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 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 the applicability of this method when applied 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, it is impossible to use this method in the visible range due to even higher attenuation.

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. The device is simple – it consists of gratings and an array of 32 temporally- and spatially-resolved single-photon avalanche diodes (SPAD) [9, 10], shown in Fig. 1(a,c). The system of two gratings maps the wavelength of the incident photon onto the pixels of the array.

There are two main applications for the device: measurements of single-photon spectra and 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).

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 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 is determined by the gratings. The SPAD array can detect photons in the range 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, which is 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 %. 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 requiring 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 then 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. This effect is negligible and can be eliminated entirely by introducing a time delay between photons. Cross-talk events usually show up one after the other, 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 is 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].

![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 clearly visible peak consisting of around 600 counts in a range of 500 ps. b) only accidental coincidences totaling in 16 counts for channels 1-10, 2-10, 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 exemplary temperature settings 50°C and 65°C, corresponding to the first (second) photon’s central wavelength, 802nm (814nm) and 813nm (803nm), respectively.](image-url)
1) frequency-correlated narrow-band single photon pairs emitted by a spontaneous parametric down-conversion (SPDC) source and 2) spectrally broadband coherent states emitted by an attenuated femtosecond laser (Ti:SF50M, Atseva).

We use the SPDC source, which has two single mode fiber (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 50°C. By tuning the temperature in the range 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 minutes 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 Fig. 2(a-c). One sees only accidental coincidences for channel pairs 1-10, 2-10 and 3-10 as plotted in Fig. 2(a). However, there is a clearly visible peak for channels 5-10 in Fig. 2(b). The resolution of our spectrometer is finite, which results in few coincidences between channel pairs 4-10 and 6-10, which we depict in Fig. 2(c). 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. We plot coincidences as a histogram of the first photon channel versus the second photon channel. The SPDC source we use for the characterization is narrowband. This in combination with the resolution of our spectrometer results in single point to represent the pairs which occur most often. To show the capabilities of our spectrometer and for the clarity of presentation, we plot the results for two exemplary temperature settings 50°C and 65°C, see Fig. 2(d).

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. We then plot the histogram of the array counts and compare them with the spectrum measured by commercial spectrometer, as shown in figure Fig. 2 (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. 2(b). As expected, the histogram is perfectly symmetric, showing no spectral correlations between the two photons.

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.

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