Invited Paper

Study on noise reduction in up-conversion single photon detectors[1]

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ABSTRACT

Up-conversion single photon detector technology has become efficient for photons in the near infrared range. However, its dark count rate is a major concern for some applications in quantum optics. We have theoretically and experimentally studied the causes of dark counts, and developed an up-conversion detector with an ultra low dark count rate. A reduced dark count rate of only 320 counts per second is achieved at the maximum overall detection efficiency of 18% and a dark count rate of less than 100 counts per second is achieved at a detection efficiency of 10%. The ultra low dark count rate enables this type of up-conversion detector to be utilized in a variety of applications where weak signals in the near IR region are only at a level of few thousand photons per second.

Keywords: Single photon detector, Frequency up-conversion, Dark count rate.

1. INTRODUCTION

InGaAs based single photon detectors operate in the near infrared range but the performance is rather poor. On the other hand, the performance of silicon based single photon detectors (Si-APDs) is excellent in the visible range but they do not work when the wavelength is longer than 1000 nm. Single photon detectors using frequency up-conversion technology, simply called up-conversion detectors, are able to detect single photons in the infrared region with high detection efficiency. An up-conversion detector uses a non-linear optical media to up-convert the frequency of the signal photons in the infrared range to a lower frequency in the visible range by a process known as sum frequency generation (SFG). The emerging photons at visible wavelengths are then detected using visible region single photon detectors, such as Si-APDs. The Si-APDs typically have high detection efficiency, low noise, can be operated in ambient temperatures, are compact and inexpensive, making them a practical device for many applications.

To date, several groups have successfully developed highly efficient up-conversion single photon detectors in the near infrared range based on periodically poled lithium niobate (PPLN) bulk or waveguide crystals combined with Si-APDs [1-9]. The internal conversion efficiency of the waveguide can reach as high as 100 %, and the overall detection

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efficiency for this type of detector is about 10% ~ 35%. The dark count rate of these up-conversion detectors is typically several thousand to several ten thousand counts per second. For some applications, such as high speed quantum key distribution (QKD) systems, this dark count level is acceptable, and this type of detector has been successfully used in fiber-based QKD systems [4-6]. However, in other applications in quantum optics, such as entangled photon sources based on spontaneous parametric down conversion [10] or single photon sources based on semiconductor quantum dots [11], the signal is extremely weak and contains only a few thousand photons per second or less. In these cases, such dark count rates would significantly limit their usefulness, and detectors with dark count rates at a few hundred or even tens of counts per second are desired.

We previously developed up-conversion detectors for photons at 1310 nm and used them in a QKD system. 1310-nm photons are up-converted to 710 nm in a PPLN waveguide pumped by a 1550-nm laser and then detected by a Si-APD [6, 7, 9]. For applications with a very weak signal of a few thousand or a few hundred photons per second, these up-conversion detectors need to be further improved and their dark count rate should be reduced to around 100 counts per second. We present our theoretical and experimental study on the causes of dark counts in up-conversion detectors, and the development of an up-conversion detector with an ultra low dark count rate of 100 per second.

2. THE SOURCES OF DARK COUNTS IN UP-CONVERSION DETECTORS

Dark counts are the photon detection events when no signal photons are present. Dark counts are mainly caused by three sources: the intrinsic dark counts of the Si-APD (DCR_{APD}), the noise photons that leak through the filter from the pump ($DCR_{leakage}$), and noise photons due to Raman scattering by the strong pump (DCR_{Raman}).

$$DCR_{total} = DCR_{\mathrm{APD}} + DCR_{leakage} + DCR_{Raman} \tag{1}$$

The first item, the intrinsic APD dark count rate, is independent of the pump power and conversion efficiency of the up-conversion detector. The APD intrinsic dark counts are almost constant, though they exhibit shot-noise deviation. Currently, the dark count rate of a Si-APD itself can be lower than 25 counts per second [12].

Leaked light from the pump will cause dark counts at the up-conversion detector. Although the peak of pump power is in the pump wavelength (1550 nm in our case), it does have a low level broad spectrum that includes some photons at signal wavelength (1310 nm in our case) and up-converted wavelength (710 nm in our case). The photons at signal wavelength can be up-converted to up-converted wavelength. These photons, up-converted of photons at signal wavelength and the photon at up-converted wavelength, are detected by the Si-APD and become dark counts. The number of these photons increases linearly as pump power increases and therefore this term can be expressed by:

$$DCR_{leakage}(P) = \eta_T \eta_{APD} \alpha P + \eta_T \eta_C(P) \eta_{APD} \beta P \,, \tag{2}$$

where P is the pump power, α and β are the noise coefficient of the pump source at the up-converted wavelength and the signal wavelength respectively. η_{APD} is the detection efficiency of Si-APD at the up-converted wavelength. η_T is the overall transmission efficiency of an up-conversion detector, which is mainly determined by input/output coupling of the waveguide and the transmission loss in the waveguide and other optical components. η_C is the conversion efficiency in the PPLN waveguide and is determined by the following [1-8]:

$$\eta_C(P) = \eta_0 \sin^2\left(k\sqrt{P / A_{eff}} \cdot L_{PPLN}\right). \tag{3}$$

where η_0 is the peak conversion efficiency. η_0 is dependent on the quality of PPLN waveguide. The value of η_0 can reach 1 in a high poling quality waveguide. The pump intensity is the ratio of the power, P, to the effective area, A_{eff}. L_{PPLN} is the length of PPLN waveguide. k is a constant and determined by

$$k = \left(\frac{\omega_s \omega_p d_{eff}^2}{n_s n_p c^2}\right)^{1/2}, \tag{4}$$

where ω_s and ω_p are the signal and pump wavelengths, n_s and n_p are the refractive index of lithium niobate for signal and pump wavelengths. d_{eff} is an effective nonlinear coefficient and c is the speed of light.

From Eqs. (2) ~ (4), one can see the pump noise is dependent on the pump power. One can reduce the pump power to reduce the noise, but this would also reduce the detection efficiency. The best way to reduce the noise is to filter out the noise photons at the signal wavelength and its up-converted wavelength ranges, so as to greatly reduce the noise coefficient α and β.

It is widely believed that a major source of dark counts in an up-conversion detector is from Raman scattering generated both in the fiber before the PPLN and in the PPLN. The strong pump generates Stokes photons and these Stokes photons are further up-converted to the detection wavelength. Such up-converted Stokes photons contribute a large amount of the dark counts.

One can estimate the significance of each Raman scattering component by first neglecting the SFG, loss, and pump depletion, and then solving the photon number for a given Stokes mode N_{s} using the differential equation of the Raman scattering [13] in a known length of fiber followed by a PPLN waveguide. The solution is given by

$$N_{\mathrm{s}} = e^{g_{\mathrm{PPLN}} L_{\mathrm{PPLN}}} - 1 + \left(e^{g_{\mathrm{Fiber}} L_{\mathrm{Fiber}}} - 1\right) e^{g_{\mathrm{PPLN}} L_{\mathrm{PPLN}}}, \tag{5}$$

where the Raman gain, g , equals $\gamma P / A_{eff}$ and L represents the length. For the fiber, L_{Fiber} is the length between the PPLN and the wavelength division multiplexer (WDM) that combines the signal and pump. The quantity γ is the gain factor and the pump power P divided by the effective area A_{eff} gives the pump intensity. The first term describes the Stokes photons generated in the PPLN if there are no Stokes photons at the input. The second term describes the Stokes photons generated in the fiber and then Raman amplified in the PPLN.

Equation (5) shows that the amount of the Stokes photons generated in the fiber is dependent on L_{Fiber}. However when we vary this fiber length from 1 meter to 15 meters we cannot distinguish any change in the dark count rate. Therefore, most of the Stokes photons are induced in the PPLN and the second term in Eq. (5) is negligible.

The length of a typical PPLN waveguide is less than 5 cm. In pump schemes using either a longer wavelength pump or a shorter wavelength pump, for example, a signal wavelength at 1310 nm with a pump at 1550 nm or a signal wavelength at 1550 nm with a pump at 1310 nm, the 240-nm wavelength spacing between the pump and the signal is much larger than the peak Raman shift frequency of PPLN [14]. Therefore,

$$e^{g_{\text{PPLN}} L_{\text{PPLN}}} - 1 \approx g_{\text{PPLN}} L_{\text{PPLN}} , \tag{6}$$

and the stimulated Raman scattering inside the PPLN is also negligible since a relatively low pump power is used. Therefore, we can assume that most of the Stokes photons are induced by the spontaneous Raman scattering inside the PPLN and this assumption enables a simple solution for the dark count.

Using the above assumptions in Eq. (5), one can get a differential equation for the Stokes photon: $dN_s / dz = g_{\text{PPLN}} = \gamma P / A_{eff}$ with z being a distance inside the waveguide from the PPLN input. A generated Stokes photon will be up-converted to the detection wavelength and induce a dark count. Consequently, by further applying the well-known conversion efficiency of PPLN, we write the dark count rate, DCR, as a function of pump power:

$$\begin{aligned} DCR_{Raman}(P) &= \eta_{\text{APD}} \eta_{\text{C}} \int_0^{L_{\text{PPLN}}} \frac{\gamma \times P}{A_{\text{eff}}} \sin^2\left[(L_{\text{PPLN}} - z) k \sqrt{P / A_{eff}} \right] dz \\ &= \frac{\gamma}{2 A_{\text{eff}}} \eta_{\text{APD}} \eta_{\text{C}} P L_{\text{PPLN}} \left[1 - \frac{\sin\left(2k \sqrt{P / A_{eff}} L_{\text{PPLN}}\right)}{2k \sqrt{P / A_{eff}} L_{\text{PPLN}}} \right] \end{aligned} \tag{7}$$

where η_{C} is the overall coupling efficiency (input coupling factor of the pump multiplied by the output coupling of the up-converted photons) and η_{APD} is the detection efficiency of the Si-APD. The linear term of the pump power, P, in the integral describes the generation of Stokes photons via the spontaneous Raman scattering and the sinusoidal term describes the up-conversion of the Stokes photons generated at z contributing to a dark count at the PPLN output (z = L_{PPLN}). In above derivation we also neglected the optical loss in the PPLN waveguide. This assumption is justified by the fact that low waveguide loss is achieved with current manufacturing techniques and nearly 100 % internal conversion efficiency has been reported. The anti-Stokes process fits the same differential equation as the Stokes process except for a much lower Raman gain. Therefore, the above analysis can be applied to pump schemes using both the longer wavelength pump or the shorter wavelength pump.

Following Eqs. (1) ~ (7), one can obtain the total dark count rate of an up-conversion single photon detector as follows:

$$DCR_{total}(P) = DCR_{\mathrm{APD}} + \eta_T \eta_{APD} \alpha P + \eta_T \eta_C(P) \eta_{APD} \beta P + \frac{\gamma}{2A_{\mathrm{eff}}} \eta_{\mathrm{T}} \eta_{\mathrm{C}}(P) \eta_{\mathrm{APD}} P L_{\mathrm{PPLN}} \left[1 - \frac{\sin\left(2k\sqrt{P/A_{eff}}L_{\mathrm{PPLN}}\right)}{2k\sqrt{P/A_{eff}}L_{\mathrm{PPLN}}} \right] \quad (8)$$

with $\eta_C(P)$ described by Eqs. (3) and (4).

From Eq. (8), one can see the dark count rate of an up-conversion single photon detector is dependent on the pump power. When the amount of leakage photons at the up-converted wavelength from the pump is small, the dark count rate also shows a peak near the detection efficiency peak as the pump power increases.

Based on the above analyses, one can adopt the following measures to reduce the dark count:

1) Use Si-APDs with a low intrinsic dark count rate.
2) Use proper filtering for the pump to remove noise at the up-converted wavelengths and the signal wavelength. Because the up-converted wavelength is usually far away from the pump wavelength, the amount of these photons is small. However, the signal wavelength is relatively close to pump wavelength, and the noise photons at this range are usually very strong and must be filtered with high attenuation.
3) Use a pump at a wavelength longer than the signal wavelength. Because the anti-Stokes component of the Raman process is much weaker than the Stokes component, long pump wavelength can greatly reduce the noise caused by Raman scattering.
4) Use a longer waveguide. From Eq. (3), one can see the conversion efficiency is determined by $\sqrt{P} \cdot L_{PPLN}$. For certain conversion efficiency, the required pump power is proportional to $1/L_{PPLN}^2$. Therefore, a longer waveguide will reduce the required pump power significantly. A long waveguide can greatly reduce the noise from the pump and the Raman noise.
5) Reduce pump power. By using a lower pump power, one can reduce the dark count rate, but the conversion efficiency is also reduced. From Eq. (8), the ratio of the dark count rate to the conversion efficiency can be obtained as follow:

   $$DCR_{total}/\eta_C = DCR_{\mathrm{APD}}/\eta_C + \eta_T \eta_{APD} \alpha P/\eta_C + \eta_T \eta_{APD} \beta P + \frac{\gamma}{2A_{\mathrm{eff}}} \eta_{\mathrm{T}} \eta_{\mathrm{APD}} P L_{\mathrm{PPLN}} \left[1 - \frac{\sin\left(2k\sqrt{P/A_{eff}}L_{\mathrm{PPLN}}\right)}{2k\sqrt{P/A_{eff}}L_{\mathrm{PPLN}}} \right] \quad (9)$$

   From Eq. (9), when the intrinsic dark count rate of the APD is low, using lower pump power can get a lower dark count rate to conversion efficiency ratio. There exists an optimal setting of the pump power that compromises the requirements for high detection efficiency and low dark counts. The criterion for such an optimal setting is determined according to the signal level. For a very weak signal level, reducing the pump power can provide a better signal to noise ratio.
6) Use a bandpass filter with a very narrow bandwidth after the waveguide. The pump and the Raman scattering noise photons that cause dark counts have a broad spectrum, while the spectrum of up-converted signal is usually quite narrow. Therefore, a narrow bandpass filter can help to further reduce the dark count rate.

3. REDUCTION OF DARK COUNTS AT UPCONVERSION DETECTORS

Based on the above analysis, we upgraded the system and its dark count rate has reached as low as 100 counts per second with a reasonable conversion efficiency. Similar to our previous work [5, 6], the up-conversion detector is designed to detect photons from a signal at 1310 nm, one of the standard telecom wavelengths. 1310-nm photons are up-converted to 710 nm in a PPLN waveguide pumped by a 1550-nm laser and then detected by a Si-APD. Fig. 1 schematically shows the up-conversion single photon detector. In this detector, 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 communication systems. The light is then amplified by an erbium-doped fiber amplifier (EDFA) (IPG: EAR-0.5K-C). Two 1310/1550 wavelength division multiplexer (WDM) couplers with a 25-dB extinction ratio are used in series to suppress noise around 1310 nm at the output of the EDFA. The amplified pump light is then combined with a weak signal in the 1310-nm range 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 the polarization controllers before entering the coupler. The longer the waveguide length, the lower the pump power needed to reach the maximum conversion efficiency. The up-conversion detector uses a 5-cm PPLN waveguide, which is the longest possible with current manufacturing techniques. The input of the PPLN waveguide is fiber coupled, and the output is free-space with a 710-nm anti-reflection (AR) coating. The major improvement from our previous detector is a holographic bandpass filter inserted after the waveguide. The holographic filter consists of a holographic grating and an iris. The distance between the holographic grating and the iris is about 1m resulting in a filter with a bandwidth of about 2 nm. Because of the 1m distance required, several mirrors are used to make the detector compact such that it can be placed into a smaller box. The photons that pass through the filter are then detected by a Si-APD with a low intrinsic dark count rate (PerkinElmer SPCM-AQR-16).

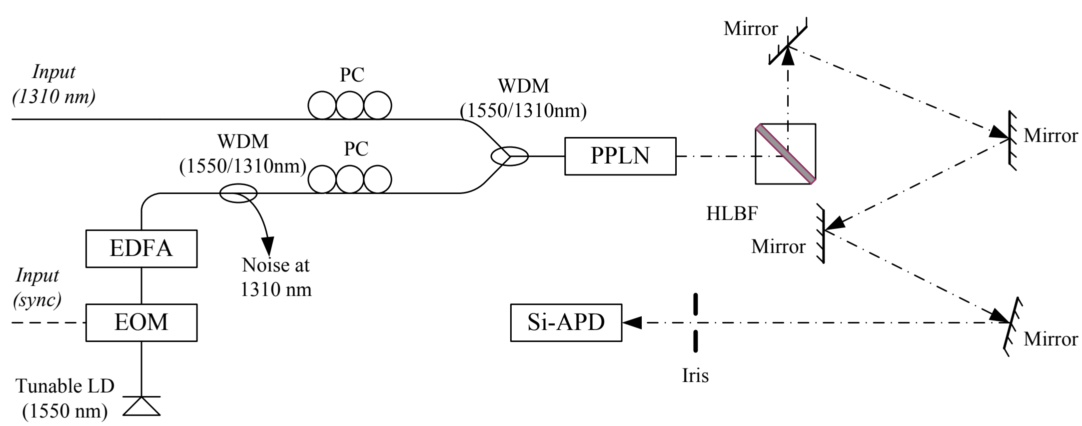

Fig. 1. Schematic diagram of the up-conversion detector. EOM: Electric-optic Modulator; EDFA: Erbium-doped fiber amplifier; WDM: Wavelength-division multiplexing coupler; PC: Polarization controller; PPLN: Periodically-poled LiNbO3 waveguides; HLBF, Holographic Laser Bandpass Filter. Solid line: Optical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

In this configuration, we adopt the above mentioned measures to reduce the dark count rates. The up-converted photons are detected by a Si-APD that has the lowest intrinsic dark count rate available on the market. The noise from the pump was filtered by the WDM couplers. We use a pump at a wavelength longer than the signal wavelength. A holographic bandpass filter after the waveguide with a 2-nm bandwidth significantly reduces the noise around the up-converted signal photons. Fig. 2 shows the performance of the improved detector. The dark count rate at the maximum overall detection efficiency (18 %) is only about 320 counts per second. When the pump power is reduced, we can get less than 100 dark counts per second at an overall detection efficiency of 10 %. Such a low dark count rate enables this up-conversion detector to be used for applications with very weak signal levels.

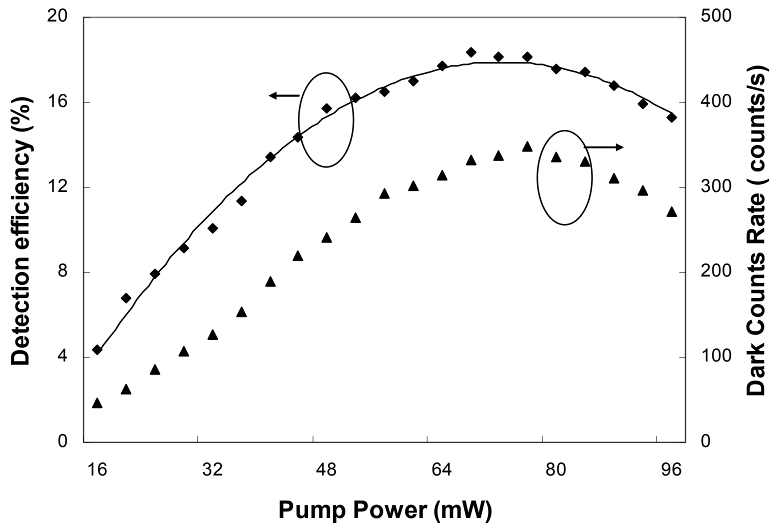

Fig. 2 Detection efficiency and dark count rate vs. pump power of a single photon up-conversion detector. Square: measured detection efficiency, solid line calculated detection efficiency, triangle: measured dark count rate.

4. CONCLUSION

We theoretically and experimentally studied the sources of dark counts in an up-conversion detector. Based on this analysis, we developed guidelines to produce an up-conversion detector with an ultra low dark count rate. Based on these guidelines, we upgraded an up-conversion detector, resulting in only 320 dark counts per second at the maximum overall detection efficiency of 18 %. The dark count rate can be further reduced to below 100 dark counts per second at an overall detection efficiency of 10 % when a lower pump power is used.

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