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Detection and Spectral Measurement of Single Photons in Communication Bands Using Up-Conversion Technology[1]

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Abstract—Quantum information systems are commonly operated in conventional communication bands (1310 and 1550 nm) over an optical fiber to take advantage of low transmission loss. However, the detection and spectral measurement of single photons in these communication bands are limited due to high noise and low sensitivity of single photon detectors in the wavelength ranges. To demonstrate high efficiency detection and high sensitivity spectral measurement, we have implemented a single photon detector and a spectrometer based on frequency up-conversion technology. This detector and spectrometer uses a 5-cm periodically poled lithium niobate (PPLN) waveguide and a tunable pump laser around 1550 nm, to convert signal photons around 1310 to 710 nm. The converted photons are then detected by a silicon-based avalanche photodiode (APD). The overall detection efficiency of the single photon detector is as high as 32%, which is three times higher than commercial InGaAs APDs. The sensitivity of the spectrometer is measured to be –126 dBm, which is at least three orders-of-magnitude better than any commercial optical spectrum analyzer in this wavelength range.

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1. INTRODUCTION

Quantum information systems usually take advantage of the low transmission loss of optical fiber at the conventional communication bands (1310 and 1550 nm). However, at these wavelengths, the detection and spectral measurement of single photons is limited due to high noise and low sensitivity of single photon detectors at these ranges. 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 PMTs, InGaAs MCPs, InGaAs APDs and two types of superconducting single photon detectors (transition edge sensor (TES) and superconducting single-photon detector (SSPD)) can be operated in the 1310/1550 nm wavelength range. InGaAs PMTs [2] and InGaAs MCPs [3] have very low detection efficiency (< 1%) at these wavelengths. An InGaAs APD has about 10% detection efficiency at these wavelengths, but it suffers from a high dark count rate and afterpulsing and usually works in gated mode only [4]. Recently, a self-differencing technique was developed for an InGaAs APD that suppresses some of the afterpulsing noise, allowing it to be operated at gigahertz clock rate in a gated mode [5]. The InGaAs APD has about 10% detection efficiency, but still has about 6% after-pulse probability which would adversely contribute to the quantum bit error rate (QBER). Superconducting single photon detectors have excellent performance, including an extremely low dark count rate and a flat sensitivity for wavelengths from ultraviolet to infrared. TES can approach almost 100% detection efficiency when proper optical coupling is furnished [6], and an SSPD has a very short response time and timing jitter with no hold-off time and no afterpulsing [7–9]. The drawback for superconducting detectors is the need for cooling to a fraction of a Kelvin for TES or the liquid helium temperature (about 3 K) for SSPD, making them impractical in many applications.

In comparison, single photon detectors available in the visible range have solid performance characteristics and are usually inexpensive. For example, a silicon APD (Si-APD) [10] has a high detection efficiency in visible range (70% at 650 nm), a low dark count rate (<100 Hz) and can be operated at room temperature in free-running mode. However, its detection efficiency drops greatly at wavelengths longer than 1000 nm and does not work at the telecom wavelength of 1310 and 1550 nm. Recently, the nonlinear process of sum frequency generation (SFG) has been applied to solve the issue of spectral discrepancy. Using a nonlinear optical 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 or 1550 nm can be converted to a wavelength shorter

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

Detection range	Single photon detectors	Temperature, K	Maximum count rate, MHz	Detection efficiency, %	DCR, kHz	Timing jitter, ns
Photocathode detector	InGaAs PMT (Hamamatsu)	193	10	1	160	1.5
	InGaAs MCP (Burle)	210	1	1	100	1
APD-based detector	InGaAs APD (id Quantique)	220	4 (gated)	10	10	0.06
	InGaAs APD (Toshiba, UK)	243	100	10	10	0.06
Superconducting detector	SSPD (NIST)	<0.1	1000	3	0.01	0.06
	TES (NIST)	<3	0.1	95	0.4	100
Up-conversion detector	Up-conversion detector (NIST)	Room (heated)*	5	31	2.5	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.

than 1000 nm, where they can then be detected by a Si-APD with high detection efficiency. The performance and characteristics of the main single photon detectors for communication bands are summarized in table.

Spectrum analysis at single photon levels is important in quantum information research, especially for spectral characterization of entangled photons. For light at wavelengths in UV, visible and shorter than 1 μm NIR wavelengths, 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 conventional communication bands. Currently, spectrometers for this wavelength range either have 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).

An up-conversion detector can be integrated into a spectrometer. In an up-conversion detector, only those very specific photons whose momentum and energy are satisfy the quasi-phase-matching condition in the waveguide can be converted and then detected. Based on this principle, an up-conversion spectrometer can be constructed when a tunable pump source is used [17–20]. 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 [20].

We have developed a low noise up-conversion detector for 1310 nm using a periodically-poled $LiNbO_3$ (PPLN) waveguide. In our setup, a signal photon at 1310 nm is up-converted to 710 nm in the PPLN waveguide by using a pump laser at 1550 nm and then detected by a Si-APD. The 1550 nm CW pump laser is modulated into a pulse train with a trigger synchronized to the 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 have integrated this up-conversion detector into a spectrometer with very high sensitivity. In this paper, we introduce the single photon up-conversion detector and the spectrometer we developed and present some experimental results.

2. DETECTOR WITH UP-CONVERSION TECHNOLOGY

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 1550 nm light is then amplified by an erbium-doped fiber amplifier (EDFA) (IPG: EAR-0.5K-C) but it also produces noise at 1310 nm. To suppress noise around 1310 nm at the output of the EDFA, we used two 1310/1550 wavelength division multiplexer (WDM) couplers, which have a 50 dB extinction ratio in total. The input polarization states of both the weak signal around 1310 nm and the amplified pump light around 1550 nm are adjusted by the polarization controllers (PCs), before they are combined in another WDM coupler and inserted into a PPLN waveguide. In the waveguide, the weak signal is then converted to 710 nm by using the strong pump light. The longer the waveguide length, the lower the pump power needed to reach the maximum conversion efficiency. The PPLN waveguide for our up-conversion detector is 5-cm long, which is the longest length possible with current manufacturing capabilities. 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-con-

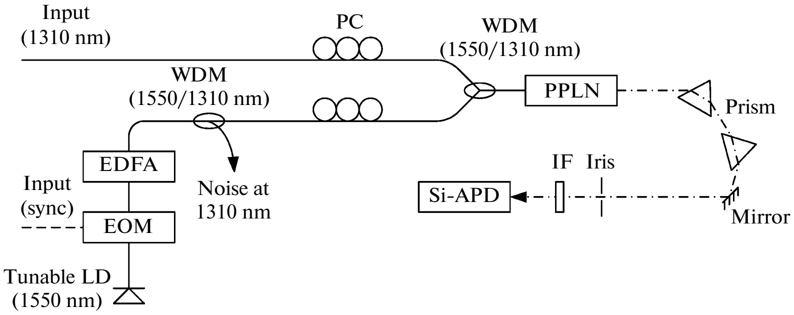

Fig. 1. Schematic diagram of the up-conversion detector. EOM, electric-optic Modulator; EDFA, erbium-doped fiber amplifier; WDM, wavelength-division multiplexing coupler; PC, polarization controller; PPLN, periodically-poled $LiNbO_3$ waveguides; IF, interference filter. Solid line: optical fiber, dash line, free space optical transmission.

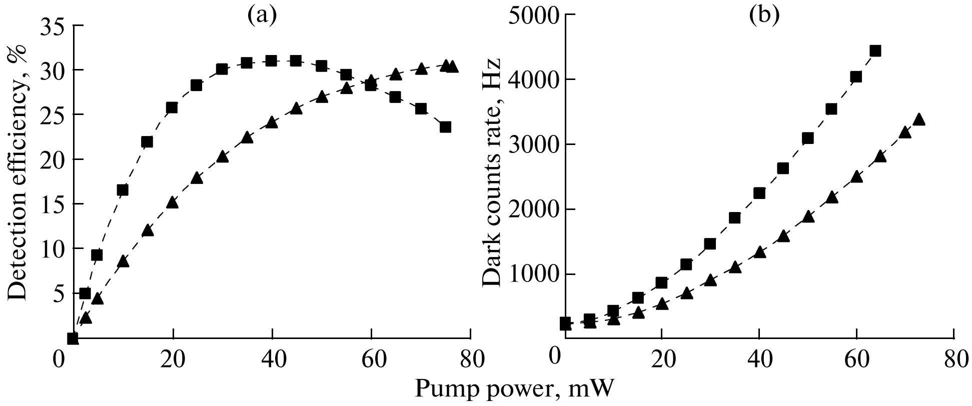

Fig. 2. Performance of up-conversion detector. (a) The detection efficiency as a function of pump power. (b) The dark count rate as a function of pump power at the PPLN input. Two cases are studied: CW pump (triangle) and pulsed pump (square).

verted 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.

Detection efficiency is an important performance metric 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 [21]:

$$\eta_o = \eta_{loss}\eta_{det}\eta_{con} \approx \eta_{loss}\eta_{det}\sin^2(\alpha\sqrt{P_{pump}}L), \qquad (1)$$

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; η_{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 our Si-APD, η_{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 in the form of $\sin^2(\sqrt{\ })$ as shown in Eq. (1). The measured conversion efficiencies as a function of pump power for continuous wave (CW) mode and pulse pump mode is shown in Fig. 2a. 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 if we take the insertion loss and the detection efficiency of Si-APD (η_{loss} and η_{det}) in account.

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 this synchronized signal. The detection efficiency measured here is from a 625 MHz 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 pulsed pump mode can reach the maximum conversion efficiency with a lower average pump power, which helps to reduce the noise. In cases where there is not a synchronized signal, a CW pump is needed. For pulsed and CW pump modes, the optimal pump power (average) is about 38 and 78 mW, respectively.

For a single photon detector, the noise level, or dark count rate, is another 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 single-photon frequency up-conversion technology [11–16]. The dark counts are caused mainly by three sources: the intrinsic dark counts of the Si-APD, dark counts caused by the noise in the pump tail at the signal wavelength, and dark counts caused by the Raman scattering. The intrinsic dark count rate is constant, about 100 counts per second in our case [10]. The dark counts caused by the noise in the pump tail occur as this pump noise at 1310 nm is up-converted to 710 nm and detected by a Si-APD. At the maximum conversion efficiency in CW pump mode, this type of dark count rate was observed to be about 20 kHz in our experiment. We use two WDM couplers (a 50 dB extinction ratio in total) to greatly suppress this noise. Some other dark counts are generated by Raman scattering due to the strong pump light in the transmission fiber and waveguide, and then up-converted to 710 nm and detected by a Si-APD. In this up-conversion detector, we use a 1550 nm laser as a pump, whose wavelength is longer than that of the signal being measured. Because the anti-Stokes component of the Raman process is much weaker than the Stokes component, the dark counts caused by the Raman scattering are reduced greatly. The high conversion efficiency of the PPLN waveguide reduces the required pump power, and therefore reduces the dark counts caused by the noise in the pump tail and from the Raman scattering.

As shown in the Fig. 2b, the pulsed 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. 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 2500 counts/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 counts/s. Consequently, a pulse pump can use lower power and effectively reduce the dark count rate compared to a CW pump.

In comparison with other direct single photon detectors, the up-conversion detector has two unique characteristics: narrow acceptance spectral bandwidth and polarization sensitivity. 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 noise at wavelengths other than the signal wavelength. However, this may be a drawback when the detector is used to measure signals with a 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 sinc^2( ) as follows [21, 22]:

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

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

$$\Delta k_Q = 2\pi\left(\frac{n_o}{\lambda_o} - \frac{n_p}{\lambda_p} - \frac{n_s}{\lambda_s} - \frac{m}{\Lambda}\right), \tag{3}$$

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 indices for the three wavelength. Λ is the poling period for the mth, order quasi phase matched condition of the PPLN waveguide. According to Eqs. (2), (3), the acceptance spectral width is dependent on the length of the waveguide. The longer the waveguide is, the narrower the acceptance spectral width will be. Figure 3a shows the measured detection efficiency as a function of signal wavelength at a certain fixed pump wavelength and temperature. From the figure, we can see that the spectrum is similar to the 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.

Another characteristic of the up-conversion detector is polarization sensitivity. Because the PPLN waveguide used in the detector is based on proton-exchange, it is effective only for guiding the e-wave, and the o-polarized light is not transmitted. In addition, the QPM condition of the PPLN waveguide is also polarization sensitive. In effect, the device is

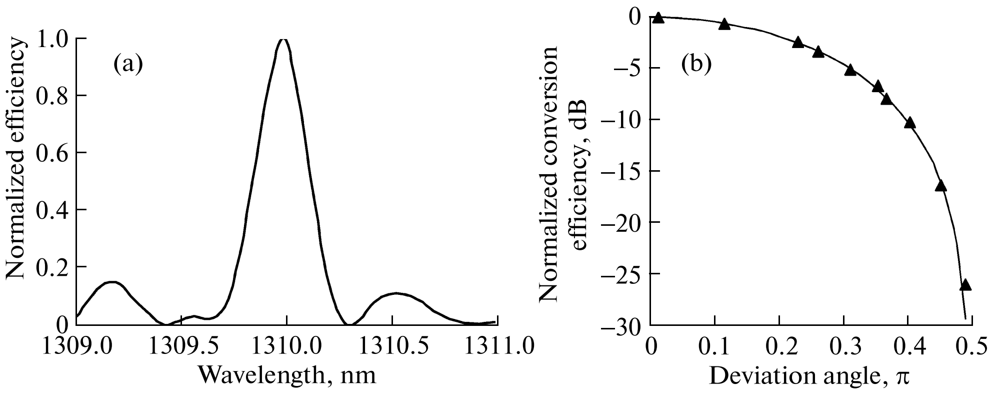

Fig. 3. (a) The normalized detection efficiency as a function of signal wavelength, when the pump wavelength and temperature of the waveguide are fixed. (b) The normalized conversion efficiency of the PPLN waveguide as a function of deviation angle of the input signal at 1310 nm. The deviation angle is the angle between the given polarization stale and the state al which the conversion efficiency is maximized. Triangle, measurement results; solid line, $\cos^2(\ )$ curve.

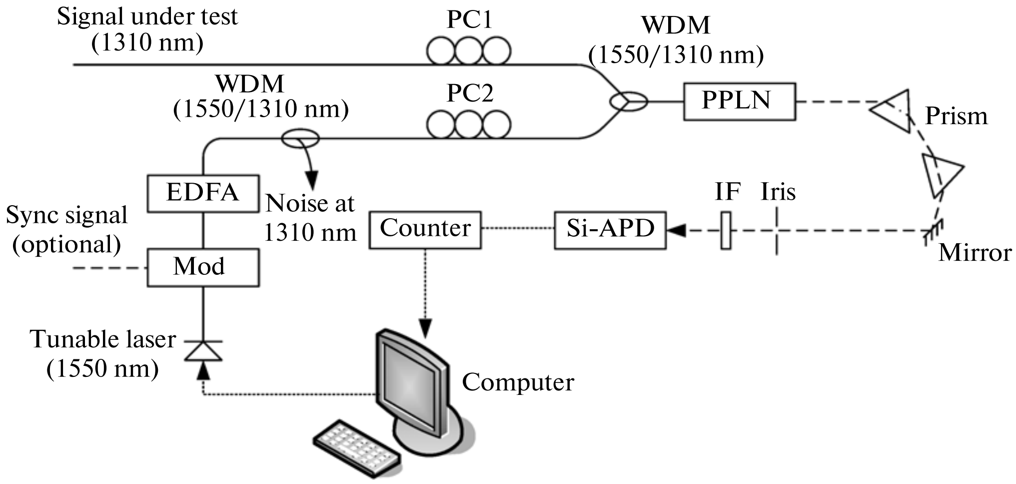

Fig. 4. Schematic diagram of the up-conversion spectrometer. Mod: wavelength insensitive modulator; EDFA: erbium-doped fiber amplifier; WDM: wavelength-division multiplexing coupler; PC: polarization controller; PPLN: periodically-poled $LiNbO_3$ waveguides; IF: interference filter. Solid line: optical fiber; dash line: free space optical transmission; dot line: electrical line.

therefore sensitive to polarization. If its polarization extinction ratio is sufficiently high, the device can be used as a polarizer in addition to its frequency conversion. This feature is very useful in polarization-encoding quantum communications systems. Figure 3b shows the dependence of the 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. 3b, 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. In this case we can avoid the additional insertion loss that an otherwise required polarizer would add.

3. SPECTROMETER WITH UP-CONVERSION TECHNOLOGY

Based on the up-conversion detector described above, we have also implemented an up-conversion spectrometer [17], as shown in Fig. 4. The seed light is provided by a tunable CW laser near 1550 nm (New focus: TLB 6321), which is controlled by a computer

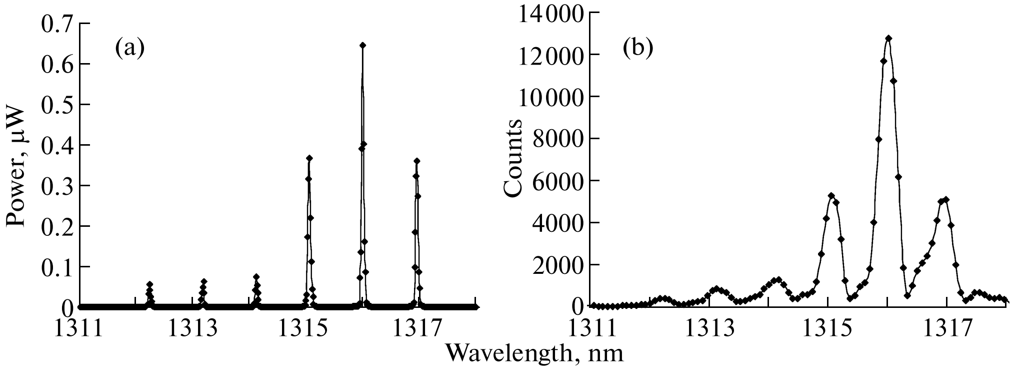

Fig. 5. (a) The spectrum of strong light measured by a commercial OSA. (b) The spectrum of greatly attenuated light measured by the up-conversion spectrometer.

via a GPIB port. The computer tunes the 1550 nm tunable laser and synchronously collects the signal counts from the Si-APD. In the frequency conversion process the energy conservation condition must be satisfied, i.e., $E_p + E_s = E_c$, where E_p, E_s and E_c denote photon energies for the pump, signal and converted photons. The converted photon energy is fixed. When E_p is tuned, only those $E_s = E_c - E_p$ are converted and counted correspondently, which forms a spectrum of the signal. Thus, this setup becomes a spectrometer. In comparison with other types of spectrometer, it does not need any dispersive elements or tunable narrowband filters.

The spectral resolution of the up-conversion spectrometer is jointly determined by the acceptance bandwidth of the PPLN waveguide and the linewidth of the tunable laser. According to Eqs. (2), (3), 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 0.25 nm and the line-width of our 1550 nm tunable laser is only 150 kHz. Therefore, in our case, the resolution of the up-conversion spectrometer is determined only by the QPM acceptance bandwidth of the waveguide.

The spectrometer sensitivity is limited by both the detection efficiency and the variation of the dark counts. Our measured maximum overall detection efficiency is 32%. The dark count spectrum can be measured and subtracted from signal spectrum measurement results, and therefore, the variation of the dark counts limits the sensitivity of the spectrometer. The dark counts have a shot noise behavior, whose deviation is equal to the square root of the average number of counts. The maximum dark count rate in the measurement range is about 2500 counts per second, and the maximum dark count deviation is about 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. When taking the detection efficiency of 32% into account, the signal count rate corresponds to 1563 photons/s or –126 dBm of signal power, which is at least three orders of magnitude better than any commercial optical spectrum analyzers in the near infrared (NIR) range.

A major limitation to the maximum measurement power is imposed by the "dead-time" of a 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 operational state before detection of the next photon can occur. This is especially significant when the intensity of the signal under test becomes strong. In this case, some photons that come to the detector during its dead time will not be counted. So the detector will be saturated when the signal power exceeds a certain level. According to theoretical calculations and experimental data, when the signal power is lower than –95 dBm, the influence of the dead-time is negligible. If the signal power is between –95 to –80 dBm, the influence of the dead time is significant. The measured data should be calibrated to recover the actual spectrum. When the signal power is higher 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 this up-conversion spectrometer for measuring signals above –80 dBm without attenuation of the signal.

To demonstrate and verify the functionality of the spectrometer, we measured the spectrum of a multimode diode laser to observe its longitudinal mode structure. For comparison, an optical spectrum analyzer (OSA, Ando AQ-6315A) was used first to record the strong light spectrum, as shown in Fig. 5a. The spectrum shows one main peak with an amplitude of –33 dBm at 1316 nm, two side peaks (–35 dBm) at 1315 and 1317 nm, and some smaller peaks (less than –40 dBm) at the 1312–1314 nm range. Then we used the up-conversion spectrometer to measure the same spectrum after we attenuated it by 75 dB. The tuning range of the pump laser is set from 1540 to 1550 nm with a scanning step of 0.1 nm. The integration time for each step is 500 ms. The measured six peaks are clearly shown in Fig. 5b. The intensity of all six peaks is less than −110 dBm and the intensity of the smallest peak is as weak as about −120 dBm. The total time used to record this spectrum is about 1 min. This experiment demonstrates the ultra high sensitivity of our up-conversion spectrometer. The resolution of our up-conversion spectrometer is limited by the QPM condition, which can be improved by increasing the length of the waveguide.

4. CONCLUSIONS

We developed a low-noise up-conversion single photon detector 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 about 2500 Hz. The detector has a narrow acceptance bandwidth that functions as a bandpass filter. The detector is sensitive to polarization of input signals with a high polarization extinction ratio that functions similar to a polarizer. We further integrated it into an up-conversion spectrometer. The up-conversion spectrometer has a −126 dBm sensitivity and a 0.25 nm resolution. The up-conversion detector and spectrometer are very useful tools for quantum information research in the optical fiber telecommunication bands.

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