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 in periodically poled $KTiOPO_4$. Its wavelength can be stabilized to 850 or 854 nm, thus allowing to address two transitions in $^{40}Ca^+$ 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). © 2008 Optical Society of America

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Entangled photon pairs have become an important resource in experiments on fundamental quantum mechanics [1] as well as in quantum communications [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]. Owing to the weak phase-matching conditions in small size crystals, these sources usually produce rather broad output spectra with widths on the order of terahertz. For many applications this is convenient, since the photons interact only with detectors that are not energy selective on this scale. In recent years new SPDC sources have been developed also for narrowband applications [6–8], which are mostly aimed at coupling photonic and atomic systems [9,10]. Still, the reported bandwidths are rather broad ($\sim$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 $D_{3/2}-P_{3/2}$ and $D_{5/2}-P_{3/2}$ optical transitions in $^{40}Ca^+$, which are centered at 849.8 and 854.2 nm and have a width of $\sim$20 MHz. As a prerequisite for efficient coupling, we achieve tunability over this range, a bandwidth reduction of 6 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 setup.

The experimental setup is sketched in Fig. 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 of output power. The remaining light from the diode is used to stabilize its frequency to a Fabry–Perot cavity with a finesse of 1000 and a linewidth of 1 MHz 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 triborate 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 focused into a second nonlinear crystal, where photon pairs are created via SPDC. This crystal is a flux-grown periodically poled $KTiOPO_4$ (PPKTP) crystal of dimensions 20 mm $\times$6 mm $\times$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, which is legitimate owing to the narrow bandwidth of the source [16]. The optimum focusing parameter, the ratio of the crystal length, and the Rayleigh range $\xi = L/z_R = 5.68$ [12,17] require a pump beam waist of $w_0 = 16.1$ μm. 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 a 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 nonpolarizing or polarizing beam splitter (BS or PBS), depending on whether their polarization entanglement shall be exploited or not. To perform the tomographic reconstruction of the photon pair polarization state, a set of quarter- and half-wave

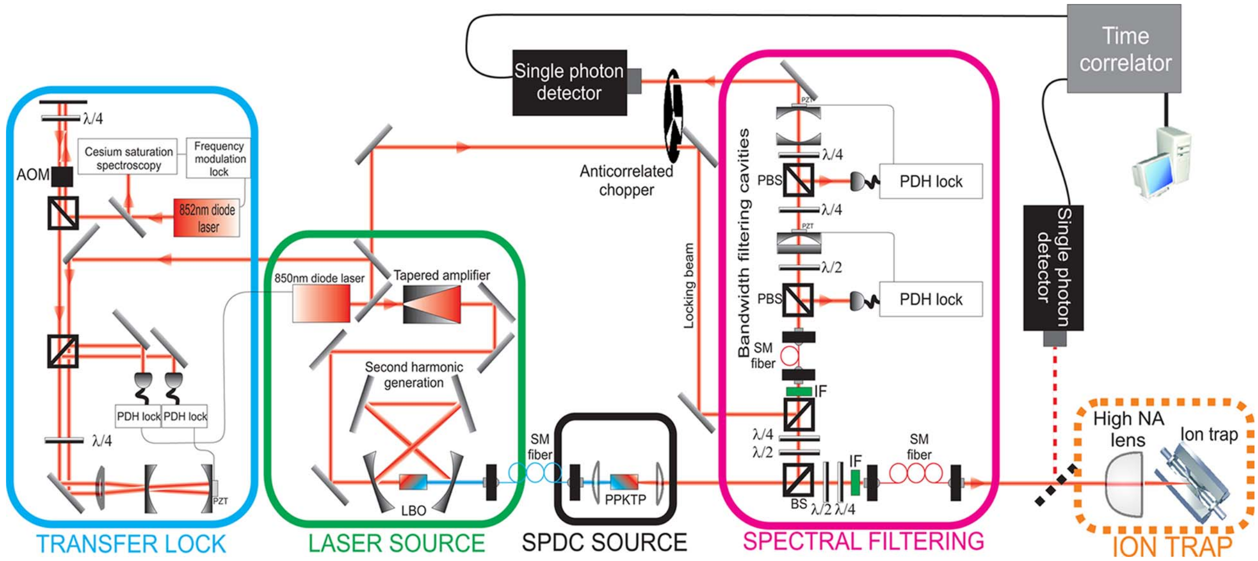

Fig. 1. (Color online) Scheme of the experimental setup. The master laser is stabilized to an atomic line (transfer lock), amplified, and frequency doubled (laser source). The doubled light is downconverted in a type-II phase-matched PPKTP crystal (SPDC source). The photon pairs are split and fiber coupled; 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.

plates and a PBS are placed in each arm. Finally, after passing optical edge filters (Semrock LP02-442RS-25), the output modes of the BS are coupled into polarization-maintaining SM fibers. The single-photon coupling 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 BS is coupled into a filtering line for bandwidth reduction of the photon pairs. It consists of two Fabry–Perot cavities placed in a cascade, designed to cover the whole crystal output spectrum and to provide a single narrow transmission window of the desired bandwidth. Each cavity consists of two high-reflectivity mirrors (Layertec) with a measured finesse of around 620. The first cavity of 77.5 μm in length has a 3.7 GHz transmission bandwidth; the second cavity of 10 mm in length sets the final filter bandwidth of ~25 MHz. Each cavity has a measured transmission, on resonance, of 88%. Together with a 42% fiber coupling efficiency and a 45% detector efficiency, 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 $D_{3/2}$ (or $D_{5/2}$) to $P_{3/2}$ 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 ensures that, if a photon is transmitted through the filtering line, its partner photon will be on resonance with the atomic transition. The cavity stabilization is long-time drift-free through the transfer lock of the master laser to atomic Cs. All the PDH locking electronics in the experiment are self-built.

Photons are detected by fiber-coupled avalanche photodiodes (Perkin-Elmer SPCM-AQR-15) with ~45% quantum efficiency, <50 dark counts/s, and <1 ns time resolution. The detection pulses are sent to a correlation 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 allows to remotely run a complete measurement series, such as a full-state tomography protocol.

For characterizing the spectral properties of the narrowband pair photon source, a temporal correlation measurement was performed. The photon pairs were split on a polarization BS and detected after 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 that originates from the correlated photon pairs. It shows a characteristic exponential decay owing to the filter cavity ringdown.

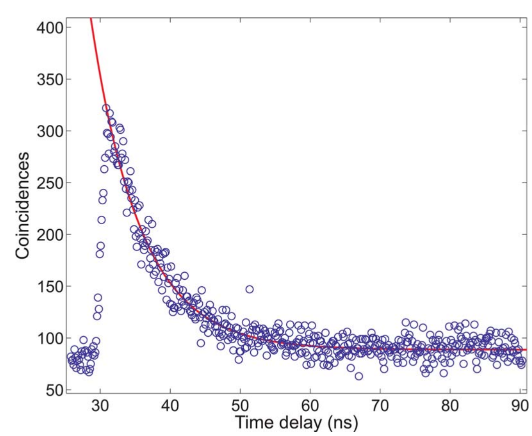

Fig. 2. (Color online) Time correlation between photons in the filtered and the unfiltered arm (points) and exponential fit (curve). The time origin is shifted by an electronic delay.

From the decay time we deduce the photon pair bandwidth to be 22.4±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 number 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 into account the bandwidth and the detector efficiencies, we find the spectral brightness of generated narrowband pairs to be 1.0/(s MHz mW). This is comparable to or brighter than other downconversion-based sources [6–8] and within a spectral band is well suited to interaction with calcium ions.

To explore the polarization entanglement of the photon pairs, they are split by a 50/50 nonpolarizing BS 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 ρ as shown in Fig. 3. As a measure of the entanglement quality we calculate the concurrence $C=0.948\pm0.015$. The overlap fidelity $F=\langle\Psi^-|\rho|\Psi^-\rangle$ with the maximally entangled singlet state $|\Psi^-\rangle=1/\sqrt{2}(|H\rangle|V\rangle-|V\rangle|H\rangle)$, amounts to 0.976 ± 0.011. Another practical figure of merit are the visibilities of the polarization anticorrelations in the horizontal-vertical and the ±45° polarization bases, which we find to be $V_{HV}=99.1\pm0.9\%$ and $V_{\pm}=97.5\pm0.9\%$.

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].

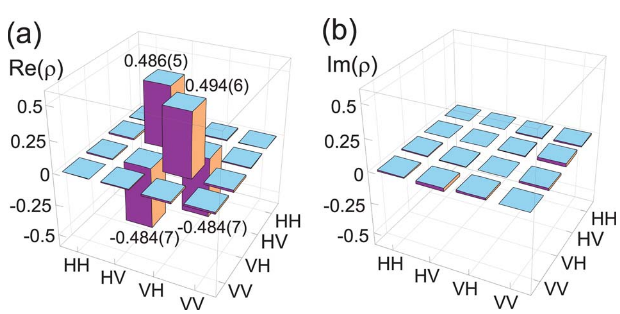

Fig. 3. (Color online) (a) Real and (b) imaginary parts of the polarization state density matrix ρ of the photon pairs in the horizontal-vertical polarization basis.

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