# Influence of domain disorder on parametric noise in quasi-phase-matched quantum frequency converters

**J. S. Pelc,* C. Langrock, Q. Zhang, and M. M. Fejer**

*E. L. Ginzton Laboratory, Stanford University, 450 Via Palou, Stanford, California 94305, USA*

**Corresponding author: jpelc@stanford.edu*

Received April 21, 2010; revised July 8, 2010; accepted July 9, 2010;
posted July 26, 2010 (Doc. ID 127329); published August 16, 2010

Ideal quantum frequency conversion (QFC) devices enable wavelength translation of a quantum state of light while preserving its essential quantum characteristics, namely photon statistics and coherence. However, the generation of noise photons due to spontaneous scattering of the strong classical pump used in the three-wave mixing process can limit QFC fidelity. We experimentally and theoretically characterize the noise properties of a difference-frequency generation device for QFC and find that fabrication errors in the quasi-phase-matching grating enhance generation of noise photons by parametric fluorescence. © 2010 Optical Society of America

*OCIS codes:* 190.4360, 190.4975, 230.7405, 270.5565.

Frequency conversion in $\chi^{(2)}$ media via sum- or difference-frequency generation (SFG/DFG) can interchange the quantum states of light between two wavelengths in a process known as quantum frequency conversion (QFC) [1]. QFC devices may assist in the development of quantum networks, in which photons are used to transfer quantum information between two nodes via a quantum channel [2], by allowing the flexibility to couple nodes operating in the visible or near-IR using telecom infrastructure at 1.3 or 1.5 $\mu$m [3]. In the QFC process, an input quantum state at frequency $\omega_1(\omega_2)$ can be upconverted (downconverted) to $\omega_2(\omega_1)$ via a three-wave mixing process with a pump at $\omega_p$, where $\omega_1+\omega_p=\omega_2$. If, for instance, light is input at $\omega_2$ and is being downconverted to $\omega_1$, the conversion efficiency $\eta$ is

$$\eta \equiv \frac{\langle \hat{n}_1(L)\rangle}{\langle \hat{n}_2(0)\rangle} = \sin^2\left(\sqrt{\eta_{\mathrm{nor}}P_p}L\right), \tag{1}$$

where $P_p$ is the pump power, $L$ is the device length, and $\eta_{\mathrm{nor}}$ is a normalized efficiency measured in $\mathrm{W}^{-1}\ \mathrm{cm}^{-2}$ [4].

Although it has been recognized that QFC works for both upconversion and downconversion of quantum states [3], experimental implementations have focused on upconversion of IR signals to enable single-photon (SP) detection using silicon detectors. Such experiments have been demonstrated using either waveguide [4] or bulk [5] periodically poled materials. QFC has been shown to preserve the photon statistics [6] and coherence [7] of an input telecom-band signal. However, a common issue affecting QFC devices is the generation of noise photons when there is no input signal. In an upconversion detector, such noise photons manifest as dark counts dependent on $P_p$ and are due to spontaneous scattering processes involving the strong classical pump. For pump and input frequencies that are relatively closely spaced (e.g., 1.32 and 1.55 $\mu$m [4,6]), it has been shown that spontaneous Raman scattering is the dominant noise source [4]. However, when the frequencies are further apart (e.g., 1.06 or 0.98 $\mu$m and 1.55 $\mu$m [5,7]), it has been speculated that spontaneous parametric downconversion (SPDC) of the pump is the dominant noise source [5]. However, the details of this suspected SPDC-induced noise have not been investigated in detail. By utilizing pump wavelengths that are substantially longer than the input signal wavelength (e.g., $\omega_p<\omega_1<\omega_2$), this noise source can be averted; upconversion detectors limited by the intrinsic dark-count rate of the single-photon detector have been demonstrated for both pulsed [8] and cw pumps [9].

In this Letter, we address the effects of parasitic SPDC on the performance of a DFG device designed to downconvert a quantum signal at $\omega_2$ in the visible to a target at $\omega_1$ in the 1.5 $\mu$m telecommunications band using a pump field at $\omega_p$, where $\omega_1=\omega_2-\omega_p$. A schematic of this process is shown in Fig. 1(a). Specifically, we show that nonidealities in the quasi-phase-matching (QPM) grating, as shown in Fig. 1(b), imply a QPM pedestal that enhances the rate of pump SPDC relative to an ideal grating, thereby creating noise photons and degrading the device performance.

Fabrication errors in which the local duty cycle of the QPM grating varies while the long-range order (or period) of the grating is preserved are called random duty-cycle (RDC) errors. While it is well known that RDC errors reduce the efficiency of $\chi^{(2)}$ mixing processes [10], RDC errors also result in a broad pedestal in the Fourier transform of the QPM grating and therefore produce a QPM pedestal that can extend hundreds of nanometers from the phase-matching peak [11]. Random duty-cycle errors occur when the error in the position of the $k$th domain edge $\delta z_k=z_k-z_{k,0}$ has a variance that is stationary with respect to $z$: $\sigma^2_{z_k}=\sigma^2_z$, owing to the

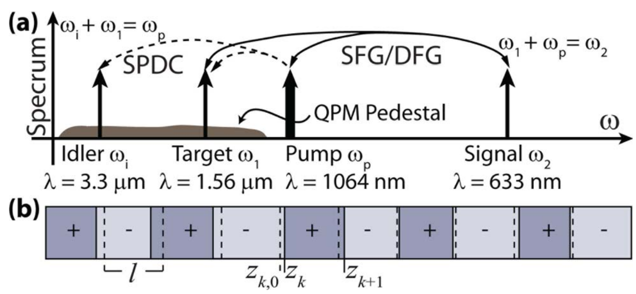


Fig. 1. (Color online) (a) Schematic of QFC between $\omega_1$ and $\omega_2$, showing broadband parasitic SPDC of the pump due to the disorder-induced QPM pedestal. (b) Random duty-cycle errors in a nonideal QPM grating: $\langle \delta l_k\rangle=0$, where $\delta l_k=\delta z_{k+1}-\delta z_k$ and $\delta z_k=z_k-z_{k,0}$, where $z_{k,0}=kl$.

 

lithographic definition of domain positions. We assume the errors are statistically independent, such that domain length variance $\sigma_l^2 = 2\sigma_z^2$. Assuming Gaussian statistics for the RDC errors, the height of the QPM pedestal and, hence, the rate of off-phase-matched SPDC $N_1$ compared to a perfectly quasi-phase-matched process with the same wavelengths $N_{1,\mathrm{pm}}$, can be calculated analytically:

$$\langle |g|^2 \rangle \equiv \frac{N_1}{N_{1,\mathrm{pm}}} = \frac{1}{N_D}\left[1 - \exp\left(-\frac{\pi^2\sigma_l^2}{2l^2}\right)\right], \qquad (2)$$

where $l$ is the average domain length and $N_D = L/l$ is the total number of QPM domains in the device [11]. For example, a device with $N_D = 10^4$ domains and normalized width error $\sigma_l/l = 0.15$ has a QPM pedestal height $\langle |g|^2 \rangle = 1.1 \times 10^{-5}$.

We fabricated waveguides in periodically poled lithium niobate using the reverse-proton-exchange technique [12], with length 5.2 cm and poling period $\Lambda_G = 2l = 10.27\ \mu$m. We downconverted a weak classical signal from a He–Ne laser ($\lambda_2 = 633$ nm) via DFG with a pump at $\lambda_p = 1.06\ \mu$m, producing radiation at a target wavelength $\lambda_1 = 1.56\ \mu$m. This interaction simulates the downconversion of SPs from a nitrogen-vacancy color center in diamond, which have a zero-phonon emission line at 637 nm [13]. The waveguide included a narrow input coupler of 3 $\mu$m width to facilitate coupling to the fundamental spatial mode, followed by an adiabatic taper to a mixing region of 7.75 $\mu$m width. Because overall efficiency was of little concern for this characterization experiment, no special effort was made to optimize coupling to the waveguide; light was coupled in using an aspheric lens ($f = 8$ mm) with an efficiency of 40% (5%) at the pump (signal) wavelength. With a constant signal power $P_2(0) = 50$ nW, we measured the generated target-wavelength power $P_1(L)$ as a function of the pump power $P_p$ by coupling the light at the output of the waveguide into an optical spectrum analyzer (OSA). We calculated the conversion efficiency and plotted the results as squares in Fig. 2; the solid curve is a fit to Eq. (1), showing good agreement. The maximum conversion efficiency was estimated to be 80% and was reached at $P_p = P_{\max} = 78$ mW. At $P_{\max}$, we observed 95% depletion of the input signal using the OSA, which was limited by residual higher-order spatial mode content at $\omega_2$. The conversion efficiency was also limited by propagation losses, which were measured (estimated) to be 0.2 (0.1) dB cm$^{-1}$ at $\omega_1$ ($\omega_2$). An input coupler has been designed that will enable higher coupling efficiency (>80%) and reduced higher-order mode content and will be utilized in future experiments involving single photons.

To analyze the noise behavior, we turned off the signal laser and measured the output power at the target frequency as a function of $P_p$. Observing the weak SPDC near 1.5 $\mu$m poses a challenge; due to the difficulty of counting photons in this spectral range, we used a lock-in technique whereby the pump was intensity-modulated and the SPDC was detected using a linear-mode InGaAs avalanche photodiode. The light exiting the waveguide was spectrally filtered using a dispersive prism and dichroic mirror to remove the residual pump. The collection bandwidth $\Delta\lambda = 44$ nm ($1/e^2$ full width) was measured by sweeping a tunable laser across the 1.55 $\mu$m spectral region, and absolute calibration was done by inserting a 1.56 $\mu$m signal of known strength into the filtering/detection system. The data are shown in Fig. 2 and are well fit by a linear dependence on pump power as expected for a spontaneous scattering process. We find a noise-photon spectral density (NSD) of $1.45 \times 10^6$ s$^{-1}$ nm$^{-1}$ at $P_p = P_{\max}$. The expected NSD for a nominally identical device with $\sigma_l = 0$ and $P_p = P_{\max}$ is approximately $10^2$ s$^{-1}$ nm$^{-1}$ [14]. Additionally, we note that any noise produced in waveguides without a QPM grating was below the estimated $10^5$ s$^{-1}$ nm$^{-1}$ sensitivity of the detection system.

We can combine Eqs. (1) and (2) with an expression for the rate of SPDC [14] to yield tolerances for the maximum RDC error $\sigma_l/l$ allowed to achieve a conversion efficiency $\eta$ and NSD $dN_1/d\lambda_1$. For a device with $N_D$ domains, an approximation valid for $\sigma_l/l \lesssim 0.2$ gives

$$\left(\frac{\sigma_l}{l}\right)^2 = \left(\frac{2N_D n_i \lambda_i \lambda_1^2}{\pi^2 n_3 \lambda_3 c}\right) \frac{dN_1}{d\lambda_1} \frac{r}{\sin^{-1}\sqrt{\eta}}, \qquad (3)$$

where the factor $r = 1$ for plane-wave interactions. This plane-wave model is easily extended to other plane-wave-like interactions: in waveguides, $r$ becomes a ratio of the square of mode-overlap integrals [15] and, for near-field Gaussian interactions, $r$ becomes a ratio of spatial coupling factors for the SPDC and QFC processes [16].

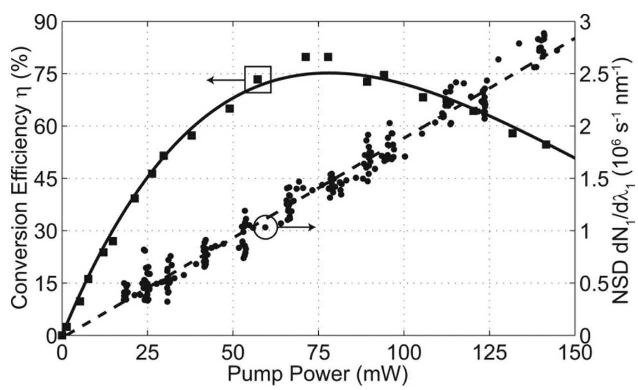


Fig. 2. DFG conversion efficiency versus $P_p$ (squares) and fit to Eq. (1) (solid line); SPDC noise-photon spectral density (NSD) $dN_1/d\lambda_1$ (dots) and linear fit (dashed).

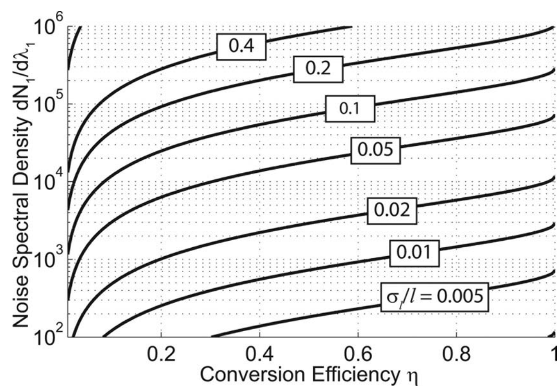


Fig. 3. Contours of constant $\sigma_l/l$ required to achieve conversion efficiency $\eta$ and noise-photon number spectral density $dN_1/d\lambda_1$, for a device with $N_D = 10^4$.

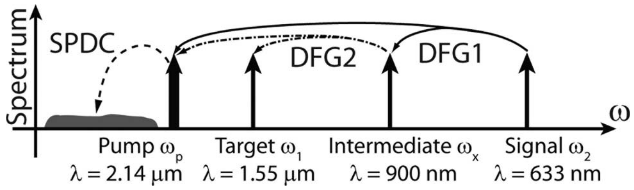


Fig. 4. Schematic of long-$\lambda$-pumped QFC between $\omega_2$ and $\omega_1$ via cascaded conversion steps.

Equation (3) is plotted as a contour map in Fig. 3. It is evident that for high-efficiency and low-noise performance, RDC errors need to be controlled to significantly better precision than our current fabrication procedures allow: $\sigma_l/l \lesssim 0.5\%$. We can apply this analysis to upconversion-assisted single-photon detectors, such as in [5]; any noise photons generated within the acceptance bandwidth of the device are indistinguishable from signal photons and will be efficiently upconverted. Considering the parameters of the experiment presented in [5], one finds that $\sigma_l/l = 28\%$ would explain the observed noise level, a value consistent with the observation of lower $\eta_{\mathrm{nor}}$ than was predicted for an ideal QPM grating.

In our experiment, the idler field is in the cutoff region of the waveguide and radiation modes must be considered. An extension of the analysis of parametric interactions in the Čerenkov-idler configuration presented in [17] to include the domain-disorder-induced QPM pedestal has been performed. While the details are beyond the scope of this Letter, the completeness relation for the idler radiation modes [15] implies that $r$ becomes $\iint |E_p E_1^*|^2 \mathrm{d}^2x / |\iint E_2 E_1^* E_p^* \mathrm{d}^2x|^2 \geq 1$, where the $E_j$ are the normalized modal field profiles for the bound modes. Simulations of mode profiles for our waveguide structure give $r = 1.03$, which yields $\sigma_l/l = 21\%$. This value is consistent with direct measurements of RDC error using Zygo interferometry on another wafer poled using the same lithographic mask, which gave $\sigma_l/l = 8\%$.

As was discussed above, long-wavelength pumping can eliminate the effects of SPDC noise on QFC. But when $\omega_2 > 2\omega_1$, as is the case in this experiment, it is not possible to use a long-wavelength-pump scheme for QFC via a single conversion step. As an alternative, one can use a cascaded conversion scheme, as shown in Fig. 4, whereby the input signal at $\omega_2$ is first converted to an intermediate frequency $\omega_x$ by a first DFG process, $\omega_x = \omega_2 - \omega_p$, and the same pump is used to convert the intermediate to the target: $\omega_1 = \omega_x - \omega_p$. With this scheme, the pump wavelength can be longer than the target wavelength as long as $\omega_1 < 3\omega_2$, eliminating SPDC in the target band. A two-component QPM grating [18] can be used to phase match both processes in the same device.

In conclusion, we have analyzed the impact of random duty-cycle errors on the performance of quantum frequency conversion systems. For pump wavelengths substantially shorter than a signal or target wavelength, the phase-matching pedestal induced by RDC errors increases the effect of parasitic spontaneous parametric downconversion that generates noise photons and reduces the QFC fidelity. In Fig. 3, we see that the RDC error $\sigma_l/l$ must be controlled extremely well to simultaneously enable high conversion efficiency and low noise counts for short-wavelength pumping schemes. To circumvent this restriction for quantum frequency downconverters when $\omega_2 > 2\omega_1$, we have proposed a cascaded conversion scheme that should eliminate the effects of RDC-error-induced SPDC noise. In future work, we will build a long-wavelength-pumped cascaded downconverter and measure the converted photon statistics.

J. S. P. is supported by a Stanford University Robert N. Noyce Stanford Graduate Fellowship. Additional support is provided by the United States Air Force Office of Scientific Research (USAFOSR) under grant FA9550-09-1-0233 and the United States Army Research Office (USARO) under grant DAAD19-03-1-0199.

**References**

1. P. Kumar, Opt. Lett. **15**, 1476 (1990).
2. H. J. Kimble, Nature **453**, 1023 (2008).
3. Z. Y. Ou, Phys. Rev. A **78**, 023819 (2008).
4. C. Langrock, E. Diamanti, R. V. Roussev, Y. Yamamoto, M. M. Fejer, and H. Takesue, Opt. Lett. **30**, 1725 (2005).
5. M. A. Albota and F. N. C. Wong, Opt. Lett. **29**, 1449 (2004).
6. S. Tanzilli, W. Tittel, M. Halder, O. Alibart, P. Baldi, N. Gisin, and H. Zbinden, Nature **437**, 116 (2005).
7. A. P. VanDevender and P. G. Kwiat, J. Opt. Soc. Am. B **24**, 295 (2007).
8. H. Dong, H. Pan, Y. Li, E. Wu, and H. Zeng, Appl. Phys. Lett. **93**, 071101 (2008).
9. H. Kamada, M. Asobe, T. Honjo, H. Takesue, Y. Tokura, Y. Nishida, O. Tadanaga, and H. Miyazawa, Opt. Lett. **33**, 639 (2008).
10. M. M. Fejer, G. A. Magel, D. H. Jundt, and R. L. Byer, IEEE J. Quantum Electron. **28**, 2631 (1992).
11. J. Huang, "Multifunctional optical signal-processing devices in periodically poled lithium niobate," Ph.D. dissertation (Stanford University, 2007).
12. K. R. Parameswaran, R. K. Route, J. R. Kurz, R. V. Roussev, M. M. Fejer, and M. Fujimura, Opt. Lett. **27**, 179 (2002).
13. F. Jelezko and J. Wrachtrup, Phys. Status Solidi A **203**, 3207 (2006).
14. M. Fiorentino, S. M. Spillane, R. G. Beausoleil, T. D. Roberts, P. Battle, and M. W. Munro, Opt. Express **15**, 7479 (2007).
15. D. Marcuse, *Theory of Dielectric Optical Waveguides* (Academic, 1974).
16. R. L. Byer in *Quantum Electronics, a Treatise*, H. Rabin and C. L. Tang, eds. (Academic, 1975), Vol. 1.
17. V. Rastogi, K. Thyagarajan, M. R. Shenoy, P. Baldi, M. De Micheli, and D. B. Ostrowsky, J. Opt. Soc. Am. B **14**, 3191 (1997).
18. M. Asobe, O. Tadanaga, H. Miyazawa, Y. Nishida, and H. Suzuki, Opt. Lett. **28**, 558 (2003).