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Generation of amplitude squeezed green light from a high efficiency PPKTP frequency doubler

Yongmin Li, Shurong Yang, Sujing Zhang, 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

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Abstract

We report on a high-efficiency 532 nm green light conversion from an external cavity-enhanced second harmonic generation of a home-made 1064 nm single-frequency Nd:YVO$_4$ laser with a periodically poled KTP crystal. A stable green power of 60 mW with a conversion efficiency of 75% was measured. Meantime, we investigate the quadrature amplitude noise of the green light at the same experimental setup and 0.6 dB green light squeezing was experimentally observed (taking into account the total detection efficiency of 58%, the squeezing should be 1.1 dB). The squeezing as a function of input power was also studied and we found qualitative agreement with theoretical prediction.

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Keywords: High efficiency resonant doubling; Squeezing light; Quasi-phase-matched

Since the electric field poling technique for LiNbO$_3$ was established by use of lithographically defined electrodes, interest in quasi-phase-matching (QPM) applications has been growing steadily. In a QPM crystal, the nonlinear coefficient is modulated with a period twice the coherence length of the interaction to offset the accumulated phase mismatch. The main advantage of QPM is that any 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; also the interacting waves can be chosen so that coupling occurs through the largest nonlinear coefficient [1]. Many applications such as second-harmonic generation (SHG), difference-frequency generation, and optical parametric oscillation have been demonstrated by using the QPM technique. SHG is an attractive technique for the generation of light in the visible range. For instance, a coherent green source can be readily developed by the frequency doubling of 1.06 micron laser [2,3]. SHG is not only an effective method to extend the spectrum of laser to short wavelength, but also has been proved to be an effective means of generating bright squeezed light [4–6]. The squeezing light can improve precision measurements below the standard quantum noise limit (QNL) for optical detection [7], also the nonclassical states (squeezed as well as entangled states) are essential resources for the field of quantum information science: such as teleportation [8], cryptography [9], quantum computing [10] and error correction [11].

Recently, some experiments have utilized QPM crystals to achieve efficient SHG [3] and generated continuous-wave squeezing light in periodically poled LiNbO$_3$ (PPLN) [12] and in periodically poled KTP (PPKTP) [13] by SHG. PPKTP has a relatively large optical nonlinearity and good power-handing capability in the UV and the visible spectra. For green light generation, PPKTP is preferred to periodically poled LiNbO$_3$ (PPLN) which exhibits strong photon-

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[*] Corresponding author. Tel.: +86 351 7010554; fax: +86 351 7011500.
E-mail address: kuanshou@sxu.edu.cn (K. Zhang).

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refractive damage when 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 report on a high-efficiency amplitude squeezed green light generation from a standing-wave external cavity-enhanced SHG of a home-made 1064 nm single-frequency Nd:YVO$_4$ laser with a PPKTP crystal. A stable green light of 60 mW with a conversion efficiency of 75% was measured. 0.6 dB amplitude squeezing of green light was experimentally observed at the same experimental setup (taking into account the total detection efficiency of 58%, the squeezing should be 1.1 dB). The squeezing as a function of input power was also studied. Comparing with Ref. [12], we used PPKTP (because of the advantages as mentioned above) instead of PPLN as our nonlinear crystal. Rather than a ring cavity which was used in Ref. [13], a standing wave cavity was employed to enhance the nonlinear conversion efficiency in our experiment. Therefore, better results were obtained in our experiment.

The experimental setup for high-efficiency SHG and generating amplitude squeezed light is depicted in Fig. 1. A homemade all-solid-state single frequency Nd:YVO$_4$ laser delivers 700 mW of infra-red power at 1064 nm. A faraday isolator is used to eliminate the back reflection laser that will disturb the stable operation of the laser. Because the transverse mode of the laser is not an ideal Gaussian mode (a little elliptical), this will decrease the efficiency of mode-matching between the laser and frequency doubling cavity. Also the laser light is influenced by excess intensity noise at frequencies up to 20 MHz (mainly because of intrinsic relaxation oscillations in the laser), this excess noise can degrade and even destroy the squeezing of the second-harmonic (SH). So a narrow line-width empty cavity (mode cleaner) was used to improve the transverse mode and reduce the excess intensity noise. When the mode cleaner was locked to the laser frequency, the transverse mode of the output laser is a Gaussian mode, and the intensity noise of laser reaches the QNL at 5 MHz (the corresponding frequency before the mode cleaner is 20 MHz). After the mode cleaner, a half-wave plate (HWP) and a polarizing beam splitter (PBS) was used to adjust the power incident upon the frequency doubling cavity. The HWP before the frequency doubling cavity was used to adjust the polarizing of the laser to satisfy the requirement of the phase-matching. The frequency doubling cavity consisted of an input coupler with a transmission of 5% at 1064 nm and high reflectivity at 532 nm, an output coupler that is high reflectivity at 1064 nm and high transmission at 532 nm. The radius of each of the two curved mirrors is 20 mm. The effective length of the cavity is 38.5 mm and thus we have a waist of 36 μm for the fundamental beam. The PPKTP crystal was positioned at the center of the cavity and its dimension is 1 mm × 2 mm × 10 mm (thickness × width × length). The crystal has a 9.00 μm grating period and both end faces antireflection coated for both 1064 nm and 532 nm. The intracavity loss is determined to be 1.2% by measuring the finesse of the cavity.

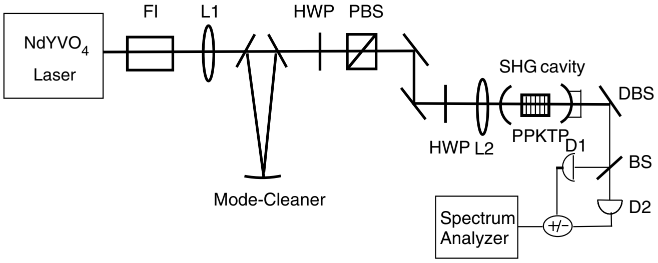

Fig. 1. Schematic diagram of the experimental setup. FI, Faraday isolator; L1, L2, mode-matched lens; HWP, half wave plate; PBS, polarizing beam splitter; DBS, dichroic beam splitter; BS, 50/50 beam splitter; D1, D2, photodiode.

At first, we measured the doubling efficiency of the PPKTP crystal as a function of the temperature. The experimental result is shown in Fig. 2. We can see that the optimal phase matching temperature is 30.4 °C and the full width half maximum is about 3.6 °C. Wide phase matching range ensures very stable and reliable operation. A homemade high precision temperature controller was used to accurately control the temperature of the PPKTP crystal to the optimal phase matching temperature. The mode-matching efficiency of the mode cleaner to the frequency doubling cavity was 95%. An electric servo was utilized to lock the cavity to ensure that the cavity frequency coincide with the pump laser frequency. The green light output was separated from the infrared light by a dichroic beam splitter. The green light output power and conversion efficiency as a function of the mode matching pump power is plotted in Fig. 3. At the pump power of 80 mW, 60 mW green light was obtained and frequency doubling efficiency is 75%. By fitting the experimental results to the theory (nonlinear conversion factor $\gamma_{\rm shg}$ is the only fitting parameter), we find the double-pass nonlinear conversion factor $\gamma_{\rm shg} = 0.032\ {\rm W}^{-1}$.

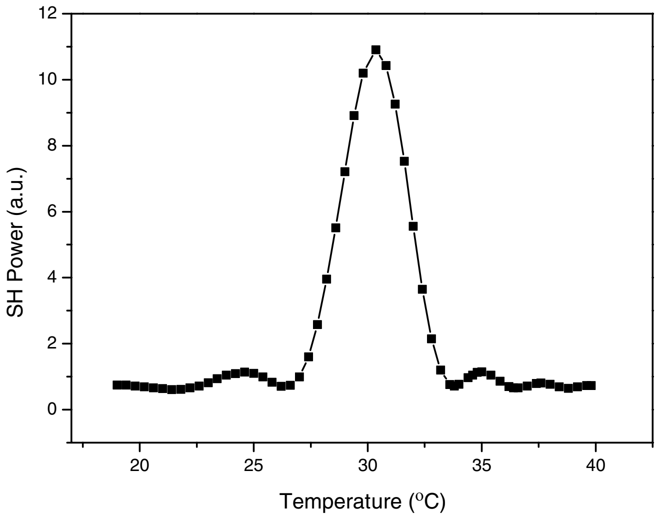

Fig. 2. Temperature tuning bandwidth for frequency doubling in PPKTP.

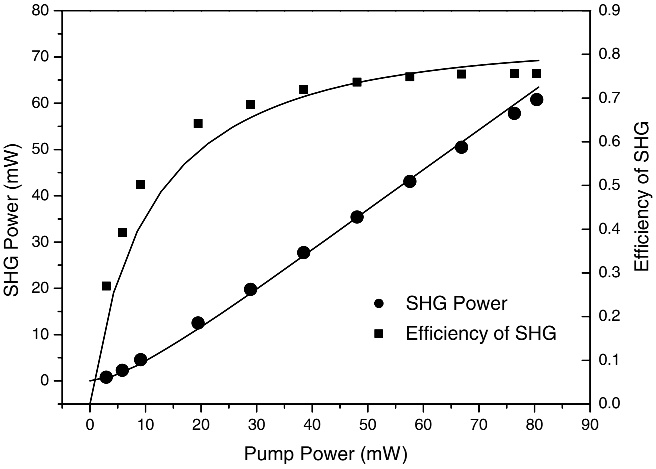

Fig. 3. SH power and conversion efficiency as a function of mode-matched pump power. The solid lines are theoretical results.

The quadrature amplitude noise of the high efficiency green light was measured by a self-homodyne system. The green light was sent to a 50/50 beam splitter and the resultant beams were sent to two balanced detectors whose currents were either added (the quadrature amplitude noise) or subtracted (QNL) and measured on a spectrum analyzer. The typical spectrum of the squeezed green light together with the QNL at frequencies from 0 MHz to 10 MHz is shown in Fig. 4 (the pump power is 56 mW and the green light power is 40 mW). The squeezing is evident from 3.5 MHz to 10 MHz. The maximum squeezing of 0.6 dB was experimentally observed at 8 MHz. Taking into account the total detection efficiency of 58%, the inferred amount of squeezing is 1.1 dB. We also investigate the squeezing of the green light at different pump power. Fig. 5 shows the observed squeezing as a function of the pump power. Considering the saturation of the detectors, the squeezing of green light cannot be measured at the power more than 40 mW. The solid line in Fig. 5 is the theoretical prediction corresponding to the experimental parameters calculated from the following equation [6]

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

where V_{sh} is the green light quadrature amplitude noise spectrum, μ is the two-photon damping rate, α is the average amplitude of the fundamental beam inside the cavity, γ is the total linear damping rate, and v is the frequency in hertz. It is obvious that the squeezing is improved when the pump power increased and there is a qualitative match between theory and experiment. The deviation between theoretical and experimental values is probably the excess noise in our experimental situation and stochastic variation of domain length for QPM crystal [15].

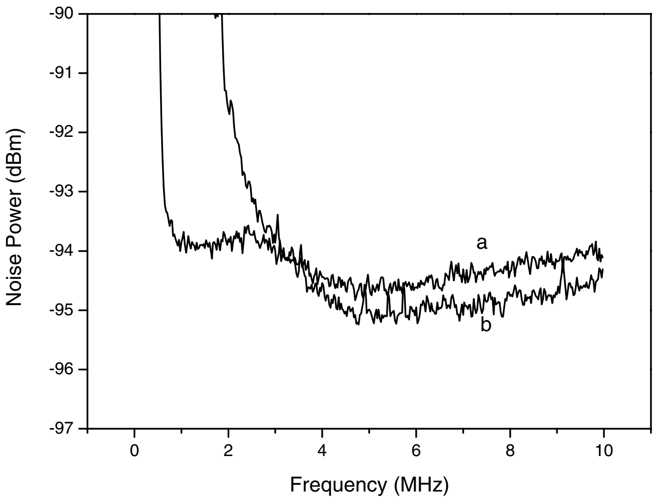

Fig. 4. The quadrature amplitude squeezing of green light (b) and corresponding QNL (a).

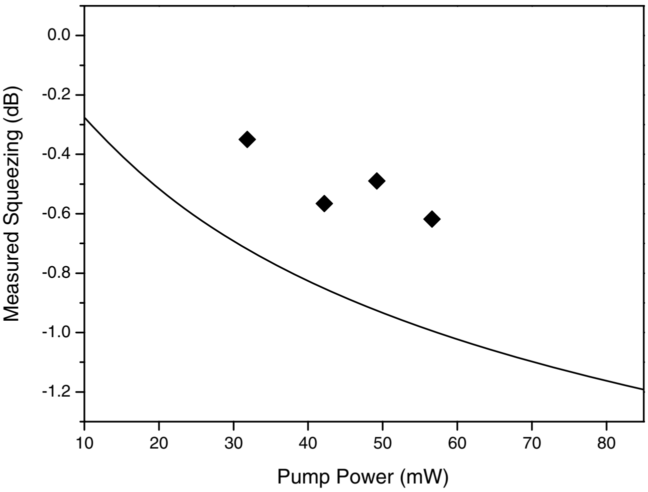

Fig. 5. The quadrature amplitude squeezing of SH at 8 MHz versus the pump power. Solid square, experimental results; solid line, theoretical value corresponding to the experimental parameters: $\mu = 0.029\ \mathrm{s}^{-1}$, $\gamma = 9.7 \times 10^7\ \mathrm{s}^{-1}$, $v = 8$ MHz, α can be determined by using standard nonlinear optics.

In conclusion, we report on an high efficiency amplitude squeezed green light generation from an external cavity-enhanced SHG of a home-made 1064 nm single-frequency Nd:YVO$_4$ laser with a PPKTP crystal. When the pump power is 80 mW, the output power of green light is 60 mW with efficiency of 75%. The 0.6 dB quadrature amplitude squeezing of the green light is experimentally observed (considering the total detection efficiency, the real squeezing is 1.1 dB). The squeezing as a function of input power is also investigated and we found qualitative agreement with theoretical prediction. Further optimization including better coatings of the cavity mirrors and the PPKTP crystal, or utilize a semi-monolithic/monolithic SHG cavity, to reduce greatly unwanted losses. At the same time a narrower line-width mode cleaner is employed to eliminate the excess laser intensity noise at lower frequency. Higher SHG efficiency and larger squeezing should be possible at a broader frequency range. For example, if the intracavity loss is reduced to be 0.5%, the quantum efficiency of the detector is improved to be 85%, the pump power is increased to be 250 mW and otherwise the same parameters in our experiment, 2.5 dB of squeezing can be observed at 5 MHz (considering detection efficiency, the real squeezing is 3.1 dB).

Acknowledgements

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