Third- and Fourth-Order Coherences Measured with a Multi-Element Superconducting Nanowire Single-Photon Detector

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Abstract: We demonstrate a technique for measuring third- and fourth-order coherences using a multi-element detector consisting of four independent, interleaved superconducting nanowire single-photon detectors, and observe strong bunching from a chaotic light source.

OCIS Codes: (270.1670) Coherent optical effects; (270.5290) Photon statistics

Measurements of the second-order temporal coherence, $g^{(2)}(\tau)$, are a staple of modern quantum optics, used for characterizing single-photon sources and identifying features such as bunching and antibunching. Due to the experimental complexity, coherences higher than second order are not routinely measured, even though they can reveal information not contained in $g^{(2)}$ [1,2]. Typically, $g^{(2)}(\tau)$ is measured with a Hanbury Brown-Twiss interferometer, which consists of a beamsplitter, two discrete single-photon detectors, and timing electronics that record the number of counts for time delays, τ, between photons registered by the two detectors. In principle, this technique can be scaled to measure higher-order coherences by adding beamsplitters and detectors, provided that the timing electronics have a sufficient number of independent channels. However, previous measurements of third- and fourth-order temporal coherences,

$$g^{(3)}(\tau_1,\tau_2)=\left\langle \hat{a}^\dagger(t)\hat{a}^\dagger(t+\tau_1)\hat{a}^\dagger(t+\tau_2)\hat{a}(t+\tau_2)\hat{a}(t+\tau_1)\hat{a}(t)\right\rangle \Big/ \left\langle \hat{a}^\dagger(t)\hat{a}(t)\right\rangle^3, \tag{1}$$

$$g^{(4)}(\tau_1,\tau_2,\tau_3)=\left\langle \hat{a}^\dagger(t)\hat{a}^\dagger(t+\tau_1)\hat{a}^\dagger(t+\tau_2)\hat{a}^\dagger(t+\tau_3)\hat{a}(t+\tau_3)\hat{a}(t+\tau_2)\hat{a}(t+\tau_1)\hat{a}(t)\right\rangle \Big/ \left\langle \hat{a}^\dagger(t)\hat{a}(t)\right\rangle^4, \tag{2}$$

have been performed with only one or two detectors and two-channel electronics, and thus have been limited by detector and electronics dead times to delays away from zero delay, and to fixed values of at least one delay [1,2].

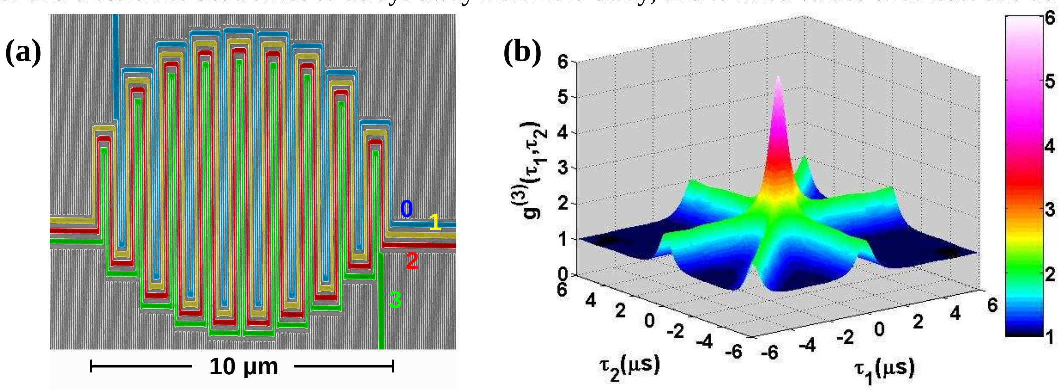

Fig. 1 (a) Scanning electron microscope image of four-element SNSPD, with nanowire elements 0-3 traced out in color. (b) Third-order coherence data from pseudo-thermal source, where both color and height indicate measured value of $g^{(3)}$.

Here, we use a novel four-element detector and four-channel timing electronics to measure $g^{(3)}(\tau_1,\tau_2)$ and $g^{(4)}(\tau_1,\tau_2,\tau_3)$. The detector, shown in Fig. 1(a), is a multi-element superconducting nanowire single-photon detector (SNSPD), in which four independent, interleaved nanowire elements sample a single spatial mode. This device is held at a temperature of ~3 K in a closed-cycle helium cryocooler, and light is coupled to it via a single-mode optical fiber whose mode field diameter is matched to the active area of the multi-element SNSPD. Fast electronics record photon arrival times for the four elements by time-tagging events on four independent, synchronized channels. We post-process the time-tagged data to obtain multi-start, multi-stop correlation histograms between all possible combinations of two, three, and four SNSPD elements. Normalizing these correlation histograms by the

This work was sponsored by the United States Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States government.

number of counts expected in each time bin for completely uncorrelated events yields a good approximation to the second-, third- and fourth-order correlation functions, $g^{(2)}(\tau_1)$, $g^{(3)}(\tau_1,\tau_2)$ and $g^{(4)}(\tau_1,\tau_2,\tau_3)$, where $\tau_{i=1,2,3}$ is the time delay between a photon registered by element 0 and a photon registered by element *i*. Having four independent detector elements and timing channels with no inter-element dead time allows us to determine these coherences for arbitrary values of the time delays, including $\tau_1 = \tau_2 = \tau_3 = 0$, which is often the most relevant point.

To illustrate the technique, we measure coherences up to fourth order for two different sources. One source is a 1070 nm-wavelength diode laser, operated well above threshold, coupled into a single mode optical fiber and directed to the multi-element SNSPD. The other source is a chaotic, pseudo-thermal source, in which light from the same laser is scattered off a rotating ground glass disk; the resulting speckle pattern is sampled in the far field with the fiber and again directed to the SNSPD. We expect the laser to be coherent to all orders, so that the n^{th} order coherence, $g^{(n)}$, should be equal to one for all delays. The chaotic source, by contrast, should exhibit bunching, so that $g^{(n)} = n!$ at the origin and approaches one as $\tau_i \to \infty$ for all *i* and $(\tau_i - \tau_j) \to \infty$ for all $i \neq j$ [2,3].

Third-order coherence data from the pseudo-thermal source are shown in Fig. 1(b). At the origin, $g^{(3)}(0,0) \approx 5.8$, close to the value of 3! = 6 expected for a chaotic source. The three ridges, which intersect the origin along lines at $\tau_1 = 0$, $\tau_2 = 0$ and $\tau_1 = \tau_2$, correspond to two of the three detectors firing simultaneously; $g^{(3)}$ reaches a peak value of ~2.0 along each of these ridges. Far from the origin and away from the ridges, $g^{(3)} \approx 1.0$, as expected for uncorrelated events.

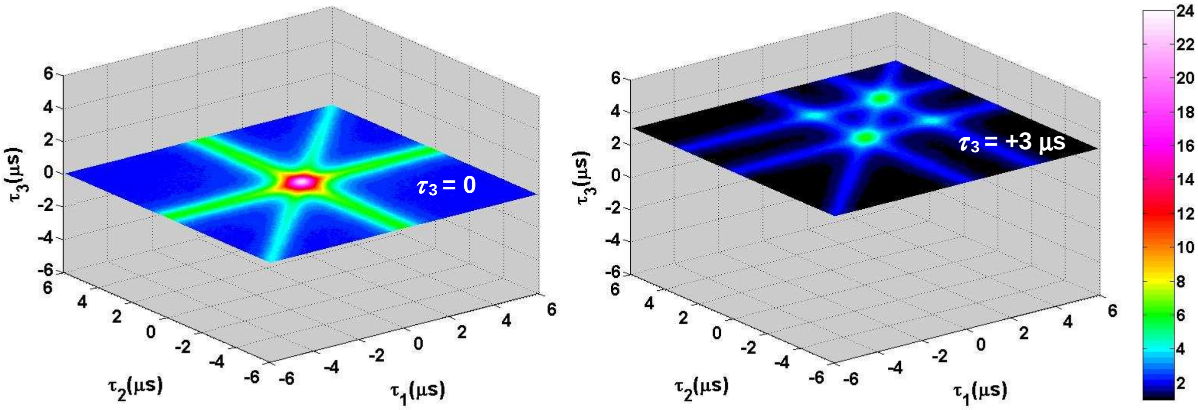

Fig. 2 Slices of $g^{(4)}(\tau_1,\tau_2,\tau_3)$ data from the psuedo-thermal source for two fixed τ_3 delays, with color indicating measured value of $g^{(4)}$.

Figure 2 plots an illustrative subset of the fourth-order coherence data from the pseudo-thermal source for two fixed values of τ_3. When $\tau_3 = 0$ (elements 0 and 3 fire simultaneously), the $g^{(4)}$ data appear qualitatively similar to the $g^{(3)}$ data, but the values are very different. Here, $g^{(4)}$ reaches a value of ~23.2 at the origin (all four elements fire at the same time), and falls off to ~2.1 far from the origin, where $\tau_1 \neq \tau_2 \neq \tau_3 = 0$. For $\tau_3 \neq 0$, the features are quite different: at the center of the dark blue bands, where two of the four detectors register a photon at the same time, $g^{(4)}$ reaches a value of ~2. Where any two of these bands intersect, the value increases to ~4 (small light blue areas); where any three intersect, $g^{(4)} \approx 6$ (larger green areas). We have performed simulations assuming an ideal Gaussian scattering process, using the model in [2]; these simulations reproduce all the major features visible in the data, with values of $g^{(3)}(0,0) = 6$ and $g^{(4)}(0,0,0) = 24$ at the origins. As a control, we have repeated all these measurements with the laser coupled directly into the fiber, bypassing the rotating ground glass, and measured $g^{(3)} \approx 1.0$ and $g^{(4)} \approx 1.0$, independent of delays (not shown). This last result indicates there is little or no crosstalk between any of the elements.

The combined timing jitter of the SNSPD and electronics is ~50 ps, making it useful for characterizing processes with much faster temporal evolution than the chaotic source studied here. Thus, multi-element SNSPDs could enable advances in characterizing single-photon sources, investigating the physics of low-threshold and thresholdless lasers, or exploring non-Gaussian processes in dynamic light scattering experiments.

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