Ultra low dark-count-rate up-conversion single photon detector

Xiao Tang, Lijun Ma and Oliver Slattery
Information Technology Laboratory, National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899
xiao.tang@nist.gov

Abstract: We have demonstrated an ultra low noise up-conversion single photon detector using a periodically poled lithium niobate waveguide. The dark count rate of this detector is lower than 100 counts/second at 10% detection efficiency.

1. Introduction

Due to the poor performance of InGaAs-based single photon detectors in the near infrared (NIR) range, frequency up-conversion detectors have been a better alternative for efficient detection of single photons in the NIR range. Recently, several groups have demonstrated highly efficient up-conversion single photon detectors in that range based on periodically poled lithium niobate (PPLN) waveguides or bulk devices combined with silicon avalanche photodiodes (Si-APDs) [1-7]. The dark count rate of these up-conversion detectors is from several thousands to several tens of thousands per second. For some applications, such as high speed quantum key distribution (QKD) systems, this level of dark counts is acceptable, and these detectors have been successfully used into fiber-based QKD systems [4-6]. However, for other applications in quantum optics, where low light signals are only a few thousand photons per second or less, such high dark count rate can limit the effectiveness of an up-conversion detector. A dark count rate at several hundreds and even tens of counts per second is desired.

The dark count rate of frequency up-conversion detectors mainly come from three sources: intrinsic dark counts of Si-APD; noise photons that leak through the filter from the pump; and noise photons due to Raman scattering by the strong pump. By using an optical pump at a wavelength longer than the signal wavelength and proper filtering configuration, we have greatly suppressed the noise and achieved a dark count rate of around 2000 counts per second in previous work [5, 6]. Recently we upgraded the system and achieved a dark count rate as low as 100 counts per second with reasonable conversion efficiency.

2. Configuration of up-conversion single photon detector

Similar to our previous work [5, 6], this up-conversion detector is designed to detect single photons at 1310 nm, one of the standard telecom wavelengths. A 1310-nm photon is up-converted to 710 nm in a PPLN waveguide pumped by 1550-nm laser and then detected by a Si-APD. Figure 1 schematically shows the up-conversion single photon detector.

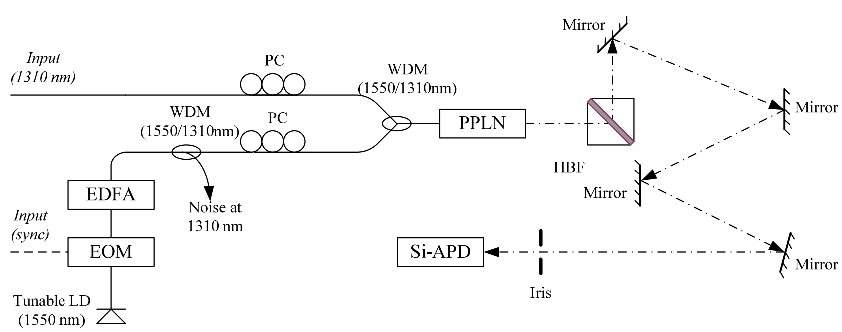

Fig. 1. Schematic diagram of the up-conversion detector. EOM: Electric-optic modulator; EDFA: Erbium-doped fiber amplifier; WDM: Wavelength-division multiplexing coupler; PC: Polarization controller; PPLN: Periodically-poled LiNbO3 waveguide; HBF: Holographic Bandpass filter. Solid line: Optical fiber; Dash line: Free space optical transmission.

A 1550-nm CW laser provides the pump seed. If needed, the seed light can be modulated to an optical pulse train by a synchronized signal. This feature is similar to an optical gate, which is very useful for noise reduction or high speed gating operation in a communications system. The light is then amplified by an erbium-doped fiber amplifier (EDFA). Two 1310/1550 wavelength division multiplexer (WDM) couplers with a 25 dB extinction ratio are used to suppress noise near 1310 nm at the output of the EDFA. The amplified pump light is then combined with a weak signal at 1310 nm by another WDM coupler and the combined pump and signal are then coupled into the PPLN waveguide. The input polarization state of both the signal and the pump are adjusted by two polarization controllers, before entering the coupler. The longer the waveguide length, the lower the pump power needed to reach the maximum conversion efficiency [7]. The PPLN waveguide for the up-conversion detector is 5-cm long, which is the longest length possible for current manufacturing. The input of the PPLN waveguide is fiber coupled, and the output enters into free space passing through a 710-nm anti-reflection (AR) coating at the end of the waveguide. The output light from the PPLN waveguide consists of the up-converted (SFG) weak signal light at 710 nm, residual pump light at 1550 nm and its second harmonic generation (SHG) light at 775 nm. A holographic band-pass filter is used to filter out all noises that are not at 710 nm. The up-converted photons are then detected by a Si-APD.

3. Results and discussion

In this detector, we use a Si-APD with a low dark count rate (Perkin Elmer SPCM-AQR-16), and its intrinsic dark count rate is less than 25 Hz. The noise from the pump was filtered by the WDM couplers and the holographic filter after the waveguide. The Raman scattering caused by the strong pump is the major noise source. Because the anti-Stokes component of the Raman process is much weaker than the Stokes component, we use a pump at a wavelength longer than the signal wavelength. Although the longer wavelength pump can reduce the dark count rate significantly, the dark count rate is still thousands of counts per second. The wavelengths of the noise photons are spectrally broadend and flat and are evenly distributed around the narrow signal spectrum at 710 nm. Therefore, a narrow filter can help to further reduce the dark count rate. We use a holographic band-pass filter after the waveguide. By adjusting the distance between the holographic grating and the iris, the bandwidth of the filter is about 2 nm. The performance of this detector is shown in the Fig. 2. The dark count rate at the maximum detection efficiency (18%) is only 320 counts per second. When the pump power is reduced, less than 100 dark counts per second can be achieved with a detection efficiency of 10%. Such low dark count rates enable this up-conversion detector to be used for a variety of applications in quantum optics as well as weak signal spectrometry in the near IR [8].

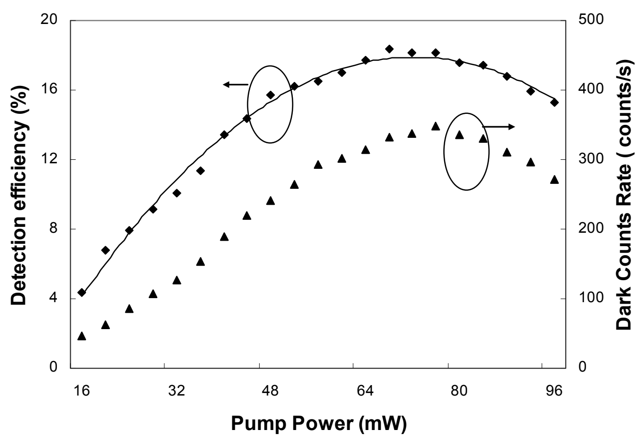

Fig. 2. Detection efficiency and dark count rate over pump power at a single photon up-conversion detector. Square: measured detection efficiency, solid line calculated detection efficiency, triangle: dark count rate.

References

1. A. P. Vandevender and P. G.Kwiat, “High efficiency single photon detection via frequency up-conversion”, J. Mod. Opt., Vol. 51, 1433-1445 (2004).
2. M. Albota and F.Wong, “Efficient single-photon counting at 1.55um by means of frequency upconversion,” Opt. Lett. 29, 1449-1451 (2004).
3. C. Langrock, E. Diamanti, R. V. Roussev, Y. Yamamoto, M. M. Fejer, and H. Takesue, “Highly efficient single-photon detection at communication wavelengths by use of upconversion in reverse-proton-exchanged periodically poled LiNbO3 waveguides” , Opt. Lett. 30, 1725-1727 (2005).
4. Diamanti, E., Takesue, H., Honjo, T., Inoue, K. and Yamamoto, Y. “Performance of various quantum-key-distribution systems using 1.55-µm up-conversion single-photon detectors,” Phys. Rev. A, 72, 052311, (2005).
5. R. T. Thew, S. Tanzilli, L. Krainer, S. C. Zeller, A. Rochas, I. Rech, S. Cova, H. Zbinden, and N. Gisin, “Low jitter up-conversion detectors for telecom wavelength GHz QKD”, New J. Phys., 8, 32 (2006).
6. H. Xu, L. Ma, A. Mink, B. Hershman, and X. Tang, “1310-nm quantum key distribution system with up-conversion pump wavelength at 1550 nm”, Optics Express, Vol 15(12): 7247~ 7260 (2007).
7. L. Ma, O. Slattery, and X. Tang, “NIR single photon detectors with up-conversion technology and its applications in quantum communication systems” in the book of “Advances in Lasers and Electro Optics”, ISBN: 978-953-307-088-9, INTECH, Chapter 15, page 315-336, April 2010.
8. L. Ma, O. Slattery, and X. Tang, “Experimental study of high sensitivity infrared spectrometer with waveguide-based up-conversion detector,” Opt. Express 17, 14 395–14 404 (2009).