Supplementary Material: Ultrafast photon-photon interaction in a strongly coupled quantum dot-cavity system

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QUANTUM NATURE OF THE COUPLED SYSTEM:

The quantum nature of the coupled QD-cavity system is proved by performing photon auto-correlation measurement of the cavity transmitted light. All the photon statistics measurements were performed using the Hanburry Brown and Twiss (HBT) setup. We measure the histograms corresponding to the coincidences between two counters. We tune the pulsed laser to the dip in the transmission spectrum (between two polaritons) and perform second-order correlation measurement on light transmitted through the cavity cavity (as in our prior work - [2]). Figure 1a shows the histogram, where the coincidence counts at zero time delay are increased compared to the non-zero time delays. This is a signature of photon bunching, and indication of photon-induced tunneling. Similar experiment with the laser tuned slightly above the polariton frequency results in anti-bunching, where the coincidence count at zero time delay is smaller than the coincidence counts at non-zero time delay (Figure 1 b). This is the signature of photon blockade. We estimate $g^{(2)}(0)$ as the ratio of the coincidence counts at zero-time delay and non-zero time delay. The observation of these photon blockade and photo-induced tunneling thus proves the quantum nature of the coupled QD-cavity system.

SWITCHING WITH CONTROL AND SIGNAL BEAMS AT DIFFERENT FREQUENCIES:

In applications such as quantum non-demolition measurements, the interaction between two frequency-detuned probe and signal fields is of interest. We have previously performed all optical switching with two slightly frequency detuned CW control and signal beams ([3]). We now perform our pulsed switching experiment when the control beam is detuned by up to $\Delta\lambda = 0.15$ nm from the cavity frequency while the CW signal field is maintained on resonance with the cavity. Two instances are displayed in Fig.2, corresponding to detunings of $\Delta\lambda = \{0.07, 0.14\}$ nm for the top and bottom plots, respectively. After the alignment is done at comparable averaged CW and pulsed powers ('align' curve in Fig.2(a)), the experiment is conducted with similar intracavity photon number for the CW and pulsed beams. The experiment shown uses a CW-beam and a pulsed beam with 160 nW (corresponding to $\langle a^\dagger a\rangle \sim 0.07$) and ~ 2 nW, respectively (measured before the lens). Fig. 2(b) displays the

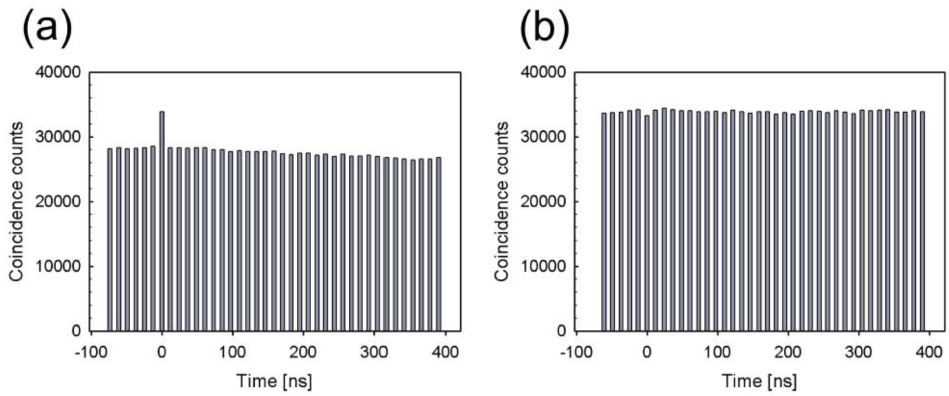

FIG. S 1: (color online) Experimental observations of photon induced tunneling and blockade under pulsed excitation ($\tau_p \sim 24$ ps pulses with 80 MHz repetition frequency). (a) Coincidence measurement obtained when the laser is tuned to the dip between polaritons. Increased coincidence counts at $t = 0$ indicate the photon induced tunneling regime. (b) Coincidence measurement obtained when the laser is tuned to the polariton (in this case, the one at lower frequency). The reduced coincidence counts at $t = 0$ indicate the photon blockade regime. The average laser power for the measurement is $P_{avg} = 0.2$nW.

transmitted power acquired on the streak camera, which shows a strong nonlinear increase for the pulse duration.

ANALYTICAL MODEL

The QD is described as a two level system with a ground state $|g\rangle$ and an excited state $|e\rangle$. The system is characterized by a dipole decay rate γ, a cavity field decay rate κ, and a QD-cavity field coupling at the Rabi frequency g. The driving field is described by $\Omega(t)$. The interaction of the laser field with the coupled QD-cavity system is described by the Jaynes Cummings Hamiltonian (in a frame rotating at the laser frequency)

$$H = \Delta\omega_c a^\dagger a + \Delta\omega_d \sigma^\dagger \sigma + ig(a^\dagger \sigma - a\sigma^\dagger) + i\sqrt{\kappa}\Omega(t)(a - a^\dagger) \tag{1}$$

where $\Delta\omega_c = \omega_c - \omega_l$ and $\Delta\omega_d = \omega_d - \omega_l$ are respectively the cavity and dot detuning from the driving laser.

To incorporate the incoherent losses in the system we find the Master equation, given by

$$\frac{d\rho}{dt} = -i[H, \rho] + 2\kappa\mathcal{L}[a] + 2\gamma\mathcal{L}[\sigma] + 2\gamma_d\mathcal{L}[\sigma^\dagger\sigma] \tag{2}$$

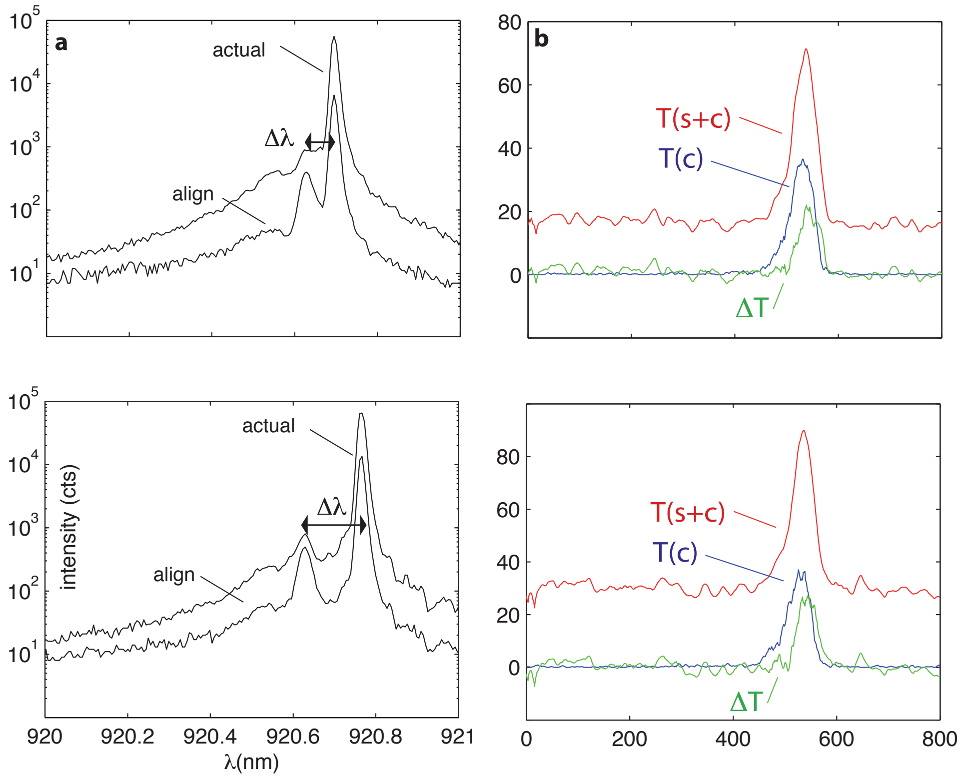

FIG. S 2: Nonlinear interaction between a CW-signal beam tuned to the cavity and a control pulse detuned by $\Delta\lambda$. (a) The 'align' curve shows the time-averaged control and the attenuated laser intensities; the 'actual' shows the average powers of the pulsed control and cw signal beams used in the experiment: ~ 2 nW for the control, 160 nW for the CW beam. (b) The control pulse results in a nonlinear transmission of the signal of ΔT.

where ρ is the density matrix of the coupled QD/cavity system and γ_d is the quantum dot pure dephasing rate. $\mathcal{L}[D]$ is the Lindblad operator corresponding to a collapse operator D. This is used to model the incoherent decays and is given by:

$$\mathcal{L}[D] = D\rho D^\dagger - \frac{1}{2}D^\dagger D\rho - \frac{1}{2}\rho D^\dagger D \tag{3}$$

The Master equation is solved using Monte Carlo integration routines (for the mixed CW and pulsed case) and by using the numerical integration routines (for the two pulse switching case) provided in the quantum optics toolbox[1]. For the two pulse switching, we assume a Gaussian pulse-shape for the pulses.

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