Using Temperature to Reduce Noise in Quantum Frequency Conversion

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Abstract: A main source of noise in quantum frequency conversion is spontaneous Raman scattering, which can be reduced by lowering the operating temperature. We show reduction in dark count rates that agrees well with theory.

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1. Introduction

Quantum frequency conversion (QFC) will be required in hybrid quantum networks to interface between nodes that operate at different wavelengths and to enable long-distance transport at telecommunications wavelengths. Typically, a QFC device consists of guided-wave $\chi^{(2)}$ device, like a periodically poled lithium niobate (PPLN) waveguide, that performs sum- or difference-frequency generation in the high-conversion regime. System conversion efficiencies up to 45% in single-stage QFC have been demonstrated [1]. Noise photons are mainly due to spontaneous Raman scattering (SRS) and spontaneous parametric downconversion (SPDC) [2]. We focus on SRS noise photons since SPDC noise is not significant in the long-wavelength pumping-scheme employed here [3].

The Raman-scattered photons are associated with the strong pump beam. The PPLN waveguide was designed such that the pump had the longest wavelength to avoid SPDC at the signal wavelength and also have less-efficient anti-Stokes Raman-scattered photons contribute to the noise. Raman scattering is a temperature-dependent process whose efficiency decreases with decreasing temperature. In this work, we describe the theoretically expected relative anti-Stokes Raman noise and show that it agrees well with experimental data.

The spectrum of spontaneous anti-Stokes Raman scattering is given by [3,4]

$$I(\Delta\nu,T) = I_0\sigma_0(\Delta\nu)n(\Delta\nu,T) \tag{1}$$

where

$$n(\Delta\nu,T) = \left[\exp\left(\frac{hc\Delta\nu}{kT}\right)-1\right]^{-1} . \tag{2}$$

h is Planck's constant, c is the speed of light, $\Delta\nu$ is the detuning between the wavelength of the Raman scattered photon and the pump, k is Boltzmann constant, and T is the temperature. The frequency-dependent cross-section, $\sigma_0(\Delta\nu)$, describes the Raman spectrum at a fixed temperature. For PPLN, this spectrum is given in Ref. [3]. There are two major peaks in the Raman spectrum of PPLN at $\Delta\nu$ = -260 cm^{-1} and -630 cm^{-1}. Changing the temperature of the waveguide changes the phasematching wavelengths and therefore $\Delta\nu$.

2. Experiment

The experimental setup is shown in Fig. 1. Frequency conversion was performed in a 52-mm-long PPLN reverse-proton-exchanged waveguide that was designed for sum-frequency generation (SFG) between a 1813-nm

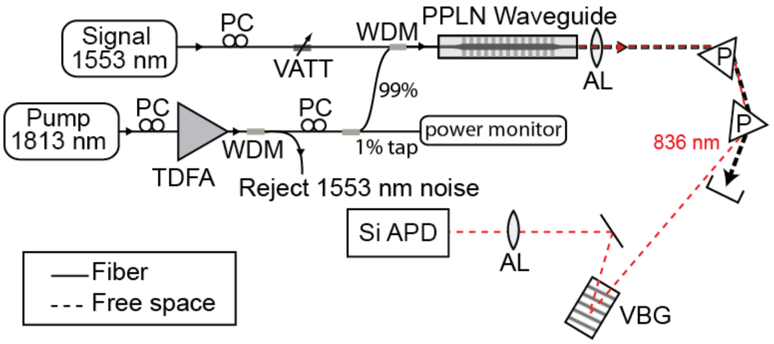

Figure 1. Experimental setup. PC, polarization controller; VATT, variable attenuator; WDM, wavelength division multiplexer; AL, aspheric lens; P, prism; TDFA, thulium-doped fiber amplifer; Si APD, silicon avalanche photodiode; VBG, volume Bragg grating.

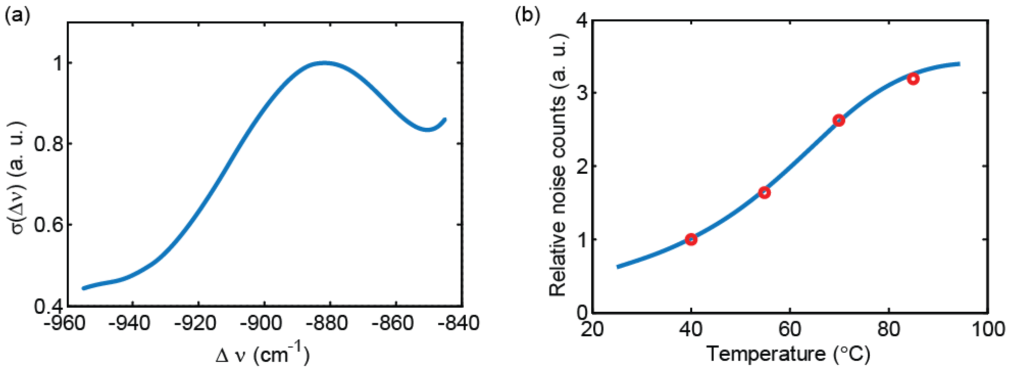

Figure 2. (a) Normalized Raman cross-section near -900 cm^{-1} detuning (after Ref. [3]). (b) Normalized noise counts (relative to T=40 °C). Solid line is theory and red circles are experimental measurements.

Table 1. Temperature tuning results including power at maximum conversion, P_{max}, maximum system conversion efficiency, $\eta(P_{max})$, and dark count rate at maximum conversion, $DCR(P_{max})$. The pump is fixed to 1812.55 nm.

Temperature (°C)	Signal wavelength (nm)	$\Delta\nu$ (cm^{-1})	P_{max} (mW)	$\eta(P_{max})$	$DCR(P_{max})$ (counts/sec)
40	1554.14	-917.3	215.4	0.20	2.79e3
55	1557.49	-903.5	207.8	0.19	4.38e3
70	1561.41	-887.4	204.5	0.23	8.74e3
85	1565.57	-870.4	199.9	0.25	11.4e3

pump and a 1553-nm signal at 40 °C; the SFG wavelength is hence at 836 nm. While holding the pump wavelength fixed, we varied the PPLN temperature between 40 °C and 85 °C, which caused the phasematched signal wavelength to tune between 1553 nm and 1565 nm. The input to the waveguide was fiber-pigtailed and the upconverted photons were detected with a Si avalanche photodiode (PerkinElmer SPCM-AQR-14). A prism pair after the waveguide was used to separate residual pump and signal beams from the upconverted photons. We also used a volume Bragg grating (VBG) tunable between 835-840 nm to reduce the Raman noise counts. At near normal incidence, the VBG bandwidth is constant but the diffraction efficiency slightly decreases as the angle of incidence increases (decreasing wavelength). In the analysis, we accounted for the wavelength-dependence of the VBG by normalizing the dark count rates to the system conversion efficiency.

Figure 2a shows the Raman cross-section spectrum for lithium niobate (after Ref. [3]) across the frequency range of interest. Using this data and Eqs. (1) and (2), we calculated the theoretical Raman scattering intensity, shown as the solid line in Fig. 2b (normalized to the value at 40 °C). The circles in Fig. 2b show the experimental noise count rates divided by the maximum conversion efficiency. There is excellent agreement between theory and experiment. The data used to calculate the red circles are shown in Table 1. We see an increase in system conversion efficiency at higher temperature when the VBG is tilted closer towards normal incidence. Non-ideal photon collection can be seen in certain measurements of $\eta(P_{max})$, which is the reason we divided $DCR(P_{max})$ by $\eta(P_{max})$ in Fig. 2b.

3. Conclusion

In conclusion, we have shown that the reduction in noise counts due to temperature during quantum frequency conversion is well-described by the theory of anti-Stokes Raman scattering, which includes accounting for the Raman cross-section spectrum. We observed a 3-fold decrease in noise counts when the PPLN temperature is reduced from 85 °C to 40 °C. This result suggests an interesting path forward to reducing dark count rates in quantum frequency conversion.

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