Two-photon interference from a bright single-photon source at telecom wavelengths: supplementary material

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Published 1 June 2016

This document provides supplementary information to “Two-photon interference from a bright single-photon source at telecom wavelengths,” <http://dx.doi.org/10.1364/optica.3.000577>. © 2016 Optical Society of America
<http://dx.doi.org/10.1364/optica.3.000577.s001>

1. Background levels in $g^{(2)}(\tau)$ measurement

For the correlation measurement, we used cooled InGaAs single photon detectors (ID230, Picoquant). Compared to conventional Si detectors, InGaAs detectors have a lower quantum efficiency of 20% and higher dark counts of ~200 Hz. We determined the background level in the correlation histograms in Fig. 3(b) and Fig. 5(a,b) as below.

The obtained correlation histogram ($g^{(2)}(\tau)$) is a product of two detector signals given by

$$N_{m1} \cdot N_{m2} = (N_{s1} + N_{b1}) \cdot (N_{s2} + N_{b2}) = N_{s1} \cdot N_{s2} + N_{s1} \cdot N_{b2} + N_{b1} \cdot N_{s2} - N_{b1} \cdot N_{b2} \approx N_{s1} \cdot N_{s2} + 2N_{m1} \cdot N_{b2} - 3N_{b1} \cdot N_{b2} \approx N_{s1} \cdot N_{s2} + 2N_{m1} \cdot N_{b2}$$

, where N_{mi} , N_{si} , and N_{bi} indicate the measured signal, the quantum dot signal, and the background signal at detector i , respectively. Most background signal originates from the detector dark counts in our pulsed measurements.

Based on the fact that two detectors have a similar efficiency and $N_{m1} \gg N_{b2}$, the second term, $2(N_{m1} \cdot N_{b2})$, describes the background level in the measured histogram. To quantify the background level, we made detector 1 measure both the quantum dot and background signals while detector 2 only measure the detector dark counts by disconnecting the signal channel. We then calibrated the correlation data with time and took double this value.

2. Bulk quantum dot spectrum

In Fig. 4(c), we compared the intensity of the bulk dot and dot A. For this comparison, we chose one of bulk dots that has a similar wavelength to dot A and higher intensity than that of the average dots as shown in Fig. S1.

Fig. S1. Photoluminescence spectrum for bulk dots. The red dot indicates the bulk dot chosen for the comparison to the cavity-coupled dot A in Fig. 4(c).

3. Power dependence of $g^{(2)}(0)$

We investigated the excitation power dependence of $g^{(2)}(0)$ value of dot A. Figure S2(a) shows the measured correlation histograms at various excitation powers. The figure shows that the $g^{(2)}(0)$ values remain low at low power but start to increase near the saturation power ($P_{\text{sat}}=12$ nW). The increased $g^{(2)}(0)$ values at high excitation power originates from the increased background emission by other dots and the enhanced cavity emission by nonradiatively coupled to other dots [1, 2]. To reduce the probability of multiple photon events, we should use low excitation powers, which could limit the brightness of single photon sources. We plot the $g^{(2)}(0)$ values and the measured collection efficiency as a function of power. Figure S2(b) shows the $g^{(2)}(0)$ value remains below 0.5 up to the maximum dot intensity. From non-zero $g^{(2)}(0)$ values, we correct the multi-photon events in the measured collection efficiency by multiplying the term, $(1-g^{(2)}(0))^{1/2}$ [3]. This reduces the collection efficiency from 46 % to 36 % at the maximum dot intensity.

(a)

(b)

Fig. S2. (a) Photon correlation histogram at various excitation power levels. Green solid lines are fitted curves. (b) Plots of $g^{(2)}(0)$ values (black-solid dots), measured collection efficiency (red-solid dots), and multi-photon corrected collection efficiency (red-empty dots) as a function of excitation power.

4. Spatial coupling between cavities and dots

In our photonic crystal cavity with the measured Q of 380 and the simulated mode volume (V) of $0.66(\lambda/n)^3$ for mode M3, we calculate the Purcell factor of 44 when we assume an ideal coupling between dots and cavities. However, the measured dots show one order of magnitude lower Purcell factors than the calculated value even at zero spectral detuning. This is mostly due to the spatial and polarization mismatches. To consider non-ideal spatial coupling, we multiply a spatial mismatch term, $|\mathbf{E}(\mathbf{r})|^2/|\mathbf{E}_{\text{max}}|^2$ in the Purcell factor, where $\mathbf{E}(\mathbf{r})$ and $\mathbf{E}_{\text{max}}$ denote the electric field at the position of dots and the maximum field intensity. Figure 3(a-c) shows the simulated spatial map of $|\mathbf{E}(\mathbf{r})|^2/|\mathbf{E}_{\text{max}}|^2$ for mode M3 and their intensity profiles along x and y directions. Mode M3 has a two maximum peaks at the middle of cavity, denoted as P1 and P2. Figure 3(b,c) shows that the Purcell factor drops by a factor of 10 when the dot is about 150 nm (85 nm) away from the field maximum along x (y) direction. This small size of localized modes makes the spatial coupling difficult, and becomes a main cause of the reduced Purcell factor in the experiments [4-7].

Fig. S3. (a) Simulated spatial map of $|\mathbf{E}(\mathbf{r})|^2/|\mathbf{E}_{\text{max}}|^2$ for mode M3. (b,c) Intensity profiles of $|\mathbf{E}(\mathbf{r})|^2/|\mathbf{E}_{\text{max}}|^2$ along (b) x and (c) y directions. Yellow lines indicate the positions of the curves in (b) and (c).

5. Purcell effect on cavity-coupled dots

Purcell effect enables dots to emit single photons with an enhanced spontaneous emission rate, and therefore, it also increases the maximum brightness of the dots by increasing the saturation power level. To investigate the influence of the Purcell effect on the saturation power of dots, we chose two cavity-coupled dot 1 and dot 2 in Fig. S4(a), which have different lifetimes of 650 ps and 1.8 ns, respectively. Figure S4(b) plots the integrated intensities of dot 1 and dot 2 as a function of excitation power. To record the dot intensity we used a charge coupled detector because the single photon detectors have a strong saturation effect due to their dead time and require additional calibration process, performed for Fig. 4(c) in the manuscript. From the fitting, we determine dot 1 and dot 2 have the saturation powers at 540 ± 28 nW and 240 ± 15 nW, respectively. Dot 1 shows 2.3 times faster lifetime and 2.8 times higher saturation power compared to dot 2. This enhanced spontaneous emission rate and saturation power by the Purcell effect would be helpful to reduce timing jitter and to generate bright single photons.

Fig. S4. (a) Statistical distribution of lifetimes of individual cavity-coupled dots. Dot 1 and dot2 indicate two dots with different lifetimes for comparison in (b). Cavity mode M3 is shown in gray color. (b) Plot of integrated intensities of dot 1 (red-solid dots) and dot 2 (blue-solid dots) as a function of excitation power. Solid lines are fitted curves for calculation of saturation intensity.

6. Indistinguishability vs. brightness

In Fig. 5(b), the cavity-coupled dot shows indistinguishable nature of single photons from two-photon interference. However, the strong dephasing limits the indistinguishable visibility of the dot and requires post-selection method to achieve high indistinguishability. Figure S5 shows that the indistinguishability increases as we reduce the time window for post-selection, while we lose the brightness of single photons. To achieve both high indistinguishability and brightness we can consider quasi-resonant [8, 9] or s-shell resonant excitations [10-13] that reduce the influence of dephasing.

Fig. S5. Indistinguishability (black dots) and brightness (red dots) of single photons as a function of temporal post-selection in Fig. 5(b).

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