Third-Order Antibunching from an Imperfect Single-Photon Source

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Abstract: We measure second- and third-order coherences of an imperfect single-photon source. The magnitude of third-order antibunching indicates that imperfect second-order antibunching results from background emission with Poissonian photon number statistics.

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The standard metric for the determining the quality of a single-photon source is the second-order temporal coherence, $g^{(2)}(\tau)$. For an ideal single-photon source, $g^{(2)}(0) = 0$, indicating zero probability of the source emitting more than one photon at a time. If this is the case, then all higher-order coherences ($g^{(n)}(0,0...)$, $n > 2$) are identically zero [1] and not worth the effort to measure. However, some finite probability of multi-photon emission appears to be unavoidable in real-world single-photon sources. Many sources allow a trade-off of higher efficiency—and thus higher photon count rates—in exchange for higher $g^{(2)}(0)$. For any given quantum information or metrology application, one would like to know how to optimize this trade-off. Unfortunately, although $g^{(2)}(0) \neq 0$ indicates the presence of multi-photon emission, the measured value contains limited information about the details of this emission, and thus the value of $g^{(2)}(0)$ that an application can tolerate is no simple matter to determine. High-order coherence measurements offer one way of gaining more insight into the details of multi-photon emission.

Here, we measure second- and third-order coherences of an imperfect single-photon source and present, to our knowledge, the first experimental demonstration of antibunching in third-order coherence. The magnitude of third-order antibunching allows us to test the validity of two very different sources that could have produced the measured second-order value. We will show that the data are consistent with an ideal single-photon source added to a background having a Poissonian photon number distribution.

Our single-photon source is a self-assembled InGaAs quantum dot embedded in a micropillar cavity held at a temperature of ~4 K. The source is optically pumped with either a CW or pulsed laser, and the emission is spectrally filtered to block the pump and pass only the emission from a single transition in the quantum dot, at a wavelength of ~960.6 nm. To measure the second- and third-order coherences, we use a modified Hanbury Brown-Twiss geometry with two beamsplitters followed by three Si single-photon avalanche diodes (SPADs). Time-tagging electronics record the arrival times of all detected photons at the three detectors. We post-process the time-tagged data to obtain multi-start, multi-stop correlation histograms between combinations of two or three detectors [2]. Normalizing these correlation histograms by the number of counts expected in each time bin for completely uncorrelated events yields a good approximation to the second- and third-order correlation functions, $g^{(2)}(\tau_1)$ and $g^{(3)}(\tau_1, \tau_2)$, where $\tau_{i=1,2}$ is the time delay between a photon detected by SPAD 0 and a photon registered by SPAD i.

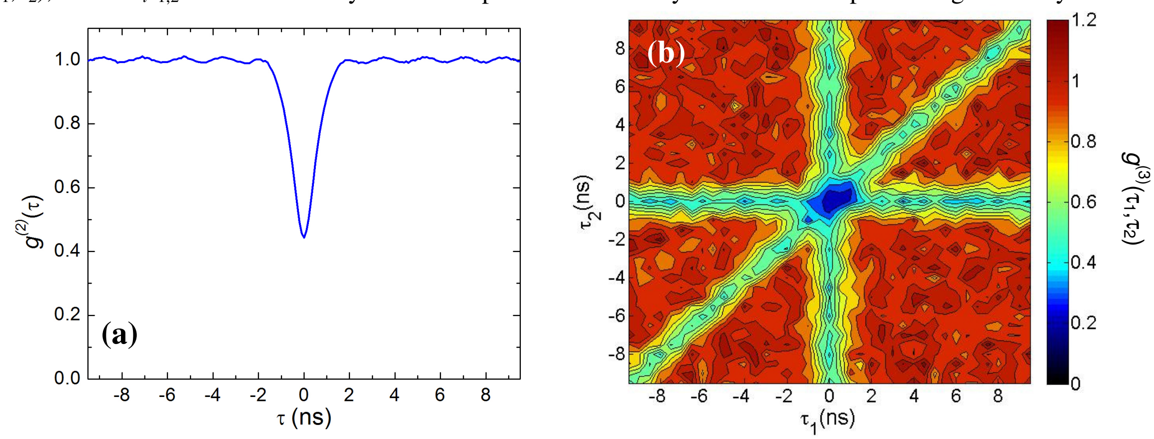

Fig. 1. Measured (a) second- and (b) third-order coherence of the single-photon source with CW excitation.

Measured coherences for the imperfect single-photon source pumped with a CW laser are shown in Fig. 1. The second-order coherence exhibits the well-known antibunching behavior of a single-photon source, albeit not a very good one, with $g^{(2)}(0) \approx 0.44$. The third-order data display more complex features. The three valleys that intersect the origin along lines at $\tau_1 = 0$, $\tau_2 = 0$ and $\tau_1 = \tau_2$ correspond to two of the three SPADs detecting photons simultaneously. $g^{(3)}$ reaches a minimum value of ~0.5 along each of these valleys, close to the measured $g^{(2)}(0)$, as expected. At the origin, where each of the three SPADs must detect a photon at once to register a count, the value is further reduced to $g^{(3)}(0,0) \approx 0.3$. Far from the origin and away from the valleys, $g^{(3)} \approx 1$.

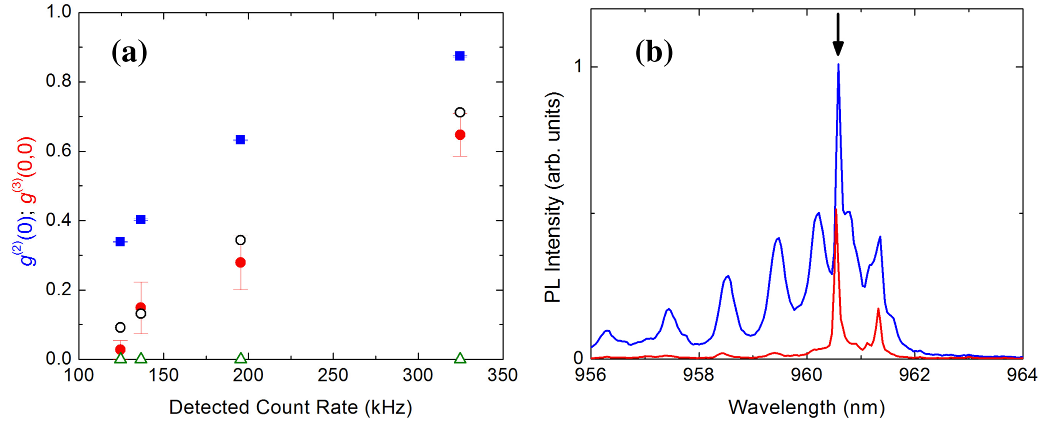

Fig. 2. (a) Zero-delay coherences as a function of detected count rate, showing data and uncertainties for $g^{(2)}(0)$ (blue squares) and $g^{(3)}(0,0)$ (solid red circles). The open circles and triangles denote the expected $g^{(3)}(0,0)$ values computed from the measured $g^{(2)}(0)$ and the two hypotheses described in the text. (b) Unfiltered photoluminescence (PL) spectra of the quantum dot source for the lowest (red) and highest (blue) pump powers in (a), corresponding to ~125 kHz and ~325 kHz detected count rates, respectively. The arrow denotes the approximate central wavelength of the ~0.06 nm-wide tunable bandpass filter used for the measurements in (a).

Figure 2(a) shows measured coherences at zero delay for a *pulsed* pump laser at a series of excitation powers. As pump power is increased (from left to right in the figure), the detected count rate, $g^{(2)}(0)$, and $g^{(3)}(0,0)$ all increase dramatically. The increase in $g^{(2)}(0)$ could be caused by several different mechanisms. For example, the single-photon-like state emitted by the quantum dot could have some non-zero two-photon emission probability, $|\psi\rangle = c_0|0\rangle + c_1|1\rangle + c_2|2\rangle$, with the magnitude of c_2 increasing with pump power. This might be the case if, for example, there were a biexcitonic transition close enough in energy to the excitonic transition to be transmitted through the bandpass filter. If this hypothesis were correct, then we would expect $g^{(3)}(0,0) = 0$ for all pump powers, as shown by the open green triangles. The measured $g^{(3)}(0,0)$ values clearly disprove this hypothesis.

We next test a second hypothesis, that the quantum dot emission can be modeled as an ideal single photon source with zero probability of multi-photon emission, $|\psi\rangle = c_0|0\rangle + c_1|1\rangle$, added onto a background with Poissonian photon number statistics. Using the measured $g^{(2)}(0)$, we can determine the ratio of the magnitudes of the single-photon and background contributions: these range from ~4.4:1 at the lowest pump power to ~1:1.8 at the highest power. From these relative magnitudes, we predict the $g^{(3)}(0,0)$ values shown as open black circles in Fig. 2(a); within our experimental uncertainties, they agree reasonably well with the data.

Further confirmation of the validity of this second hypothesis can be gleaned from the quantum dot emission spectra shown in Fig. 2(b). For low pump power, we observe a strong single QD emission line, a somewhat weaker line at a longer wavelength, and a very weak, spectrally broad background. As pump power increases, the intensity of the QD emission line increases somewhat, but the broad background increases much more dramatically. When detuning the bandpass filter by ~0.3 nm to pass only the broad background, we measure $g^{(2)}(0) \approx 1$, indicating that the photons emitted in this background are not from a single emitter, but instead follow—at least approximately—a Poissonian number distribution [3].

Although we have shown that our second hypothesis is consistent with the measured data, this is not a unique solution, since we could have allowed the single-photon source to emit three or more photons with some low probability. Nonetheless, $g^{(3)}$ clearly gives new information not contained in $g^{(2)}$. This information could be used to construct a more accurate picture of the internal physics of the quantum dot or to better determine the suitability of this source in a particular quantum information application.

References

[1] R. Loudon, *The Quantum Theory of Light*, Third Edition (Oxford University Press, Oxford, 2000).
[2] M. J. Stevens *et al.*, "High-order temporal coherences of chaotic and laser light," Opt. Express **18**(2), 1430 (2010).
[3] Technically, these photons should follow a thermal distribution, but with a coherence time far too short for our detectors to resolve the consequent bunching.