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# High Efficiency Single Photon Detection via Frequency Up-Conversion

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## ABSTRACT

We propose a method of single photon detection of infrared (IR) photons at potentially higher efficiencies and lower noise than allowed by traditional IR band Avalanche Photodiodes (APD). By up-converting the photon from IR, e.g., 1550 nm, to a visible wavelength in a nonlinear crystal, we can utilize the much higher efficiency of visible wavelength APDs. We have used a nonlinear crystal—Periodically Poled Lithium Niobate (PPLN)—and a pulsed 1064-nm Nd:YAG laser to perform the up-conversion to a 631-nm photon. When properly quasi-phase-matched, PPLN provides a large enough second order nonlinear susceptibility that near unit conversion efficiency of the IR photon into the visible should be possible. We have been able to observe peak conversion efficiencies as high as 80%, and have demonstrated scaling down to the single photon level while maintaining a background of $3 \times 10^{-4}$ dark counts/count. Since the PPLN only acts on one polarization of the single photon, we also propose a 2-crystal extension of this scheme whereby orthogonal polarizations may be up-converted coherently, thereby enabling complete quantum state transduction.

**Keywords:** Quantum Information, Quantum Cryptography, Single Photon Detection, Up-Conversion

## 1. INTRODUCTION

There are many applications which would benefit from the ability to detect single photons in the infrared. The physical characteristics of fiber optics lend themselves naturally to transmission at 1550 nm, and many telecommunications applications have gravitated to this wavelength. However, for applications which require fidelity at the single photon level, 1550-nm light has shown to be difficult to work with. Telecommunications systems where distance is limited by attenuation in fiber could extend their range by using detectors which were sensitive to single photons. In quantum information applications such as quantum teleportation and quantum cryptography, efficient detection of single photons is critical, since detector efficiency directly relates to the distance over which one can securely send messages.[1] Other uses include infrared astronomy and detection of single molecules that have transitions in the infrared.

Consequently, the best means of detecting these photons has been with infrared-optimized APDs. However, these detectors suffer from low quantum efficiency, high dark counts and the need for cryogenic cooling. Richard Hughes, George Morgan, and Glen Peterson[1] of Los Alamos National Laboratory have demonstrated implementations of the B92[2] and BB84[3] quantum key distribution protocols using a 1550-nm source. They found the optimal efficiency of their InGaAs detector to be around 11%. This efficiency limits the bit rate and distance achievable by the key distribution protocol; hence, any improvements in detecting infrared photons over standard IR APDs would be benificial to this type of application.

The nonlinear process of frequency up-conversion[4] can enable superior single-photon detectors in the infrared. By up-converting an infrared photon to a visible one, we can use silicon APDs which have much lower noise and higher efficiency for visible wavelengths. We are developing a method of quantum state transduction whereby a single photon of one frequency in an *arbitrary* polarization state can be faithfully up-converted to a higher frequency while preserving the polarization state. Such a capability is highly desirable, e.g., for distributed quantum computing. The transmission of qubits between quantum computers, especially over large distances, would most easily be accomplished by photons at 1550 nm (which has the highest transmission through fiber

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optics). Depending on the scheme used for computation, processing of qubits may likely require photons in the visible spectrum, e.g., corresponding to some atomic transition, and so a method must be developed for converting between wavelengths at the single photon level while coherently maintaining the polarization state.

## 2. SETUP

To achieve high efficiency frequency up-conversion, we utilize an intense escort laser pulse, a very weak input laser, and a bulk crystal of Periodically Poled Lithium Niobate (PPLN). The latter has been quasi-phase-matched to the frequencies of the initial and escort photons, as shown in Figure 1. This allows us to create a system which up-converts one photon from the input beam and one photon from the escort beam into a single output photon. Due to energy conservation, the output frequency $\omega_o$ is the sum of the input frequency $\omega_i$ and the escort frequency $\omega_e$. The relations that describe the nonlinear field evolution in a periodically poled nonlinear medium were given by Myers *et al.*.[5]

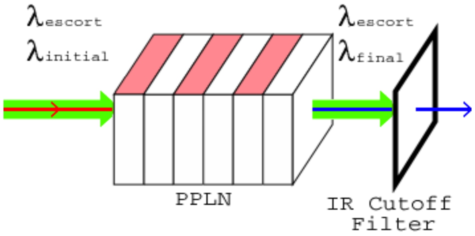

**Figure 1.** Scheme to efficiently convert an infrared initial photon to a visible wavelength final photon. For example, an initial photon at 1550 nm and a 1064-nm escort pulse are sent into a sample of Periodically Poled Lithium Niobate (PPLN). For appropriate crystal and escort pulse parameters, there is a near-unity probability of up-converting to a 631-nm photon.

$$\frac{dE_i}{dz} = i\frac{\omega_i d_Q}{n_i c} E_o E_e^* \exp(i\Delta k_Q z) \tag{1}$$

$$\frac{dE_e}{dz} = i\frac{\omega_e d_Q}{n_e c} E_o E_i^* \exp(i\Delta k_Q z) \tag{2}$$

$$\frac{dE_o}{dz} = i\frac{\omega_o d_Q}{n_o c} E_i E_e \exp(-i\Delta k_Q z), \tag{3}$$

where $E_i$, $E_e$, and $E_o$ are the electric field strengths of the input, escort, and output beams, respectively; $n_i$, $n_e$, and $n_o$ are the indexes of refraction of the three frequencies, $d_Q$ is the effective nonlinear coefficient of the Lithium Niobate (LiNbO$_3$); $z$ is the longitudinal position within the crystal; and $\Delta k_Q$, defined in Equation 4, is the parameter which sets the phase matching condition. We can derive a simple relation of the output power on the input power by noting that our input and output beams will have intensities at the single photon level, while the escort beam will have a peak power of several kilowatts. This means that we are operating safely in the non-depletion regime, where the escort beam is not significantly depleted by up-conversion of the input beam. Thus, we can approximate $dE_e/dz \approx 0$. We also assume that the phase-matching condition is satisfied, which means that $\Delta k_Q = 0$, where

$$\Delta k_Q = k_o - k_i - k_e - \frac{2\pi}{\Lambda}, \tag{4}$$

$k_i$, $k_e$, and $k_o$ are the wavenumbers of the three beams, and $\Lambda$ is the poling period of the PPLN crystal. The system then reduces to two coupled first order differential equations:

$$\frac{dE_i}{dz} = i\frac{\omega_i d_Q}{n_i c} E_o E_e^* \tag{5}$$

$$\frac{dE_o}{dz} = i\frac{\omega_o d_Q}{n_o c} E_i E_e. \tag{6}$$

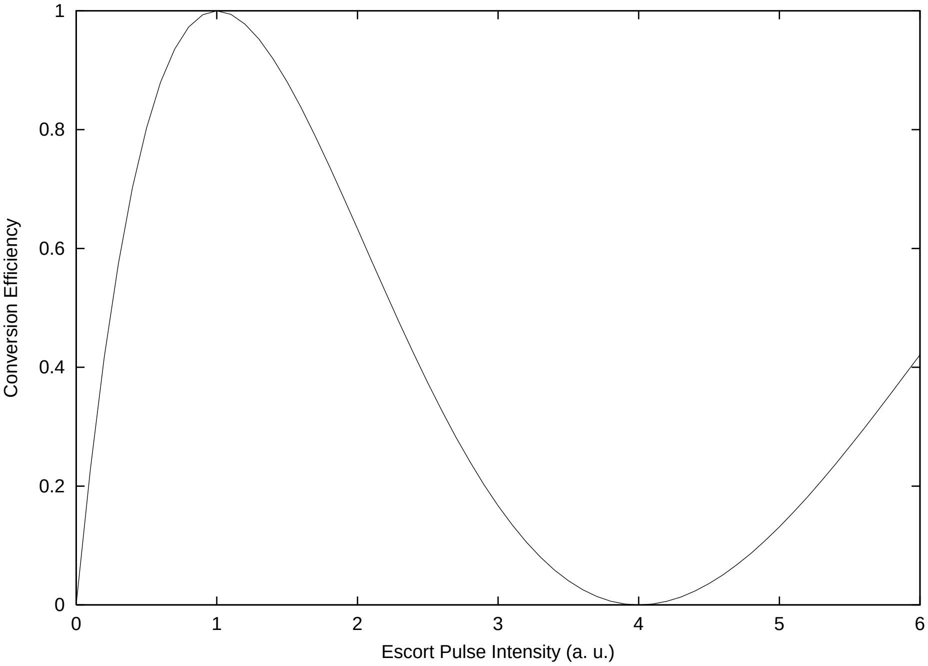

**Figure 2**. Up-conversion efficiency of a weak input beam versus the intensity of the escort light.

Solving for $E_o$, we see that the evolution of the system as a function of the distance $z$ through the crystal is essentially analogous to a Rabi oscillation between the input and output states:

$$E_o = \sin\left(\sqrt{\frac{\omega_i \omega_o}{n_i n_o}} \frac{d_Q E_e}{c} z\right), \tag{7}$$

or

$$I_o = \sin^2\left(A\sqrt{I_e} z\right), \tag{8}$$

where $A$ is a constant. The spatial period $L_c$ for this process is

$$L_c = \sqrt{\frac{\pi^2 n_i n_o c^2}{\omega_i \omega_o d_Q^2 |E_e|^2}}. \tag{9}$$

For a crystal of length $L_c$ (where $L_c$ implicitly depends on the escort intensity), the input light will be completely up-converted to the output frequency, and then down-converted back to the original input frequency before leaving the crystal. By choosing a crystal length equal to $L = L_c/2$, we can achieve very high conversion from $\omega_i$ to $\omega_o$, as shown in Figure 2.

## 2.1. Quasi-Phase-Matching in Periodically Poled Crystals

Maximizing the nonlinear coefficient is important since $L$, the length of crystal required to achieve full conversion, is inversely proportional to $d_Q$. We chose to utilize a periodically poled nonlinear crystal rather than a traditional bulk nonlinear crystal because it allows us to achieve quasi-phase matching and take advantage of larger elements in the nonlinear susceptibility tensor.[6] In any nonlinear process, both energy and momentum must be conserved, implying the following phase matching conditions:

$$\omega_o = \omega_i + \omega_e \tag{10}$$

$$n_o \omega_o = n_i \omega_i + n_e \omega_e, \tag{11}$$

Because all nonlinear crystals are also dispersive (i.e., $n = n(\omega)$), it is impossible to satisfy both conditions simultaneously if all three beams are polarized in the same direction. Traditional phase matching overcomes this obstacle by using crystals which not only have a nonlinear response, but are also birefringent. For example, by properly orienting the optic axis of the crystal and making either one or both of the input and escort beams have ordinary polarization, the output beam is polarized in the extraordinary direction. This is known as Type-I (ordinary + ordinary → extraordinary) or Type-II (ordinary + extraordinary → extraordinary) phase matching. The problem with such birefringent phase-matching in general is that nonlinear crystals, only very weakly couple modes that are polarized perpendicular to each other, so the second-order nonlinear coefficients which dictate these processes are very small. For example, for stoichiometric $LiNbO_3$ the maximum coefficient[7] is $d_{22} = 2.46 \pm 0.23$ pm/V.

In contrast, the $d_{33}$ nonlinear coefficient, which regulates the coupling of three *extraordinarily* polarized modes, is typically much larger than the elements which govern Type-I and Type-II processes. For $LiNbO_3$ $d_{33}$ can be as high[7] as 40 pm/V, more than an order of magnitude higher than $d_{22}$. In order to take advantage of this larger tensor element, we must have a way to satisfy momentum conservation when all the interacting fields are identically polarized. In quasi-phase-matching the periodic ferroelectric domains in a poled crystal contribute to the momentum, thus adding an extra term to Equation 11. This can be understood by noting that in Equations 1-3, where $\Delta k_Q$ is taken to be the parameter which describes the regular phase-matching condition, the sign of $dE_o/dz$ changes every time $z$ changes by $\pi/\Delta k_Q$. Thus, any increase of $E_o$ in the first $\pi/\Delta k_Q$ length of crystal is immediately canceled out by the second $\pi/\Delta k_Q$ length of crystal. The process of periodically poling a crystal uses a photolithography technique to create a mask of evenly spaced regions (ideally spaced at $\pi/\Delta k_Q$) running perpendicular to the optic axis of the crystal. An intense electric field is then applied to the regions exposed by the mask.[8] The electric field flips the direction of the nonlinear susceptibility of the crystal, which has the effect of changing the sign of the nonlinear coefficient. Consequently, we change the sign of $d_Q$ every $\pi/\Delta k_Q$ length of crystal, thus canceling out the overall sign of $dE_o/dz$. By properly selecting $\Lambda$, the poling period of the crystal, we can create a quasi-phase matching situation which allows us to take advantage of the larger $d_{33}$ nonlinear coefficient. Figure 3 explicitly shows the effect of periodically poling the crystal.

## 2.2. Escort Laser

Because of the intense electric fields required of the escort laser (on the order of a megavolt per meter) we are required to use a pulsed laser. We use an Nd:YAG "Nanolaser" [JDS Uniphase #NP-05011-110] as the escort beam, which provides high intensity pulses (˜500 ps; see Figure 4a) at 1064 nm, at an approximate repetition rate of 7.2 kHz. For a crystal length of 15 mm, with poling period $\Lambda = 11.2\,\mu m$, and a 13-kW escort pulse, we calculate that the peak conversion efficiency of a 1550-nm photon to a 631-nm photon should be close to 100%. Furthermore, as long as this process operates in the non-depletion regime where $E_i \ll E_e$, the relationship between input power and output power is strictly proportional. This means we can scale down the input power to the single photon level (or less) and the output photon statistics should match the input statistics, but at the higher frequency.[9]

## 2.3. Detection of Up-Converted Photon

Once the photon has been up-converted, it must be separated out from the escort photons before it can be detected. We use a system of prisms, dichroic beamsplitters, lenses and irises to separate the single 631-nm photon from the remaining $10^{13}$ 1064-nm photons in each pulse. After the escort beam is filtered out, the up-conversion photon is detected using a silicon APD [Perkin Elmer SPCM-22-AQR], with a typical efficiency of 60%.

## 2.4. Limitations of Escort Pulses

The single input photon and the escort photons must arrive at the crystal at the same time. Moreover, since the conversion efficiency is a function of the intensity of escort light, and we want the entire photon to be converted, it is necessary to make the single photon somewhat shorter than the escort pulse, such that in the region of overlap, the escort intensity looks relatively constant. We are helped by the fact that the conversion efficiency's dependence on escort intensity varies like $\sin^2(\sqrt{I_e})$, where $I_e$ is the escort intensity (Figure 2). This function

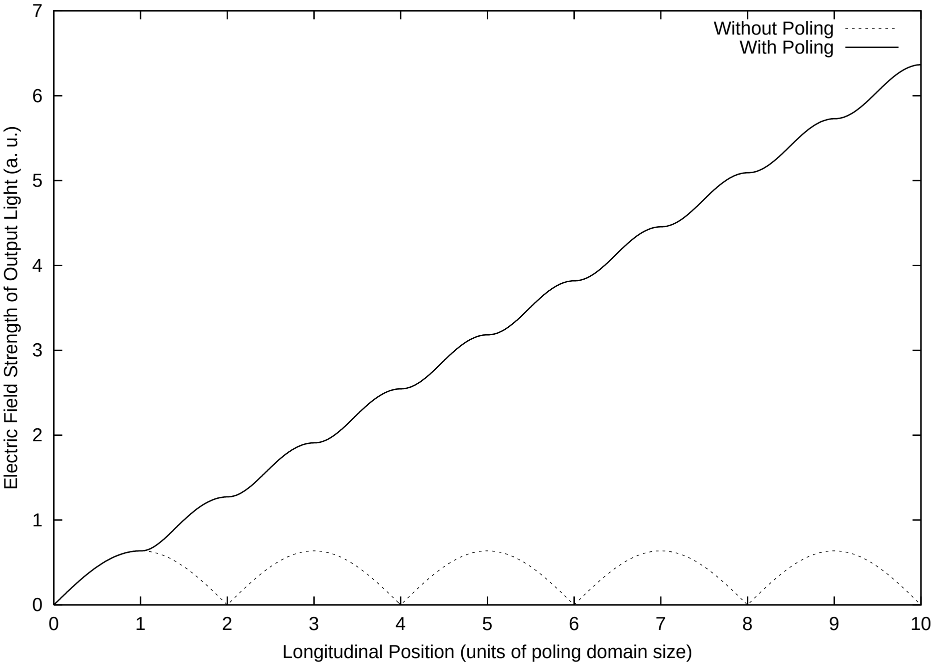

**Figure 3.** Electric field strength of output light versus longitudinal light, assuming *no* birefringent phase matching. By reversing the ferroelectric domain every $\pi/\Delta k_Q$, we achieve a steady growth in the output field. For the case of no poling, the light is alternately up-converted and down-converted, yielding at best a very small net conversion probability.

actually flattens out the conversion efficiency near the peak, and so it is not necessary for the single photon to be drastically shorter than the escort pulse, as shown in Figure 4b. In fact, if the duration of the single photon wave-packet is too short, its corresponding spread in frequency (and hence momentum) increases eventually violating the conservation of momentum phase-matching condition, as shown in Figure 5. We must balance between making the escort pulse appear constant and keeping the frequency spread to a minimum in order to achieve maximum conversion efficiency. For our system parameters we calculate an optimal pulse width of 100 ps; however, for widths less than 450 ps the conversion efficiency is still greater than 90%.

## 3. RESULTS

We have measured this up-conversion process, and have verified that it is a linear process with the input intensity. Figure 6 shows a graph of the output intensity measured using a silicon photodiode [Newport 818-SL] at various input intensities. In this experiment the escort beam is pulsed while the input beam is continuous, creating an output beam which is also pulsed. The absolute conversion efficiency from input to output is thus very low, since most of the input light passes through the crystal in between escort pulses. However, by knowing the escort intensity profile (Figure 4a) and the pulse repetition rate ($\approx$ 7.2 kHz), we can extrapolate a peak conversion efficiency of greater than 80%.

In addition to measuring the up-converted intensity produced by a 1.3-mW input beam, we have also measured high efficiency up-conversion at the single photon level. By using a series of neutral density filters, we attenuate our 1550-nm source such that, on average, only a single photon overlaps with the escort pulse. By counting 631-nm photons in coincidence with the escort pulse, we can determine the efficiency at the single photon level. Our results are in agreement with the 80% efficiency that we observed at the higher input intensities. We have also measured the background of single photon detection—defined as the probability of a dark count occuring during a 1 ns window around the photon arrival—of $3 \times 10^{-4}$, mostly due to fluorescence effects from the escort pulse. We anticipate that further design improvements can reduce this background by another order of magnitude.

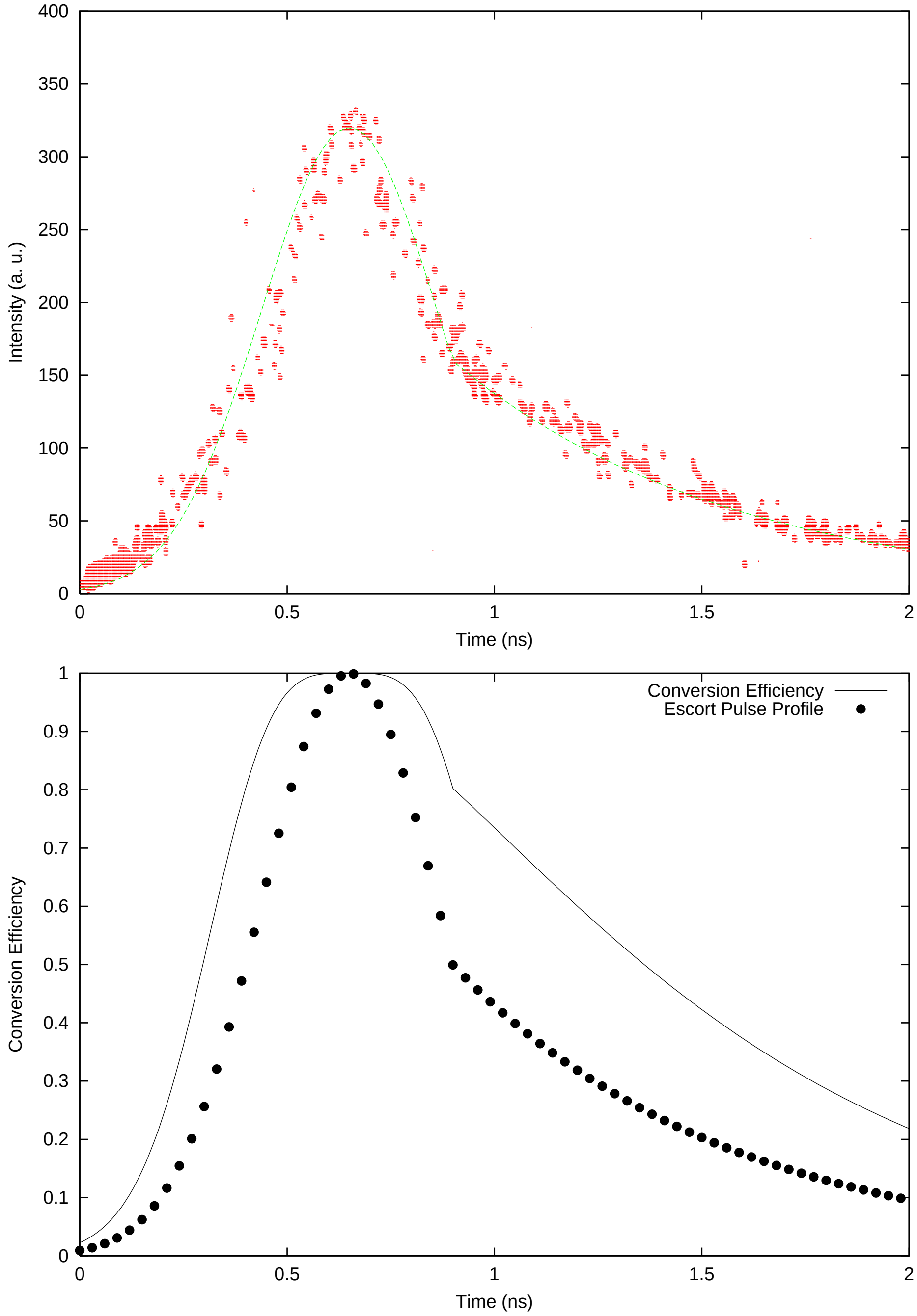

**Figure 4.** (a) Intensity profile for the 1064nm escort laser. (b) Predicted conversion efficiency for our measured escort pulse profile is shown on top of the pulse profile.

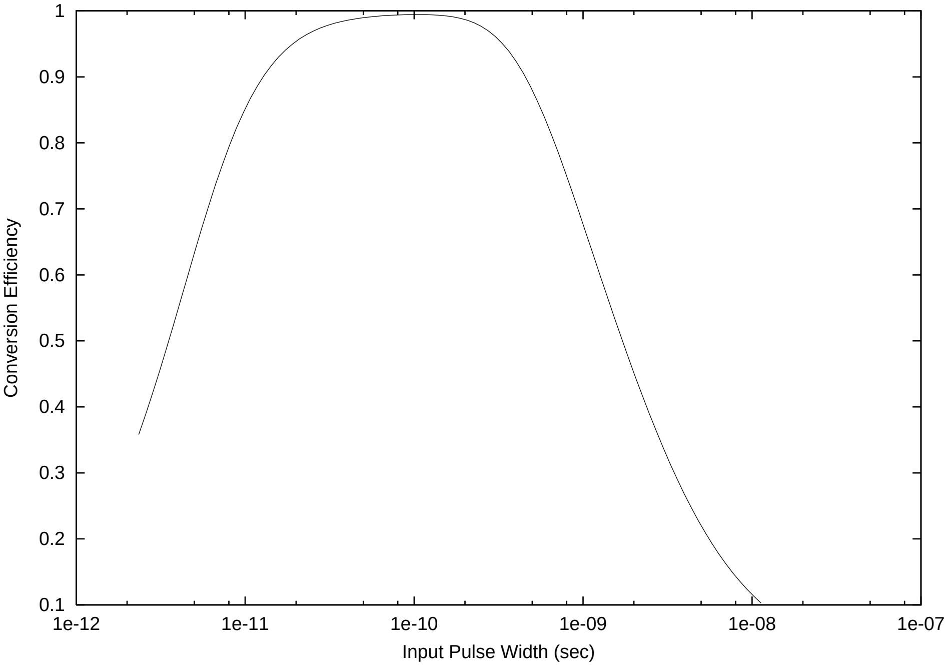

**Figure 5.** Conversion efficiency as a function of input pulse width. This illustrates the trade off between using pulses shorter than the escort pulse (to prevent averaging over different conversion probabilities) and minimizing the spread in frequency, and consequently in momentum (to satisfy the phase-matching condition). The peak theoretical conversion efficiency is 99.4% and occurs with an input pulse width of 45 ps.

## 4. STATE TRANSDUCTION

The scheme described above operates on only one of the polarizations of the initial photon, since it must be extraordinary in the PPLN. To faithfully convert an *arbitrary* polarization state we propose to employ a second PPLN crystal in series with the first, but oriented such that its optic axis is rotated by 90° around the propagation direction. By using an escort laser polarized at 45° (i.e., with equal horizontal and vertical components), we can up-convert the horizontal component of the input photon in the first crystal and the vertical component in the second, as shown in Figure 7. As long as the group-velocity dispersion effects do not lead to a time-labeling of the conversion processes (i.e., as long as the process of up-conversion in one crystal is *indistinguishable* from up-conversion in the other) these two processes will occur *coherently*, and an arbitrary initial quantum state can be up-converted. After filtering out all of the remaining escort photons, we will be left with only a single output photon. Dispersion and birefringence effects in the PPLN crystal will cause this final photon to have an additional phase $\phi$ between its horizontal and vertical components. However, using an appropriate birefringent element to compensate for this phase, we believe we can prepare a single high-frequency photon which has the identical polarization state as the initial photon. Moreover, if the initial photon were *entangled* to another photon, the entanglement would be transfered to the higher frequency photon (Note that the reverse process—mapping the polarization state of a pump photon onto two correlated down-conversion photons—is now a standard method to prepare high fidelity (polarization) entangled photon pairs.[10] See also the recent work on complete Bell state analysis by Kim, Kulik, and Shih[11]).

## 5. CONCLUSIONS

Infrared single photon detection through frequency up-conversion using periodically poled $\mathrm{LiNbO_3}$ is shown to be a viable alternative to traditional InGaAs and Ge APDs, which suffer from high noise and low efficiency. By poling the ferroelectric domains of a nonlinear crystal to satisfy the quasi-phase-matching conditions we

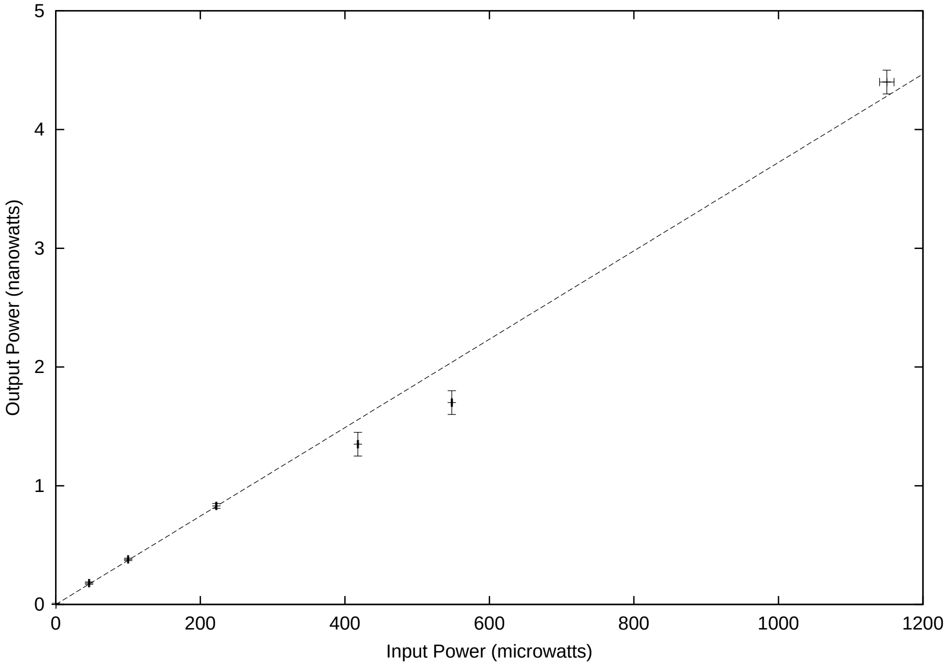

**Figure 6.** Output intensity of 631-nm light, as a function of input 1550-nm intensity. The dotted line is a linear fit to the data. Note that the efficiency is very low because the initial light was CW, i.e., most of the time there was no escort light.

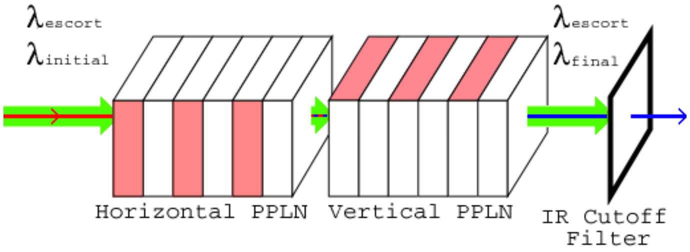

**Figure 7.** An arbitrarily polarized initial photon and an escort laser polarized at 45° are sent into two samples of PPLN, which respectively up-convert the H and V components of the initial photon. After the escort photons are filtered out, and the phase between the H and V components is corrected, we are left with a single high-frequency photon whose polarization state matches that of the initial photon.

can efficiently convert a 1550-nm photon into a 631-nm photon, which can then be detected by a silicon APD. Further avenues of research include attempting to convert an arbitrary polarization state using the 2-crystal scheme described above and investigating the use of a waveguide structure to increase the conversion efficiency. In this case, the benefit could be a reduction in the required escort power by several orders of magnitude due to the much smaller mode volume (implying a higher electric field for the same optical power). In particular, it was recently demonstrated that waveguides can be created in nonlinear crystals without disturbing the ferroelectric domain poling using the soft proton exchange method.[8] If sufficient gains on the conversion efficiency can be made, it may be possible to run with a CW escort beam. this would enable up-conversion of photons arriving at arbitrary times, thus greatly expanding the applicability of this IR detector.

## ACKNOWLEDGMENTS

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## REFERENCES

1. R. J. Hughes, G. L. Morgan, and C. G. Peterson, "Quantum key distribution over a 48-km optical fiber network," *J. Modern Optics* **47**, p. 533, 2000.
2. C. H. Bennett, "Quantum cryptography using any two nonorthogonal states," *Phys. Rev. Lett.* **68**, p. 3121, 1992.
3. C. H. Bennett and G. Brassard, "Quantum cryptography: Public key distribution and coin tossing," *Proceedings of IEEE International Conference on Computers, Systems and Signal Processing*, 1984.
4. A. Yariv, *Quantum Electronics*, Wiley, New York, 1988.
5. L. E. Myers, R. C. Eckardt, M. M. Fejer, R. L. Beyer, W. R. Bosenberg, and J. W. Pierce, "Quasi-phase-matched optical parametric oscillators in bulk periodically poled $LiNbO_3$," *J. Opt. Soc. Am. B* **12**, pp. 2102–2116, 1995.
6. L. E. Myers and W. R. Bosenberg, "Periodically poled lithium niobate and quasi-phase-matched optical parametric oscillators," *IEEE Journal of Quantum Electronics* **33**, pp. 1663–1672, 1997.
7. V. G. Dmitriev, G. G. Gurzadyan, and D. N. Nikogosyan, *Handbook of Nonlinear Optical Crystals*, Springer-Verlag, Heidelberg, Germany, 1999.
8. L. Chanvillard, P. Aschiéri, P. Baldi, D. B. Ostrowsky, M. de Micheli, L. Huang, and D. J. Bamford, "Soft proton exchange on periodically poled $LiNbO_3$: A simple waveguide fabrication process for highly efficient nonlinear interactions," *App. Phys. Lett.* **76**, pp. 1089–1091, 2000.
9. J. Huang and P. Kumar, "Observation of quantum frequency conversion," *Phys. Rev. Lett.* **68**, p. 2153, 1992.
10. A. G. White, D. F. V. James, W. J. Munro, and P. G. Kwiat, "Exploring Hilbert space: Accurate characterization of quantum information," *Phys. Rev. A* **65**, p. 012301, 2002.
11. Y. H. Kim, S. P. Kulik, and Y. Shih, "Quantum teleportation of a polarization state with a complete Bell state measurement," *Phys. Rev. Lett.* **86**, p. 1370, 2001.