Highly efficient single-photon detection at communication wavelengths by use of upconversion in reverse-proton-exchanged periodically poled $LiNbO_3$ waveguides

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Conventional single-photon detectors at communication wavelengths suffer from low quantum efficiencies and large dark counts. We present a single-photon detection system, operating at communication wavelengths, based on guided-wave frequency upconversion in a nonlinear crystal with an overall system detection efficiency (upconversion + detection) exceeding 46% at 1.56 μm. This system consists of a fiber-pigtailed reverse-proton-exchanged periodically poled $LiNbO_3$ waveguide device in conjunction with a silicon-based single-photon counting module. © 2005 Optical Society of America

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Highly efficient single-photon detection at communication wavelengths, specifically 1.55 and 1.32 μm, has gained importance in quantum optics because of interest in quantum key distribution (QKD) over standard low-loss telecommunication fiber for increased distance and speed. Other applications requiring low light sensitivity, such as optical time-domain reflectometry (OTDR),[1] laser detection and ranging (LADAR), and astronomy and deep-space communication would also greatly benefit from an efficient and simple single-photon detector at IR wavelengths.

Current single-photon detectors operating at IR wavelengths suffer from several drawbacks. InGaAs/InP avalanche photodiodes (APDs) are most commonly used.[2] Because of afterpulses of trapped charge carriers causing large dark count (DC) rates, these detectors have to be operated in a gated mode, employing active or passive quenching circuits. Yet DC rates remain high (10^4–10^5 /s). For asynchronous applications where the arrival time of a signal photon is not known *a priori* (e.g., OTDR), gated-mode operation limits the usefulness of such detectors. For these detectors, a trade-off between detection efficiency and speed exists, owing to the temperature scaling of afterpulse probability and quantum efficiency (QE). Detectors operating at speeds beyond 10 MHz have been reported recently with QEs between 10 and 15%.[3,4] The dead-time limited detection rate of these detectors did not exceed 400 kHz.

On the other hand, commercially available silicon-based single-photon counting modules (SPCMs) are very efficient (>70% at 700 nm) and have low DC rates (~25 /s). These detectors also offer Geiger-mode operation with short dead time (50 ns typically), compactness, and ease of use.

With the help of highly efficient nonlinear optical frequency converters, one can detect IR radiation while taking advantage of the properties of near-IR (NIR) SPCMs.[5] We accomplish this conversion by sum-frequency generation (SFG) between a weak signal and a strong pump in a reverse-proton-exchanged (RPE) periodically poled $LiNbO_3$ (PPLN) channel waveguide,[6] followed by efficient detection with a SPCM. The DC rates of such a system are currently limited by parasitic nonlinear interactions inside the nonlinear crystal, whereas the system detection efficiency is determined as follows. Waveguides allow 100% internal signal conversion with low average pump power owing to tight mode confinement over distances of several centimeters.[7] Hence, the internal QE of the device is limited only by propagation losses, whereas the external QE is further reduced by coupling and reflection losses. Finally, the overall system detection efficiency has to take the collection efficiency and the SPCM's intrinsic QE into account.

An analytical solution of the coupled-mode equations describing three-wave interactions inside waveguides in the absence of propagation losses and pump-wave depletion is given in Ref. 7. In this case, the signal conversion efficiency, i.e., the internal QE of the waveguide device, can be expressed as

$$\mathrm{QE}_{\mathrm{int}} = \frac{N_{\mathrm{SFG}}(L)}{N_{\mathrm{sig}}(0)} = \sin^2(\sqrt{\eta_{\mathrm{nor}} P_{\mathrm{pump}}} L), \qquad (1)$$

where N represents the photon number, η_{nor} the normalized power efficiency in the low-gain limit, L the effective interaction length, and P_{pump} the pump power. Maximum conversion is achieved when $P_{\mathrm{pump}} = \pi^2/(4\eta_{\mathrm{nor}} L^2)$. Operating at the 100% conversion point and assuming equal propagation losses (α) at the signal and SFG wavelengths, the overall sys-

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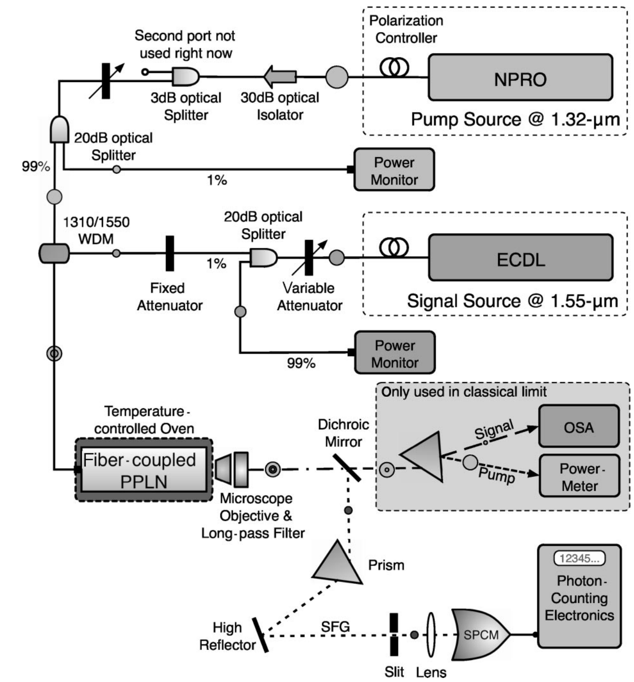

Fig. 1. Experimental setup for single-photon detection at 1.56 μm. OSA, optical spectrum analyzer.

tem detection efficiency η_{sys}, including both the effects of loss and finite detector quantum efficiency η_{NIR}, is given by $\eta_{\mathrm{sys}} = \tau_{\mathrm{WG}} \tau_{\mathrm{CS}} \eta_{\mathrm{NIR}}$, where $\tau_{\mathrm{WG}} = T_{\mathrm{in}}^{\mathrm{sig}} \exp(-\alpha L) T_{\mathrm{out}}^{\mathrm{SFG}}$ is the passive signal power transmission through the waveguide of length L, and τ_{CS} is the SFG transmission through the optical collection system. These transmissions, ideally unity, are reduced by the nonunity coupling ($T_{\mathrm{in}}^{\mathrm{sig}}$) of the signal at the input owing to Fresnel reflections and modal mismatch and at the output by Fresnel reflections ($T_{\mathrm{out}}^{\mathrm{SFG}}$) at the sum frequency, as well as propagation losses.

As shown in Fig. 1, a highly attenuated IR signal is combined with a strong pump inside a wavelength division multiplexer (WDM) before being injected into the fiber-pigtailed PPLN waveguide device, heated to 75°C in a temperature-controlled oven. To detect single photons at 1.55 μm, a fiber-coupled nonplanar ring oscillator (NPRO) at 1.32 μm (Innolight Mephisto) was used as the pump source (as shown in Fig. 1), whereas the pump source for 1.32 μm detection was an amplified C-band external-cavity tunable diode laser (ECDL, New Focus Vidia-Swept 6428). Separation of the converted signal, pump, and spurious light after the chip was achieved with a combination of long- and short-pass filters (Omega Optical LPF-690 and SP-760), a prism, and a spatial filter. The light was then focused onto the SPCM (Perkin-Elmer SPCM-AQR-14) with a high-numerical-aperture lens coated for the NIR.

Experimental results are shown in Fig. 2. The QE was calculated by dividing the number of detected counts after DC subtraction and detector linearity correction by the number of signal photons before the WDM as measured by a fiber-coupled powermeter (Advantest Q2208). No loss terms or SPCM detection efficiency were taken into account to arrive at these QEs, leading to a true overall system detection efficiency. We achieved an overall QE of 46% at 1.56 μm and 40% at 1.32 μm. The DC rates at these pump power levels were 8×10^5 counts/s and 1.5×10^4 counts/s, respectively. They are partially due to spontaneous Raman scattering inside the fiber leading to the PPLN waveguide followed by upconversion inside the device but are mainly generated by spurious nonlinear interactions inside the waveguide itself (e.g., spontaneous Raman scattering, parametric fluorescence followed by upconversion). For the case here, where the strong absorption of the 8.5 μm idler associated with parametric fluorescence suggests that stimulated Raman scattering dominates the DCs, the difference in DC rates can be explained by the larger gain for Stokes shifted scattering (1.32 μm pump) as compared to anti-Stokes scattering (1.56 μm pump) owing to the thermal occupation factor $\exp(-h\nu/kT)$ of excited vibrational states. The difference in QE can be explained by the transmission characteristics of the filters used in this setup. The SP-690 transmission at the SFG wavelength, used in the 1.32 μm detection setup, is 8% lower than the transmission of the LPF-760 used in the 1.56 μm setup.

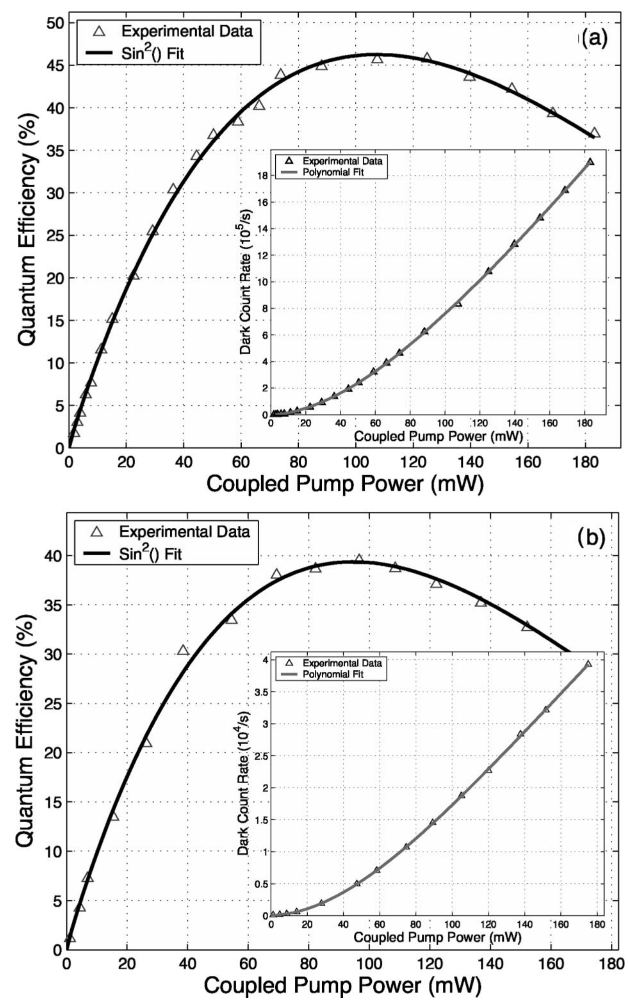

Fig. 2. QES and DC rates for a (a) 1.56 μm and (b) 1.32 μm single-photon detection experiment. The DC rate curve fits are merely meant to guide the eye.

Table 1. Comparison of NEP/f for Single-Photon Detectors Operating at 1.56 and 1.32 μm for Our PPLN Waveguide Setup

System	η (%)	R_{DC} (counts/s)	NEP/$h\nu$ ($\sqrt{\mathrm{Hz}}$)	Rate f (MHz)	NEP/$h\nu f$ (10^{-6} / $\sqrt{\mathrm{Hz}}$)
cw PPLN Waveguide SFG	46	8×10^5	2750	15	183
cw PPLN Waveguide SFG at 1.32 μm	40	1.5×10^4	433	15	29
cw Bulk PPLN SFG[a]	34	5×10^5	2941	15	196
Pulsed Bulk PPLN SFG[b]	25	3×10^5	3098	15	207
InGaAs/InP APD[c]	15.5	4.3×10^4	1892	0.4	4730
TES[d]	20	0.01	0.71	0.02	36

[a]Ref. 5.
[b]Ref. 8.
[c]Ref. 4.
[d]Ref. 9.

Since the PPLN waveguide chip was not antireflection (AR) coated, Fresnel reflections off of the facets reduced the QE by 19.7%. Such an AR coating will increase the QE to 55% (48%) for 1.56 μm (1.32 μm) single-photon detection with the current setup. Improvements in design and fabrication of the PPLN waveguide device will further increase the QE by lowering the propagation and coupling losses, as well as reduce the required pump power by 20–30%. Since the DC rate strongly depends on the pump power level, we expect ~50% fewer DCs. A further reduction in DCs owing to spontaneous Raman scattering can be achieved by cooling rather than heating the chip with a Peltier module.

We have demonstrated highly efficient cw single-photon detection at telecommunication wavelengths with upconversion in a RPE PPLN waveguide device. System detection efficiencies of 46% (40%) for detection of 1.56 μm (1.32 μm) photons have been achieved in high-speed Geiger mode. Further device improvements will lead to increased QE and lower DC rates. We are currently evaluating the effect of the pump wavelength on the DC rate. Minimizing spurious nonlinear effects (e.g., spontaneous Raman scattering, parametric fluorescence) inside the device by choosing a different pump wavelength may allow a significant reduction.

Table 1 compares several implementations of the upconversion detection scheme with an InGaAs/InP APD detector and a superconducting transition-edge sensor (TES) microcalorimeter.[9] As a figure of merit, we list the noise equivalent power defined by NEP $=h\nu\sqrt{2R_{\mathrm{DC}}}/\eta$ divided by the dead-time limited detection rate f,[3] where $h\nu$ is the energy of the signal photon and R_{DC} is the DC rate. This number is not only significant for the key generation rate in QKD systems but also determines the data acquisition time in general. Only the cw PPLN waveguide implementation fulfills the requirements for practical high-speed QKD because of its simple and robust design, high QE, and Geiger-mode operation. Although the TES is superior with respect to negligible DCs, its operating speed of only 20 kHz and complicated setup make it impractical for QKD and other applications outside the research laboratory. Preliminary calculations show that our system can increase the communication rate for QKD by 3 orders of magnitude and extend the communication distance by tens of kilometers as compared to InGaAs and Ge APDs. Further studies demonstrating this specific application are currently under way.

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