and α_{in} is the fundamental input field, μ is the two-photon damping rate, γ_0 is the input coupling for the fundamental mode and γ_1 is the intracavity loss rate at the fundamental, $\gamma = \gamma_0 + \gamma_1$ is the total linear damping rate and ν is the frequency in hertz.

For SHG, it is known that the lower intracavity loss rate and stronger nonlinear interaction can lead to higher SH amplitude squeezing. In real experiments, the available pump power α_{in}, the nonlinear coupling μ, the intracavity loss rate γ_1 and the detection frequency ν are usually fixed. To get the highest SH amplitude squeezing, there exists an optimal input coupling γ_0 [15] which can be numerically determined by using equation (1). The behaviour of the fundamental mode amplitude squeezing is different from that of the SH amplitude squeezing. By using equation (2), the best fundamental mode squeezing is

$$V_{\mathrm{fu}} = 1 - \frac{4\gamma_0\sqrt{\gamma^2 + 4\pi^2\nu^2}}{3\left(4\pi^2\nu^2 + \left(\gamma + \sqrt{\gamma^2 + 4\pi^2\nu^2}\right)^2\right)}, \tag{4}$$

when $\mu|\alpha|^2 = \sqrt{\gamma^2 + 4\pi^2\nu^2}/3$. From equation (4), we can see that the lower intracavity loss rate γ_1 and higher input coupling γ_0 can lead to stronger fundamental mode squeezing. The equations given above will be used to determine all the theoretical values of the following experimental data.

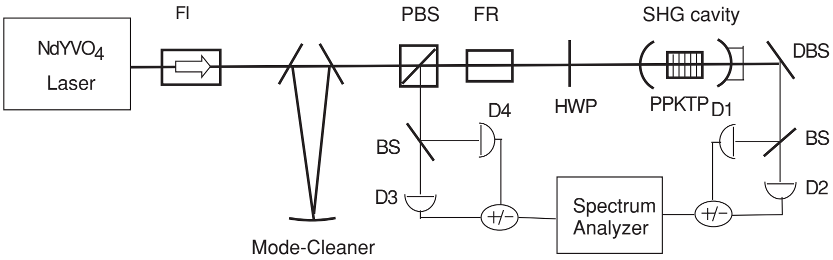

Figure 1. Schematic diagram of the experimental setup for generating both fundamental and SH amplitude squeezed lights. FI, Faraday isolator; PBS, polarizing beam splitter; FR, Faraday rotator; HWP, half-wave plate; DBS, dichroic beam splitter; BS, 50/50 beam splitter; D1, D2, D3, D4, photodetectors.

3. Experimental generation of bright SH amplitude squeezed light

The experimental setup for generating both fundamental and SH amplitude squeezed lights is depicted in figure 1 [16]. A homemade all-solid-state single frequency Nd:YVO$_4$ laser delivers 700 mW of infrared power at 1064 nm. A narrow line-width empty cavity (mode cleaner) was used to filter spatially and temporally the 1064 nm laser. After the mode cleaner, a TEM$_{00}$ beam was obtained, and the intensity noise of the laser reaches the quantum noise limit (QNL) at 5 MHz (0.1 dB above the QNL for a power of 32 mW). The frequency doubling cavity consisted of three different input couplers with transmission values of 1%, 2% and 5% at 1064 nm and high reflectivity at 532 nm and an output coupler with high reflectivity at 1064 nm and high transmission at 532 nm. The radius of each of the two curved mirrors is 20 mm and the beam waist of the fundamental beam inside the cavity is about 36 μm. The PPKTP crystal was positioned at the centre of the cavity, and its dimension is $1 \times 2 \times 10\,\mathrm{mm}^3$ (thickness × width × length). Both end faces of the PPKTP were antireflection-coated at 1064 nm and 532 nm, respectively. The experimental value of the single-pass nonlinearity is 0.008 $\mathrm{W}^{-1}\,\mathrm{cm}^{-1}$. The intracavity loss is determined to be 1.2% by measuring the finesse of the cavity.

The green light was separated from the infrared by using a dichroic beam splitter and then its amplitude noise was measured by a self-homodyne detection system. A sample of our data with a 2% input coupler is shown in figure 2. The squeezing is evident above 2 MHz and the maximum measured squeezing is 1 dB around 5 MHz. Considering the detection efficiency of 58.5%, the inferred squeezing is 1.9 dB.

Figure 3 shows the SH amplitude squeezing observed with three different input couplers of 1%, 2% and 5%. The theoretical values calculated from experimental parameters are also shown, corrected with the detection efficiency of 58.5%. It can be seen that higher pump power can lead to stronger squeezing when the pump power is lower than 50 mW or so. When the pump power is higher than 50 mW, the squeezing degraded for the input couplers of 1% and 2%, which is inconsistent with the theoretical prediction. The probable reason is the onset of a parasitic intracavity nondegenerate optical parametric oscillator [17]. The deviation between theoretical and experimental values is probably due to the stochastic variation of the domain length for QPM crystals [18] and destructive interference that results from a double-passed standing cavity [10]. The theoretical values give the optimal input coupling of 0.92% with a pump power of 45 mW. Experimentally, the best input coupler was the one with a transmission of around 2%.

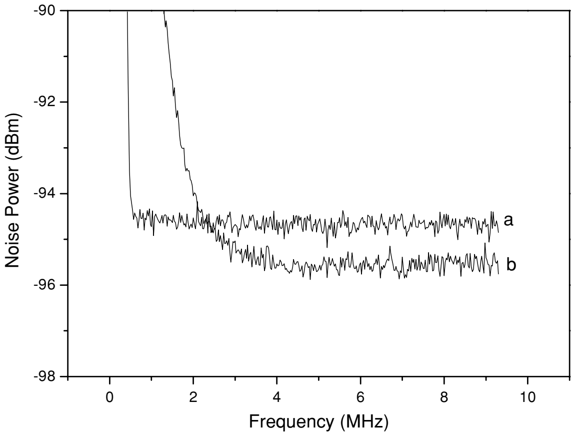

Figure 2. Typical green light amplitude squeezed spectrum of a 2% input coupler with pump power of 55 mW. a is the QNL and b is the green light amplitude noise. The resolution bandwidth and the video bandwidth are 30 kHz and 100 Hz, respectively.

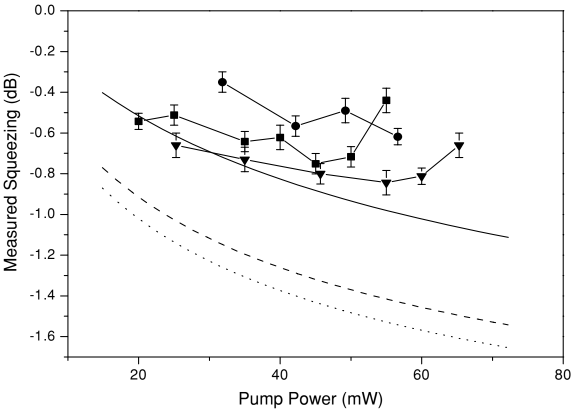

Figure 3. Observed SH amplitude squeezing as a function of input power for three different input coupler transmissions. Solid square: experimental data of a 1% input coupler, solid triangle: experimental data of a 2% input coupler, solid circle: experimental data of a 5% input coupler, error bars: statistical errors, solid line: theoretical values of a 5% input coupler, dashed line: theoretical values of a 2% input coupler and dotted line: theoretical values of a 1% input coupler.

4. Experimental generation of bright fundamental amplitude squeezed light

In figure 1, the reflected pump beam, after the interaction with the SHG cavity, is reflected by a PBS after the double passage through the FR. Its amplitude noise was measured by a self-homodyne detection system. A typical noise spectrum with a 5% input coupler is shown in figure 4. The squeezing is evident above 4 MHz and the maximum measured squeezing is 0.67 dB at 8 MHz. Considering the detection efficiency of 79%, the inferred squeezing is 0.86 dB.

Figure 5 shows the fundamental amplitude squeezing observed with two different input couplers of 2% and 5%. We also presented the theoretical values calculated from

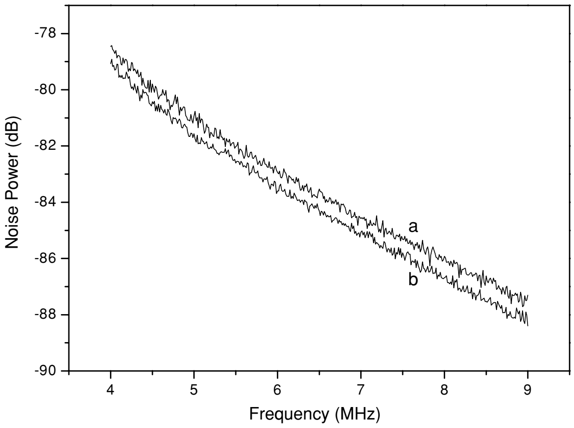

Figure 4. A sample of fundamental light amplitude squeezed spectrum of a 5% input coupler with a pump power of 9 mW. a is the QNL and b is the fundamental light amplitude noise. The resolution bandwidth and the video bandwidth are 30 kHz and 100 Hz, respectively.

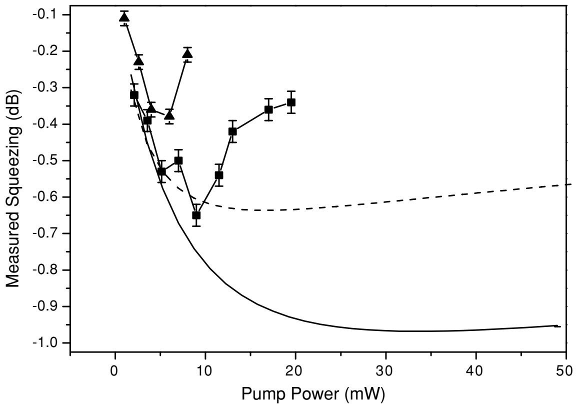

Figure 5. Measured fundamental amplitude squeezing as a function of input power for two different input coupler transmissions. Solid square: experimental data of a 5% input coupler, solid triangle: experimental data of a 2% input coupler, error bars: statistical errors, solid line: theoretical values of a 5% input coupler, dashed line: theoretical values of a 2% input coupler.

experimental parameters, corrected with a detection efficiency of 79%. In our experiment, we also tried to employ an input coupler of 1%, but no squeezing can be observed. Both theory and experimental results showed that a higher input coupler is desired for greater fundamental amplitude squeezing. The probable reason for the deviation between theoretical and experimental values is the same as that of SH squeezing.

5. Conclusion

In this work, an external cavity-enhanced singly resonant PPKTP frequency doubler was utilized to generate fundamental and SH amplitude squeezed lights. The effect of input coupling and fundamental power on the squeezing was experimentally investigated; it was shown that the optimal conditions (input coupling and fundamental power) are different for the squeezing of the fundamental and SH lights. A qualitative agreement between experiment and theoretical prediction was found. Further optimization of the system including better coatings for the cavity mirrors and the PPKTP crystal, or utilization of a semi-monolithic/monolithic SHG cavity, reduced greatly unwanted losses. In addition, a wedged QPM crystal [10] should be used to ensure perfect double-pass SHG. After these improvements, a higher degree of squeezing is achievable at relatively lower input power levels, making the QPM singly resonant doubler a promising source of bright squeezed light.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (no. 60478007, no. 60527003), the Shanxi Province Young Science Foundation (no. 2006021003) and the Shanxi Province Foundation for Returned Overseas Chinese Scholars.

References

[1] Wang H, Zhang Y, Pan Q, Su H, Porzio A, Xie C D and Peng K C 1999 *Phys. Rev. Lett.* **82** 1414
[2] Furusawa A, Sorensen J L, Fuchs C A, Kimble H J and Polzik E S 1998 *Science* **282** 706
[3] Ralph T C 2000 *Phys. Rev.* A **61** 010303
[4] Vincenzo Di D P 1995 *Science* **270** 255
[5] Braustein S L 1998 *Phys. Rev. Lett.* **80** 4084
[6] Pereira S F, Xiao M, Kimble H J and Hall J L 1988 *Phys. Rev.* A **61** 4931
[7] Sizmann A, Horowicz R J, Wagner G and Leuchs G 1990 *Opt. Commun.* **80** 138
[8] Paschotta R, Collett M, Kurz P, Fiedler K, Bachor H A and Mlynek J 1994 *Phys. Rev. Lett.* **72** 3807
[9] Maeda J and Kikuchi K 1996 *Opt. Lett.* **21** 821
[10] Juwiler I, Arie A, Skliar A and Rosenman G 1999 *Opt. Lett.* **24** 1236
[11] Lawrence M J, Byer R L, Fejer M M, Bowen W, Lam P K and Bachor H A 2002 *J. Opt. Soc. Am.* B **19** 1592
[12] Andersen U L and Buchhave P 2002 *Opt. Express* **10** 887
[13] Myers L E, Eckardt R C, Fejer M M, Byer R L and Bosenberg W R 1995 *Opt. Lett.* **12** 2102
[14] Oron M, Katz M, Eger D, Rosenman G and Skliar A 1997 *Electron. Lett.* **33** 807
[15] Bell A S, Riis E and Ferguson A I 1997 *Opt. Lett.* **22** 531
[16] Li Y M, Yang S R, Zhang S J and Zhang K S 2006 *Opt. Commun.* at press
[17] White A G, Lam P K, Taubman M S, Marte M A M, Schiller S, McClelland D E and Bachor H A 1997 *Phys. Rev.* A **55** 4511
[18] Maeda J, Matsuda I and Fukuchi Y 2000 *J. Opt. Soc. Am.* B **17** 942