Low noise up-conversion single photon detector and its applications in quantum information systems[1]

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ABSTRACT

We developed low-noise up-conversion single photon detectors for 1310 nm based on a periodically-poled $LiNbO_3$ (PPLN) waveguide. The low-noise feature is achieved by using a pulsed optical pump at a wavelength longer than the signal wavelength. The detectors were used in a quantum key distribution (QKD) systems based on polarization encoding, measurement for entangled photon pairs and spectrum measurement at single photon levels. In this paper, the overall detection efficiency and noise level of the detectors are characterized and the polarization and wavelength sensitivity of the detection efficiency is analyzed. The applications of this detector in quantum information systems are also described.

Keywords: Frequency up-conversion, Single photon detector, Quantum key distribution, Entangled photon pair, Optical fiber communication.

1. INTRODUCTION

The performance of a quantum communications system depends on both transmission loss and detection efficiency. For current fiber systems, the transmission loss is small in near infrared (NIR) range, and many fiber-based communication systems and devices have tended to use this wavelength range. Therefore, the 1310 nm and 1550 nm bands have become the mainstream telecom wavelength windows.

Currently available single photon detectors include photocathode-based detectors (such as a photomultiplier (PMT) and a micro-channel plate (MCP)), avalanche photodiode (APD)-based detectors, and superconducting detectors [1]. Among these detectors, InGaAs PMT, InGaAs MCP, InGaAs APD and two types of superconducting single photon detectors (transition edge sensor (TES) and superconducting single-photon detector (SSPD)) can work in the NIR range. An InGaAs PMT [2] and InGaAs MCP [3] have very low detection efficiency (DE) (<1%) at NIR range. An InGaAs APD has about 10% DE in the NIR range, but it suffers from a high dark count rate and afterpulsing and usually works at gated mode only [4]. Recently, a self-difference technique was developed for an InGaAs APD that suppresses the afterpulsing noise, allowing it to be operated in free-running mode [5]. The InGaAs APD has about 10% detection efficiency, but still has about 6% after-pulse probability which would contribute to the error rate of quantum information systems. Superconducting single photon detectors have excellent performance, including an extremely low dark count rate and a flat wavelength sensitivity from ultraviolet to infrared light. TES can approach almost 100% DE when proper optical coupling is provided [6], and SSPD has a very short response time and timing jitter with no hold-off time and no

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afterpulsing [7,8]. The drawback for superconducting detectors is the need for cooling to a fraction of Kelvin for TES or the liquid helium temperature for SSPD, making them impractical in many applications.

By comparison, single photon detectors available in the visible light range are usually inexpensive and have solid performance characteristics. For example, silicon APD (Si-APD) [10] has high detection efficiency at visible light wavelengths (70% at 650 nm), low dark count rate (<100 Hz), can be operated at room temperature, and can operate in free-running mode. However, its DE reduces greatly at wavelengths longer than 1000 nm, and does not work at the telecom wavelength of 1310 nm and 1550 nm. Recently, the nonlinear process of sum frequency generation (SFG) has been applied to solve this issue of spectral discrepancy. Using a nonlinear optics waveguide, one can convert the light at longer wavelengths to a shorter wavelength with nearly 100% conversion efficiency [11~16] and this technique is called frequency up-conversion or simply, up-conversion. By this technique, photons at a wavelength around 1310 nm or 1550 nm can be converted to a wavelength shorter than 1000 nm, where they can then be detected by a Si-APD with high efficiency. The performance and characteristics of the main single photon detectors and an up-conversion detector with a Si-APD are summarized in Table 1.

Table 1. Performance of single photon detectors. The data are from [1~12].

Detection range	Single photon detectors	Temperature, ° K	Maximum Count rate, MHz	DE, %	DCR, kHz	Timing jitter (ns)	Cost
VI	GaAs PMT	240-290	5	30	0.001-1	1	$
	GaAs MCP	240-290	0.5	30	0.001-1	0.1	$$
	Si-APD	room	5	70	0.1	0.05	$
NIR	InGaAs PMT (Hamamatsu)	193	10	1	160	1.5	$$
	InGaAs MCP (Burle)	210	1	1	100	1	$$
	InGaAs APD (id Quantique)	220	4 (gated)	10	10	0.06	$$
	InGaAs APD (Toshiba, UK)	243	100	10	10	0.06	$$
VI and NIR	SSPD (NIST)	<0.1	1000	3	0.01	0.06	$$$
	TES (NIST)	<3	0.1	95	0.4	100	$$$
	Up-conversion detector (NIST)	room (heated) *	5	31	25	0.05	$$

* Although the up-conversion system itself is operated at room temperature, the non-linear crystal is heated locally to satisfy the phase matching condition required for optimal condition.

We have developed a low noise up-conversion detector for 1310 nm using a periodically-poled $LiNbO_3$ (PPLN) waveguide. In our setup, a 1310 nm signal photon is up-converted to 710 nm in the PPLN waveguide pumped by a 1550 nm laser and then detected by a Si-APD. The 1550 nm pump is modulated into a pulse with a synchronized signal. The low noise feature of the detector is achieved with a pulsed pump at a wavelength longer than that of the signal to be detected. We integrated the up-conversion detector into various quantum information systems, including a polarization-encoding quantum key distribution (QKD) system, and we performed related measurements such as the detection of entangled photon pairs and the spectrum measurement of signals at single photon level. In comparison with other detectors, the up-conversion detectors provide some unique advantages in these applications. For example, the high polarization extinction ratio sensitivity serves as a polarizer to replace an otherwise required polarizer in a polarization-encoding QKD system and therefore the extra insertion loss is avoided. The spectral sensitivity can be utilized as a narrow band-pass filter to block noise from other wavelengths when quantum and classical channels share the same fiber. The narrow spectral acceptance bandwidth also can be used to measure the spectrum of weak light signals. In this paper, we will show the performance of the up-conversion detector and describes its application in quantum information systems and quantum measurements.

2. LOW NOISE UP-CONVERSION DETECTORS

3.1 Up-conversion detector configuration

The configuration of our up-conversion detector is shown in Fig. 1. 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) (IPG: EAR-0.5K-C). Two 1310/1550 wavelength division multiplexer (WDM) couplers with a 25 dB extinction ratio are used 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 waveguides. The input polarization state of both the signal and the pump are adjusted by the polarization controllers, PC1 and PC2 respectively, before entering the coupler. The longer the waveguide length, the lower the pump power needed to reach the maximum conversion efficiency. 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 is free-space with a 710 nm anti-reflection (AR) coating. The output light of PPLN waveguide consists of a 710 nm (SFG) up-converted weak light signal, residual 1550 nm pump light and its second harmonic generation (SHG) 775 nm light. These beams are separated by two dispersive prisms and the 710 nm photons are detected by a Si-APD (PerkinElmer: SPCM-AQR-14). An iris and a 20 nm band-pass filter (Omega Optical, Inc.: 3RD700-720) are used to reduce other noise, such as photons leaked from the environment.

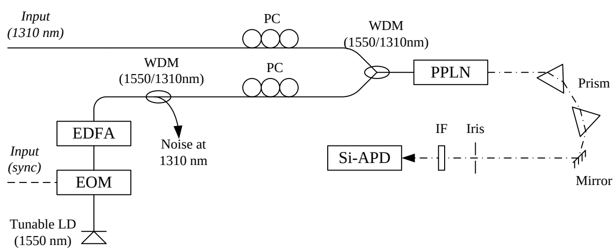


Fig. 1. Schematic diagram of the up-conversion detector. EOM: Electric-optic Modulator; EDFA: Erbium-doped fiber amplifier; WDM: Wavelength-division multiplexing coupler; PC: Polarization controller; PPLN: Periodically-poled LiNbO3 waveguides; IF: Interference filter. Solid line: Optical fiber; Dash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

3.2 Detection efficiency

Detection efficiency is one of the most important performance metrics of single photon detectors. The overall detection efficiency of an up-conversion detector is determined by the internal conversion efficiency in the PPLN waveguide, the insertion loss due to coupling and the components in the system, and the detection efficiency of Si-APD at the converted wavelength. The overall detection efficiency of an up-conversion detector can be estimated by the following formula [16]:

$$\eta_o = \eta_{loss} \cdot \eta_{\det} \cdot \eta_{con} \approx \eta_{loss} \cdot \eta_{\det} \cdot \sin^2(\alpha \cdot \sqrt{P_{pmup}} \cdot L) \quad (1)$$

where η_o is the overall detection efficiency of the up-conversion detector; η_{loss} is the total loss in the detector, including the component insertion loss and waveguide coupling loss; η_{con} is the internal conversion efficiency in the PPLN, and can be estimated by Eq. (2); $\eta_{\det}$ is the detection efficiency of the Si-APD at the converted wavelength, which, in our case, is 710 nm. According to the specification of the Si-APD, $\eta_{\det}$ is about 65%.

In a complete up-conversion detector unit, the insertion and coupling loss, the detection efficiency of the Si-APD and the structure of the waveguide are fixed. Therefore, the overall conversion efficiency of the detector is determined by the internal conversion efficiency of the waveguide (η_{con}), which is dependent on the pump intensity, and has a $\sin^2(\sqrt{\ })$ relationship according to Eq. (1). The measured conversion efficiency over pump power in a continuous wave (CW) mode and in pulse pump mode is shown in Fig. 2. The measured results are in good agreement with the estimated value from Eq. (1). The maximal detection efficiency is 32% for both pump modes, which corresponds to 100% internal conversion efficiency after we exclude the insertion loss and the detection efficiency of Si-APD (η_{loss} and $\eta_{\det}$).

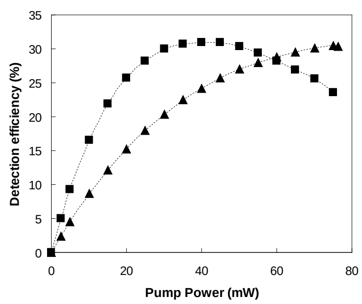


Fig. 2. The detection efficiency as a function of pump power. Two cases are studied: CW pump (triangle) and pulsed pump (square).

In many quantum information systems, the photons arrive with a synchronized classical signal. Therefore, the up-conversion detector can be operated in pulsed pump mode using the synchronized signal. The detection efficiency measured here is from a 625MHz synchronized classical signal with 600 ps (FWHM) pulses. The quantum optical pulse is pumped with the same synchronized signal but has a shorter 300 ps (FWHM) pulse width. The detector operating in pulse pump mode can reach the maximum conversion efficiency with a lower average pump power, which helps to reduce the noise (we discuss this in some detail in the next section). In these cases where there is not a synchronized signal, a CW pump is needed. For pulse and CW pump modes, the optimal pump power (average) is about 38 mW and 78 mW, respectively.

3.3 Noise reduction

For a single photon detector, the noise level, or dark count rate, is the most important performance parameter: a higher dark count rate can cause more errors in the quantum information system and degrade the system's fidelity.

The dark count rate has been extensively studied in frequency up-conversion technology [11~15], and these are three main causes: intrinsic dark counts of Si-APD, linearly induced noise photons that leak through the filter from the pump, and nonlinearly induced noise photons due to scattering by the strong pump. The intrinsic dark count rate of the Si-APD is listed in the manufacturer's product specification. It is about 100 c/s in our case. The linearly induced dark counts are caused by the photons in the spectral tail from the pump source, which extends to the signal wavelength range. We use two WDM couplers to greatly suppress this noise. The nonlinear process that causes the dark counts is widely believed to be from the Raman scattering process, in which photons in the signal band are generated by the strong pump and then up-converted to the detection wavelength, though this has not been strictly proven. In this up-conversion detector unit, we use a 1550 nm laser as a pump, whose wavelength is longer than that of the quantum signal we want to measure. Because the anti-Stokes component of the Raman process is much weaker than the Stokes component, a dark count rate of less than 2400 c/s is achieved when the conversion efficiency is maximized.

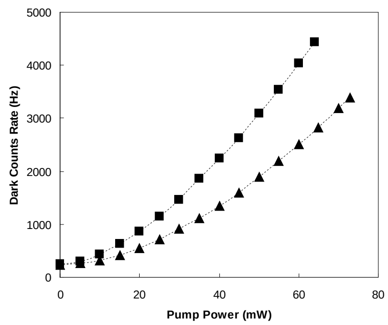


Fig. 3. The dark count rate as a function of pump power at the PPLN input. Two cases are studied: CW pump (triangle) and pulsed pump (square).

As shown in the Fig. 3, the pulse pump generates more dark counts than the CW pump for a given average power since the peak power of the pulse pump is higher than the average power. We refer to pump power as the average power of the pump, because the pulse pump needs less power than the CW pump to achieve a given detection efficiency. Therefore, the pulse pump can achieve a given detection efficiency with less dark counts in comparison with CW pump. For example, the maximum detection efficiency is reached when using the pulse pump at 38 mW and the dark count rate is 2400 c/s. For the CW pump, a power of 78 mW is needed to achieve the maximum detection efficiency, which incurs a dark count rate of 3100 c/s. Consequently, a pulse pump can use lower power and effectively reduce the dark count rate compared to a CW pump.

3.4. Wavelength and temperature response

When the quasi-phase matching condition in a PPLN waveguide is satisfied at a particular signal wavelength, the maximum up-conversion efficiency is achieved. When the signal is shifted from that wavelength the up-conversion efficiency is reduced. This means that the up-conversion detectors have a narrow wavelength acceptance width, and is similar to a narrow band pass filter. It helps to filter out noises at wavelengths other than the signal wavelength. However, this may be a drawback when the detector is used to measure signals with wider spectrum. The acceptance spectral width of the up-conversion detector is determined by the transfer function response of the PPLN waveguide. The transfer function response of a finite-length uniform QPM grating in the waveguide is a function of a $\text{sinc}^2(\ )$ as follows:[17, 18]

$$I_o(\Delta k_Q) \propto I_p \cdot I_s \cdot \text{sinc}^2(A \cdot \Delta k_Q \cdot L) \tag{2}$$

where I_o, I_p, I_s are the intensity of SFG, pump, and signal beam; A is a constant; L is the waveguide length; and Δk_Q is the phase-mismatching, which can be calculated by the following relation with the system wavelengths as follows:

$$\Delta k_Q = \frac{n_o}{\lambda_o} - \frac{n_p}{\lambda_p} - \frac{n_s}{\lambda_s} - \frac{m}{\Lambda} \tag{3}$$

where λ_o, λ_p and λ_s are the wavelengths for output, pump, and signal, respectively, and n_o n_p and n_s are the reflective index for the three wavelength. Λ is the poling period for the mth order quasi phase matched condition of the nonlinear PPLN waveguide. According to Eq. (2, 3), the acceptance spectral width is dependent on the length of he waveguide. The longer the waveguide is, the narrower the acceptance spectral width will be. Fig. 4 shows the measured detection efficiency as a function of signal wavelength at certain fixed pump wavelength and temperature. From the figure, we can see that the spectrum is similar to the $\text{sinc}^2(\ )$ function and the acceptance spectral width of the main peak is about 0.25 nm (FWHM). If we use a short waveguide or a pump light with wider spectrum, the acceptance spectral width can be broadened.

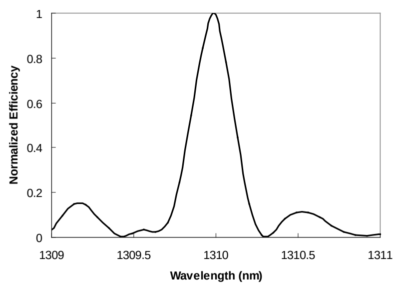
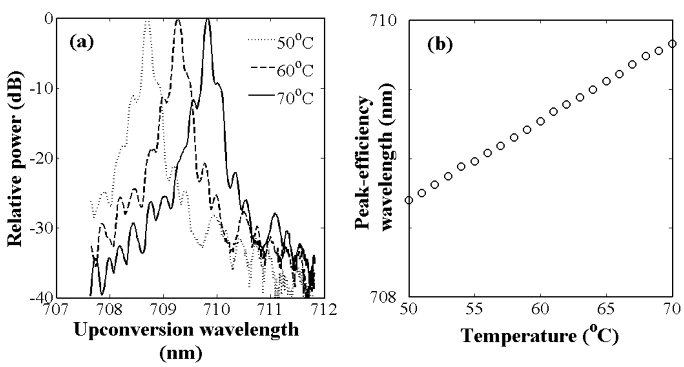


Fig. 4. The normalized detection efficiency as a function of signal wavelength, when the pump wavelength and temperature of the waveguide are fixed.

The up-conversion wavelength peak is also temperature sensitive. Therefore, one or both of the pump and the signal wavelength, as well as the waveguide temperature needs to be accurately tuned to achieve the mscimum up-conversion efficiency. To investigate the temperature sensitivity of the up-conversion, we sent a 1-mW CW 1310 nm laser beam with a linewidth less than 10 MHz into the PPLN waveguide. Moreover, we turned off the pump seed laser so that the amplified spontaneous emission (ASE) noise from the EDFA acted as the pump. Using an optical spectrum analyzer (OSA), we measured the spectrum at the output of PPLN waveguide at different temperatures from 50°C to 70°C. The output spectrum is normalized to the peak power after we subtracted the ASE spectrum. The result is shown in Fig. 5.



(a) (b)

Fig. 5 (a) The normalized output spectrum of the PPLN at the different temperatures shown in inset. (b) The up-conversion wavelength peak as a function of temperature.

As shown in Fig. 5(a), the spectral width of the sum frequency at 710 nm is about 0.15 nm. The result is consistent with the spectral width of 0.25 nm for the signal at 1310 nm as shown in Fig. 4. Also from Fig 5(a), the peak wavelength is shifted as the temperature changes, which means that the quasi-phase matching condition can be achieved by either varying the converted wavelength (via tuning of the pump wavelength and/or signal wavelength), or varying the waveguide temperature, as shown in Fig. 5(b). Within a temperature variation range of 20 degrees, the central wavelength for maximal efficiency linearly varies by approximately 1.1 nm. The temperature response of the waveguide provides a method to tune the up-conversion detector to reach to the maximum detection efficiency, even if the signal and pump wavelengths are fixed.

3.5 Polarization characterization

The up-conversion process in a PPLN waveguide is polarization sensitive. If its polarization extinction ratio is sufficiently high, the device can be used as a polarizer. This feature is very useful in polarization-encoding quantum communications systems. Fig. 6 shows the dependence of detection efficiency on the polarization direction of an input signal at 1310 nm. The deviation angle is the angle (in Jones space) between the given input polarization state and the one at which the conversion efficiency is maximum. We also compared the measurement results with a $\cos^2(\ )$ curve, the function which represents an ideal polarizer. The curve agrees well with the measured data and we believe that the slight difference is caused by the measurement uncertainty of the polarimeter. As shown in the Fig. 6, the polarization extinction ratio of the PPLN is over 25 dB. Therefore, an up-conversion detector can be used as a polarizer in a polarization-based quantum information system, and therefore avoids the additional insertion loss that an otherwise required polarizer would add.

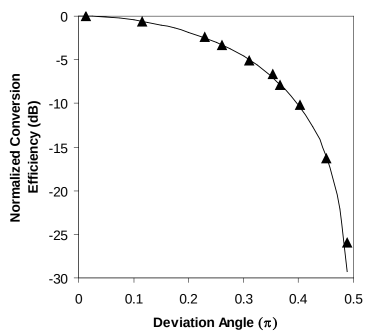


Fig. 6. The normalized conversion efficiency of the PPLN waveguide as a function of deviation angle of the input signal at 1310 nm. The deviation angle is the angle between the given polarization state and the state at which the conversion efficiency is maximized. Triangle: Measurement results; Solid line: $\cos^2()$ curve

3. APPLICATIONS TO QUANTUM INFORMATION SYSTEMS

3.1 Polarization-based QKD system with attenuated laser source

A single photon detector is one of the key elements for a QKD system since the information being transmitted is encoded as the quantum state of single photons [19]. Due to its high detection efficiency, low dark count rate and unique characteristics, such as narrow acceptance spectral width and polarization sensitivity an up-conversion detector is a very suitable device for polarization-based QKD systems.. Among its advantages are :

1. High detection efficiency: many QKD systems use narrow linewidth attenuated laser light as the single photon source, which is much narrower than the acceptance bandwidth of up-conversion detection. Therefore, an up-conversion detector can reach its max detection efficiency, and results in a higher secure key rate.
2. Low dark count rate: many QKD system recover clock from their classical channel, which can be used as the synchronized trigger signal for the pulse pump operation in the up-conversion detector, which can lead to a lower dark count rate and, therefore, a lower error rate in the system.
3. Narrow acceptance spectral width: each up-conversion detector has a relatively narrow acceptance spectral width that functions as a band-pass filter, rejecting the noise due to crosstalk from strong signals in classical channel that may shares the same fiber.

4. Polarization sensitivity: this feature can be used as a polarizer, which avoids the additional insertion loss that an extra polarizer would add.

We integrated our up-conversion detector into a QKD system [11]. The quantum keys are encoded by photons at 1310 nm with the B92 protocol [20], as shown in Fig. 7. The QKD system uses a custom printed circuit board with a field-programmable gate array (FPGA) [21-23] to generate a random stream of quantum key data and to transmit and receive the classical data, which will be encoded and decoded by the quantum key. The classical data is carried by the optical signal in the 1550 nm band. To polarization-encode the quantum channel with the random quantum key, we first modulate a 1310 nm CW light into a 625 MHz pulse train which is evenly split into two polarization channels. Each pulse train is further modulated by one of two complementary 625 Mbit/s quantum channel data streams. The two quantum channels are combined by a 45-degree polarization-maintaining combiner and attenuated to a mean photon number of 0.1 per bit, and then multiplexed with the classical channel and sent to a standard single-mode fiber. At Bob, another WDM is used to demultiplex the quantum and classical channels. The quantum channel is polarization-decoded and detected using the up-conversion single-photon detectors, and the detection events are recorded to generate raw keys. Bob's board informs Alice of the location of the detection events via the classical channel. After reconciliation and error correction, Alice and Bob obtain a common version of shared secrets keys, which are further used to encode and decode information.

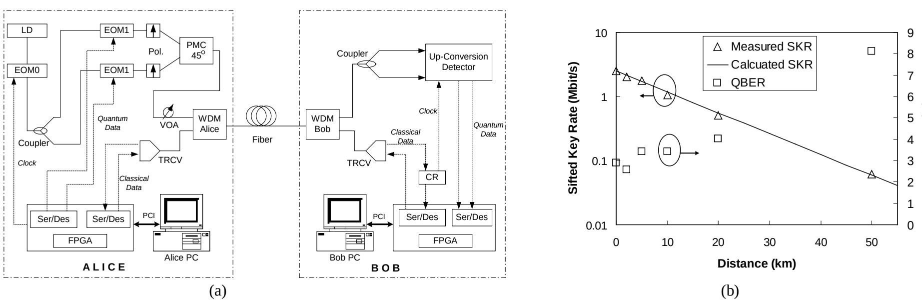


Fig. 7. (a) The B92 polarization coding QKD system. LD: Laser diode; EOM: Electric-optic modulator (LiNbO3); PC: Polarization controller; PMC-45º: Polarization maintaining combiner that combines two light signals that are separated by 45 degrees; VOA: Variable optical attenuator; WDM: Wavelength-division multiplexer; SMF: Standard single-mode fiber; TRCV: Optical transceiver; CR: Clock recovery module; FPGA: Custom printed circuit board controlled by a field-programmable gate array; PCI: PCI connection; Dotted line: Electric cable; Solid line: Optical fiber. (b) The system performance of the B92 polarization-based QKD system

The system performance is shown in Fig. 7 (b). During our measurements, the pump power was fixed at 40 mW. The sifted-key rate is 2.5 Mbit/s for a back-to-back connection, 1 Mbit/s at 10 km, and 60 kbit/s at 50 km. The quantum bit error rate (QBER) is approximately 3% for the back-to-back configuration, remains below 4% up to 20 km, and reaches 8% at 50 km. The finite extinction ratio of the modulator and the system timing jitter induce a background QBER of approximately 2.5% and the rest is from dark counts generated by both the pump light and the classical channel. We also calculated the theoretical sifted-key rate and QBER and they agree well with the measured results. Although we fixed the pump power close to the maximum up-conversion efficiency, the QBER remains small until 20 km due to the low dark count rate of the 1550 nm up-conversion detector. The QKD system can generate secure keys in real time for one-time-pad encryption of continuous 200 Kbit/s encrypted video transmission over 10 km. The system performance demonstrates that the up-conversion detectors are suitable for the fiber-based polarization-encoding QKD system.

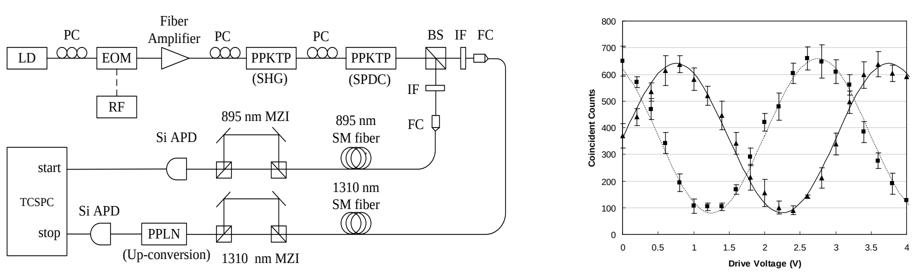
3.2 Entangled photon pair source

Entanglement is one of the most important tools for the realization of complex quantum communication protocols, such as quantum teleportation or entanglement swapping. For fiber-based system, one wavelength of the entangled photon source should be in the telecom band, and the other one should be suitable for convenient quantum memory. We implemented a sequential time-bin entangled photon source by using a periodically poled potassium titanyl phosphate (KTP) waveguide[24]. One of the wavelengths generated is 1310 nm (suitable for long range fiber communications) and the conjugate wavelength is 895 nm that is resonant with the transition line of the cesium (atomic symbol 'Cs') atoms. The up-conversion detector is used for the detection of the 1310 nm photon from the source.

Figure 8 schematically shows the experimental setup. A continuous wave (CW) 1064 nm laser beam is emitted from a tunable laser (New Focus: TLB 6321). The emitted beam has a narrow line-width (300 kHz), which corresponds to a coherence time of 3.3 µs. The coherence time is much longer than 1 ns and therefore satisfies the requirement to generate 1 GHz sequential time-bin entanglement. The CW laser is modulated into a 1GHz pulse train with 330 ps FWHM pulses by an electric-optic modulator (EOM), and a RF pulse generator (Tektronix: DTG5274) provides the electrical pulse signal. Simultaneously, another channel in the pulse generator provides a 1 GHz pulse train with a 500 ps FWHM pulses to the up-conversion detector for pulsed-pumping of the PPLN waveguide, and the time delay between the two channels is tunable . The 1064 nm optical pulses are further amplified by a fiber amplifier (IPG: YAR-1K-LP) that can set the output power. A polarization controller (PC) is used to launch the proper polarization into the first PPKTP waveguide, which is used for the second-harmonic-generation (SHG) of the 532 nm pump pulses. The pump pulses are then coupled into a 532 nm single-mode fiber, which removes the 1064 nm light and other noise from the fiber amplifier. The second 2 cm long PPKTP waveguide is periodically poled to convert single photons from 532 nm to 1310 nm and 895 nm, both vertically polarized, with type I phase matching. A series of time correlated photon pairs is generated in the waveguide by spontaneous parametric down conversion (SPDC). By adjusting the pump power one can have an average of 1 pair of SPDC photons per N pump pulses. Under the condition N >> 2 and $T_c >> \tau >> \tau_p$ (in our experiment, T_c = 3.3 µs, τ = 1 ns, and τ_p = 330 ps), the quantum state of the photon pair is

$$\left|\Psi\right\rangle = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} e^{in\phi_\tau} \left|n\tau\right\rangle_{signal} \left|n\tau\right\rangle_{idler} \tag{4}$$

where ϕ_τ is the phase difference between consecutive pump pulses; i is the imaginary unit; and signal and idler states represent the states of the signal (895 nm) and idler (1310 nm) photons. The signal and idler photons are separated using a dichroic beam splitter, and then coupled into 895 nm and 1310 nm single mode fibers, respectively. A bandpass filter is used to reduce the residual pump photons and other noise in the 895 nm photon path, while the noise in the 1310 nm path will be filtered by the up-conversion detector itself. Two free-space 1 ns unbalanced Mach-Zehnder interferometers are used to measure the two-photon-interference-fringe visibility. The phases of the interferometers can be adjusted by a piezo nanopositioning stage. A Si-APD is used to measure photons at 895 nm, and the up-conversion detector is used for detecting the single photons at 1310 nm. The detected signals are fed into a time-correlated single photon counting module (TCSPC) for coincidence measurement.



(a) (b)

Fig. 8. (a) Experimental setup for entangled photon source: LD: 1064 nm CW laser Diode; EOM: Electric-optic modulator; RF: RF pulse generator; PC: Polarization controller, PPKTP: Periodically-poled KTP waveguide; BS: 895/1310 nm Dichroic beam splitter; IF: Interference filter; FC: Fiber

collimator; MZI: Mach-Zehnder interferometer; Si-APD: Silicon based avalanche photo diode; PPLN: Periodically-poled $LiNbO_3$ waveguide for frequency up-conversion; TCSPC: Time-correlated single photon counting module. (b) Coincidence interference fringes measured in the experiments. Solid line/ triangle and dash line/square are the coincidence counts when the piezo drive voltages of the 850nm interferometer are 0 and 1 volt, respectively

To determine the two-photon-interference-fringe visibility of the entangled photon pairs, we measured the photon coincidence through the interferometers, in which we fixed the phase for the signal interferometer (895 nm) and varied the phase for the idler interferometer (1310 nm). To demonstrate entanglement, we set two different fixed phases for the signal and got two interference patterns with the varied phase of the idler, as shown in fig. 8 (b). The entangled-photon-pair flux that we measured is 650 Hz and the two-photon-interference-fringe visibility is 79.4 % without abstracting any noise, which is above the visibility required for violation of the Bell inequality. The imperfection of the visibility is mainly caused by multi-photon pairs being generates, the timing jitter of the detectors and the imperfect visibility of the interferometers.

Because the spectral width of the 1310 nm photon generated from SPDC in the PPKTP waveguide is about 2 nm (FWHM), which is much wider than the acceptance bandwidth of PPLN waveguide (0.2 nm), the detection efficiency of the up-conversion detector is reduced to 3% when it is used to detect the photons. However, the narrow bandpass property of the up-conversion detector provides an advantage. We do not need to use any other narrow band pass filter in the 1310 nm optical path, since other photons at different wavelength do not satisfy the QPM condition required for conversion and therefore remain at a wavelength that cannot be detected.

3.3 High sensitivity spectrum measurement

Spectrum analysis is very important for research of quantum information, especially in studying on the spectrum of entangled photons. For light at UV, visible and wavelengths shorter than 1 µm, there are many choices for single photon detection with excellent performance, such as Si-APDs. One can use either dispersive elements or a tunable narrow-band filter to separate, or select, light at different wavelengths, which can then be suitably detected by a Si-APD. However, as we have discussed, there are no suitable detectors for the NIR range. The current IR spectrometer technology either has high noise characteristics (in the case of non-cooling InGaAs array detectors), which limits its sensitivity, or need a bulky cryogenic cooling system (in the case of liquid-nitrogen-cooled InGaAs array detectors).

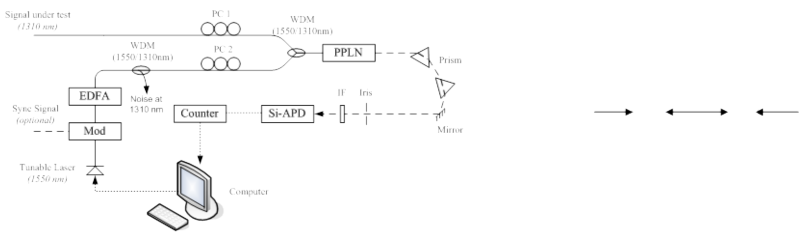
Up-conversion detectors can be integrated into a NIR spectrometer. In an up-conversion detector, only those photons whose momentum and energy conservation requirements are satisfied with the phase-matching condition in the waveguide can be converted and detected. Based on this principle, an up-conversion spectrometer can be constructed when a tunable pump source is used [25-27]. In this case, we can obtain a spectrum of the signal without using dispersive elements or tunable narrow-band filters. Furthermore, by using a pulsed pump scheme, time-resolution spectroscopy can be conveniently realized [26].

Based on the up-conversion detector described above, we implemented an up-conversion spectrometer[27], as shown in fig. 9(a). The seed light is provided by a tunable CW laser near 1550 nm (New focus: TLB 6321), which is controlled by a computer via a GPIB port. The output count signal of the Si-APD is then sent back to the same computer. The computer controls the 1550 nm tunable laser to scan the pump light wavelength and also collects and processes the counts from Si-APD. The spectrum of signal light can be obtained by sweeping the pump laser wavelength and using the the quasi-phase-matching condition to obtain the signal spectrum.

The resolution of the up-conversion spectrometer is jointly determined by the acceptance bandwidth of the PPLN waveguide and the linewidth of the tunable laser. In theory, the longer the QPM structure (waveguide) is, the narrower the acceptance bandwidth will be. In our case (5 cm PPLN waveguide), the measured acceptance bandwidth is 0.2 nm. Because the line-width of the 1550 nm tunable laser is just 150 kHz, the up-conversion spectrometer resolution is determined by the QPM acceptance bandwidth of the waveguide.

The sensitivity is jointly limited by the detection efficiency and the variation of the dark counts. Our measured maximum overall detection efficiency is 32%. The dark counts have a shot noise behavior, whose deviation is equal to the square root of the average number of the counts. The maximum dark count rate in the measurement range is about 2500 counts per second, and the maximum dark count deviation is 50 counts per second. To get a clear spectrum, the signal counts should be one order of magnitude greater than the dark count deviation, or 500 counts per second, which corresponds to 1563 photons/s or -126 dBm of the signal when taking the detection efficiency of 32% into account, which is at least two orders of magnitude better than commercial optical spectrum analyzers in NIR range.

A major limitation to the maximum measurement intensity is imposed by the “dead-time” of Si-APD. After the Si-APD receives a photon, the avalanche process generates an electrical output signal. The device then needs a certain amount of time, called “dead time”, to recover its initial operation state before detection of the next photon. This is especially significant when the intensity of the signal under test becomes strong. According to theoretical calculations and experimental data, when the signal intensity is lower than -95 dBm, the influence of the dead-time is negligible. If the signal intensity is between -95 dBm to -80 dBm, the influence of the dead time is significant. The measured spectrum should be calibrated to recover the actual spectrum. When the signal intensity is larger than -80 dBm, more than half of the signal photons are lost due to the dead time and, additionally, the Si-APD is saturated. Therefore it is not suitable to use the spectrometer to measure the signals above -80 dBm directly. The most suitable measurement intensity range of the spectrometer is from -126 dBm to -95 dBm while the signal between -95 dBm to -80 dBm could be calibrated to remove the influence of the dead-time. Any signal above -80 dBm should to be attenuated before using the up-conversion spectrometer.



(a) (b)

Fig. 9. (a) Schematic diagram of the waveguide-based spectrometer. Mod: Wavelength insensitive modulator; EDFA: Erbium-doped fiber amplifier; WDM: Wavelength-division multiplexing coupler; PC: Polarization controller; PPLN: periodically-poled LiNbO3 waveguides; IF: Interference filter. Solid line: optical fiber; dash line: free space optical transmission; dot line: electrical line.. (b) The spectrum of 1310 nm photons generated from 1 cm and 2 cm PPKTP waveguide, measured by the up-conversion spectrometer.

The up-conversion spectrometer is a very useful tool to measure the spectra of single photon levels. We have used it to measure the spectra of entangled photons source. The Fig. 9 (b) shows the spectra of the photons generated in a 1 cm and a 2 cm PPKTP waveguides, which are measured by the up-conversion spectrometer. It shows that the longer the waveguide length, the narrower the spectrum of generated photons. Because the resolution of the up-conversion spectrometer is much greater than the spectrum of photons generated from SPDC, and since the intensity of the photons is quite low and require a highly sensitive device for detection, the up-conversion spectrometer is a most suitable spectrum measurement tool for quantum information research in the NIR range.

4. CONCLUSION

We developed low-noise up-conversion single photon detectors for 1310 nm based on a PPLN waveguide. The low-noise feature is achieved by using a pulsed optical pump at a wavelength longer than the signal wavelength. The maximum overall detection efficiency reaches 32% and the dark count rate is 2500 Hz. The detector has a narrow acceptance bandwidth that functions as a bandpass filter and narrow wavelength selector, and a high polarization extinction ratio that works like a polarizer. We used the detector in a polarization encoding QKD system as well as for the measurement of entangled photon pairs. We further integrated it into a spectrometer to study the spectrum of the photons generated from SPDC. The up-conversion detector is a very useful tool in the research of quantum information in the NIR range.

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