Non post-selected indistinguishable single photons generated by a quantum dot under resonant excitation

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We report on two-photon interferences from highly indistinguishable single photons emitted by a quantum dot. Strictly resonant excitation with picosecond laser pulses allows coherent state preparation with a significantly increased coherence time ($T_2 \sim 1$ ns) and reduced lifetime ($T_1 \sim 650$ ps), as compared to a non-resonant excitation scheme. Building-up the Hong-Ou-Mandel dip without post-selection of the interfering photons, visibilities greater than 70 % have been observed. Near-unity indistinguishable photons could be achieved for every dot if charge noise is controlled. Indeed, the remaining decoherence mechanism is likely due to the fluctuating electrostatic environment of the dots.

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Solid state single photon emitters have demonstrated the past decade their high potential for many new applications in the field of nanophotonics 1 and quantum information technology 2 . The requirements for efficient on-demand generation of single photons have been partially fulfilled by using quantum dots which have high internal quantum efficiency, embedded in microcavities or photonic crystals for a high extraction efficiency into a specific single mode 3 . Furthermore, quantum computing schemes with linear optics and quantum teleportation 4 require indistinguishable photons, a fundamental property which can be tested by two-photon interferences on a beam splitter in a Hong-Ou-Mandel (HOM) experiment 5 . Such two-photon interference experiments have been realized the past few years with post-selection of the single photons emitted by a quantum dot (QD), showing their interesting potential but also revealing the limitations of incoherent excitation 6-7 . Ideally the photons must be Fourier-transform limited, so the coherence time is truly limited by radiative lifetime. However, for a solid-state emitter like a QD, this is at present difficult to achieve. QDs are strongly interacting with their environment mainly through phonons and trapped charges, leading to dephasing processes 8 . Resonant excitation is a necessary condition to keep coherence and a lot of effort has been devoted to this task 9 . On resonance excitation allows coherent state preparation increasing the coherence time $T_2$ while reducing the spontaneous emission rate $T_1$ without the need of a cavity 10,11 . Moreover, pulsed excitation rather than continuous-wave laser excitation must be used in order to generate single photons in a deterministic way 12,13 . Having on-demand near-unity indistinguishable photons will open the way for realizing entangled photon pairs from one single dot or from remote emitters and recent experimental demonstrations are leaning in this direction 14.

In this Letter, we report on resonant luminescence from a single InAs/GaAs QD under resonant picosecond (ps) pulsed excitation. The QD two-level system, is addressed with $\pi$ pulses corresponding to maximum population on the excited level, a neutral exciton in our case. Independent measurements of lifetime $T_1$ and coherence time $T_2$ show a degree of indistinguishability $T_2/2T_1 \sim 0.7$. Second order correlation measurements of the photoluminescence show an antibunching of the order of $g^2(0) = 0.07$, with a very low background and without any laser filtering. Two-photon interference on a beam-splitter of two single-photon wave packets without post-selection, show a maximum visibility of 0.73, in very good agreement with the direct measurements of $T_1$ and $T_2$. Varying the delay between the arrival time of the two photons on the beam-splitter allows to built the Hong-Ou-Mandel dip. The measurements agree very well with the theoretical dependence of the second-order correlation function on the time delay without any adjustable parameters.

InAs/GaAs self assembled QDs were grown by MBE on a planar [001] GaAs substrate and embedded in a planar microcavity made of unbalanced AlGaAs/GaAs Bragg mirrors, with 24 pairs below and 12 pairs above the QDs plane (Fig. 1a). The purpose of the Bragg mirrors is just to enhance the luminescence collection efficiency rather than achieving a QD-cavity strong coupling regime with a significant Purcell effect. Therefore the quality factor of the overall structure is low, about 500 but the luminescence signal is increased by a factor 20 to 50. In addition, micrometer ridges (0.8 to 1.2 $\mu$m) are etched on the top surface to design single-mode one dimensional waveguides 15. The QDs are excited along the waveguide by picosecond pulses from a tunable mode-locked Ti-Sapphire laser which polarization along the y axis is imposed by the geometry (Fig. 1a). Thus, on resonance a single eigenstate of the fine structure split exciton state is addressed. In this geometry, the laser is confined in
Figure 1: (Color online) a) SEM image of one ridge. One can see the Bragg mirrors above and under the QD plane which has been emphasized with a red dashed line. Red arrows show the excitation and the collection paths. b) Schematic drawing of the experimental setup. A pulsed ps Ti:Sapphire laser comes through a first delay line resulting in two pulses separated by $\tau_0 \pm \Delta \tau$ with $\tau_0 = 3$ ns every 12.2 ns. The luminescence is collected by a large N.A. microscope objective, coupled into an optical fiber and sent either into a spectrometer or a fibered Mach-Zender interferometer with two fibered beam splitters (FBS) with fixed $\tau_0$ delay for photon correlation studies. A fibered polarization setup equivalent to one $\lambda/2$ and $\lambda/4$ plates controls the outcoming photons polarization. c) Resonant spectrum in semi-logarithmic scale of the studied QD at 7 K: experimental data (black dots) are fitted with a Lorentzian line (red) and a wide gaussian (blue dashed line) corresponding to the scattered laser. The inset shows the polar diagram of the QD resonant emission. d) Rabi oscillation of the studied QD population. The luminescence intensity is represented by squares and plotted as a function of the square root of the excitation power. The red line is a simulation from optical Bloch equations including excitation-induced damping. The blue dashed line is a simulation of the oscillation without excitation-induced decoherence.

The guided mode enhancing the light-matter interaction and the QD luminescence is collected from the ridge top surface by a confocal microscope (Fig. 1a,b). The scattered laser is thereby greatly suppressed, leading to almost background-free spectra without any need for further polarization filtering. Strictly resonant experiments can then be performed (Fig. 1c). Polar diagrams can be realized to further characterize the QD eigenstates, as shown in the inset in Fig. 1c, where the probed QD emission is linearly polarized, a characteristic of a neutral exciton\(^1\). The luminescence is coupled into a single-mode optical fiber that can be connected to different setups for spectroscopy, or for first order and second order correlation measurements (Fig. 1b). Our setup enables to detect up to 250,000 counts per second on a single-photon avalanche detector (SPAD).

It is worth noticing that resonant excitation is not systematically observed for all the probed QDs. Indeed, it has been reported that resonant excitation can be suppressed due to the presence of trapped charges in the vicinity of the QDs\(^2\). In that case, adding a very low power He-Ne laser helps to recover the resonant luminescence. More details on the influence of an additional He-Ne laser will be discussed in the following. The resonant interaction between the QD and the excitation field gives rise to the well-known Rabi oscillations (RO) of the excited level population. The luminescence intensity is represented by squares and plotted as a function of the square root of the excitation power (Fig. 1d). The damping behavior of such RO under pulsed excitation has been analyzed in Ref [11] for similar samples but without Bragg mirrors. Excitation-induced dephasing processes are mainly due to the resonant coupling between the QD and LA-phonon modes. We have also evidenced that the resonant coupling between the 1D optical mode and the two-level system leads to an acceleration of the radiative lifetime responsible for an additional excitation-induced dephasing mechanism\(^3\). In the following, all the ex-
A similar behavior has been observed for the radiative lifetime which varies slightly from 650 ps to 700 ps. This effect can also be explained by the local modification of the electrostatic potential that alters the overlap of the hole and electron wavefunctions inside the dot, thus modifying the transition probability. The fluctuating electrostatic environment has also been indirectly observed through a lessening of the resonant luminescence intensity. In that case, the charges may tunnel from a nearby defect into the QD, modifying the first excited state from a neutral to a charged exciton, therefore suppressing the resonance with the excitation laser as reported in Ref. [17]. We had also to deal with the same problem and using a very low power (few pW) He-Ne laser, the neutral exciton resonant luminescence intensity was increased tenfold, from 25,000 to 250,000 counts/s on the SPAD. Laser scattering and luminescence due to the He-Ne laser solely, has been estimated to be less than 100 counts/s, comparable to the detector’s dark counts.

In a two-photon interference experiment, two in-
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tors, thus extracting the second order correlation func-
togram between the photons arriving on the two detec-
tion

every excitation delay we build the coincidences his-
tory of the HOM dip for a neutral QD with strictly

distinguishable photons arriving at the same time on

a 50/50 beam splitter coalesce and emerge along the

same output port of the beam splitter. Then, no simul-
taneous detection occurs on the two output detectors.

The setup for the realization of the HOM experiment

in shown in Fig 1b, where one laser pulse is split into

two pulses separated by delay $\tau_0 = 3$ ns. The delay

line can be adjusted from 1 to 5 ns. After two pulses

excitation, the QD emits two sequential photons that

are sent into an all-fibered unbalanced Mach-Zehnder

interferometer with a fixed delay $\tau_1$. We insert in both

arms a fibered polarization control setup equivalent to

a $\lambda/2$ plate followed by a $\lambda/4$ in order to compen-
sate the birefringence induced in the optical fibers. Each

interferometer output is coupled to an SPAD and for

every excitation delay we build the coincidences his-
togram between the photons arriving on the two detec-
tors, thus extracting the second order correlation func-
tion $g^{(2)}(\Delta \tau)$.

The data are plotted versus the difference between

to noise ratio for each measurement.

For long delays, the temporal overlap of the two suc-
cessive photons is reduced and the limit value of 1 is

reached as the two photons are totally distingui-

shable. As $\Delta \tau$ goes to zero, the two photons interfere

constructively, until perfect time matching for $\Delta \tau = 0$

and for totally indistinguishable photons and per-
fet 50/50 beam splitter, $g^{(2)}(0) = 0$. From equation

(1), $g^{(2)}(0) = 1 - \frac{2RT}{1 - 2RT} \frac{T_2}{T_1}$, and gives a direct value

of the degree of indistinguishability defined by the ra-
tio $T_2/2T_1$. In the case of the probed dot, we measure

$T_2/2T_1 = 0.73 \pm 0.05$, which is also in perfect agree-
ment with the direct measurement of $T_2/2T_1 \sim 0.7$.

In summary, we have reported on the first observa-
tion of the HOM dip for a neutral QD with strictly

resonant pulsed excitation, without polarization post-
selection of the emitted photons. The resonant ex-
icitation preserves coherence and accelerates the ra-
diative lifetime, enhancing by a factor of 7 the ratio

$T_2/2T_1$. Therefore, near-unity indistinguishability of

dispersive photons could be reached systematically for ev-
ey dot once charge noise is controlled. Applying an

electric field in a suitably designed structure could be a

way to clear out this dephasing mechanism and achiev-
ing radiatively-limited optical linewidths.

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Figure 4: (Color online) Two-photon interference experiment

showing the Mandel dip. $\Delta \tau$ is relative delay between the two

Mach-Zehnder interferometers, counted positively when the

excitation interferometer delay is longer than the detection

one. The red square and green triangle lines are theoretical

evolutions of $g^{(2)}(\Delta \tau)$ for two extreme measured values of $T_1$

and $T_2$ (see text).

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$g^{(2)}(\Delta \tau) = 1 - \frac{2RT}{1 - 2RT} \frac{T_2}{2T_1} e^{-2|\Delta \tau|/T_2}$

$+ \frac{T_2}{2T_1} \left( e^{-|\Delta \tau|/T_1} - e^{-2|\Delta \tau|/T_2} \right)$

(1)

where R and T are the (intensity) reflection and transmis-
sion coefficients of the beam splitter which has

been measured independently to be 60/40 at the QD

wavelength. $T_2^*$ is a pure dephasing time defined by:

$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{1}{T_2}$. From the measured values of $T_2$ and $T_1$

can deduce that $T_2^* \sim 3$ ns, which reflects that pure

dephasing which is related among others to the pres-

ence of fluctuating charges can have an important im-

pact on the coherence properties since it is of the same

order of magnitude as $T_2$. The red (squares) and green

(triangles) curves in Fig. 4 represent the calculated

$g^{(2)}(\Delta \tau)$ using equation (1) with the measured values

of $T_2$ and $T_1$. The red (squares) curve correspond to the

least advantageous case where $T_2$ is minimum (900 ps)

and $T_1$ is maximum (700 ps) while the green (triangles)
curve correspond to the most advantageous case with

$T_2$ maximum (950 ps) and $T_1$ minimum (650 ps). The

experimental data agree very well with the calculated

curves, except for the longest negative delays where a

discrepancy is observed likely due to experimental un-
certainties. Each experimental data point corresponds
to one hour acquisition time, which is long enough so
fluctuations of the light coupling occur, therefore in-
creasing the noise. The error bars represent the signal
to noise ratio for each measurement.

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