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Time and spectrum-resolving multiphoton correlator for 300–900 nm

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We demonstrate a single-photon sensitive spectrometer in the visible range, which allows us to perform time-resolved and multi-photon spectral correlation measurements at room temperature. It is based on a monochromator composed of two gratings, collimation optics, and an array of single photon avalanche diodes. The time resolution can reach 110 ps and the spectral resolution is 2 nm/pixel, limited by the design of the monochromator. This technique can easily be combined with commercial monochromators and can be useful for joint spectrum measurements of two photons emitted in the process of parametric down conversion, as well as time-resolved spectrum measurements in optical coherence tomography or medical physics applications. © *2014 AIP Publishing LLC*.
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I. INTRODUCTION

There are a great number of applications which benefit from the ability to characterize either low-intensity light or correlations between single photons. Some examples are single photon sources,[1–4] time-resolved fluorescence spectroscopy, single molecule detection,[5] and optical coherence tomography.[6] These experiments often require knowledge of the spectral nature of individual photons, but it is difficult to get this information at the single photon level. Measurement techniques based on scanning detectors and the dispersive properties of materials have been employed to this end but have certain disadvantages that need to be overcome.

One can distinguish three main techniques that are used to characterize the spectral properties of single photons. (1) Typical commercial spectrometers, based on CCD cameras, are capable of performing measurements of low intensity light. However, this technique does not include timing information, which limits applicability to single photons. Furthermore, it does not allow for multiple photon correlation measurements. (2) Alternatively, monochromators based on scanning single-photon detectors[7] are used to collect spectral information. These devices are single-particle sensitive but are incapable of measuring more than one piece of information at a time. As such, it is not possible to measure multi-photon spectra using this method. (3) A third method is time-multiplexed single-photon spectroscopy,[8] which is based on photon arrival timing measurements. The resolution of this method depends on the jitter of the single-photon detector, time stamping electronics resolution, and dispersion of optical fibers. While this method is already hard to implement in the telecom band because of low dispersion, low detection efficiency, and attenuation in single mode fibers (SMFs), it is impossible to use this method in the visible range due to even higher attenuation.

II. MULTIPHOTON CORRELATOR

A. Setup

Here, we present the design and characterization of a multi-photon spectrometer for 300–900 nm. Timing resolution allows us to measure multiple photon spectral correlations. Note that this method is not phase sensitive. The device is simple—it consists of gratings and an array of 32 temporally and spatially resolved single-photon avalanche diodes (SPADs),[9,10] shown in Figs. 1(a) and 1(c). The system of two gratings maps the wavelength of the incident photon onto the pixels of the array. This setup can be operated without the need for any cooling elements.

There are two main applications for the device: measurements of single-photon spectra and measurements of spectral correlations between multiple photons. For the first, one needs to acquire the statistics of detection events for identical photons. This spectrometer measures the arrival time of photons, which can be used to evaluate the spectral correlation of two or more photons. For this application, the following steps must be followed: (1) if the goal is to measure the statistics of correlations between two photons, each photon should be delayed with respect to the previous photon by at least the hold-off time of the detector (the time after a detection during which the detector is off), (2) the location and time of detection are collected as a list of detector numbers and time stamps, and (3) finally, the data is processed. This processing consists of looking through the time tags of detections and keeping the ones that arrive within an expected time range. Based on this data, the correlation can be computed as a histogram of pairs of detector numbers that clicked (in the case of two photons).

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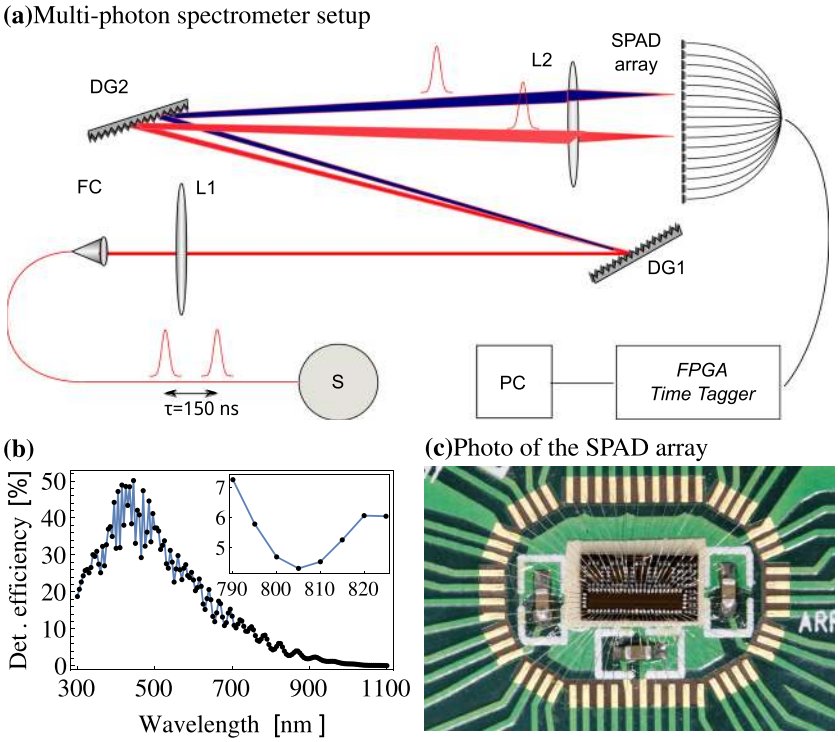

FIG. 1. (a) The multi-photon spectrometer experimental setup. Photons from a pair source S are delayed with respect to each other by $\tau = 150$ ns and sent to the spectrometer through single mode fiber using FC connector. Next, they travel through lens L1 ($f = 35$ mm), which collimates the spatial mode, two diffraction gratings DG1 and DG2 (1200/mm at 750 nm), and a lens L2 ($f = 55$ mm), which focuses the mode on the SPAD array. Next, individual signals from the detectors are registered by an FPGA time tagging unit. The time and channel number data are post-processed in a computer. (b) The photon detection efficiency of the SPAD array. Note that the ripple of the photon detection efficiency curve is due to interference effects of the light in the passivation layer deposited above the detection chip.[9,10] (c) The photo of the SPAD array detector.

B. Performance

The timing resolution of the device depends on both the SPAD array and time stamping electronics. The detector has a timing jitter of 110 ps, and the field programmable gate array (FPGA) electronic time tagging unit records the timing information with 156 ps resolution.

The spectral resolution of this implementation and the range of the multi-photon spectrometer are determined by the gratings. The SPAD array can detect photons in the range of 300–900 nm. For this demonstration, we set our grating system in the range of 790–830 nm so that it is compatible with our single-photon sources. Due to the limited spectral resolution of the gratings, we only use 16 pixels. This corresponds to a resolution of approximately 2 nm/pixel.

The overall photon detection efficiency is related to the quantum efficiency of the SPAD array, plotted in Fig. 1(b), and the transmission of the optical system. The quantum efficiency of the SPAD depends on the wavelength and reaches 50% for 450 nm. In our experiment, we use two single-photon sources (discussed in detail later in this paper), whose photons are centered around 810 nm. The single-photon detection efficiency at this wavelength is around 5% and the transmission of the grating system is approximately 50%. Thus, the overall photon detection efficiency of our spectrometer is around 2.5%. The probability of detecting n photon coincidences is $(2.5\%)^n$. For a photon pair, this is approximately 0.06%.

In this setup, noise comes from two sources: dark counts and the afterpulsing effect. The dark count rate of the SPAD array is very low, approximately 100 counts per second/pixel at room temperature. For the photon spectrum measurement, the dark count statistics can be used to subtract noise from the detection statistics. In the case of photon correlation measurements—when multiple photon detection events are analyzed—noise originating in dark counts is negligible. However, these correlation measurements can be significantly affected by the afterpulsing effect. This issue is one of the main problems that requires careful attention.[9] During the detection of a photon, many charge carriers flow through the SPAD. Some of these are captured by deep-level traps inside the depleted region of the detector and are released. If a charge carrier is released when the bias voltage is above the breakdown voltage, it could re-trigger an avalanche and cause a fake count, which would then be counted as a coincidence of two photons incident at the same detector. In order to reduce this correlated noise, the SPAD has to be off for a specific amount of time after each avalanche. This hold-off time is on the order of tens of ns for the SPAD array used in this spectrometer. By using a 150 ns delay between the photons and setting a long hold-off time (140 ns), we decrease the afterpulsing probability per ns to as low as 10^{-4}%.

Cross-talk between neighbouring detectors is another problem when taking time-resolved correlation measurements. After a photon is detected, the SPAD pixel emits new photons which in turn can be detected by neighboring pixels.[10] This effect has a probability of less than 0.1%[11] and therefore can be eliminated entirely by introducing a time delay between photons. Cross-talk events usually show up sequentially, since these events occur in a time interval of about 1.5 ns after the avalanche ignition. Therefore, cross-talk does not impact our measurements, since we look for coincidences between events with a time-distance of 150 ns.

The photon detections are limited predominantly by the hold-off time. The photon detection efficiency of the system is constant for low rates and decreases for high count rates because the detector count rate saturates. With a hold-off

time of 140 ns, the detection rate of each pixel is linear with the impinging photon flux up to approximately 1 MHz.[9,10]

III. CHARACTERIZATION

We move on to the characterization of the multi-photon spectrometer using two single-photon sources emitting photons with known characteristics. We perform two tests using (1) frequency-correlated narrow-band single photon pairs emitted by a spontaneous parametric down-conversion (SPDC) source[12] and (2) spectrally broadband coherent states emitted by an attenuated femtosecond laser (TiF50M, Atseva).

A. Correlated photons

We use the SPDC source, which has two SMF outputs through which the photons propagate, to test the spectrometer's capability of measuring multi-photon correlations. We characterize the temperature tunability of our photon pair spectra with a commercial spectrometer by looking at each SMF output. The source produces frequency-degenerate photons at 809.6 nm when the temperature is 59 °C. By tuning the temperature in the range of 40 °C– 70 °C, we spectrally separate the photons by up to 15 nm. The photons are initially coupled into two distinct SMFs. For testing purposes, we send one photon through 30 m of SMF, which results in a delay of 150 ns. The two photons are then combined by a polarizing beam splitter and coupled into SMF, which is then attached to the multi-photon spectrometer.

We acquire photon detection timing information for 60 min at a given temperature. We repeat this measurement for two temperature settings: 50 °C and 65 °C. This data is then post-processed to collect coincidences, and any photon pairs that arrive at the SPAD detector array with a delay of 150 ns between each other are collected. The detections resulting from dark counts, afterpulsing, or stray light are discarded. From this data, we plot a set of histograms, which convey information about the number of coincidences between detector pairs. These histograms are shown in Figs. 2(a)–2(c). One sees only accidental coincidences for channel pairs 1–10, 2–10, and 3–10 as plotted in Fig. 2(b). However, there is a clearly visible peak for channels 5–10 in Fig. 2(a). There are few coincidences between channel pairs 4–10 and 6–10, as depicted in Fig. 2(c). This is attributed to the finite resolution of our spectrometer and the cross-talk between pixel 5 and its two nearest neighbors. However, this effect is small; there are only approximately 600 coincidences between channels 5 and 10 and approximately 20 coincidences for channel pairs 4–10 and 6–10. Note that the different positions of the peaks in Fig. 2(c) are related to the time delay between the absorption of the photon and the output of the electric signal, which is different for individual pixels (in the range of around 2 ns for this array). Next, by looking at the time histograms, we compile a list of detector number pairs where the first of the pair corresponds to the photon which arrived first, and the second corresponds to the following photon. The detection of two photons is considered a coincidence only if the following criteria hold: (1) there is a specific time delay between detections (e.g., 153.3 ns for channel pair 5–10, see Fig. 2(a)) and (2) the later detection is within a specific window of time limited by the timing jitter of the detectors and the timing resolution of the FPGA electronics (624 ps). Based on the list of photon detection pairs, we plot coincidences as a histogram of the first photon

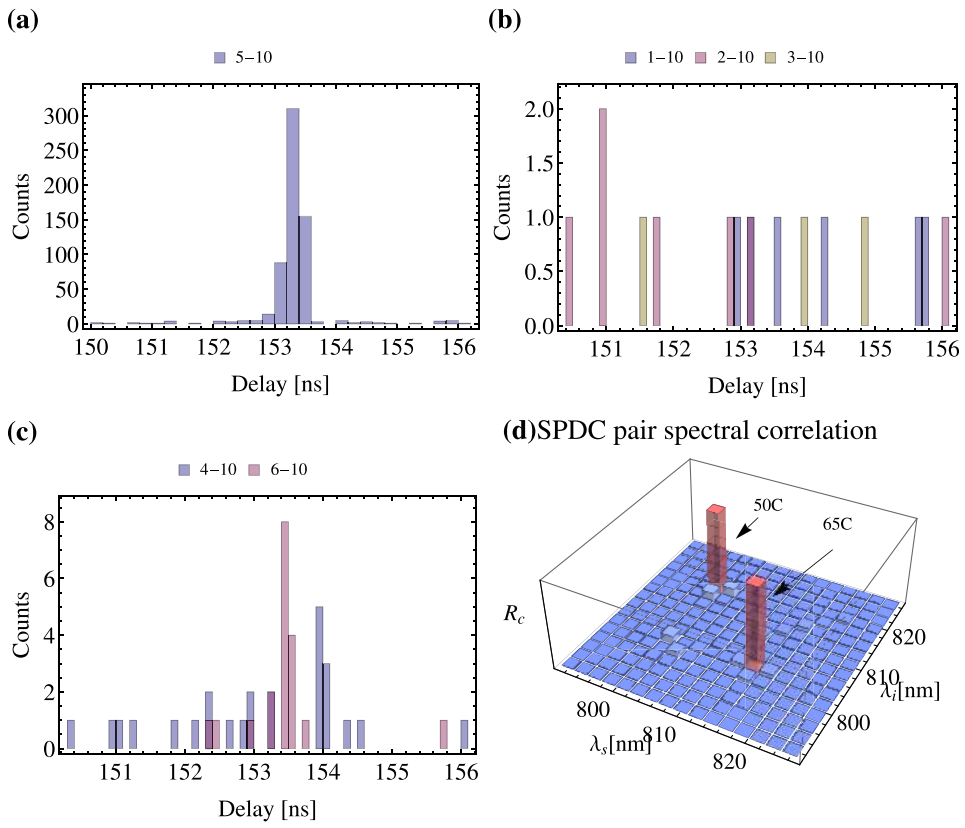

FIG. 2. Exemplary time histograms for SPDC source set at the temperature 50 °C. The coincidences histogram for a channel pair (a) 5–10 shows a clearly visible peak consisting of around 600 counts in a range of 500 ps, (b) only accidental coincidences totaling 16 counts for channels 1–10, 2–10, and 3–10, and (c) small peaks for channels 4–10 and 6–10, which are related to finite resolution of the spectrometers. (d) Photon pair coincidences for SPDC source for two temperature settings 50 °C and 65 °C, corresponding to the first (second) photon's central wavelength, 802 nm (814 nm) and 813 nm (803 nm), respectively.

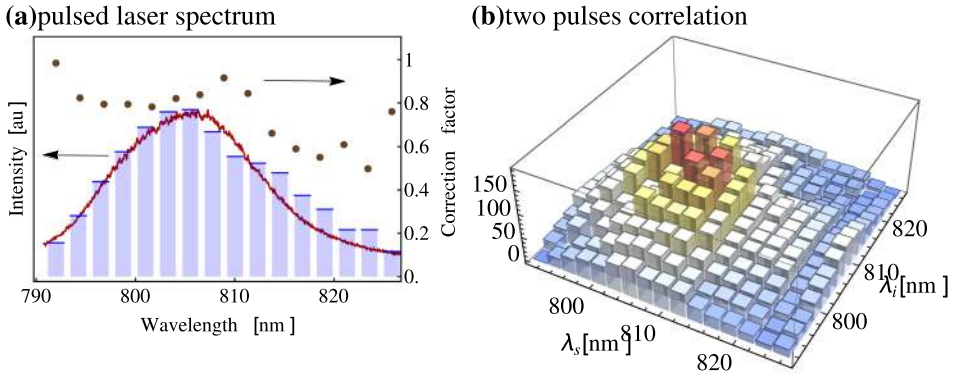

FIG. 3. (a) The spectrum of the coherent state generated by a Ti:sapphire femtosecond laser attenuated to the single photon level. The blue bar plot shows the photon counts measured by the multi-photon spectrometer, the red line represents the spectrum measured by the commercial Acton spectrometer, and the brown dots depict the correction factors for the efficiency of each pixel. The error bars are of the order of the marker size. (b) Spectral correlation of two photons in coherent states. The magnitude of the correlations is plotted. Here, the bar plot corresponds to the SPAD array counts multiplied by the pixels' correction factors.

channel versus the second photon channel. The plot in Fig. 2(d) shows the sum of the data sets taken at 50 C and 65 C. The SPDC source we use for the characterization is narrowband. This in combination with the resolution of our spectrometer results in a single point to represent the pairs which occur most often.

B. Broadband pulses

Next, we move on to the spectrally broadband pulsed source in order to test the accuracy of our intensity measurements. We use 67 fs pulses from a Ti:sapphire laser, attenuated to the single-photon level and SMF coupled. The repetition rate is 80 MHz, which results in single photons separated by approximately 12 ns. There is no spectral correlation between photons from consecutive pulses. We record the timing information and post-process this data as outlined above, and we then plot the histogram of the array counts and compare them with the spectrum measured by commercial spectrometer, as shown in Fig. 3(a). We assume proper calibration of the commercial spectrometer, which allows us to correct the effective photon detection efficiencies of each of the pixels. The relative correction factors are depicted as brown dots in Fig. 3(a). Next, we use the same data to see the spectral correlation between two coherent states originating in attenuated consecutive pulses. This histogram is depicted in Fig. 3(b). As expected, the histogram is perfectly symmetric, showing no spectral correlations between the two photons.

IV. SUMMARY

We demonstrate a multi-photon correlation spectrometer based on a grating monochromator and an array of single photon avalanche diodes. It is a step forward in the accurate characterization of single-photon sources and is useful in many areas of quantum optics. This technique can be used in combination with existing commercial spectrometers for increased accuracy in measurement of single-photon spectra or multi-photon correlation measurement. It is also worthwhile to mention that the typical timing jitter of the SPAD is on the order of $\Delta t = 110$ ps FWHM, which, according to Heisenberg's relation, results in the related wavelength uncertainty $4\lambda^2\ln(2)/(2\pi c\Delta t) = 9.4$ pm FWHM for 800 nm. This is far beyond the resolution of the setup.

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