Indistinguishable single photons with flexible electronic triggering: supplementary material

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This document provides supplementary information to "Indistinguishable single photons with flexible electronic triggering," <http://dx.doi.org/10.1364/optica.3.000493>. We provide additional information about our experimental setup regarding pulses generated by electro-optic modulation and the spectral filtering of the resonance fluorescence (RF) photons in the two-photon interference (TPI) experiment. We also present some technical details on the numerical simulations referred to in the primary manuscript as well as further details on our Rabi-oscillations measurement. © 2016 Optical Society of America

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1. NUMERICAL SIMULATION FOR PULSED RESONANCE FLUORESCENCE

Our numerical simulation is based on the master equation method (e.g., see [1–3]). We use the well known Hamiltonians describing a driven (1) two-level atom for the X^{1-} and (2) V-type three level atom for X^0 state of the InGaAs quantum dot (see Fig. S1).

Fig. S1. Level diagrams for X^0 and X^{1-} at an external magnetic field of $B_{ext} = 0$. The X^{1-} is modelled as a two-level system (due to the degeneracy of the excited and ground state levels), and the X^0 as a V-type three-level atomic system. δ_0 is the electron-hole exchange interaction energy, the red arrows represent the driving field and ω its frequency.

The Hamiltonian for the two-level system is

$$\hat{H}_{X^{1-}} = \frac{\Delta}{2}(|e\rangle\langle e| - |g\rangle\langle g|) + \frac{\Omega}{2}(|g\rangle\langle e| + |e\rangle\langle g|), \quad (\text{S1})$$

while for X^0 , we have

$$\begin{aligned} \hat{H}_{X^0} = & \frac{\Delta}{2}(|-\rangle\langle -| - |0\rangle\langle 0|) + \left(\frac{\Delta}{2} + \delta_0\right)|+\rangle\langle +| + \\ & \frac{\Omega}{2}[\cos\theta(|-\rangle\langle 0| + |0\rangle\langle -|) + \sin\theta(|+\rangle\langle 0| + |0\rangle\langle +|)], \end{aligned} \quad (\text{S2})$$

under the rotating-wave approximation. Δ is the detuning between the driving field and the transition from $|0\rangle$ ($|g\rangle$) to $|-\rangle$ ($|e\rangle$), δ_0 the electron-hole interaction energy (corresponding to a fine-structure splitting of $13\mu\text{eV}$ for the QD reported in Figs 1-4 of the manuscript). Ω represents the Rabi frequency, θ is a constant determined by the polarization angle of the (linearly polarized) driving field.

Spontaneous decay and dephasing are included in the time evolution of the system via the Lindblad terms of the master equation. The Lindblad operator acting on the density matrix ρ (for a given collapse operator $\hat{C}$) is defined as

$$L(\hat{C})\rho = \hat{C}\rho\hat{C}^\dagger - \frac{1}{2}(\hat{C}^\dagger\hat{C}\rho + \rho\hat{C}^\dagger\hat{C}) \quad (\text{S3})$$

The master equation can then be written as

$$\dot{\rho} = -\frac{i}{\hbar}[\rho, \hat{H}] + \sum_{ij} \Gamma_{ij} L(\sigma_{ij})\rho. \quad (\text{S4})$$

Here, $\sigma_{ij} = |i\rangle\langle j|$, Γ_{ij} is the decay rate from state $|j\rangle$ to $|i\rangle$ and Γ_{ii} represents the pure dephasing rate of state $|i\rangle$, where $i, j = e, g, 0, +, -$. For example, $\Gamma_{eg} = 1/T_1$, $\Gamma_{ee} = \Gamma_{gg} = 1/T_2 - 1/2T_1 = 0$ for $T_2 = 2T_1$ where T_1 is the exciton lifetime, and $1/T_2$ is the total dephasing rate.

Using the Runge-Kutta fourth-order method, we obtain numerical solutions of the master equation and calculate the auto-correlation function from the obtained density matrix elements. We simulate pulsed excitation by incorporating the corresponding temporal pulse intensity profile and pattern into the driving field $\Omega(t)$ as $I(t) \propto \Omega(t)^2$.

While we use Gaussian temporal pulse profiles to obtain the simulation results in the trend shown in Fig. 5 of the primary manuscript, for the results shown in Fig. 2(c) and (d), we use a ~ 100 -ps-wide lognormal temporal profile which is obtained by fitting to the intensity profile measured from the EOM output. This closely matches the (asymmetric) intensity profile of our excitation pulses.

2. MODULATION SETUP

We use a z-cut electro-optic modulator having a dual bias-port (for coarse- and fine-tuning) with $V_\pi = 2\text{V}$ to cause the phase shift required to change from minimum to maximum transmission. The EOM is driven by a PPG with a 12.5 Gb/s pulse amplifier at the output to ensure full modulation depth. As mentioned in the main manuscript, the high modulation extinction ratio is achieved and actively maintained by a modulator bias controller which uses two photodetectors, with different sensitivities. The lower(higher)-sensitivity detector is used in the coarse(fine) tuning of the modulator bias. Two 95:5 beam splitters are used to tap off light from the EOM output for coupling to the respective photo-detectors.

3. SPECTRAL PROFILE OF EXCITATION PULSES

We characterise the spectral profile of the 100-ps pulses from the output of the electro-optic modulator (EOM) used in the experiment with a Fabry-Perot scanning interferometer having 27-MHz resolution and a free spectral range of 5.5 GHz. There is a broadening of the modulated light in the spectral domain as compared with the continuous-wave (CW) light, with longer pulses exhibiting narrower spectral widths as expected. Fig. S2 compares the measured frequency-domain profile of the 100-ps pulses used for the two-photon interference and antibunching measurements reported in the manuscript with those of 1-ns and 4-ns pulses.

4. RF SPECTRUM/FILTERING IN TPI MEASUREMENTS

As mentioned in the main manuscript, the RF photons were spectrally filtered using a 12-GHz-bandwidth grating-based filter for the TPI experiment. We show typical spectral data for a 100-ps pulsed RF from a quantum dot in our sample in Fig. S3 to compare the unfiltered RF spectral widths with the filter bandwidth. We show the pulsed RF spectrum on a Log scale to

Fig. S2. High resolution spectrum of excitation pulses at different pulse widths w . The points and lines respectively represent experimental data and fits of Gaussian functions to the data, from which we obtain a full-width-at-half-maximum (FWHM) of 1.3 ± 0.1 GHz ($5.4 \pm 0.4 \mu\text{eV}$) for the 100-ps pulses.

highlight the phonon sideband. In this QD the phonon sideband to zero-phonon line ratio is $\sim 1 : 9$.

Fig. S3. High-power spectrum of RF photons under 100-ps pulsed excitation. Typical spectral data for a 100-ps pulsed RF from a single quantum dot ($\lambda \sim 960\text{nm}$) in our sample with no filtering plotted on log scale to show the phonon sideband and showing the bandwidth of the filter used in the Hong-Ou-Mandel-type TPI measurements. This spectral data was acquired using a $35\text{-}\mu\text{eV}$ resolution grating spectrometer. The linewidth of the zero-phonon line shown here is limited by spectrometer resolution. We note that $>87\%$ of the total signal spectra lies within the pass band of the filter.

Fig. S4. X^{1-} Rabi oscillations measurement using (a) 2-ns at ~ 188.5 nW peak power and (b) 5-ns excitation pulses at ~ 55.5 nW peak power. The red line represents a fit of the theoretical excited state population to the Rabi oscillations when the shape of the excitation pulse is taken into account, i.e., using Eq. S7 in Eq. S5 for the fit gives a dephasing time $T_2 = (2.02 \pm 0.27) T_1$.

5. FITTING FUNCTION FOR RABI-OSCILLATIONS MEASUREMENT

The function fitted to the Rabi oscillation data describing the probability of being in the excited state is obtained by solving the density-matrix equations for a resonant driving field, including the effects of decoherence due to spontaneous emission and pure dephasing, which is a well known result (e.g., it is the same result used to fit Rabi-oscillation data as reported in Ref. [4]), i.e.,

$$\rho_{22}(t) = \frac{\Omega^2/2}{\Omega^2 + 1/(T_1 T_2)} \times \left\{ 1 - \left[\cos(\xi t) + \frac{1/T_1 + 1/T_2}{2\xi} \sin(\xi t) \right] e^{-\frac{1}{2}(1/T_1 + 1/T_2)t} \right\}. \quad (\text{S5})$$

Here,

$$\xi = \sqrt{\Omega^2 - \frac{(1/T_2 - 1/T_1)^2}{4}}, \quad (\text{S6})$$

Ω is the Rabi frequency, and T_1, T_2 are again the exciton lifetime and the total dephasing time respectively.

6. TEMPORAL PROFILE OF EXCITATION PULSES FOR RABI OSCILLATION MEASUREMENTS

The 2-ns optical excitation pulse which were used for the Rabi oscillation measurement shown in Fig. 1 (d) of the main manuscript is a faithful reproduction of the electrical pulse from the PPG, which has a slow rising edge. The effect of the increasing power over the duration of the 2-ns pulse is to cause a

Fig. S5. (a) Efficiency and (b) G^2 trend with varying trigger frequency under excitation with 100-ps π pulses. An exponential decay was fit to the data in (a). We observe similar values for $G^2(0)$ (≈ 0.1) over the range of trigger frequencies 20 to 160 MHz.

slight chirp (i.e., variation with time) in the frequency of Rabi oscillation Ω . For the result presented in the main manuscript, this effect is not modelled in the function used to fit the Rabi oscillations because it has negligible consequence for the main result of $T_2 = 2T_1$.

Here, we include the effect of the temporal profile of the driving field in the fitting function, by setting Ω not as a constant but as

$$|\Omega(t)|^2 \propto (P_0 + P_1 t + P_2 t^2) \quad (\text{S7})$$

This quadratic function gives an excellent fit to the varying excitation power over the region of the Rabi oscillation fit to the RF from which we obtain the actual parameters P_0, P_1 and P_2 which we then use to define the time variation of Ω . In Fig. S4, we show examples of fits obtained when we use Eq. S7 in Eq. S5 for the fit. This gives $T_2 = (2.02 \pm 0.27) T_1$ in agreement with the case used to fit the data in the main manuscript in which the excitation pulse is assumed to be flat. For comparison, we also show the measurement obtained using 5-ns pulses which gives a consistent result.

7. EFFICIENCY AND PULSED ANTIBUNCHING AS A FUNCTION OF TRIGGER FREQUENCY

We show plots of $G^2(0)$ and overall efficiency as a function of trigger frequency under excitation with 100-ps π pulses. As shown in Fig. S5(a), we find that the overall efficiency (i.e., the

ratio of single-photon count rate and trigger rate) reduces as a function of trigger frequency with π -pulse excitation. We understand this to be mainly due to an artifact caused by the dead time of our TCSPC system which is ≤ 80 ns. In Fig. S5(b), $G^2(0) \sim 0.1$ is fairly constant until $f \sim 160$ MHz. At this point, we observe an onset of a quasi-CW operation caused by overlap between peaks in $g^2(\tau)$ leading to a background of $g^2(\tau)_{\min} \sim 0.03$ (see Fig. 2 (b) of the main manuscript). The trigger frequency at which this occurs is determined by the lifetime T_1 .

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