Bandwidth-Tunable Single-Photon Source in an Ion-Trap Quantum Network

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We report a tunable single-photon source based on a single trapped ion. Employing spontaneous Raman scattering and in-vacuum optics with large numerical aperture, single photons are efficiently created with controlled temporal shape and coherence time. These can be varied between 70 ns and 1.6 μs, as characterized by operating two sources simultaneously in two remote ion traps which reveals mutual and individual coherence through two-photon interference.

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In current designs of quantum networks based on individual quantum systems, controlled emission and absorption of single photons by single atomic systems serves for implementing local quantum memories. It also allows one to transport quantum information and establish entanglement between distant locations, or nodes [1]. The latter operation is based on the underlying entanglement between a quantum system and the photons it emits [2–4]. It also employs single- or two-photon interference as an essential resource [5]: the coincident detection of two photons emitted by distinct quantum nodes and interfering on a beam splitter can project the nodes into an entangled state [6]. Alternatively, entanglement may be generated through two indistinguishable scattering paths leading to a single-photon detection [7]. In both approaches, the coherence time of individual photons is a critical ingredient. In fact, it controls the visibility of any two-photon interference through the temporal overlap of incident photon wave packets [8]. For interfering broadband photons, high fidelity entanglement of quantum nodes thereby requires accurate synchronization of photon emissions. On the other hand, for gate operations based on single-photon interference, the photon coherence time sets the maximum path length difference between quantum nodes at the detectors.

Besides in quantum networks, single-photon sources are important building blocks in schemes of quantum communication [9], cryptography [10], and optical quantum computing [11]. The coherence length of the photons is particularly important for optimizing the efficiency of quantum information transmission, the ideal situation being tunable and Fourier transform-limited single photons which make optimal use of the available transmission bandwidth.

Single-photon sources have so far been implemented with various systems which act as functional quantum memories, for instance with quantum dots and defects, neutral atoms, and trapped ions (see [12] for a review). With single-atom devices, two approaches may be distinguished: on the one hand, single atoms (or ions) strongly coupled to high finesse resonators allow one to efficiently release individual photons with long coherence time into a single optical mode [13–16]. Quantum gates based on single- or two-photon interference can hence be implemented with flexible constraints, however, at the cost of a controlled interaction between the atom-ion and the cavity optical mode. On the other hand, single atoms or ions trapped in free space may be employed. Compared to atom-cavity devices, these in general have a multimode emission pattern which reduces the fraction of photons that can be collected in a single optical mode. Resonance fluorescence photons are furthermore broadband, with coherence times generally less than 10 ns, but exhibit a high degree of indistinguishability [17–20]. Hence, two remotely trapped ions have been entangled based on the coincident detection of two photons [21]. Moreover, note that trapped atomic ensembles also allow one to herald single photons at high efficiency [22] with a corresponding bandwidth which possibly reaches the Fourier limit [23].

In this Letter, we present experiments where single ions are trapped in front of high numerical aperture laser objectives. Such an experimental setup constitutes a tunable and narrowband single-photon source that operates with an efficiency comparable to what is reported with ion-cavity devices [14,16]. To reveal the photons coherence time, we perform Hong-Ou-Mandel interference between photons emitted by two ions in distant traps. Our analysis shows that single ions trapped in front of high numerical aperture laser objectives are relevant candidates to implement the nodes of a network with multiple and narrowband quantum communication channels.

The experimental setup is presented in Fig. 1. Single $^{40}\text{Ca}^+$ ions are trapped in two vacuum vessels separated by approximately 1 m [20]. They are excited and cooled on their $S_{1/2}-P_{1/2}$ and $D_{3/2}-P_{1/2}$ electronic transitions (see Fig. 2) by frequency-stabilized lasers at 397 nm (blue) and 866 nm (infrared), polarized perpendicularly to the quantization axis. About 4% of the blue fluorescence photons are collected by in-vacuum high numerical aperture objectives (HALOs) and coupled into the two input arms of a single-mode fiber beam splitter. Single-photon detectors placed at the beam-splitter outputs record individual photon arrival times, from which correlations are computed.

Figure 2 presents an example of the laser excitation sequence which we use to create single photons. The
FIG. 1 (color online). The experimental setup comprises two linear Paul traps confining single ions, cooled and excited by the same lasers (solid arrows) at 397 and 866 nm. The reemitted blue fluorescence is collected by two high numerical aperture objectives (HALOs) per trap (one objective is used for camera imaging and is not shown). The polarization of detected photons is selected by a combination of a quarter wave plate ($\lambda/4$) and a polarizing beam splitter (PBS). The light from the two ions is superimposed on a fiber beam splitter after further polarization control, represented by the loops. At the beam-splitter output, single photons are detected by photomultiplier tubes (PMT) with $\sim 1$ ns time resolution. A constant magnetic field along the trap-HALO direction serves as quantization axis while stray magnetic fields are compensated.

displayed timings are those used to produce the data shown in Fig. 4. Each sequence consists of alternating periods of laser cooling and manipulation of the ion’s internal state. Excitation parameters such as laser intensities and detunings, as well as the durations of the periods of the sequence, are optimized by performing numerical simulations. The latter are based on time-dependent optical Bloch equations describing the dynamics of the 8 relevant electronic levels of the single-ion wave function [24].

In Fig. 2(c), an example for the evolution of populations in the $S_{1/2}$ and $D_{3/2}$ manifolds during one excitation sequence is presented. The cooling period (part I), with both infrared “repump” and blue “pump” laser on, has a minimum duration (1 $\mu$s) such that a steady state is closely approached at its end. This ensures that the motion of the ion is efficiently cooled, before projecting the internal state into the $D_{3/2}$ manifold by switching off the repump laser (part II). Thereafter, the repump laser is turned on again while the pump laser has previously been switched off (part III). This transfers the electronic population back to the $S_{1/2}$ state and releases a blue photon.

We control the rate $\Gamma$ of this spontaneous Raman transition via the intensity of the repump laser ($\propto \Omega_r^2$, where $\Omega_r$ is the infrared Rabi frequency) and its detuning $\Delta_r$. In the regime of our experiment, $\Delta_r \sim \gamma_p$ and $\Omega_r \approx \gamma_p$, $\gamma_p = 2\pi \times 24$ MHz being the decay rate of the $P_{1/2}$ level, one expects a linear variation of $\Gamma$ as a function of the repump intensity.

The first set of experimental results, displayed in Fig. 3, characterizes one individual single-photon source implemented in one trap. Here the sequence period is set to 10 $\mu$s, and photons are collected into multimode optical fibers for higher signal to background ratio ($= 200$). The measured detection probability per excitation pulse is $4 \times 10^{-3}$. The photodetectors are gated, such that only photons emitted during the repump phase [part (III) in Fig. 2] are counted. Figure 3(a) shows the resulting second-order correlation of the arrival times of photons emitted by a single ion. Most importantly, one notes a nearly vanishing peak around zero delay time. This demonstrates that at most a single photon is emitted while exciting the spontaneous Raman transition from $D_{3/2}$ to $S_{1/2}$. The observed residual signal agrees with the expected rate of accidental correlations between emitted photons and dark counts of the photodetectors. For longer time delays, the number of correlations vanishes when the detectors are gated off, while subsequent peaks signal correlations between photons emitted during successive sequences.

In Fig. 3(b) we present the distribution of single-photon detection times, corresponding to the shape of the single-photon wave packet [14]. It is obtained by correlating photon arrival times with the logical trigger gating on the photodetectors, i.e., with the beginning of the repump phase. In these measurements we varied the intensity of the repump laser, $\propto \Omega_r^2$, for a fixed detuning $\Delta_r/2\pi = -55(5)$ MHz from the $D_{3/2}-P_{1/2}$ resonance frequency. The wave packet is characterized by a steep initial rise and a subsequent exponential decay, whose time constant $T_1 = 1/\Gamma$ we continuously control between 70 ns and 1.6 $\mu$s. The inset shows that the respective rate $\Gamma$ varies...
linearly with the excitation power, as expected. For stronger excitation one encounters more complex dynamics where the infrared laser induces coherent coupling between the $D_{3/2}$ and $P_{1/2}$ manifolds, signaled by damped Rabi oscillations in the arrival times of blue photons [see Fig. 4(a)].

The experiments reported in Fig. 3 show how we operate a single ion as a clean source of single photons emitted at a tunable rate, from nanosecond to microsecond time scales. Furthermore, light collection by the HALOs allows us to efficiently couple the generated photons into a single optical mode without the use of a cavity: with a wave-packet width of $T_1 = 250$ ns and a sequence repetition rate of 500 kHz, we reach a single-mode fiber-coupled detection rate of $\approx 200$ photons/s using a single HALO ($\approx 1000$ s before the detector).

In order to assess also the coherence time of our single-photon source, we implemented a primitive quantum network scenario, operating two sources with two single ions in independent traps (see Fig. 1). We then studied the quantum interference of two photons emitted by the distant ions. Two-photon interference, as originally shown by Hong, Ou, and Mandel, consists in the coalescence of two identical photons impinging at the two input ports of a beam splitter [8]. Both photons emerge in the same output port, inducing a dip in the coincidence rate, whose shape characterizes the coherence of the interfering light fields [25,26].

A fundamental prerequisite for two-photon interference is indistinguishability of the photons. This controls the interference contrast, i.e., the amplitude of the dip in the two-photon correlations. Hence, one must aim at ideal spatial mode matching as well as identical polarizations at the beam splitter. In our experiments this is guaranteed by the combination of a fiber beam splitter together with fiber polarization controllers. Furthermore, the frequency of the interfering photons has to be controlled accurately. This is achieved by deriving the exciting light from the same laser and by adjusting the magnetic fields in the two traps to the same value. Emitted blue photons are collected along the quantization axis. A combination of quarter-wave-plate and polarizing beam splitter ensures that solely right-circularly polarized photons are coupled into the fibers. Then, with the repump laser polarized perpendicularly to the magnetic field, electronic populations prepared in the $m = -3/2$ and $m = +1/2$ magnetic substates of the $D_{3/2}$ manifold contribute to the detected spontaneous Raman emissions. Because of the Zeeman splitting in-
duced by a magnetic field of $B = 2.2(1)\, \text{G}$, incident photons can exhibit a frequency difference of $2g_{D}\mu_{B}B = 7.5(4)\, \text{MHz}$.

Figure 4 presents results from the two networked single-photon sources. In Fig. 4(a) the normalized time distributions of emitted photons, $n(\tau)$, are shown for both sources. These were adjusted experimentally such that both ions yield near-identical profiles. One notes damped Rabi oscillations on the $D_{3/2} \rightarrow P_{1/2}$ transition, induced by the repump laser intensity being close to saturation. Precisely, we observe a dip for short time delays which reveals the coherence time of interfering photons [25].

In Fig. 4(c), emitted photons are rendered indistinguishable by adjusting their polarizations to be along the same axis. The normalized correlation function $S_{\text{in}}^{(2)}(\tau)$ exhibits a dip for short time delays which reveals the coherence time of interfering photons [25]. Precisely, we observe a 50(20)% suppression of coincidences, i.e., interference contrast, without subtracting accidental correlations.

In Fig. 4, solid lines show the results of our theoretical calculations utilizing the model described in more detail in [20]. We also include the finite optical switching of acousto-optics modulators used to create laser pulses. Indeed, for the repetition rate used in the experiments of Fig. 4 (500 kHz), we observe that a small fraction (5%) of cooling (blue) laser-light persists for 200 ns during part (III) of the sequence shown in Fig. 2. This alters the purity of our single-photon sources as it induces two-photon emission by individual ions.

In Fig. 4, we note a satisfying agreement between experimental results and theoretical predictions obtained by solely considering independently calibrated experimental parameters. We attribute the remaining discrepancy to fluctuations of experimental conditions during the overall measurement duration (12 h for Fig. 4). Furthermore, experimental and simulated values of $g_{\text{in}}^{(2)}(0)$ are similar in Fig. 4(c). This signals that observed coincidences mainly arise from correlations between photons emitted by the same ion, as correlations between detector dark counts and signal photons solely constitute 8% in our measurements. In future works, coincidences will be reduced by improved optical switching leading to high interference contrast.

As a final result, we present in Fig. 4(d) the first-order coherence of emitted photons, $g^{(1)}(\tau)$, deduced from our theoretical model. It exhibits an oscillatory behavior which we interpret as arising from the beat of the two photon frequencies of our source and the strong coherent excitation of the $D_{3/2}-P_{1/2}$ transition by the repump infrared laser. Furthermore, one notes an approximately exponential envelope with a decay time ~250 ns, which reveals the coherence time $T_{2}$ of the individual photons. An optimally coherent free-space single-photon source would feature a coherence time $T_{2} = 2T_{1}$; apart from the modulation due to the two Raman transition channels, with $T_{2} \approx T_{1}$ we are approaching this limit.

To conclude, we control and manipulate the multilevel internal structure of single ions to flexibly and efficiently engineer two nodes of a primitive quantum network, emitting photons with controlled temporal and coherence properties. In future developments, single-frequency operation will be implemented, for which individual state addressing [27] or dark resonance [28] will be employed during the pump phase. For enhanced collection efficiency, both laser objectives will be used, including enhancement by constructive single-photon interference [29], and the single-mode fiber coupling will be improved. At least tenfold efficiency improvement is hence expected.

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