Tunable up-conversion detector for single photon and bi-photon infrared spectroscopic applications

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ABSTRACT

A tunable waveguide-based frequency up-conversion detector is used for single photon level near infrared (IR) spectroscopic measurements. Applications include direct spectroscopic measurement of week near IR signals and remote bi-photon spectroscopy. We have demonstrated direct spectroscopy of single photon near IR signals from a greatly attenuated laser and a single photon source. We further applied the up-conversion spectrometer for frequency correlated bi-photon spectroscopy using a single photon source of non-degenerate photon pairs at 1310 nm (near IR) and 895 nm. In correlated bi-photon spectroscopy, the spectral function at one wavelength range of a remote object can be reproduced by locally measuring another (near IR) wavelength range using the up-conversion spectrometer and monitoring the coincidence counts. A near IR single photon detection efficiency of 32 % has been achieved with the up-conversion spectrometer. The spectral resolution of the system is approximately 0.2 nm at 1310 nm based on the acceptance width of the up-conversion chip used. In bi-photon spectroscopy, the spectral resolution for the correlated photons at 895 nm is approximately 0.1 nm. The sensitivity achieved using the up-conversion detector is -126 dBm at 1310 nm.

Keywords: Correlated bi-photon spectroscopy, up-conversion detector, up-conversion spectrometer.

1. Introduction

Silicon based avalanche photodiodes (Si-APDs) are the most efficient and low cost photon detectors for visible light – achieving very high detection efficiency (65 %) and low dark noise counts (25 /s) [1]. However, these detectors cannot be used above approximately 1 µm. In order to use Si-APDs for the detection of single photons in the near IR telecommunications wavelengths, a non-linear optical medium is used to convert the wavelength of photons in the near IR range to a shorter wavelength in the visible or near visible range. This is a frequency up-conversion process [2, 3], typically referred to as sum frequency generation (SFG). In this process, the incoming signal photons are mixed with a strong pump and the SFG process produces photons at a higher frequency, or equivalently, a shorter wavelength. The emerging photons at the visible wavelengths are then suitable for efficient detection using a Si-APD. This type of system is called an up-conversion detector.

We have previously adapted this technology and developed high efficiency and low noise up-conversion detectors for single photon detection near 1310 nm [4, 5, 6]. The total detection efficiency achieved in the up-conversion detector is 32 % with a dark-count rate of approximately 2500 /s at the peak detection efficiency. A recent experiment shows that the dark-count rate can be further reduced to 650 /s when a strict filtration scheme is used [7]. The timing jitter in the up-conversion detectors is determined by the Si-APD used, which is approximately 400 ps. The maximum count rate of 10 MHz is also limited by the Si-APD. Up-conversion detectors can be operated in a free-running continuous wave mode as well as a pulsed (optically gated) mode. The up-conversion detector demonstrated can be built entirely using commercially available components and routinely operated at a moderately elevated localized (enclosed oven) temperature.

Based on the up-conversion detector, we have implemented a highly sensitive single photon up-conversion spectrometer [8, 9, 10] by using a tunable laser as the pump in the SFG process. The up-conversion detector is wavelength sensitive and only the wavelengths satisfying the narrow acceptance width of the detector is converted. The particular wavelength converted is determined by the waveguide characteristics (which are fixed during a measurement) and the wavelength of the pump used. By using a tunable pump in the SFG process, the spectral characteristics of the incoming beam can be determined by monitoring the count rate of the emerging visible photons for different pump wavelengths.

[1] The identification of any commercial product or trade name does not imply endorsement or recommendation by the National Institute of Standards and Technology.

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Applications are wide ranging for such a sensitive near IR spectrometer. In this paper, we describe direct up-conversion spectroscopy of a greatly attenuated laser and the near IR idler beam generated in a spontaneous parametric down-conversion (SPDC) single photon source. In addition, we apply the up-conversion spectrometer for indirect or 'remote' spectroscopy in which the spectral properties of an object, such as a filter or an absorber, are measured by monitoring the coincidence counts from correlated signal and idler photon pairs generated by SPDC [11]. The signal photons at one wavelength range interact with an object at a remote or inconvenient location which is accessible only for spectrally non-resolving single photon detection. The correlated idler photons at another near IR wavelength range, which had no interaction with the object, are then available for local spectral analysis by the up-conversion spectrometer. The coincidence count rate from the two detectors is used to reproduce the spectral transmission or reflection function of the remote object.

2. Frequency Up-Conversion Detector

Frequency up-conversion is a non-linear optical phenomenon, in which two input photons (a single input photon to be measured and a single pump photon from a strong beam) at different frequencies annihilate and another photon at their sum frequency is simultaneously generated in the non-linear optical medium, according to equation 1, in terms of angular frequency, and 2, in terms of wavelength, below.

$$\omega_{input} + \omega_{up-pump} = \omega_{SFG} \quad (1)$$

$$\frac{1}{\lambda_{input}} + \frac{1}{\lambda_{up-pump}} = \frac{1}{\lambda_{SFG}} \quad (2)$$

where ω_{input}, $\omega_{up\text{-}pump}$ and ω_{SFG} are the angular frequencies of the input signal to be detected, the up-conversion pump and the SFG output light, respectively; and where λ_{input}, $\lambda_{up-pump}$ and λ_{SFG} are the wavelengths of the input, pump and the output SFG light.

The most commonly used optical medium for frequency conversion are non-linear crystals, which are dispersive materials, (i.e. the refractive index is wavelength dependent). In order for this process to occur efficiently inside the non-linear optical medium, the phase of both the input and the pump beams must be matched and they must be collinear. A technique known as quasi-phase matching was developed to allow different frequencies transverse the non-linear crystal and yet remain sufficiently in phase.

In quasi-phase matching, the crystal axis is periodically flipped. In each poling period, there is a small amount of phase mismatch which is reversed, or canceled, during the next oppositely flipped poling period, thereby ensuring that there is a continuous positive energy conversion from the input and pump beam to the SFG output beam despite all three beams being collinear and having the same polarization.

Currently, PPLN waveguides are the most suitable devices to implement single photon frequency up-conversion with almost 100 % internal conversion efficiency achievable with relatively low noise.

Based on this frequency conversion technology, we implemented an up-conversion single photon detector for near IR photons. The configuration of this detector is shown in figure 1. A 1550 nm continuous wave laser provides a pump seed which is amplified by an erbium-doped fiber amplifier (EDFA) and, following noise suppression, is combined with a weak 1310 nm beam being measured. The combined pump and input beam are then coupled into the PPLN waveguides. The longer the waveguide, the more interaction length is provided and a lower pump power will be needed to reach the maximum conversion efficiency. These output beams, consisting of the up-converted SFG output at 710 nm and unwanted excess pump and its harmonics, are separated by prisms and the 710 nm photons are suitably detected by a Si-APD.

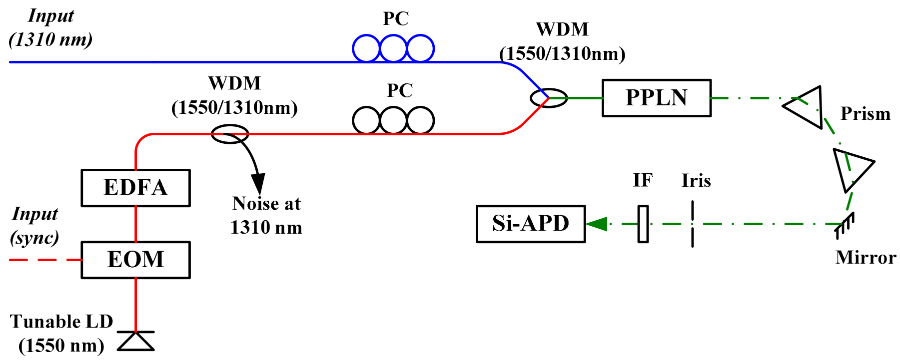


Figure 1. Schematic of the up-conversion detector. LD: Laser Diode; EOM: Electric-optic modulator; EDFA: Erbium-doped fiber amplifier; WDM: Wavelength-division multiplexer; PC: Polarization controller; PPLN: Periodically-poled $LiNbO_3$ waveguides; IF: Interference filter. Solid line: Optical fiber; Dash line: Free space transmission.

For a single photon detector, its detection efficiency is one of the most important performance metrics. 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 to the waveguide and at the various components in the system, and the detection efficiency of Si-APD (about 65 %) at the converted wavelength.

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, which is dependent on the pump intensity. A maximum overall detection efficiency 32 % is achieved in this up-conversion detector.

For a single photon detector, the dark count rate, or noise level, is one of the most important performance parameters: a higher dark count rate can cause more errors and degrade the system's fidelity. Dark counts come from two origins: the intrinsic dark counts of the Si-APD and the noise from the frequency conversion process. The intrinsic dark count rate is dependent on the Si-APD used, which is approximately 100 c/s in the Si-APDs used here. The noise generated in the up-conversion process has been extensively studied, and the main source of the noise is widely believed to be the spontaneous Raman scattering (SRS) and 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 dark counts not associated with the actual beam being measured. The noise of an up-conversion detector can be reduced by using a pump wavelength that is longer than the wavelength of the measurement beam, 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 generated at the measurement wavelength range. A dark count rate of less than 2500 c/s with a deviation of approximately 50 c/s was achieved in our experiment when the conversion efficiency was maximized at 32 %.

3. Up-Conversion Spectrometer:

When the quasi-phase matching condition in a PPLN waveguide is satisfied at a particular input wavelength, the maximum up-conversion efficiency is achieved. When the input is shifted away from that peak wavelength the up-conversion efficiency is reduced, implying that the up-conversion process is wavelength sensitive. In other words, only the input photons within the narrow wavelength range, known as the acceptance spectral linewidth, that satisfies the phase matching conditions will experience conversion to visible wavelengths and be detected. This is similar to a narrow band pass filter, which helps to filter out noise at wavelengths other than the phase matched signal wavelength. The acceptance spectral linewidth 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 $sinc^2()$ function according to the equation [12]:

$$I_{SFG}(\Delta k) \propto I_{up-pump} \cdot I_{input} \cdot sinc^2(\, A \cdot \Delta k \cdot L) \quad (3)$$

where I_{SFG}, $I_{up-pump}$, I_{input} are the intensities of the SFG output, up-conversion pump, and input beams respectively; A is a constant; L is the waveguide length; and Δk is the phase-mismatch [8, 12]. According to equation (3), the acceptance spectral width is dependent on the length of the waveguide. A longer waveguide will result in a narrower acceptance spectral width. In our system, at a fixed pump wavelength and temperature for a 5 cm long PPLN waveguide, the acceptance spectral width of the main peak is about 0.2 nm (FWHM).

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. In this case, we can measure spectra of weak input beams at single photon power level without using dispersive elements or lossy tunable narrow-band filters. We implemented such an up-conversion spectrometer [8, 9, 10], as shown in figure 2. The pump light is provided by a tunable CW laser near 1550 nm. As the 1550 nm pump laser is tuned, the phase-matched input photons are converted and detected by the Si-APD, and the subsequent counts are processed. The result is a spectrum of input light at a single photon power level.

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. As described earlier, the longer the QPM structure (waveguide), the narrower the acceptance bandwidth. In our case, using a 5 cm PPLN waveguide, the measured acceptance bandwidth is 0.2 nm. Because the linewidth of the 1550 nm tunable laser is as narrow as just 150 kHz, the up-conversion spectrometer resolution is determined by the QPM acceptance bandwidth of the waveguide. A longer waveguide will narrow the acceptance bandwidth and increase the resolution of the up-conversion spectrometer.

For an up-conversion spectrometer, the sensitivity is jointly limited by the detection efficiency and the deviation of the dark counts in the detector. To get a reliable spectrum, the detection count rate should be one order of magnitude greater than the dark count deviation. At the maximum detection efficiency of 32 %, a count rate of 500 c/s is therefore required for a reliable spectrum, which corresponds to 1563 input photons per second (at 32 % detection efficiency), or equivalently -126 dBm. Due to the influence of the so called 'dead time', a recovery period following a detection event, of the Si-APD detectors, the detection efficiency is no longer linear for intensities above approximately -95 dBm. Signals with an intensity above -95 dBm should be attenuated.

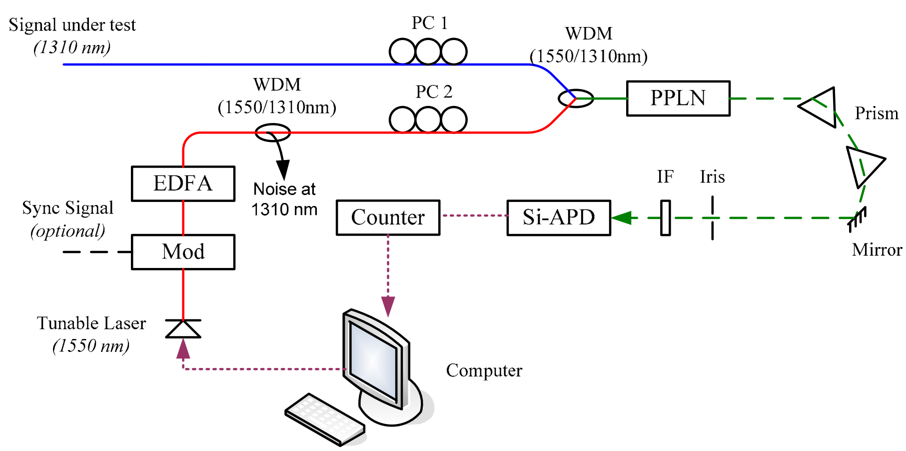


Figure 2. Schematic diagram of the waveguide-based spectrometer. Mod: Wavelength insensitive modulator; EDFA: Erbium-doped fiber amplifier; WDM: Wavelength-division multiplexing coupler; PC: Polarization controller; PPLN: periodically-poled $LiNbO_3$ waveguides; IF: Interference filter. Solid line: optical fiber; dash line: free space optical transmission; dot line: electrical line.

3.1 Up-conversion Spectrometer Results:

To demonstrate and verify the functionality of the spectrometer, we used it to measure the longitudinal-mode spectrum of a laser diode. For comparison, an optical spectrum analyzer (OSA, Ando AQ-6315A) was used first to record the strong light spectrum, as shown in figure 3 (a). The spectrum shows one main peak with an amplitude of -33 dBm at 1316 nm, two side peaks (-35 dBm) at 1315 nm and 1317 nm, and some smaller peaks (less than -40 dBm) between about 1312 nm and 1314 nm. We then used the up-conversion spectrometer to measure the spectrum of the light after it was greatly attenuated by 75 dB. The measured six peaks are clearly shown in figure 3 (b), although they appear broader than the OSA spectrum due to the resolution of the up-conversion spectrometer. The power of all six peaks is less than -110 dBm and the power of the smallest peak is as weak as about -120 dBm. The total time used to record this spectrum was about 1 minute. This experiment demonstrates the ultra high sensitivity of the up-conversion spectrometer.

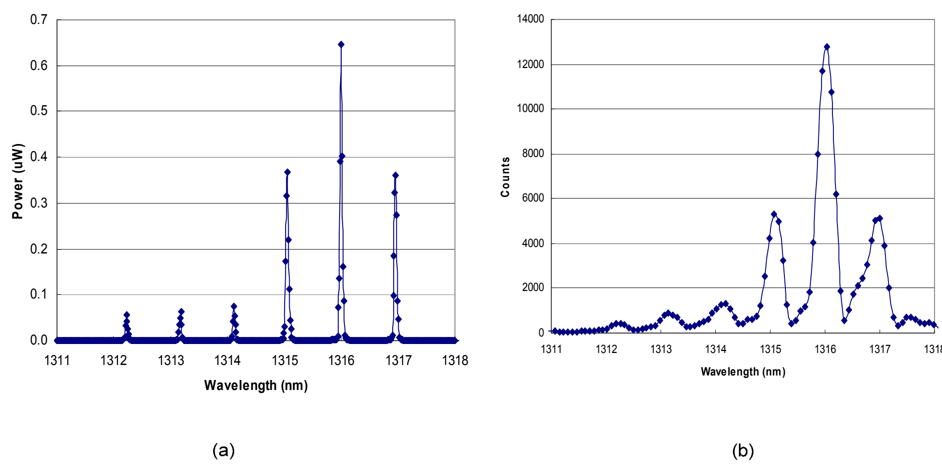


Figure 3. (a) The spectrum of strong light measured by a commercial OSA. (b) The spectrum of greatly attenuated light measured by the up-conversion spectrometer.

4. Correlated bi-photon Spectrometer:

Correlated single photon pairs may be generated in a non-linear process called Spontaneous Parametric Down-Conversion (SPDC). We have used the up-conversion spectrometer to characterize the spectra of signal and idler photon beams from a greatly non-degenerate SPDC source. The SPDC source consists of a 20 mm bulk type periodically polled lithium niobate (PPLN) crystal, pumped at 532 nm generating down-converted photon pairs at 895 nm (signal) and 1310 nm (idler). The SPDC source is designed to produce spectra of approximately 1.15 nm (at the 895 nm signal wavelength) and 2.5 nm (at the 1310 nm idler wavelength). We use direct up-conversion spectrum measurement to characterize the 1310 nm idler beam as described earlier. By adding a time correlated single photon counter (TCSPC), we further adapt our system for bi-photon spectral measurement of the 895 nm signal [11]. In addition, the correlated bi-photon spectrometer can be used to characterize an object, such as a filter, in the path of the 895 nm signal beam. We characterize a narrow band volume Bragg grating (VBG) to demonstrate the process [11].

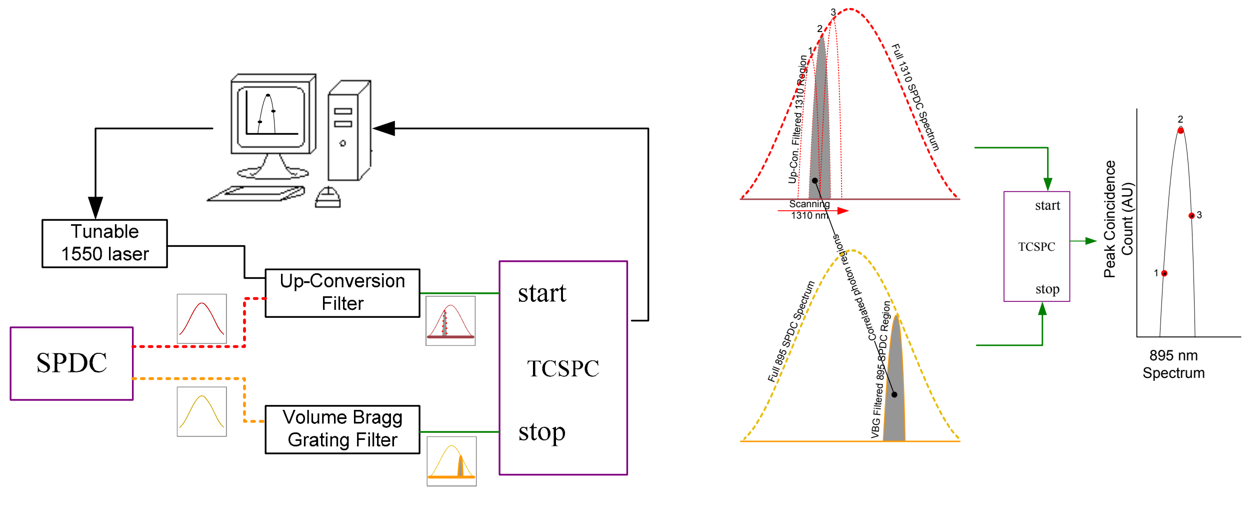


Figure 4: (a) Schematic of the up-conversion spectrometer adapted to indirectly measure the spectrum of the correlated 895 nm spectrum. (b) As the 1310 nm window is scanned across the region of its spectrum where there are photons which are correlated with the narrowband 895 nm signal, the coincidence count profile will show the 895 nm spectrum.

Figure 4 (a) show a schematic diagram of the setup for correlated bi-photon spectral measurements and figure 4 (b) illustrates the concept. As the up-conversion acceptance window is scanned across the 1310 nm spectrum, coincidence counts will begin to appear as that window begins to cross the part of its spectrum that is correlated with the 895 nm spectrum (scanning point 1 in figure 4 (b)). As the 1310 nm window is further scanned, coincidence counts will reach a peak as the correlated regions fully overlap (scanning point 2 in figure 4 (b)) and eventually, as the 1310 nm window moves beyond the part of its spectrum that is correlated with the 895 nm spectrum, the coincidence counts drop off (scanning point 3 in figure 4 (b)). The result is an indirect correlated bi-photon spectrum of 895 nm signal light at a single photon power level.

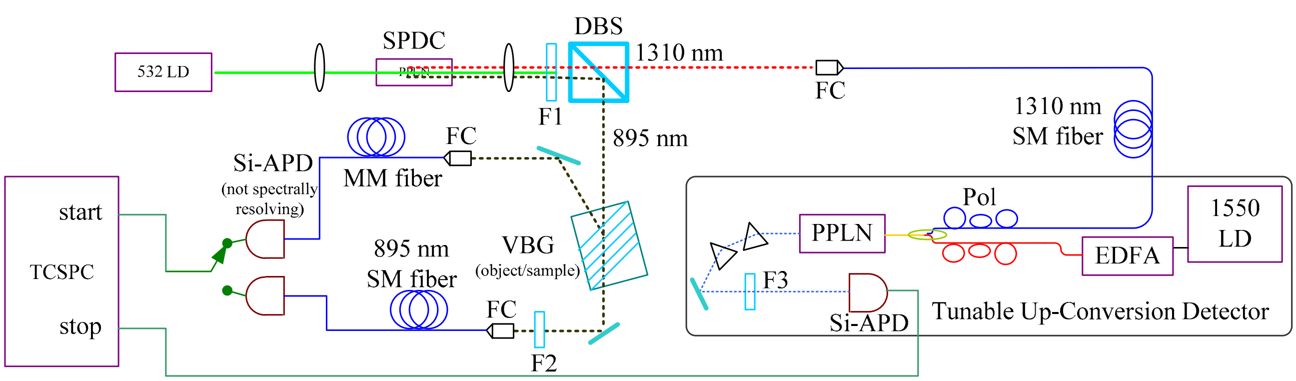


Figure 5: 532 LD: 532 nm laser diode pump; SPDC: Spontaneous parametric down-conversion periodically-poled $LiNbO_3$ bulk crystal; VBG: Volume Bragg grating; DBS: Dichroic 1310 nm/895 nm beam splitter; F1: Blocking filter at 532 nm; FC: Fiber collimator; F2: 1 nm filter at 895 nm; Si-APD: Silicon avalanche photo diode; TCSPC: Time correlated single photon counting module. Up-conversion Detector box: 1550 LD 1550 nm laser diode pump; EDFA: Erbium-doped fiber amplifier; Pol: Polarization controller; PPLN: Periodically-poled $LiNbO_3$ waveguide for up-conversion; F3: 20 nm filter at 710 nm. For characterization of the entire SPDC source, the output signal from the dichroic splitter goes directly to the fiber.

Figure 5 outlines the setup for the characterization an optical element and includes a greatly non-degenerate SPDC source of single photon pairs, an optical element (VBG) to be characterized, spectrally non-resolving single photon detectors for the signal photons (one each for the reflected and transmitted signal), a spectrally resolving up-conversion detector for the idler photons and a time-resolved coincidence counter. Following SPDC and separation from the excess pump and the idler beam, the signal beam at 895 nm interacts with the object, in this case a VBG. The VBG can achieve as much as 95 % reflection at an angularly selected wavelength around 895 nm with approximately 0.1 nm linewidth, with a corresponding notched spectrum transmitting through the VBG [13]. A 1 nm filter was used in the transmitted path for noise reduction. Both the reflected and transmitted signal beams are sent to a Si-APD (PerkinElmer: SPCM-AQR-14) for single photon detection. The signal Si-APD (maximum detection efficiency of about 65 %) detector is broadband and cannot resolve the 895 nm signal spectrum – the count rate from the signal detector is constant. The 1310 nm idler beam is sent to the up-conversion spectrometer and does not interact with the object.

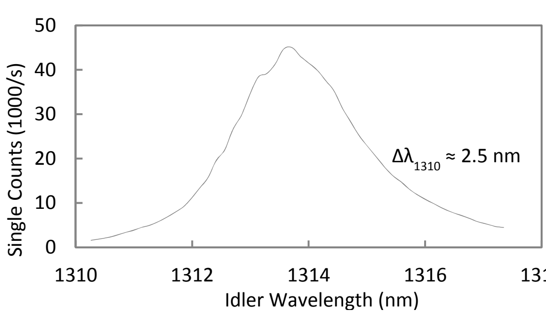
Finally, the coincidence is measured when the detectors' electrical output is fed into a time correlated single photon counter (PicoQuant: PicoHarp 300). By considering the spectral function of the up-conversion detector to be a δ-function compared to the sample and source, and by considering the spectral function of the source to be relatively flat compared to the sample, the coincidence count rate reproduces the spectral function of the object according to the equation [14]:

$$R_{coincidence} \sim |H_{object}(\omega_{SPDCpump} - \omega_{upconversion})|^2 \quad (4)$$

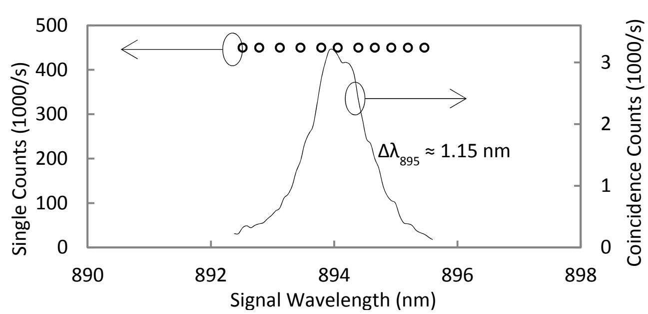
where $H_{object}(\omega)$ is the spectral function of the object; $\omega_{SPDCpump}$ is the SPDC pump wavelength satisfying the phase matching condition $\omega_{SPDCpump} = \omega_{signal} + \omega_{idler}$; and $\omega_{upconverion}$ is the central operating idler wavelength of the up-conversion detector.

4.1 Correlated Bi-photon Spectrometer Results:

To demonstrate bi-photon spectroscopy, we measured the spectral linewidth of, firstly, the entire 895 nm spectrum (no object filters) as it emerged from the SPDC source and, secondly, the reflected and transmitted 895 nm spectra following a narrowband VBG object filter. The 20 mm SPDC chip is designed for approximately a 2.5 nm total spectrum at 1310 nm, which corresponds to a total spectrum of approximately 1.15 nm at 895 nm, verified by the measurement result shown in figure 6. The 1310 nm idler spectrum (figure 6 (a), grey line) is measured using the up-conversion spectrometer. The single photon count rate from the signal beam (figure 6 (b), black circles) is measured directly by the Si-APD and is constant indicating no spectral resolution while the coincidence count rate (figure 6 (b), black line) reproduces the 895 nm signal spectrum by correlated bi-photon spectroscopy.



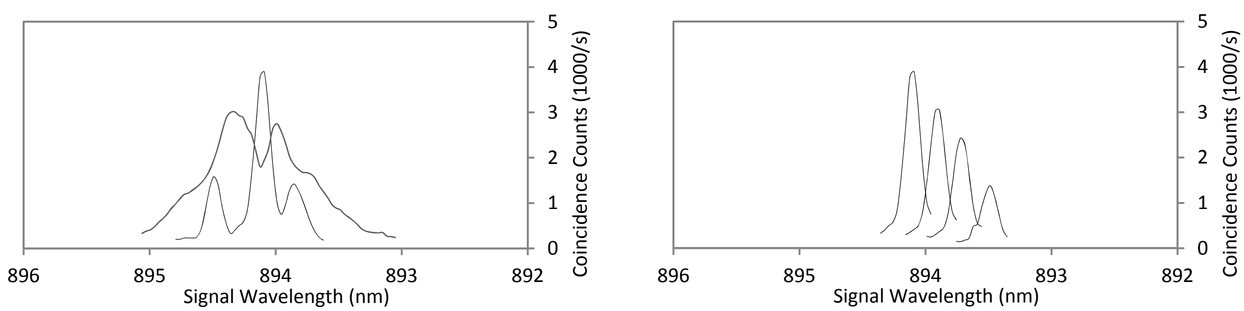
(a)



(b)

Figure 6: Measurement of the full SPDC down converted spectra. (a) The 1310 nm single photon count spectrum (grey line) was measured directly using the tunable up-conversion detector. (b) The 895 nm single photon count rate (empty black circles) was measured directly by the Si-APD. The 895 nm spectrum (black line) was calculated from the coincidence count rate measurements. Both spectra correspond to the SPDC linewidth specified for the PPLN chip.

It should be noted, however, that the measurement of the full signal spectrum cannot satisfy the assumption that the spectral function of the source is relatively flat compared to the signal being measured – they are of course the same width. In order to satisfy that condition, an object filter through which the signal is being measured must be significantly narrower than the source. The angle of incidence of the signal beam to the VBG determines the particular wavelength at which a narrow linewidth reflection occurs. Since a narrow linewidth is reflected from the VBG, the spectrum of the transmitted 895 nm beam will incur a dip at the corresponding wavelength. Figure 7 (a) shows, for particular angle of incidence to the VBG which corresponds to near the peak of the 895 nm SPDC spectrum, the correlated bi-photon spectral image of both the narrow linewidth reflection (black line, central peak only) from the VBG and the notched transmission (grey line) through the VBG. The single photon count rates from the Si-APDs were constant during these measurements indicating no spectral resolution directly from the single photon count rates. The side peaks in the spectral image of the narrow linewidth reflection are due to the convolution of the QPM transfer function (a $sinc^2(\ )$ function) of the up-conversion detector and the signal spectrum. These 'fake' side peaks can be removed using advanced deconvolution techniques. The dip in the transmitted beam does not go to zero due to the limited resolution of the system. In the example shown, the transmitted beam also passes though the 1 nm filter. As the VBG is rotated (figure 7 (b)), a different narrowband wavelength is reflected. Only the central peaks are shown in figure 7(b). The relative coincidence counts decrease as the VBG is rotated away from the peak of the 895 nm SPDC spectrum.



(a) (b)

Figure 7: (a) The 895 nm single photon count rates (empty squares for reflected beam and empty circles for transmitted beam) were measured by the Si-APD. The 895 nm spectrum for the reflected signal (black line) measuring approximately 0.1 nm (central peak only) with QPM induced fake side peaks and the corresponding transmitted signal (grey line) were reproduced using the coincidence counts. The dip in the transmitted beam does not go to zero due to the limited resolution of the system. In the example shown, the transmitted beam also passes though the 1 nm filter, limiting its linewidth. (b) Measurement of various tuning angles of the VBG reflecting different narrowband 895 nm spectra, each measuring approximately 0.1 nm (only showing the central peak).

The resolution of the up-conversion idler spectrometer, and subsequently the resolution of the bi-photon spectrometer, is limited by the phase matching process in the up-conversion detector.

5. Conclusion

We have demonstrate the use of a tunable up-conversion detector for single photon level near IR spectroscopic applications including direct spectroscopy of single photon near IR signals from single photon sources and frequency correlated bi-photon spectroscopy. In correlated bi-photon spectroscopy, the spectral function at one wavelength range of a remote object can be reproduced by locally measuring another (near IR) wavelength range using the up-conversion detector and monitoring the coincidence counts. A near IR single photon detection efficiency of 32 % has been achieved with the up-conversion spectrometer. The near IR spectral resolution of the system is approximately 0.2 nm at 1310 nm corresponding to the acceptance width of the up-conversion detector. In non-degenerate bi-photon spectroscopy, the spectral resolution at 895 nm is approximately 0.1 nm. The sensitivity achieved using the up-conversion detector is -126 dBm for a 1310 nm idler beam.

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