Up-conversion single-photon detector using multi-wavelength sampling techniques

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Abstract: The maximum achievable data-rate of a quantum communication system can be critically limited by the efficiency and temporal resolution of the system's single-photon detectors. Frequency up-conversion technology can be used to increase detection efficiency for IR photons. In this paper we describe a scheme to improve the temporal resolution of an up-conversion single-photon detector using multi-wavelength optical-sampling techniques, allowing for increased transmission rates in single-photon communications systems. We experimentally demonstrate our approach with an up-conversion detector using two spectrally and temporally distinct pump pulses, and show that it allows for high-fidelity single-photon detection at twice the rate supported by a conventional single-pump up-conversion detector. We also discuss the limiting factors of this approach and identify important performance-limiting trade offs.

OCIS codes: (040.5570) Quantum detectors; (190.4410) Nonlinear optics, parametric processes; (230.7370) Optical devices, waveguides.

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1. Introduction

In quantum communication systems, such as a quantum key distribution system, data rates are mainly limited by the system clock rate and the link losses. While the transmission clock rate is limited by the temporal resolution of the single-photon detectors, losses in a fiber-based quantum communication system can be minimized by operating in the near infrared range, at 1310 nm or 1550 nm. Commercially available InGaAs-based avalanche photo-diodes (APDs) can be operated as single-photon detectors in this wavelength range [1]. Due to the severe after-pulsing, InGaAs APDs are typically used in a gated mode and this can limit their application in high-speed quantum communication systems. Superconducting single-photon detectors (SSPDs) can work in the NIR wavelength range with good performance [2–4]. However, SSPDs require cryogenic temperatures, and are not commercially available at present.

On the other hand, silicon based avalanche photo-diodes (Si APDs) are compact, relatively inexpensive, and can be operated at ambient temperatures with high detection efficiency and low noise in the visible or near-visible range. Unfortunately they are not sensitive to wavelengths longer than roughly 1000 nm. For those wavelengths, an up-conversion technique has been developed that uses sum-frequency generation (SFG) in a non-linear optical medium to convert the signal photons to a higher frequency (shorter wavelength) in the visible or near visible range. The up-converted photons can then be detected by a Si APD [5]. Up-conversion detectors use commercially available components and devices and are a practical solution for many applications in quantum communication. 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 devices integrated with Si APDs [6–14]. In these detectors, the internal conversion efficiency of the SFG process can be close to 100%, and the total detection efficiency is typically about 10% ~35%.

In an up-conversion detector with a continuous wave (CW) pump, the temporal resolution is determined by the Si APD. The jitter-limited temporal resolution becomes a bottleneck as the transmission rate increases in a quantum communication system. The temporal resolution of an up-conversion detector can be further increased using a pulsed pump mode. A picosecond optical-sampling technique was demonstrated for a strong light signal in a number of studies [15,16]. Recently, femtosecond optical sampling was demonstrated in an up-

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conversion system using ultra-short 790-nm pump pulses [17]. However, these prior implementations use a single pump wavelength and are not suitable as means to increase the transmission rate in quantum communication systems because the sampling rate is still limited by the Si APD's timing resolution. The spectrally and temporally distinct pump in frequency conversion is an efficient way to increase the clock rate, and it has been demonstrated in a high speed nonlinear optical time-division multiplexer/demultiplexer [18]. In this work, we propose an optical sampling approach uses multiple spectrally and temporally distinct pump pulses, to realize an up-conversion single-photon detection system that can support transmission rates significantly higher than the jitter-limited transmission rate of a traditional Si APD detector. To demonstrate the principle, we report here an experimental system that supports twice the jitter-limited transmission rate of the Si APDs, and we show that the approach can be extended to support higher transmission rates. We use commercially-available and widely-used Si APDs (PerkinElmer SPCM-AQR) [19] in this demonstration, but this scheme also works for other single-photon detectors. When single photon detectors with better timing jitter, such as improved Si APD [20] and SSPD [2–4], are integrated into the scheme, the temporal resolution can be further improved.

2. Scheme description

In many current quantum communication systems, the photon source can generate and temporally encode data at rates significantly higher than single-photon detectors can resolve. For example, commercially available mode-locked lasers or optical modulators can generate sub-10 ps optical pulses, and broadband spontaneous parametric downconversion (SPDC) sources can readily prepare optical states of photon pairs with sub-100 fs correlation time. On the other hand, current high-resolution single-photon detectors exhibit a full-width-at-half-maximum (FWHM) temporal resolution of the order of 50 ps. In a quantum communication system, insufficient temporal resolution in the detector can cause inter-symbol interference (ISI), i.e., a detection signal can be recorded at a time slot adjacent to the intended one, and this can induce a significant error rate. The transmission rate is therefore limited by the temporal resolution of the single-photon detectors. As a figure of merit, a single-photon signal can be received with an acceptable error rate when the transmission period is equal to or larger than the full width at 1% maximum (FW1%M) of the single-photon detector's response histogram [21]. For most types of Si APDs the FW1%M is significantly larger than the commonly-cited FWHM. At the peak of a typical Si APD's response histogram, where the FWHM is measured, the profile is approximately Gaussian, but at lower levels the detector's response deviates significantly from Gaussian, often exhibiting a long exponential tail in its temporal response and this dramatically increases the device's FW1%M. A typical commercially-available Si APD has a FWHM of about 350 ps, but a FW1%M of about 1100 ps that limits the transmission rate to less than 1 GHz for a quantum communication system using an up-conversion detector equipped with this type of Si APD.

To increase the temporal resolution of an up-conversion detection system beyond that of its constituent Si APDs, a sequence of spectrally and temporally distinct pump pulses can be used to sub-divide the minimum resolvable time period, τ_{det}. This application of optical sampling is illustrated in Fig. 1, where n pump pulses with different wavelengths are used to sample the incident single-photon signal in intervals of duration τ_{det}/n. To ensure optimum detection efficiency we consider a pulsed single-photon signal and prepare each pump pulse with a width larger than the single-photon signal pulses. The repetition rate for each particular wavelength of the pump is $1/\tau_{det}$. When a signal photon enters and co-propagates with one of the strong pump pulses in a quasi-phase matched sum-frequency crystal, such as periodically-poled lithium niobate (PPLN), it can be up-converted to the visible range. The specific wavelength of the up-converted photon is determined by the wavelength of the pump pulse with which it interacted. A subsequent dispersive element such as a grating can separate the up-converted signal photons and distribute them to an array of Si APDs. Each Si APD in the array therefore corresponds to a particular pump wavelength, and, by extension, a particular arrival time period of duration τ_{det}/n. In such a configuration the sampling period for each Si

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APD is τ_{det}, allowing it to accurately resolve the signal without ambiguity due to the detector's temporal response. With this approach, the detection system is able to resolve the single-photon signal in a period as small as τ_{det}/n, representing an increase in temporal resolution by a factor of n.

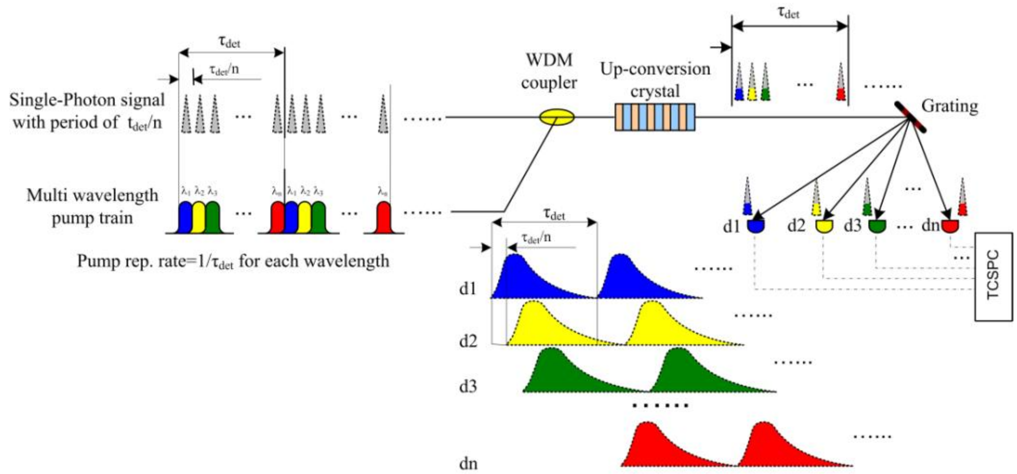

Fig. 1. Schematic diagram of up-conversion single-photon detection with multi-wavelength optical sampling. A sequence of n spectrally and temporally distinct pump pulses are used to sub-divide the minimum resolvable time bin, τ_{det}, of conventional Si APDs, increasing the temporal resolution of the overall system by a factor of n. The incident single-photon signal is combined with the sequence of pump pulses with a wavelength division multiplexer (WDM). Detection events from each of the n Si APDs are time-tagged with time-correlated single-photon counting (TCSPC).

3. Experimental demonstration

To experimentally demonstrate the scheme described above we implement an up-conversion detector with two pump wavelengths and a single-photon signal whose period is significantly less than the FW1%M of the Si APDs used in the system, as shown schematically in Fig. 2. Similar to our previous work [11,12,22], the up-conversion detector is designed to detect signal photons near 1310 nm, which is one of the standard telecommunications wavelengths. In our system the high-repetition rate single-photon signal at 1310 nm is produced by an attenuated CW laser diode and an electro-optic modulator (EOM) driven by a pattern generator (Tektronix DTG5274). This pulse-carving source produces weak coherent 220-ps (FWHM) pulses with a period of 625 ps (1.6 GHz).

As shown in Fig. 2, the pattern generator also drives pulse-carving systems for the two up-conversion pump sources at 1549.2 nm (New Focus 6328) and 1550.0 nm (Agilent 81689A). Each pump source has a period of 1.25 ns, and before the pump and the signal are combined the pulses from the first pump are aligned with the odd signal pulses, and the pulses in the second pump are aligned with the even signal pulses, by adjusting the delays in the pattern generator, as shown as in Fig. 3. The pump-pulse duration used in the experiment is 400 ps, which is wider than the signal pulse and chosen to provide higher conversion efficiency [7,8]. The two pump beams are combined by a 1x2 coupler and then amplified by a 1-Watt erbium-doped fiber amplifier (EDFA) (IPG Photonics: EAR-0.5K-C). At the output of the EDFA two 1310/1550 WDM couplers are used in series, giving a 50-dB extinction ratio in total, to suppress noise around 1310 nm. The amplified pump light is then combined with the 1310-nm signal by another WDM coupler, and the combined pump and signal are coupled into the up-conversion medium. Up-conversion takes place in a 1-cm PPLN waveguide (AdvR Inc.) that has a fiber-coupled input and a free-space output. When mixed with the slightly different pump wavelengths in the PPLN waveguide, the 1310 nm signal photons are up-converted to

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output photons at 710.0 nm and 709.8 nm. The output beam is filtered to remove noise and excess pump light and then diffracted by a holographic grating (Kaiser Optical Systems, HLBF-710). After a 3 m path the 710.0 nm and 709.8 nm photons are sufficiently separated that they can be directed onto two Si APDs (PerkinElmer SPCM-AQR-14). In this system an adjustable iris placed in front of the Si APD, in conjunction with the holographic grating, act as a 0.4-nm band-pass filter, which greatly reduces the dark count rate. The detected signals are counted by a TCSPC system.

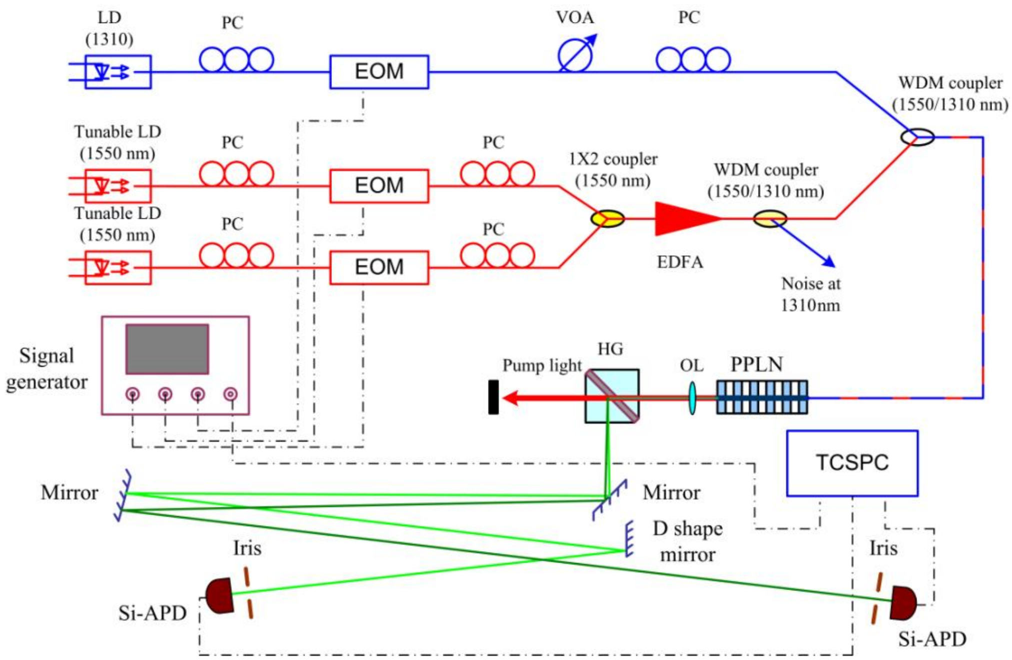

Fig. 2. Experimental setup. LD: Laser Diode, EOM: Electric-optic Modulator; EDFA: Erbium-doped fiber amplifier; WDM: Wavelength-division multiplexing coupler; PC: Polarization controller; PPLN: Periodically-poled LiNbO3 waveguides; OL, Objective Lens; HG, Holographic Grating. TCSPC: time-correlated single photon counting.

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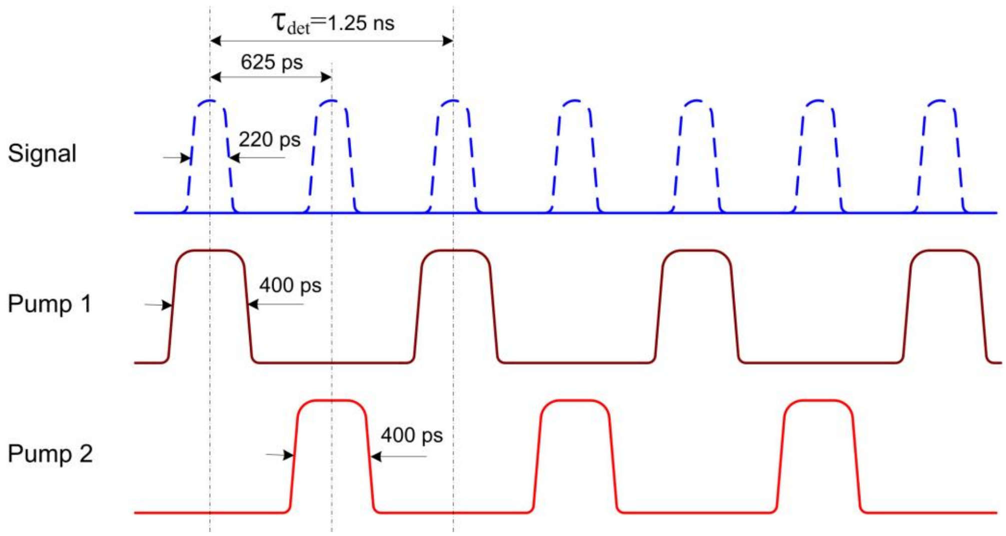

Fig. 3. Timing diagram of the signal (blue), pump 1 (brown) and pump 2 (red) used in the multi-wavelength optical sampling single-photon detection system.

4. Experimental results

In this experiment we use a 1-cm long PPLN waveguide. A shorter waveguide provides a broader spectral bandwidth, which is necessary to cover the spectral separation of the two output photons. In prior work [22] we have demonstrated high single-photon up-conversion efficiency with a longer 5-cm PPLN waveguide, but we find that the quasi-phase matched bandwidth for such a waveguide is too narrow for the current approach. The transfer function response of a finite-length uniform QPM grating is [23,24]:

$$I_{SFG}(\Delta k) \propto I_{pump} \cdot I_{signal} \cdot \mathrm{sinc}^2(\Delta k \cdot L/2), \tag{1}$$

where I_{SFG}, I_{pump} ,and I_{signal} are the intensities of SFG, pump, and signal light, respectively, L is the waveguide length, and Δk is the phase-mismatching, which determines the bandwidth of the spectral response. According to Eq. (1), for a given SFG intensity, the waveguide length and the spectral response bandwidth are inversely proportional; the shorter the waveguide, the broader the spectral response bandwidth. Figure 4(a) shows the spectral response measured experimentally for the 1-cm PPLN waveguide. Its 3-dB bandwidth is about 1.3 nm, which is about 5 times wider than that of the 5-cm PPLN (0.25 nm) [22]. In this experiment the wider bandwidth allows two pumps, at wavelengths 1549.2 nm and 1550.0 nm, to operate with almost the same conversion efficiency, which is about 85% of the maximum conversion efficiency.

Detection efficiency is a significant trade off for a short waveguide. The overall efficiency of the up-conversion detector, η_o, can be estimated by [6–14]:

$$\eta_o = \eta_{loss} \cdot \eta_{\mathrm{det}} \cdot \eta_{con} \approx \eta_{loss} \cdot \eta_{\mathrm{det}} \cdot \sin^2(\alpha \cdot \sqrt{P_{pmup}} \cdot L), \tag{2}$$

where η_{loss} is the total optical loss in the detector due to component insertion loss (mainly the waveguide coupling) and photon transmission loss in the waveguide; η_{con} is the internal conversion efficiency in the PPLN, which can be estimated by Eq. (1); η_{det} is the efficiency of

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Si APD at the detection wavelength, which is 710 nm in our case. P_{pump} represents the pump power and α is a constant. According to Eq. (2), to compensate for the reduced conversion efficiency in a shorter waveguide the pump power must be scaled quadratically. For example, the pump power required to achieve the maximum conversion efficiency in a 1-cm waveguide is 25 times higher than that for a 5-cm waveguide.

Figure 4(b) shows the detection efficiency of the up-conversion detector as a function of average pump power. The pump power on the x-axis is measured at the input fiber of the PPLN waveguide. Although maximum output power of the EDFA is 1 W, the maximum power at the input fiber is approximately 510 mW due to losses in the WDM couplers and connectors between the EDFA and the waveguide. In our system the combined pulse duration of the two pumps covers 67% of each clock period, and therefore the peak power of each pulse is only 1.5 times higher than the average power. Figure 4(b) indicates that the up-conversion efficiency of the detector does not reach its potential maximum value and is limited by the available pump power. Besides the insufficient pump power, the detection efficiency in our system is further reduced by the absence of AR coating on the waveguide ends, causing about 26% losses, and, as stated above, the fact that the two pumps operate at wavelengths that provide 85% of the peak spectral response. Due to these factors the overall detection efficiency is measured to be 7%. The detection efficiency can be improved by using a higher pump power and an AR-coated waveguide. Selecting pump wavelengths closer to the center of spectral response can also improve the overall detection efficiency, but puts more stringent demands on the spectral separation before the Si APDs.

The dark count rate is another important parameter for a single-photon detector. In an up-conversion single photon detector, the total dark counts come from the intrinsic dark count of Si-APD and the noise from the frequency conversion process. The intrinsic dark count rate is dependent on the Si-APD used in the experiment, which is about 100 counts per second [19], The noise count rate in an up-conversion detector has been extensively studied [6–14,25], and the main source of the noise counts is widely believed to be the spontaneous Raman scattering (SRS) and spontaneous parametric down conversion (SPDC) generated in the waveguide by the strong pump. If these SRS photons or SPDC photons are generated at wavelengths within the signal band they can be up-converted to the detection wavelength, generating noise counts. The noise count rate of an up-conversion detector can be reduced by using a pump wavelength that is longer than the signal wavelength, because (1) the anti-Stokes component of the Raman process is much weaker than the Stokes component, and (2) longer wavelength pumps intrinsically avoid the SPDC photons generating at signal wavelength range. To further reduce the noise count rate, it is also beneficial to use a bandpass filter with a very narrow bandwidth behind the waveguide. The SRS photons are generated over a broad spectrum, while the up-converted signal can be quite narrow. As stated above, in this experiment the iris in front of the Si APDs and the holographic grating constitute a band-pass filter with a bandwidth of about 0.4 nm. From Fig. 4 (b), the total dark count rate of the two Si APDs in the up-conversion detector are approximately 240 and 220 counts per second, respectively, at the maximum pump power.

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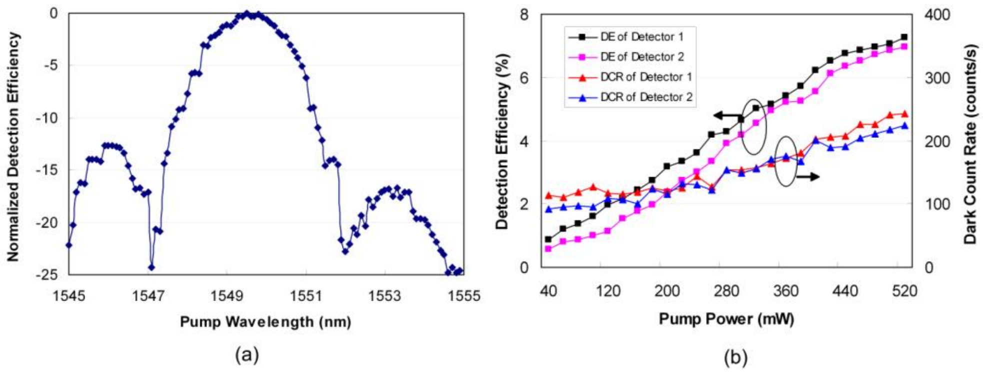

Fig. 4. (a) The spectral efficiency of the up-conversion detector. (b) The detection efficiency (DE) and dark count rate (DCR) as function of pump power. The pump power is measured in the input fiber of the PPLN waveguide.

For a quantum communication system, inter-symbol interference (ISI) can be a significant source of errors. ISI can be caused by timing jitter of single photon detectors, and to avoid a high bit-error rate, the transmission data cycle should be equal to or larger than the FW1%M of the response histogram. For the 220-ps signal pulse used in our system, the response histogram of an up-conversion detector with a single wavelength pump is shown in Fig. 5 (dark blue). The FW1%M of the histogram is about 1.25 ns and this detection system can therefore support a transmission rate of 800 MHz. When such a detection system is used to detect a 1.6 GHz signal, the insufficient temporal resolution of the detector results in severe ISI, as indicated by the poor pulse resolution shown in Fig. 5 (light blue). The application of optical sampling with two spectrally and temporally distinct pump pulses and a separate Si APD for each pump wavelength, as described above, accommodates the 1.25-ns FW1%M of each individual pump channel but supports an overall transmission rate of 1.6 GHz with low ISI. Figure 6 (a) shows the response histogram of each APD in the optical-sampling up-conversion system for a repetitive signal pattern "11111111." For each APD, the detection window is larger than FW1%M of APD response, so the ISI is not obvious. To illustrate both the temporal demultiplexing and the ISI in this system, in Fig. 6 (b), we show the response histogram of each of the two APDs for a repetitive signal pattern "10010110." The APD 1 receives the signal at odd time bins, resulting in the pattern "1001" and APD 2 receives the signal at even time bins resulting in the pattern "0110," and the original signal can be reconstructed from the data recorded by the two APDs. To measure the ISI in the optical sampling up-conversion system under conditions found in a QKD system [11] we also drove the signal with a 1.6 Gb/s pseudo-random data pattern. After comparing the received data to the original data, the error rate was found to be approximately 1.2%. Subtracting the error rate caused by the imperfect extinction ratio of the modulator and the intrinsic dark counts of APDs, the error rate caused by ISI is less than 1%. It should be noted that for most Si-APDs (including the Si-APD used in these experiments), the timing-jitter becomes larger when the count-rate is very high [26]. This effect is called "count-dependent jitter". To avoid this jitter influence, all the measurements in this experiment were implemented when the count rate of a single Si-APD is less than 400K counts/s. When the count rate increases over 600K counts/s, the extra timing jitter will cause the ISI to increase. The count-dependent jitter can be reduced by a modified output circuitry [26].

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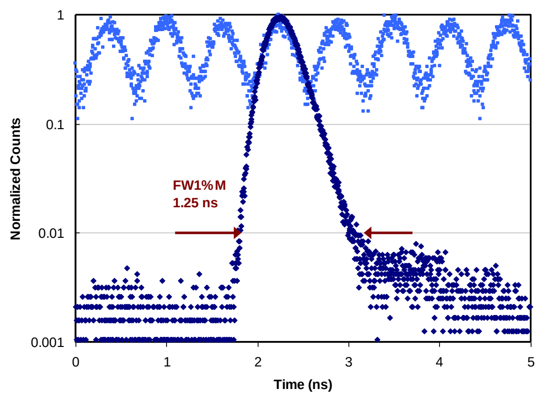

Fig. 5. Response histogram of the up-conversion detector with a single pump wavelength. The response histogram of single pulse (dark blue) shows the FW1%M is 1.25 ns and its temporal resolution is insufficient to resolve, with low ISI, the repetitive data pattern “11111111” at 1.6 GHz (light blue).

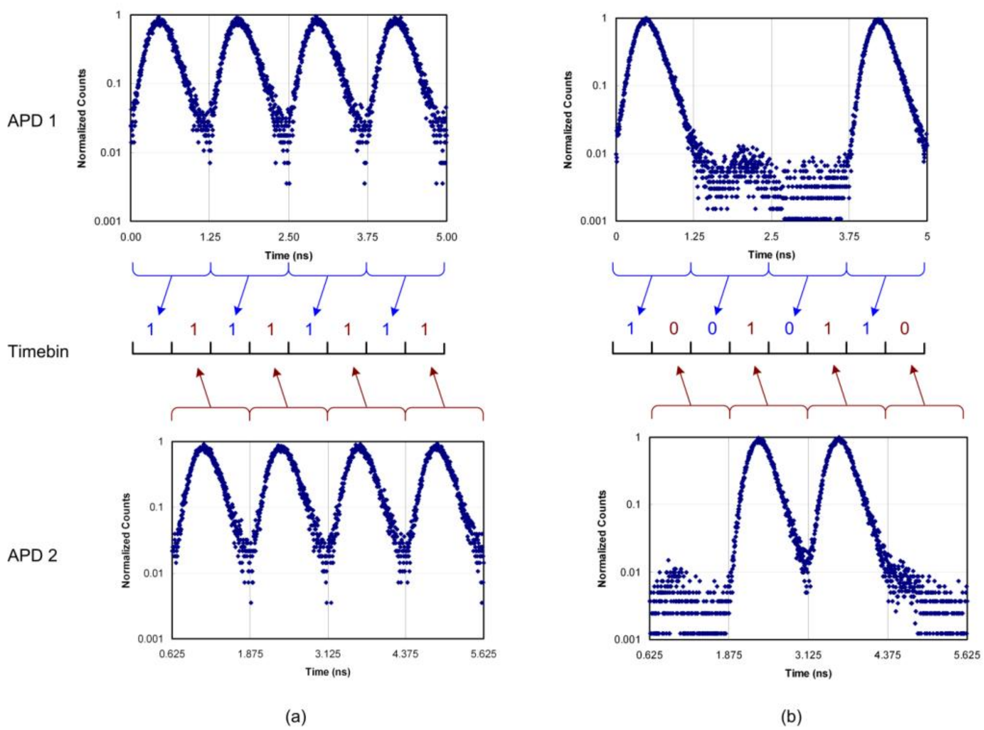

Fig. 6. Response histogram of the up-conversion detector with two spectrally and temporally distinct pump pulses (a) response histogram of APD 1 and APD 2, for a repetitive signal pattern “11111111” at 1.6 GHz. (b) response histogram of APD 1 and APD 2, for a repetitive data pattern 10010110 at 1.6 GHz.

5. Limiting factors

The above experimental results demonstrate that an up-conversion single-photon detector with two spectrally and temporally distinct pump pulses can operate at transmission rates that are twice as fast as can be supported by its constituent APDs. Further sub-division of the APD’s minimum resolvable period (e.g. the FW1%M) is possible with more pump wavelengths and a

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corresponding number of Si APDs, allowing further increases in the maximum supported transmission rate of the single-photon system. However, the ability to increase the temporal resolution is ultimately limited by the phase-matching bandwidth of the nonlinear waveguide and available pump power.

Fourier analysis shows that a shorter pulse duration corresponds to a broader frequency bandwidth. Considering only transform limited Gaussian pulses, the relationship between the pulse duration and spectral bandwidth for such “minimum uncertainty” pulses is given by [27]:

$$t_{FWHM} \cdot \omega_{FWHM} = 4\ln(2), \tag{3}$$

where t_{FWHM} and ω_{FWHM} are the FWHM of temporal width and frequency bandwidth, respectively. For the pump wavelengths in our experiment (~1550 nm), pulse widths shorter than 3 ps correspond to frequency bandwidths larger than 1.2 nm, which covers most of the 3-dB quasi-phase matching bandwidth of our 1-cm PPLN waveguide and thus precludes any other up-conversion pump wavelengths. A 100-ps pump pulse corresponds to a transform-limited bandwidth of 0.035 nm, in which case the waveguide used in our experiment could support more than 10 pump channels with greater than 50% quasi-phase matching efficiency. In this case, its temporal resolution can be increased by one order-of-magnitude compared to an up-conversion detector with just one pump wavelength. To provide uniform detection efficiency across all temporal regions, the pump power can be reduced in the well-phase-matched regions to match the conversion efficiency in the outlying spectral regions.

As the pump wavelengths become closer together, or if a shorter nonlinear waveguide is use to increase the quasi-phase matching bandwidth, technical issues associated with obtaining high optical powers in each pump, and efficient spectral separation of the up-converted photons become significant. We note that novel nonlinear crystal structures, such as chirped gratings or adiabatic gratings [28] can provide broad bandwidth and relatively high conversion efficiency. With these new technologies, we believe it is reasonable to consider an up-conversion single-photon detector using spectrally and temporally distinct pump pulses with temporal resolution better than 10 ps. It should be noted that this scheme is not only suitable for up-conversion detectors using Si APDs; other single-photon detectors with better temporal resolution, such as SSPDs, can also be integrated into the scheme for further improvement of their temporal resolution.

6. Conclusion

The temporal resolution of an up-conversion detector equipped with a Si APD is typically limited by the jitter of the APD. If such an up-conversion detector is used in a high-speed quantum communication system, the highest transmission rate for the system is limited by ISI due to jitter in the APD. We have presented a scheme to improve the temporal resolution for such detectors using spectrally and temporally distinct pump pulses. In principle, as the number of pump wavelengths is increased, the temporal resolution of the up-conversion detector can be multiplied by the same factor. We have experimentally demonstrated an up-conversion detector using two pump wavelengths that supports low ISI single-photon detection at twice the rate supported by a conventional single-pump up-conversion detector. The scheme proposed here can significantly improve the temporal performance of single-photon detectors, and by extension, the performance of high-speed quantum communication systems. Some limitations of the scheme have been identified, and a path towards an order-of magnitude improvement in single-photon timing resolution has been discussed.

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