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LETTER

Frequency correlated biphoton spectroscopy using tunable upconversion detector

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Abstract

We demonstrate a scheme for frequency correlated biphoton spectroscopy using a strongly non-degenerate downconversion source and a tunable upconversion detector. In this scheme, the spectral function at one wavelength range of a remote object can be reproduced by locally measuring another wavelength range using an upconversion detector and monitoring the coincidence counts. The spectral resolution of the system is better than 0.1 nm, corresponding to the acceptance width of the upconversion detector, while the measurement range is determined by the linewidth of the source.

(Some figures may appear in colour only in the online journal)

1. Introduction

Correlated biphoton spectroscopy is a technique used to measure the spectral characteristics of an object, such as an optical filter or an absorber, by monitoring the coincidence counts from correlated signal and idler photon pairs generated by spontaneous parametric downconversion (SPDC). 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 wavelength range, which has no interaction with the object, are then available for local spectral analysis. The coincidence count rate from the two detectors is used to reproduce the spectral function of the remote object. Biphoton spectroscopy was first reported in 2003 [1] followed by similar works with novel implementations in [2–4]. In this letter, we report a novel technique for biphoton spectroscopy using a tunable upconversion detector for local spectral analysis of the idler beam.

A number of interesting applications become possible with this type of spectral measurement technique. In the case of remote spectroscopy [1] of objects that are inconveniently located for direct spectral measurements, only an intensity bucket type detector, rather than a resolving spectrometer, is needed to capture photons interacting with the object, and the spectral measurements can be achieved by spectrally resolving the correlated photon beam located more accessibly. This technique may also provide a solution in a situation where security or privacy is required but difficult to ensure at the object site since neither the counts from the spectrally non-resolved signal, having interacted with the object, nor the spectrally resolved idler, having no interaction with the object, can provide any spectral information about the object being characterized—both are required to complete the spectral profile. Therefore, having openly interacted with the object, the signal counts can be sent over an insecure channel to a locally secure site for spectral analysis.

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

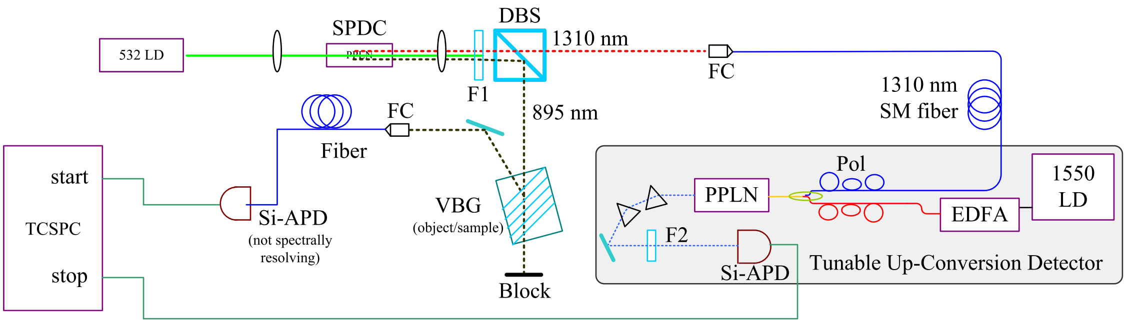

Figure 1. 532 LD: 532 nm laser diode pump; SPDC: spontaneous parametric downconversion periodically poled $LiNbO_3$ bulk crystal; VBG: volume Bragg grating; DBS: dichroic 1310 nm/895 nm beam splitter; F1: blocking filter at 532 nm; FC: fiber collimator; Si-APD: silicon avalanche photodiode; TCSPC: time correlated single photon counting module. Upconversion detector box: 1550 LD 1550 nm laser diode pump; EDFA: erbium-doped fiber amplifier; Pol: polarization controller; PPLN: periodically poled $LiNbO_3$ waveguide for upconversion; F2: 20 nm filter at 710 nm. For just SPDC source characterization, the output signal from the dichroic splitter goes directly to the fiber.

Additionally, in the case of a non-degenerate source as demonstrated in this letter, spectral analysis of an object can be performed at a wavelength that is otherwise difficult to spectrally measure by measuring the correlated photons at a more convenient wavelength. And since the spectrum is generated using coincidence measurements, rather than intensity which cannot be distinguished from noise, a significantly improved signal-to-noise ratio can be achieved in the spectral measurement [2].

Previous implementations of degenerate or non-degenerate correlated biphoton spectroscopy use a monochromator or a rotating grating to provide spectral resolution in one of the paths and achieve various resolutions and measurement ranges [1–4]. Here, we introduce the use of a high performance single photon upconversion detector which is tunable to achieve the spectral resolution [5–9] required for correlated biphoton spectroscopy. In [1, 3], the SPDC chips used were designed for degenerate SPDC with non-degeneracy achieved by rotating the chip off the optical axis of the pump. In these implementations, biphoton pairs (whether degenerate or non-degenerate) remained near or below 1 μm where high performance single photon detection is easily achieved. However, in greatly non-degenerate SPDC, photon wavelengths can reach well into the difficult-to-detect near infrared (NIR) regions. Extending the range of high performance single photon detection into the NIR telecom wavelengths can likewise expand the range and potential for correlated biphoton spectroscopy. In this letter, we use a periodically poled lithium niobate (PPLN) chip specifically designed for greatly non-degenerate SPDC biphoton generation with the signal at 895 nm and the idler at the 1310 nm NIR telecom wavelength. The resolution of our scheme is determined by the resolution of the 1310 nm upconversion detector. However, because of the principle of energy conservation and since our SPDC source is designed for greatly non-degenerate pairs using a delta function pump, the shorter signal wavelength at 895 nm, whose spectrum is being measured, has a better resolution than the longer wavelength idler at 1310 nm. A resolution of better than 0.1 nm is achieved at 895 nm using this scheme following deconvolution of the spectral transfer function of the upconversion detector. The upconversion detector does not use dispersive elements and therefore avoids losses associated with them. This allows the scheme to achieve high sensitivity [6–9]. Additionally, the upconversion detector can be used in time-resolved biphoton spectral measurements by applying a pulsed pump to the upconversion detector. On the other hand, a disadvantage of the scheme is the appearance of false side peaks in the spectral measurements due to the transfer function associated with the upconversion waveguide, although deconvolution of the waveguides' transfer function can greatly reduce or remove these artifacts [7].

For this experiment, we use biphoton spectroscopy to analyze the spectral properties of the SPDC source as well as a smaller than 0.1 nm reflection following a volume Bragg grating (VBG), representing an object filter.

2. Experimental configuration

Figure 1 outlines the setup for the characterization of an optical element and includes a SPDC source specifically designed for greatly non-degenerate single photon pairs, an optical element (VBG) to be characterized, a spectrally non-resolving single photon detector for the signal photons reflected from the VBG, a spectrally resolving upconversion detector for the idler photons and a time-resolved coincidence counter. The SPDC source consists of a 20 mm bulk type periodically polled lithium niobate (PPLN) crystal, pumped at 532 nm (0.2 mW) generating downconverted photon pairs with spectra of approximately 1.15 nm (at the 895 nm signal wavelength) and 2.5 nm (at the 1310 nm idler wavelength). For correlated photon spectroscopy with a broader spectral measurement range, a much shorter non-linear chip should be used. For example, with a 1 mm PPLN chip a spectral measurement range of approximately 50 nm can be achieved. Following separation from the excess pump and the idler beam, the signal beam is sent to the VBG. The VBG can achieve as much as 95% reflection at an angularly selected wavelength around 895 nm with a less than 0.1 nm linewidth. The reflected signal beam is sent to a silicon avalanche photodiode (Si-APD) (PerkinElmer: SPCM-AQR-14) for single photon detection. The signal Si-APD (maximum detection efficiency of about 65%) 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 spectrally resolving tunable upconversion detector system with very low noise, previously developed by this group.

In the upconversion detector, which is pumped by a strong 1550 nm laser, a single 1310 nm photon and one of the 1550 nm photons are converted inside the 50 mm PPLN waveguide via the sum-frequency-generation (SFG) process into a 710 nm photon for suitable detection using a Si-APD. Two prisms separate the SFG photons at 710 nm from the excess pump at 1550 nm and its weak second harmonic generation (SHG) at 775 nm. The maximum total detection efficiency of the upconversion detector for a wavelength near 1310 nm is about 35% [6]. The acceptance bandwidth of the upconversion detector is limited by the quasi-phase-matching (QPM) technique used. The QPM limits the acceptance bandwidth window of the detector to approximately 0.2 nm at 1310 nm. By tuning the upconversion pump, the acceptance bandwidth window moves across the 1310 nm spectrum and by monitoring the output count rate, we can achieve a spectrally resolved measurement of the incoming 1310 nm idler beam. The transfer function response of the QPM chip in the upconversion detector is a sinc^2 function [7] according to:

$$P_{\mathrm{SFG}}(\Delta k) \propto P_{\text{up-pump}} P_{\mathrm{idler}} \mathrm{sin}c^2(\Delta kL/2) \tag{1}$$

where $P_{\mathrm{SFG}}, P_{\text{up-pump}}, P_{\mathrm{idler}}$ are the powers of SFG output at 710 nm, the pump at 1550 nm, and the input idler at 1310 nm, respectively; L is the waveguide length; and Δk is the wavevector-mismatch. As a result of this, for a given idler wavelength, the output spectrum from the tunable upconversion detector is a sinc^2 function instead of a single peak. This causes 'fake' peaks to form in the spectral image of the idler beam using the tunable upconversion detector and these peaks are transferred to the biphoton spectral measurement using the scheme described here. These artifacts only become obvious for narrow linewidth measurements. In high signal-to-noise ratio (SNR) measurements, deconvolution can be used to greatly reduce or remove these artifacts (fake peaks) and achieve better resolution. In many applications, such as quantum communications [6], the pump power of the upconversion detector is set to achieve maximum detection efficiency for a particular wavelength range. In biphoton spectroscopy, however, the linearity of the detector is the critical issue and to ensure that the detector operates in the linear range, a lower upconversion pump power is used. Care is also taken to ensure that the idler photon flux does not saturate the Si-APD in the upconversion detector. Avoiding saturation of the conversion and detection processes will limit the intensity of the unwanted artifacts associated with the transfer function of the waveguide [10]. Lowering the upconversion pump power has additional advantages. A lower pump power can reduce the noise associated with the pump. In addition, by reducing the pump power to below that which achieves maximum conversion efficiency, it is possible to independently control the conversion efficiency via the pump power and maintain constant conversion efficiency as a function of the wavelength of the idler over large measurement ranges. For small measurement ranges, however, the conversion efficiency can be considered a constant, as verified below.

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 upconversion 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 sample according to the equation [1]:

$$R_{\mathrm{coincidence}} \sim \left|H_{\mathrm{sample}}(\omega_{\mathrm{SPDCpump}} - \omega_{\mathrm{upconversion}})\right|^2 \tag{2}$$

where $H_{\mathrm{sample}}(\omega)$ is the spectral function of the sample; $\omega_{\mathrm{SPDCpump}}$ is the SPDC pump frequency satisfying the phase-matching condition $\omega_{\mathrm{SPDCpump}} = \omega_{\mathrm{signal}} + \omega_{\mathrm{idler}}$; and $\omega_{\mathrm{upconversion}}$ is the central operating idler frequency of the upconversion detector.

3. Results

We verified nearly constant conversion efficiency (less than 1% variation) of the upconversion chip over the full idler spectrum from the SPDC. We measured the variation in converted output power using a constant input power from a strong laser tuned from 1305 to 1325 nm. The output power was optimized at each point by tuning the upconversion pump. For the upconversion chip used in this experiment, the optimized output power varied by less than 3% over these 20 nm. Since the input power was constant over the 20 nm wavelength range, the optimized output power (at a fixed wavelength due to the phase-matching condition of the chip) will change by approximately 1.5% due to the change in photon flux over that range. The remaining 1.5% can be attributed to a number of factors, one of which is the conversion efficiency of the chip. Since the entire measurement range used in our experiment is significantly less than 20 nm and the spectra being measured are just a few nm or less, the change in conversion efficiency over these ranges is estimated to be significantly less than 1%.

To demonstrate biphoton spectroscopy, we measured the spectral linewidth of, firstly, the entire 895 nm spectrum (no object filters) of the SPDC source and, secondly, the reflected 895 nm spectrum following a narrow band VBG object filter. The 20 mm SPDC conversion chip is designed for an approximately 2.5 nm total spectrum width at 1310 nm, which corresponds to a total spectrum width of approximately 1.15 nm at 895 nm, verified by the measurement results shown in figure 2. The single photon count rate of the idler beam (figure 2(a), gray line) is provided by the upconversion detector and shows the idler spectrum as the detector pump is tuned. The single photon count rate from the signal beam (figure 2(b), empty black circles) is measured directly by the Si-APD and is constant indicating no spectral resolution;

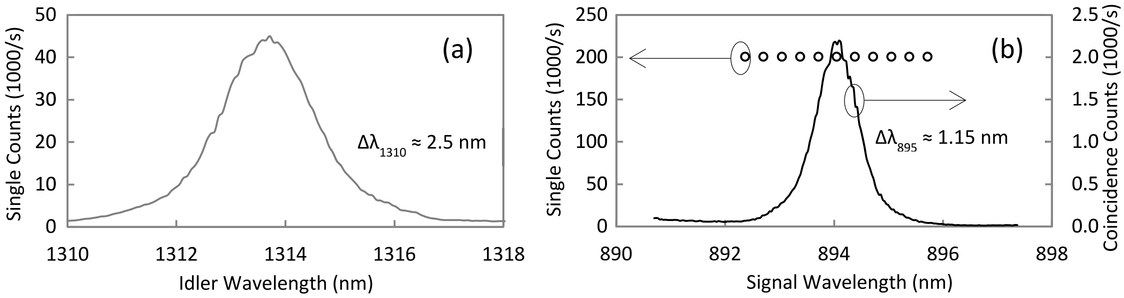

Figure 2. Measurement of the full SPDC downconverted spectra. (a) The 1310 nm single photon count spectrum (gray line) was measured directly using the tunable upconversion detector. (b) The 895 nm single photon count rate (empty black circles) was measured directly by the Si-APD. The 895 nm spectrum (black line) was calculated from the coincidence count rate measurements. Both spectra correspond to the SPDC linewidth specified for the PPLN chip. All count rates are thousands per second.

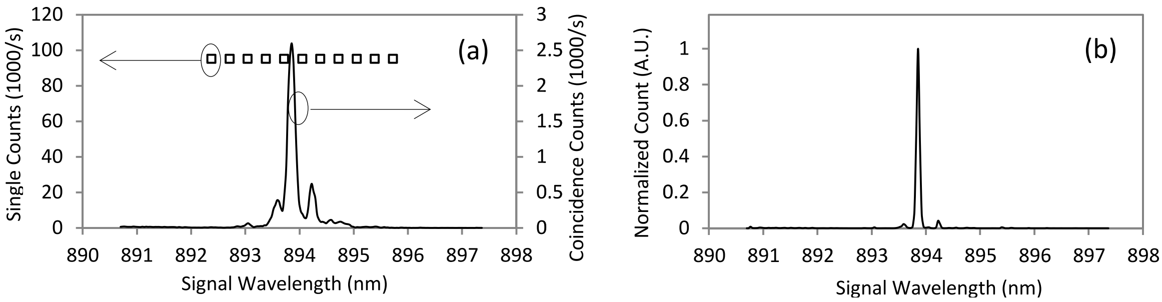

Figure 3. (a) The 895 nm single photon count rates (empty squares) were measured by the Si-APD. The 895 nm spectrum for the reflected signal (black line) with QPM-induced fake side was reproduced using the coincidence counts. (b) Signal spectrum following deconvolution of the transfer function of the waveguide. The deconvolution greatly reduces the fake side peaks in narrow linewidth spectral measurements.

while the coincidence count rate (figure 2(b), black line) reproduces the signal spectrum via biphoton spectroscopy. The low coincidence count rate to singles count rate is explained by noting that only a small portion of the idler spectrum, equivalent to the resolution of the detector, is used in any one coincidence measurement while the entire signal spectrum is included in the single photon count rate of the signal.

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. To satisfy that condition, we measure the reflected spectrum of a very narrow band (<0.1 nm) VBG.

Figure 3(a) shows, for one particular angle of incidence to the VBG, the correlated biphoton spectral image of the narrow linewidth reflection (black line, central peak only) from the VBG. The constant single photon count rate (empty squares) from the Si-APD indicate no spectral resolution directly from the single photon count rates. The spectral image of the narrow linewidth reflection from the VBG displays obvious side peaks due to the convolution of the QPM transfer function of the upconversion waveguide and the signal spectrum as described earlier. Figure 3(b) shows the narrow linewidth signal reflection from the VBG following deconvolution of the transfer function of the waveguide. Although the side peaks are not completely eliminated, they are greatly reduced and the resolution of the result is improved. The improved resolution of the measurement indicates that the VBG reflection linewidth is close to 0.08 nm.

In the data shown in figures 2(b) and 3(a), the single photon count rate is higher without VBG filtering (figure 2(b)) than for the VBG filtered reflected beam (figure 3(a)) since without filtering, the entire spectrum is measured, although that is partially offset by other losses (such as more restricted collection techniques required) in the non-filtered measurement. However, despite this, the coincidence count rate is higher for the VBG filtered beam. This is due to the more optimal linewidth matching of the reflected beam from the VBG (less than 0.1 nm at 895 nm) with the upconversion detector (about 0.2 nm at 1310 nm) [11]. In addition, the VBG acts as a very pure filter (for the reflected beam) and this allows more relaxed and efficient collection techniques and improves the signal-to-noise ratio of the coincidence count measurements [11].

4. Conclusion

We have developed a scheme for correlated biphoton spectroscopy using a greatly non-degenerate SPDC source and a tunable upconversion detector. We applied the scheme to measure the spectra of a signal beam directly from the source and following interaction with an optical element placed in the signals' spectrally non-resolving path. We generated the spectra by observing the coincidence counts between the spectrally non-resolved signal beam and the spectrally resolved idler beam, which had no direct interaction with the object. The spectral resolution of the idler beam is achieved using a single photon level tunable upconversion detector. The resolution of the system is limited by the phase-matching acceptance width of the upconversion detector for the idler beam. With deconvolution of the upconversion detector's waveguide, a resolution of better than 0.1 nm is achieved. The measurement range is determined by the spectral linewidth of the SPDC photon pairs.

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