Single photons and entangled photons from a quantum dot

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Abstract

We present an efficient source of indistinguishable single photons based on a pulsed excitation of a self-assembled InAs/GaAs quantum dot embedded in a three-dimensional micropost microcavity. The probability of generating two photons for the same pulse is reduced to 2%, compared to a Poisson-distributed source of the same intensity. An extension of this technique can be used to generate entangled photons. This photon source is crucial for practical implementations of quantum key distribution, as well as for quantum computation and networking based on photonic qubits.

Introduction

One of the best-known principles of quantum mechanics states that it is impossible to measure the state of a single quantum system without the risk of changing that state. This idea is the foundation of the growing field known as *quantum cryptography*, or *quantum key distribution*. If the transmitted message is encoded in the polarization states of single photons, as in the BB84 protocol (1), any attempt to eavesdrop on the communication channel can be detected, because it will impose a back-action on the states of transmitted photons.

Generation of single and entangled photons is crucial for practical implementation of quantum cryptography and quantum key distribution (QKD) (1,2), as well as for quantum computation (3) and networking based on photonic qubits (4,5). Three different criteria are taken into account when evaluating the quality of a single-photon source: *efficiency*, *photon statistics* (measured by the second-order coherence function $g^2(0)$), and *quantum indistinguishability*. The requirements are dependent on the specific application; for example, $g^2(0)$ should be as small as possible for BB84 QKD. The quantum indistinguishability is the most important criterion: for almost all applications in quantum information systems (except BB84 QKD), we need photons that are indistinguishable and thus produce multi-photon interference.

Our scheme for generation of single photons is based on the pulsed excitation of a self-assembled InAs/GaAs quantum dot (QD) combined with the spectral filtering (6-8), and an

extension of this technique can be used to generate entangled photons (9-10). To increase the photon extraction efficiency and reduce the duration of single-photon pulses emitted from semiconductor systems, we employ cavity quantum electrodynamics (CQED) in the low-Q regime. For this purpose, we build three-dimensional (3D) micropost microcavities around the QD emitters (11). In our single-photon sources, the probability of generating two photons for the same pulse is reduced to 2%, compared to a Poisson-distributed source of the same intensity (12). The emitted photons are efficiently coupled to fibers at high data rates - presently at 76 MHz, but potentially higher than 10 GHz (13). The external coupling efficiency is measured to be as high as 40% (14). We have also been able to generate polarization controlled single photons (12). Moreover, we have confirmed that our sources emit identical (indistinguishable) photons: the mean temporal pulse duration and coherence length are close to satisfying the Fourier transform limit (12), and consecutive photons demonstrate two-photon interference in a Hong-Ou-Mandel-type experiment (15).

Single-photon source: a single quantum dot in a micropost microcavity

Our present paradigm for generation of single photons on-demand is a combination of pulsed excitation of a single self-assembled semiconductor QD and spectral filtering (6-8,12-15). When such a QD is excited with a short (3 ps) laser pulse, electron-hole pairs are created either within the dot, for resonant excitation with the laser frequency tuned to a transition between the higher confined states of the dot, or in the surrounding semiconductor matrix, for above-band excitation with the laser frequency tuned above the semiconductor band gap. In the case of the above band-excitation, carriers diffuse towards the dot, where they relax to the lowest confined states. The created carriers recombine in a radiative cascade, leading to the generation of several photons for each laser pulse. All of these photons have slightly different frequencies, resulting from the Coulomb interaction among carriers. The last emitted photon for each pulse has a unique frequency, and can be spectrally isolated. With resonant excitation, the favored absorption of a single electron-hole pair and formation of one-exciton state is

Fig. 1. Photoluminescence spectra from a single self-assembled InAs/GaAs quantum dot under above-band (top), or resonant (bottom) excitation. With resonant excitation, the favored absorption of a single electron-hole pair and formation of one-exciton state is expected

expected (see Fig. 1). Moreover, no carriers are created in the vicinity of the QD, suppressing dephasing due to charge fluctuations.

Triggered single photons can therefore be generated using quantum dots grown in a bulk semiconductor material, but the efficiency of such a system is poor, since the majority of emitted photons are lost in the semiconductor substrate (6). In order to increase the efficiency of a single-photon source, a well-designed optical microcavity can be fabricated around a quantum dot, and CQED in the low-Q regime can be employed (11-15). The additional advantage of CQED is that the duration of photon pulses emitted from semiconductor QDs is reduced. If an emitter is located within an optical cavity of small volume and high finesse, its spontaneous emission properties are changed. The spontaneous emission rate of an emitter on resonance with a cavity mode is enhanced, and this enhancement is proportional to the ratio of the mode quality factor to the mode volume. Because of the enhanced coupling into a single cavity mode, the spontaneous emission becomes directional, and a large fraction of the photons are emitted into a nicely shaped cavity mode, and can be coupled into downstream optical components.

Our single photon source consists of a single InAs/GaAs quantum dot located in the center of a one-wavelength-thick GaAs spacer, and coupled to the fundamental mode of a three dimensional distributed Bragg reflector (DBR) micropost microcavity shown in Fig. 2. Molecular beam epitaxy is used for the growth of quantum dots and planar DBR (GaAs/AlAs) mirrors, and microposts are subsequently etched around quantum dots, after being lithographically defined. The microcavities shown in Fig. 2 have diameters ranging from 0.3 μm , and heights equal to 5 μm . The top and bottom

(a)

(b)

Fig. 2. (a) Scanning electron micrograph showing a fabricated array of 3D GaAs/AlAs microposts, with InAs/GaAs QDs. Remaining etch mask (Al_2O_3) is visible at the top of the structures. (b) Electric-field components for the fundamental HE_{11} mode in a micropost microcavity. The left figure illustrates the electric-field component parallel to the DBRs, while the figure on the right represents the electric field component perpendicular to the DBRs. The micropost parameters are as follows: the cavity diameter 0.5 μm , the refractive indices of high/low refractive index regions 3.57 and 2.94, the DBR periodicity 155 nm, the thickness of the low refractive index mirror layer 85 nm, the spacer thickness 280 nm, and the number of mirror pairs on top/bottom is 15/30.

mirrors have 12 and 30 DBR pairs, respectively, and the etch goes through the bottom 19 pairs. An InAs/GaAs QD layer, with the density of self-assembled dots equal to $50 \mu\text{m}^{-1}$, is located in the center of the spacer. The measured quality (Q) factors of these structures are around 1300, Purcell factors are around five (Fig. 3) (12), which corresponds to a spontaneous emission coupling factor into a single cavity mode $\beta \sim 80\%$, and the external coupling efficiencies are measured to be as high as 40% (14). According to the detailed theoretical treatment of the micropost device (13), the cavity Q-factor in the optimized designs can be much larger ($Q \sim 10000$), together with the mode volume smaller than two cubic optical wavelengths of light ($V \sim 1.6(\lambda/n)^3$), leading to the much higher values of Purcell factor ($F_p \sim 100$) for a QD located at the cavity center. The reduced spontaneous emission lifetime should be 5–10 ps, which allows the generation of single photons at a rate higher than 10 GHz.

By employing the previously described technique, we have been able to successfully generate triggered single photons from InAs/GaAs QDs. Sources operate at temperature below 40 K, and emit photons with wavelengths between 870 nm and 960 nm, depending on the QD properties. Structures are characterized by employing the setup illustrated in Fig. 4, which allows us to isolate the luminescence from a single quantum dot, and identify different spectral lines. For the structures shown in Fig. 2a, with Q factors around 1300 and Purcell factors around five (Fig. 3), the probability of generating two photons for the same laser pulse (estimated from $g_2(0)$) can be as small as 2% compared to a Poisson-

Fig. 3. **Top-left:** Background emission filtered by the cavity, featuring the cavity Q-factor of 1300. **Top-right:** Decay rate of the emission line as a function of the absolute value of its detuning from the cavity resonance ($|\lambda_{\text{QD}} - \lambda_c|$). The dot emission wavelength was tuned by changing the sample temperature within the 6 K - 40 K range. **Bottom:** time-dependent photoluminescence from the emission line on-resonance with the cavity, as opposed to this same emission line off-resonance. Purcell factor is equal to five in this case.

Fig. 4. Experimental setup employed in characterization of a single photon-source. The sample with microposts is placed in a liquid He cryostat. The microposts are excited from a steep angle by resonant Ti:sapphire laser pulses, 3 ps in duration, with a 76 MHz repetition rate. The emission is collected normal to the sample surface, and directed towards a streak camera preceded by a spectrometer for time-resolved photoluminescence measurements. The spectral resolution of the system is 0.1 nm, together with a time resolution of 25 ps. The right-hand-side portion of the setup (after the third lens) corresponds to Hanbury Brown and Twiss type setup, used to measure second order coherence function $g_2(\tau)$.

distributed source of the same intensity (see Fig. 5) (12). We have also been able to generate polarization controlled single photons, by employing the splitting of the one-exciton state into a linearly polarized doublet together with a polarization splitting of the fundamental cavity mode (12). Moreover, we have confirmed that our sources emit identical (indistinguishable) photons: the mean temporal pulse duration and coherence length are close to satisfying the Fourier transform limit (12), and consecutive photons demonstrate two-photon interference in a Hong-Ou-Mandel type experiment (15).

Conclusions

We have demonstrated a source of single photons on-demand, where the probability of generating two photons for the same pulse is reduced to 2%, compared to a Poisson-distributed source of the same intensity. The source is based on a single quantum dot coupled to a three-dimensional micropost microcavity. The measured quality (Q) factors of our microposts are around 1300, Purcell factors are around five, corresponding to a spontaneous emission coupling factor into a single cavity mode $\beta \sim 80\%$. The emitted photons are coupled to optical fibers at high data rates – presently at 76 MHz, but potentially higher than 10 GHz. Moreover, the emitted photons are almost identical (indistinguishable) quantum particles, as confirmed from both the coherence length measurements, and the two-photon interference in a Hong-Ou-Mandel-type experiment. The extension of the technique presented here can be used to generate entangled photons.

Fig. 5. Photon correlation histogram for the QD from Fig. 3 on resonance with the cavity under pulsed, resonant excitation. The distance between peaks is 13 ns, corresponding to the repetition period of pulses from the Ti:sapphire laser. The histogram is generated using a Hanbury Brown and Twiss-type setup. The vanishing central peak (at $\tau=0$) indicates a large suppression of two-photon pulses. The probability of generating two photons for the same laser pulse is reduced to 2%, compared to a Poisson-distributed source of the same intensity. This probability is estimated from the ratio of the areas of the central peak and the peaks at $\tau \rightarrow \infty$, integrated over 4 ns windows. The decrease in the peak height with time indicates the dot blinking behavior generally observed under resonant excitation.

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