Quantum-noise measurements in high-efficiency single-pass second-harmonic generation with femtosecond pulses

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The quantum-noise properties of single-pass second-harmonic blue-light generation with femtosecond pulses have been measured. A conversion efficiency of as much as 63.5% of second-harmonic generation at 428.8 nm was observed in a KNbO$_3$ crystal with femtosecond (130-fs) pulses with wavelengths centered at 857.6 nm. The quantum noise on the generated blue light was measured to be 1.0 dB (1.4 dB of squeezing inferred) below the shot-noise limit. The noise reduction was found to be sensitive to the average power and the center wavelength of the input fundamental pulses under the condition of strong pump depletion.

The quantum-noise properties of high-efficiency nonlinear optical frequency-conversion processes have attracted great attention because of the potential generation of novel quantum states of light. In particular, second-harmonic generation (SHG) was an attractive process for generating amplitude-squeezed light with a large amount of photon-number squeezing. In those experiments a nonlinear crystal was placed inside an optical cavity (intracavity SHG) to enhance the nonlinear interaction by multiple passes through the crystal and the input fundamental field was frequency locked to the cavity such that the power of the input fundamental field was kept at a relatively low level for quantum-noise detection with photodetectors. Such systems may provide good sources of amplitude-squeezed light for applications in sub-shot-noise laser Doppler anemometry and spectroscopic measurements.

Recently, single-pass traveling-wave (TW) SHG was proposed and experimentally demonstrated in a bulk crystal and in a quasi-phase-matched nonlinear waveguide. In the TW SHG experiment with a type II phase-matched KTP crystal, pulses from a Nd:YAG mode-locked laser (1064 nm in wavelength and 140 ps in pulse width) were used, and 0.3-dB (6%) amplitude squeezing in SHG was observed with a conversion efficiency of 15%. In the experiment with a LiNbO$_3$ waveguide, 0.8-dB amplitude squeezing in the transmitted fundamental field and 0.35-dB squeezing in the generated harmonic light were observed, with a conversion efficiency approaching 60%.

However, no amplitude squeezing has been observed to our knowledge in the conceptually simpler system of type I TW SHG in a bulk crystal. The basic obstacle is that hundreds of watts of peak power are typically required for significant harmonic conversion and for squeezing in bulk crystals. This high optical power will saturate the photodiodes that are used to detect the amplitude noise and make the squeezing difficult to measure. This difficulty can be overcome by use of high-efficiency nonlinear crystals and ultrashort pulses, which permit significant harmonic conversion with low average input power. Recently, KNbO$_3$ crystal was used in highly efficient blue-light generation. In cw SHG the single-path conversion efficiency is $2\% W^{-1}$ for a 10-mm-long crystal. In a femtosecond pulsed TW SHG a slope efficiency of 300$\% nJ^{-1}$ for harmonic conversion was observed with a 3-mm long crystal. Thus, single-pass SHG in KNbO$_3$ crystal with femtosecond pulses promises to be a simple system for the study of quantum noise.

In this Letter we report quantum-noise measurements in a high-efficiency single-pass SHG system with a mode-locked femtosecond (130-fs) pulse laser in a noncritical type I phase-matched KNbO$_3$ crystal. In this system the spectral profile of the input femtosecond pulses (with a typical bandwidth of 12 nm at 857.6 nm) is much broader than the phase-matching bandwidth ($\sim 0.7$ nm for a crystal length of 6.7 mm) of the KNbO$_3$ crystal. The conversion efficiency from fundamental pulses (centered at 857.6 nm) to blue-light pulses (at 428.8 nm) can be greater than 60%, which is in the strong depletion region for the fundamental field. The quantum noise on the blue light was observed to be 1.0 dB below the shot-noise limit in certain conditions and to be highly sensitive to the center wavelength of the input pulses.

The experimental arrangement is shown in Fig. 1. Short pulses ($\sim 130$ fs wide) at an 82-MHz repetition rate emitted from a mode-locked Ti:sapphire laser are...
focused onto an α-cut, 10-mm-thick KNbO₃ crystal with a lens of 5-cm focal length. The entrance surface of the KNbO₃ nonlinear crystal is antireflection coated for 860 nm, and the exit surface is antireflection coated for 430 nm. The crystal is kept at room temperature (∼25 °C) and is noncritically type I phase matched for SHG to 428.8 nm. The center wavelength of the Ti:sapphire oscillator is tuned to 857.6 nm, and the input average power is variable from 0 to 300 mW. The output blue light is collected with a 5-cm lens, filtered with an optical filter, and then detected either by an optical powermeter for average power or by a balanced homodyne detector for quantum-noise measurements.

The balanced homodyne detector comprises a 50–50 beam splitter and two identical photodiodes. The photodiodes are placed at angles to the incident blue-light beam, and the blue light from a photodiode’s front surface is reflected back to the photodiode by a mirror placed close to the photodiode. With this arrangement, the quantum efficiency of the photodiodes at 428.8 nm is increased from 0.65 to 0.85. The overall efficiency of blue-light detection from the exit surface of the crystal to the output photocurrents of the photodiodes is estimated to be 0.75. The output photocurrent from each photodiode is coupled to a low-pass filter (dc, 32 MHz) to reduce the 82-MHz signal that is due to the laser repetition rate and then ac coupled to a low-noise preamplifier. The amplified noise currents (i₁ and i₂) are then combined in a 0°/180° (+/−) combiner to give the sum (iₖ = i₁ + i₂) or the difference (i₉ = i₁ − i₂) noise current. The sum or difference noise current is fed by a rf switch into another amplifier and then fed into a spectrum analyzer for noise measurements. The balance of the homodyne detectors is carefully checked; a typical common-mode rejection of more than 25 dB was observed for our measurement frequency range of 5–15 MHz. Difference current i₉ gives the shot-noise limit (SNL), and sum current iₖ gives the amplitude noise of the light field incident onto the homodyne detectors.

The output powers (blue and transmitted infrared) and the frequency-conversion efficiency of the SHG at different input average powers are shown in Figs. 2(a) and 2(b). As much as 63.5% conversion efficiency was observed at the 110-mW input power. With higher input power, the SHG conversion efficiency decreased. This cause of this phenomenon can be explained as the combined effects of strong pump depletion and blue-induced absorption of the fundamental field. The spectral profiles of the input fundamental IR field and the output blue field were measured with a 0.5-m monochromator, shown in Figs. 2(c) and 2(d). The results show that the input fundamental femtosecond pulses have broad spectral bandwidths (>10 nm at 857.6 nm), whereas the output blue pulses have narrow bandwidths (<0.5 nm at 428.8 nm, limited by the resolution of the spectrometer). This means that the broadband fundamental IR pulses have been converted into narrow-band blue pulses because of the narrow phase-matching bandwidth of the KNbO₃ crystal.

A typical noise spectrum of the output SHG blue pulses is shown in Fig. 3. The input pump power is 80 mW, and the output blue power is 41.9 mW (after the filter). The dc currents of the two detectors are I₁ = I₂ = 6.3 mA. The resolution bandwidth of the spectrum analyzer was set at 300 kHz, and that of the video filter at 10 Hz. Curve (a) of Fig. 3 is the spectral power density of the difference noise current, and curve (b) is the spectral power density of the sum noise current. The background (amplifier) noise, shown as curve (a), has been subtracted from both of them. The results show that the amplitude noise of the output blue pulses is a factor of 1.0 dB (~21%) below the shot-noise limit. Taking the overall detection efficiency of 0.75 into account by F = ηSNL + 1 − η, where F is the measured Fano factor (the ratio between the amplitude noise level and the shot-noise level),
depletion condition. We experimentally observed 1.0-dB (1.4 dB inferred) amplitude noise reduction below the SNL. The quantum noise of the blue light generated in this simple process was found to be highly sensitive to the average input power and to the center wavelength of the input fundamental field. These quantum-noise measurements may provide a new physical insight into this high-efficiency nonlinear optical process. The current quantum theory of single-pass SHG\(^8\) treated both the fundamental and the harmonic fields as cw monochromatic waves, which were applied in a picosecond pulse experiment in which the spectral width of the input field was narrower than the phase-matching width.\(^{10}\) Our femtosecond pulse experiment may stimulate more theoretical interest in the system, in which the input field has a broader spectral width than the phase-matching width in SHG.

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