A tunable narrowband entangled photon pair source for resonant single-photon single-atom interaction

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We present a tunable, frequency-stabilized, narrow-bandwidth source of frequency-degenerate, entangled photon pairs. The source is based on spontaneous parametric downconversion (SPDC) in periodically-poled KTiOPO₄ (PPKTP). Its wavelength can be stabilized to 850 or 854 nm, thus allowing to address two D-P transitions in ⁴⁰Ca⁺ ions. Its output bandwidth of 22 MHz coincides with the absorption bandwidth of the calcium ions. Its spectral power density is 1.0 generated pairs/(s MHz mW).

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Entangled photon pairs have become an important resource in experiments on fundamental quantum mechanics [1], as well as in quantum communication [2], quantum computing [3], and quantum networks [4]. The best controlled and most widely applied method to create photonic entanglement is spontaneous parametric downconversion (SPDC) in nonlinear crystals [5]. Due to the weak phase matching conditions in small size crystals, these sources usually produce rather broad output spectra with widths on the order of THz. For many applications this is convenient, since the photons interact only with detectors which are not energy selective on this scale. In recent years new SPDC sources have been developed also for narrow band applications [6–8], which are mostly aiming at coupling photonic and atomic systems [9, 10]. Still, the reported bandwidths are rather broad (≈ 100 GHz) [6,7] compared to atomic transitions, or the sources emit into multiple frequency modes [8].

In this letter we report on a photon pair source designed to permit resonant interaction with single trapped ions [11]. The photon frequency and bandwidth are made to match the linewidth of the D₃/₂–P₃/₂ and D₅/₂–P₃/₂ optical transitions in ⁴⁰Ca⁺, which are centered at 849.8 and 854.2 nm and have a width of ≈ 20 MHz. As prerequisite for efficient coupling, we achieve tunability over this range, a bandwidth reduction of six orders of magnitude compared to standard SPDC sources, and suitable frequency stabilization. This novel source will allow us to perform experiments on the coupling between single quantum systems of light and matter, with applications in quantum networks.

We obtain these characteristics by optimizing the SPDC efficiency via quasi-phase matching [12], by reducing the photon pair bandwidth in a Fabry-Perot cavity filter line, and by stabilizing the absolute photon pair frequency via active feedback on all critical elements in the set-up.

The experimental setup is sketched in Figure 1. The master laser, an extended-cavity diode laser (Toptica DL-100), provides about 30 mW of light, tunable between 850 and 854 nm. About 90 % of it is amplified in a tapered amplifier (Toptica TA-100) to 600 mW output power. The remaining light from the diode is used to stabilize its frequency to a Fabry-Perot cavity of finesse 1000 and 1 MHz linewidth, using the Pound-Drever-Hall (PDH) technique. The length of this cavity is locked to a laser at 852 nm, which itself is stabilized to the D2 line of cesium by saturation spectroscopy. An acousto-optic modulator (AOM) in the 852 nm laser beam provides fine frequency tuning. This transfer lock technique yields about 125 kHz absolute frequency stability of the master laser [13].

The amplified master beam is frequency-doubled in a lithium tri-borate (LBO) crystal within a bow-tie cavity (Toptica SHG-110), resonant with the master laser wavelength for pump power enhancement, which produces around 100 mW of 425–427 nm second-harmonic light. The resulting blue beam is sent through a single mode (SM) fiber for mode cleaning and focussed into a second nonlinear crystal where photon pairs are created via SPDC. This crystal is a flux-grown periodically poled KTiOPO₄ (PPKTP) crystal of dimensions 20 × 6 × 1 mm [14]. It has two independent parallel poling gratings imprinted, with periods of 14.03 and 14.63 μm, for collinear type-II quasi-phase-matching at a temperature of 25°C for 849.8 and 854.2 nm, respectively [15].

To optimize the focus of the pump mode, we utilize the reverse process of second-harmonic generation (SHG), which is legitimate due to the narrow-bandwidth of the source [16]. The optimum focussing parameter, the ratio of crystal length and Rayleigh range $\xi = L/z_R = 5.68$ [12], requires a pump beam waist of $w_0 = 16.1 \mu$m. Fine tuning and stability of the central wavelength of the photon pairs is achieved by temperature control. The temperature of the crystal is actively stabilized with better than 10 mK precision, and a central wavelength variation of 0.034 nm/K was measured.

The generated photon pairs are collimated and split by
a non-polarizing or polarizing beam splitter (BS or PBS),
depending on whether their polarization entanglement
shall be exploited or not. In order to perform the tomo-
graphic reconstruction of the photon pair polarization
state, a set of quarter and half-waveplates and a PBS are
placed in each arm. Finally, after passing optical band-
pass filters (IF) (Semrock FF01-440/40-25), the output
modes of the beam splitter are coupled into polarization
maintaining single-mode fibers. The single-photon cou-
pling efficiencies are on the order of 42%. The spectral
width of the fiber coupled photon pairs was measured to
be 143 ± 4 GHz.
After passing through the fiber, the transmission mode
of the beam splitter is coupled into a filtering line for
bandwidth reduction of the photon pairs. It consists of
two Fabry-Perot cavities placed in cascade, designed to
cover the whole crystal output spectrum and to provide a
single narrow transmission window of the desired band-
width. Each cavity consists of two high-reflectivity mir-
rors (Layertec) with a measured finesse of around 620.
The first cavity of 77.5 μm length has a transmission
bandwidth of ~ 25 MHz. Each cavity has a measured transmission, on resonance, of 88%. Together
with 42% fiber coupling efficiency and 45% detector ef-
ciency, the overall photon detection probability in the
filtered arm amounts to ~ 15%.
Both cavities are individually stabilized to the master
laser wavelength (850 or 854 nm), and therefore to the
desired D-P transition in $^{40}$Ca$^+$, by means of an auxiliary beam using again the PDH technique. Conservation
of energy in the downconversion process together with the
narrow frequency bandwidth of the master laser en-
sures that, if a photon is transmitted through the filtering line, its partner photon will be on resonance with the
atomic transition.
Photons are detected by fiber-coupled avalanche pho-
todiodes (Perkin Elmer SPCM-AQR-15) with ~ 45% quantum efficiency, <50 dark counts/s, and <1 ns time resolution. The TTL detection pulses are sent to a cor-
relation electronics module (Picoquant Picoharp 300) which is used primarily as a time discriminator to measure the delay between the pulses in two channels. The data are analyzed with an integrated control software
based on LabviewV8.5, which furthermore controls all input and output parameters of the experiment. This al-
 lows to remotely run complete measurement series like a
full state tomography protocol.
For characterizing the spectral properties of the nar-
rowband pair photon source, a temporal correlation
measurement was performed. The photon pairs were
split on a polarization beam splitter and detected af-
ter filtering in one of the arms. The distribution of the
time delays between photons in the two arms is shown in Fig. 2. A peak is resolved which originates from the
correlated photon pairs. It shows a characteristic expo-
nential decay due to the filter cavity ring-down. From
the decay time we deduce the photon pair bandwidth to
be $22.4 \pm 0.5$ MHz, in agreement with the measured filter
cavity linewidth. The background is caused by accidental
coincidences of photons with lost partners.
The brightness of the source is obtained from the num-
ber of counts in the peak, measured while varying the
pump power. The measured rate is 4.8 pairs/(s mW).
For the maximum pump power of 70 mW this results in
an extrapolated detection rate of 340 pairs/s [18]. Taking

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Fig. 1. Scheme of the experimental setup: The master laser is stabilized to an atomic line (transfer lock), amplified and
frequency doubled (laser source). The doubled light is down-converted in a type II phase-matched PPKTP crystal
(SPD source). The photon pairs are split and fiber-coupled; one of the photons is spectrally filtered (spectral
filtering). The time correlator detects the coincident pairs. Later, the unfiltered photon will be sent to a single ion
experiment. Symbols are explained in the text.
As a measure of the entanglement quality we calculate the concurrence, as shown in Fig. 3. We find the spectral brightness of generated narrowband entangled photons to be 1.0/(s MHz mW).

To explore the polarization entanglement of the photon pairs, they are split by a 50/50 non-polarizing beam splitter and analyzed by polarization state analyzers in front of the fiber couplers. We perform a full polarization state tomography measurement following [19]. After subtracting the accidental coincidences, we reconstruct the pair photon density matrix \( \rho \), as shown in Fig. 3. As a measure of the entanglement quality we calculate the concurrence \( C = 0.948 \pm 0.015 \). The overlap fidelity \( F = \langle \Psi^- | \rho | \Psi^- \rangle \) with the maximally entangled singlet state \( | \Psi^- \rangle = \frac{1}{\sqrt{2}} (|H\rangle |V\rangle - |V\rangle |H\rangle) \), amounts to 0.976 \pm 0.011. Another practical figure-of-merit are the visibilities of the polarization anti-correlations in the horizontal-vertical and the \( \pm 45^\circ \) polarization bases, which we find to be \( V_{HV} = 99.1 \pm 0.9\% \) and \( V_\pm = 97.5 \pm 0.9\% \).

In conclusion, we have set-up and characterized a narrow-bandwidth, tunable, high spectral density photon pair source, which will allow for efficient coupling to single trapped Ca\(^{+}\) ions. The temporal correlation of the photon pairs permits studying the interaction of single atoms with heralded single photons. Exploiting the high-purity entanglement of the source, the coupling of photonic and atomic qubit pairs will be feasible. Prospective experimental applications are entanglement distribution [10] and quantum repeaters [20].

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