PAPER

Heralded wave packet manipulation and storage of a frequency-converted pair photon at telecom wavelength

Tim Kroh, Andreas Ahlrichs, Benjamin Sprenger and Oliver Benson
Department of Physics, Humboldt-Universität zu Berlin, Newtonstraße 15, D-12489 Berlin, Germany
E-mail: tim.kroh@physik.hu-berlin.de

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Abstract
Future quantum networks require a hybrid platform of dissimilar quantum systems. Within the platform, joint quantum states have to be mediated either by single photons, photon pairs or entangled photon pairs. The photon wavelength has to lie within the telecommunication band to enable long-distance fibre transmission. In addition, the temporal shape of the photons needs to be tailored to efficiently match the involved quantum systems. Altogether, this requires the efficient coherent wavelength-conversion of arbitrarily shaped single-photon wave packets. Here, we demonstrate the heralded temporal filtering of single photons as well as the synchronisation of state manipulation and detection as key elements in a typical experiment, besides of delaying a photon in a long fibre. All three are realised by utilising commercial telecommunication fibre-optical components which will permit the transition of quantum networks from the lab to real-world applications. The combination of these renders a temporally filtering single-photon storage in a fast switchable fibre loop possible.

1. Introduction
Quantum networks could be composed of four main constituents in reference to David DiVincenzo’s criteria for quantum computation [1]: (1) bright sources of indistinguishable single photons and photon pairs which are standardised in frequency, (2) frequency conversion to the telecom band for long-distance transmission of quantum states, (3) tailoring of the temporal envelope of the photons to optimise their shape for absorption processes in stationary quantum systems and (4) the possibility to store quantum states in a quantum memory.

Photon-pair states will play a major role in long-distance quantum networks as transmitters of heralded quantum information and as carriers of entanglement between remote nodes [2]. Many sources of high-quality photons that provide indistinguishable [3–7] and entangled photons [8–10] already exist in the near-infrared spectral region. However, these photons have to be synchronised and matched with respect to their specific task in the network. For example, their transmission over long distances in optical fibres requires wavelengths in the telecommunication bands to reduce absorption losses to a minimum. Additionally, short-range sections of a network, which perform operations on the quantum states, depend upon a shared frequency standard, e.g. based on transitions in rubidium or caesium (Cs) vapour cells, to ensure indistinguishability.

The generation of non-degenerate pairs of photons at an atomic transition and in the telecom band have been proposed [11] and implemented [12]. But quantum communication applications will ultimately require deterministically generated single photons and photon pairs, e.g. to grant unconditional security. In the aforementioned spontaneous processes, this is prohibited by the non-vanishing probability of multi-photon-pair generation. Coherent frequency conversion in nonlinear crystals, on the other hand, is a well-established and highly efficient tool to convert photons to the telecom band while preserving photon statistics and indistinguishability [13–18] as well as entanglement [19]. Also, quantum correlations were established between atomic ensembles, as an example for a stationary node in a network, and a frequency-converted photon in the telecom band [20, 21].
Beside the frequency, the polarisation and the spatio-temporal wave packet of the photons have to be matched as well to optimise the storage efficiency in a quantum memory [22]. Proposals exist that indicate full control over the converted photon’s waveform by spectral [23] or fast temporal [24] modulation of the pump light. But surprisingly, only few studies [25–27] exploit nonlinear processes to control and modify single-photon wave packets, for example, to improve photon indistinguishability.

Finally, photon storage is crucial to synchronise the operation of quantum logic gates, error correction or entanglement distillation. Promising photon storage techniques which utilise atoms as a quantum memory demand resonance of the involved photons with atomic transitions [28–30]. Optical fibres, on the other hand, allow for simple realisations of broadband, low-loss delay lines and storage devices for photons at telecom wavelengths. One realisation is a fibre loop combined with a fast switching electro-optic modulator to inject and retrieve the photon at discrete times [31, 32]. To compare different types of quantum memory, the product of storage time and retrieval efficiency represents an eligible figure of merit. In a loop delay the storage time is defined by the speed of light in the fibre \( c_f \) and its length \( L \). This would promise arbitrarily long storage times if the non-zero photon absorption in the fibre did not fundamentally limit the transmission due to losses. The global maximum of the time-efficiency product \((L/c_f) \cdot 10^{-0.23 \text{dB/km} \cdot L/10 \text{ dB}}\) for telecom fibres is found at a length of about 18.9 km being 90 \( \mu s \) · 37 %. In cold atomic vapours, storage times and retrieval efficiencies of up to 68 ms · 4 % have been achieved [33]. However, for easily maintainable long-distance networks simpler solutions, preferable at room temperature, are needed. Similar atomic vapour experiments at room temperature only yield up to 1.5 \( \mu s \) · 13 % [34, 35]. Hence, a fibre loop would perform at an order of magnitude better than atoms at room temperature when comparing the storage-time retrieval-efficiency product.

In this work, we approach the implementation of long-distance quantum networks by tackling the requirements (2)–(4) that were mentioned in the beginning. We demonstrate the coherent frequency conversion of a pair photon, initially matched to the Cs D\(_1\) transition at 894 nm, into the telecom band to 1557 nm. In other studies, the temporal envelope was shaped by modulation of the pump field during frequency conversion [25–27] or photons from an atomic ensemble have been electro-optically modulated directly after emission [36]. Here, an heralded photon is modulated subsequently to the frequency conversion to the telecom band. We employ commercial telecom equipment to show heralded shaping of the complex comb-like temporal wave packet of the converted photon at the timescale of a nanosecond. In a final step, a frequency-converted photon in the telecom band is further delayed in an optical fibre for 45 \( \mu s \). The different experiments of this work represent key elements towards a synchronised quantum network, which could be combined to a fibre loop photon storage, as a simple quantum memory consisting of commercially available telecom components.

2. Methods

2.1. Photon-pair source

In all measurements described in this paper, we used photon pairs which were generated by cavity-enhanced parametric down-conversion [37]. This process provides photons which can be locked to a specific frequency standard with a bandwidth determined by the cavity properties. In our single-photon experiments, the Cs D\(_1\)-line at 894 nm represents the frequency standard [38]. A nonlinear crystal is placed inside a low-finesse cavity resembling the configuration of a triply-resonant optical parametric oscillator (OPO) pumped far below the threshold. The OPO is pumped by a frequency-doubled, grating-stabilised continuous wave diode laser which is locked to a hyper-fine transition of the Cs D\(_1\)-line. By tuning the temperature of the nonlinear crystal, pairs of degenerate photons at the Cs wavelength can be produced. The OPO cavity is locked to a resonance of the blue 447 nm pump beam. Without additional spectral filtering, a mode-locked two-photon state is produced. The second order signal/idler cross-correlation function [4] can be approximated by

\[
G_{\text{ii}1}(\tau) = \begin{cases} 
\exp[-\Omega_p \tau] \sum_n \exp[-(\tau - 2n \pi \text{FSR})^2 / \tau_p^2], & \tau \geq 0 \\
\exp[\Omega_p \tau] \sum_n \exp[-(\tau + 2n \pi \text{FSR})^2 / \tau_p^2], & \tau < 0.
\end{cases}
\]

Here, \( \Omega_p = 170 \text{ MHz} \) is the signal/idler cavity decay rate, \( \text{FSR}_{\text{ii}1} \) is the signal/idler free spectral range and \( \tau_p \) is the coherence time which is determined by the crystal’s length and phase-matching properties. For the crystal used in our experiments \( \tau_p \approx 10 \text{ ps} \). Due to the type-II phase matching which yields orthogonally linear polarised photon pairs, signal and idler photons can easily be separated by a polarising beam splitter. With a pump power of typical 20 mW about \( R = 9 \times 10^6 \) signal and idler photons per second are collected into single-mode fibres. Details of the setup can be found in [4].
2.2. Coherent conversion setup

Single photons from around the wavelength of the Cs D\textsubscript{1} transition at 894 nm are converted to a telecommunication wavelength in the C-band by generating the difference frequencies at 1557 nm and 2100 nm by a sequence of filters: two dichroic mirrors which act as a 1800 nm shortpass (SP), a 25 nm dielectric bandpass (BP) at 1550 nm, and a 3.5 nm fibre Bragg-grating (FBG) at 1557 nm. The conversion efficiency is defined as the ratio of photon flux directly after the the PMF $\Phi_{in}$ to photon flux after the FBG $\Phi_{out}$.

We define the overall efficiency of our quantum frequency conversion (QFC) setup $\eta_{QFC}$, as in [39] to be

$$\eta_{QFC} = \frac{\Phi_{out}}{\Phi_{in}}$$

$\Phi_{in}$ is the 894 nm photon flux (in terms of photons per second) directly after the input fibre. $\Phi_{out}$ is the flux of wavelength converted 1557 nm photons in the output fibre after all filtering steps (figure 1). The maximum efficiency achieved in our setup is $\eta_{QFC} = 13.1 \pm 0.2\% \approx \eta_{if} \cdot \eta_{c} \cdot \eta_{eff} \cdot \eta_{det} \cdot \eta_{l}$.

It consists of five contributing factors that will each be discussed in the following. Before, the waveguide contributes the free-space transmission $\eta_{if}$ from the input fibre to the waveguide coupling lens $L_1$. The waveguide throughput depends on the coupling efficiency into the waveguide $\eta_{c}$ and the internal conversion efficiency $\eta_{eff}$. The fibre coupling efficiency $\eta_{fib}$ after frequency conversion and the transmission through all filtering steps $\eta_{l}$ determine the losses after the waveguide.

The first of the aforementioned factors is the transmission $\eta_{fib}$ of 894 nm photons from the input fibre to lens $L_1$, which couples them into the conversion waveguide. A half-wave plate is used to optimise the photon polarisation to the phase-matching axis in the conversion crystal. The losses are below 2 % due to highly reflective coatings on the dielectric mirrors and the anti-reflection coated half-wave plate, resulting in $\eta_{if} > 98\%$. The second factor, $\eta_{c} = 90\%$, is the coupling efficiency of 894 nm photons into the waveguide. It is measured as the ratio of the light which is coupled into the waveguide by lens $L_1$ and detected behind the recollimating lens $L_2$ divided by the intensity just before lens $L_1$. The internal conversion efficiency of $\eta_{eff} \approx 70\%$ is inferred from the 894 nm power depletion in the waveguide when the pump laser is added [13]. In this experiment the internal conversion efficiency is limited by the available pump laser power of 300 mW. A maximum internal conversion efficiency for this waveguide can be extrapolated to be $\eta_{eff,max} = 79\%$ percent at 450 mW pump power [13]. About $\eta_{fib} = 35\%$ of the converted 1557 nm photons are coupled into an optical single mode (SM) fibre. The fibre coupling efficiency is currently limited by imperfect mode matching.

The converted light is separated from the pump light, the remaining photons at 894 nm and noise photons in the vicinity of 1557 nm by spectral filtering. Broadband noise photons can be generated e.g. by fluorescence or Raman scattering [13] inside the waveguide or directly by the pump laser. The filter setup (figure 1) consists of three stages. A dielectric 50 nm bandpass filter at 1550 nm (Edmund Optics, transmission $T > 97\%$) suppresses 2.1 \textmu m pump light and unconverted 894 nm photons first (BP in figure 1). In a second step, a set of two dielectric 1800 nm longpass filters (Thorlabs, DMLP1800T) is utilised to couple the converted single photons at 1557 nm with a reflectivity of $>98\%$ per filter into the SM fibre. They thus function as a shortpass (SP in figure 1) for 1557 nm photons. Further pump light is transmitted $(>90\% \text{ per filter})$ and therefore spatially separated from the converted light at the dielectric filters. Finally, the converted photons are reflected at a 3.5 nm fibre Bragg-grating at 1557 nm (Advanced Optics Solutions GmbH) which is spliced to the second port of a fibre circulator (Thorlabs 6015-3-APC) while remaining pump light and 894 nm photons are transmitted. Only the converted 1557 nm photons leave the fibre circulator at the output port. Therefore, the overall filter transmission is $\eta_{l} \approx 60\%$. At a pump power of 300 mW, the rate of detected noise photons is $N < 5000/s$. This rate was measured without any 894 nm input photons present and a detection efficiency of $\eta_{Det} = 14\%$ of a superconducting single-photon detector (SSPD, Scontel).

Figure 1. Setup for the coherent frequency conversion of single photons. Single photons at 894 nm are collected into a polarisation maintaining fibre (PMF). The polarisation can be rotated by a half-wave plate (HWP). Single photons and pump laser light at 2.1 \textmu m are superimposed by a dichroic mirror (DM) and focused into the conversion waveguide (WG) with lens $L_1$. The WG is anti-reflection (AR) coated for three all involved wavelengths. The frequency-converted photons are coupled into a single mode fibre (SMF) by lens $L_2$ (1550 nm AR coating) after leaving the WG. Remaining pump laser light and photons at 894 nm are suppressed afterwards by a sequence of filters: two dichroic mirrors which act as a 1800 nm shortpass (SP), a 25 nm dielectric bandpass (BP) at 1550 nm, and a 3.5 nm fibre Bragg-grating (FBG) at 1557 nm. The conversion efficiency is defined as the ratio of photon flux directly after the the PMF $\Phi_{in}$ to photon flux after the FBG $\Phi_{out}$.
Altogether, a signal-to-noise ratio for the converted single photons of up to $\text{SNR} = \frac{\eta_{\text{spec}} \cdot \eta_{\text{det}} \cdot R}{N} = 33$ could be achieved in this experiment. The SNR is limited by the random noise detections of rate $N$ on the one side and, on the other, the maximum photon rate $R$ from the pair photon source before conversion. Reduction and increase of $N$ and $R$, respectively, could further improve the SNR. In practice, $R$ is often bound by the saturation of emission rates of single-photon emitters. In the experiments show here, $R$ is limited by the effort to keep the multi-pair generation rate of the photon-pair source low. As discussed in section 4, the noise rate $N$ could be diminished by orders of magnitude in subsequent experiments without reduction in conversion efficiency.

3. Results

3.1. Conversion of the complex temporal wave packet of a pair photon

In a first experiment, we convert a single photon of the photon pair from the OPO source and verify that the temporal shape of the single-photon wave packet is not altered by the conversion process. The two photons (signal and idler) of the pair leaving the OPO have a complex comb-like correlation in time (equation (1)) caused by the longitudinal mode structure of the OPO cavity. In the time domain which is probed by photon correlation measurements shown in figure 2, this can be understood as follows. Detection of either photon from a pair projects the other to a wave packet bouncing back and forth inside the cavity. The second photon can then only be detected after integer multiples of the cavity’s round-trip time, resulting in an exponentially decreasing comb-like structure in the correlation measurement. The experimental configuration is depicted in figure 2(a).

The signal and idler photons from the OPO photon pair with a wavelength at the Cs D1-line are split at the polarising beam splitter (PBS). The second order cross-correlation $G^{(2)}(\tau)$ between the signal and the idler photon (cf equation (1)) was measured with the superconducting single-photon detectors SSPD1 and SSPD2.

The measurement results (figure 2(b)) are in good agreement with the signal and idler photon cross-correlation function $G^{(2)}(\tau)$ (equation (1)) convoluted with a Gaussian instrument response function $\text{IRF} \ast G^{(2)}(\tau)$. The IRF has a full width at half maximum of 96.25 ± 0.17 ps resulting from the timing resolutions of the two SSPDs and the counting electronics. The correlation between the two unconverted photons (figure 2(b)) is then compared to the correlation between an unconverted signal photon (SSPD1) and an idler photon converted to the telecom band at 1557 nm (SSPD3). The results plotted in figure 2(c) reveal that the normalised cross-correlation retains its shape upon frequency conversion. The same fitting function (blue) with identical parameters as in the unconverted case (figure 2(b)) is displayed in figure 2(c) to demonstrate the preservation of the temporal wave packet. The frequency conversion of the idler photon causes only negligible broadening of the peaks. A fit to the data of the converted photon, with only the FWHM of the IRF being a free parameter, yields 96.4 ± 0.2 ps which overlaps with the value before conversion within the margin of error. All features remain the same and no influence on the cross-correlation measurement can be resolved within the IRF of the detection electronics.

This is a remarkable, although expected [41–43], result. In a frequency conversion process, only the central frequency of an electromagnetic wave is changed while its spectro-temporal shape remains the same if (1) the phase-matching bandwidth of the nonlinear material is much broader than the spectra of all involved electromagnetic waves, (2) the pump laser spectrum can be approximated as a delta-function and (3) the pump field is not varied in frequency, phase, or amplitude in time [43, 44]. In our experiments, the latter two conditions are fulfilled by the continuous wave pump laser. It emits constantly at 2.1 μm wavelength and its narrow linewidth of < 100 kHz [40] very small compared to the pair photon spectrum of 100 GHz (< 0.3 nm) on the one hand, or the single features in the spectrum of > 100 MHz [4] on the other. The first aspect is only partly satisfied because the phase-matching bandwidth of ~0.3 nm in our experiment is almost coinciding with the photon’s spectral width. This can be a feature to filter out redundant frequencies during conversion [39]. But in our case the slight suppression of the shoulders in the converted spectrum should cause a broadening of the temporal features in the cross-correlation measurement (figure 2(c)). This broadening is apparently small enough that it does not influence the measurement of which the temporal resolution is still mainly limited by the detectors’ and counting electronic’s IRF of 96.4 ps.

3.2. Heralded shaping of a converted single-photon wave packet

Future quantum networks will require triggered events in successive processes of qubit manipulation and basic shaping of the temporal photon profile. This has already been demonstrated for heralded single photons from the rubidium $^{85}\text{Rb}$ D1 transition at 795 nm with an electro-optic modulator at the atomic life-timescales of tens to a hundred nanoseconds [36]. But in telecom quantum networks even faster processes will be required. Fibre optical equipment for high-speed modulation of light is already commercially available for various applications at telecommunication wavelengths. The frequency conversion of photonic qubits into the telecom band
therefore brings the advantage that this technology can, in many cases, directly be used for experiments at the single-photon level. In the following we demonstrate this advantage by showing that the complex wave packet of a converted idler photon can be arbitrarily shaped with an off-the-shelf fibre Mach-Zehnder modulator (Avanex SD20, MZM in figure 3(a)).

The signal and idler photon of the photon pair are separated at a polarising beam splitter and sent to different parts of the experiment. The detection of the signal photon at SSPD₁ triggers an arbitrary waveform generator (Programmable Pulse Generator PPG 512 from PicoQuant, 5 Gsamples/s, AWG in figure 3(a)) which sends a voltage pattern to the MZM. The applied voltage defines the transmission of the MZM, continuously adjustable from full transmission to maximum suppression of \(-20\) dB of the incoming light. Arbitrary shaping of the outgoing wave packet is possible by means of partial transmission of the wave through the MZM within in the resolution limits of the partaking optoelectronics. In the meantime, the idler photon is frequency converted to 1557 nm and transmitted to the MZM. The insertion loss of the MZM of 3.1 dB reduces the telecom single-photon rate at SSPD₃, and consequently the coincidence rate, by roughly 50%.

Cross-correlation measurements between the signal and the frequency-converted idler photon are depicted in figures 3(b) and (c) for two exemplary AWG pulse forms In this experiment the voltage patterns are compiled from 102.4 ns long sequences of 512 values with an 8-bit resolution in amplitude. The temporal profile of the MZM transmission was measured in both cases as the transmission signal of a cw laser. Respective fits $T_i(\tau)$ are

![Figure 2. Measurement of the temporal cross-correlation of an optical parametric oscillator (OPO) photon pair with and without conversion. (a) The signal photon of an OPO photon pair is separated from the orthogonally polarised idler photon at the polarising beam splitter PBS and detected by a superconducting single-photon detector SSPD₁. The idler photon is either detected directly at SSPD₂ (b) or after conversion at SSPD₃ (c). The measured temporal correlations between the pair photons before (b) and after (c) conversion of the idler photon to the telecom band are almost identical. The blue line in (b) displays a fit to the measurement with an unconverted idler photon. The fitting function constitutes of the convolution of the signal and idler photon cross-correlation function $G_s,i(\tau)$ (cf equation (1)) with a Gaussian instrument response function (IRF) with a full width at half maximum of 96.25 ps. The fit from (b) is also plotted in (c) with identical parameters to testify conversion without influence on the shape of the wave packet. The temporal structure in the correlation measurement is due to round trips of the pair photons in the resonator after parametric down-conversion. No background correction has been performed on any measurement of this work due to the high signal-to-noise ratio between detected converted photons and false detections.](image-url)
Transmission pulses with a full width at half maximum of 770 ps could be realised. The pulse width was mainly limited by the AWG rise time of about 500 ps, while the 20 GHz bandwidth MZM should assure optical rise times well below 100 ps. The cross-correlation measurements (red dots) demonstrate the modulation of the single-photon wave packet at timescales of a nanosecond. A fit of $A \cdot T_i(\tau - \tau_0) \cdot \text{IRF} \ast G_{\text{SI}}^i(\tau)$ to this data is displayed in blue, where only the amplitude $A$ of the transmission function $T_i$ and its relative time $\tau_0$ with respect to $G_{\text{SI}}^i$ were used as fitting parameters, while $\text{IRF} \ast G_{\text{SI}}^i(\tau)$ is the fit to the reference measurement (black). The accurate overlap of fit and data confirms that no change of the fine temporal features of the signal-idler cross-correlation is detected within the experiment’s timing resolution of 96.4 ps.

The major limitation for the fast modulation of the frequency-converted idler photon in this experiment is the speed of the AWG. With improved AWGs [45] and MZMs [46] it would be possible to cut-out individual temporal peaks of the wave packet which renders very useful in single-photon quantum key distribution with larger alphabet keys [47].
Figure 4. Storage of the converted photon in a 9.3 km long telecom fibre. (a) The idler photon is delayed in a 9.3 km long fibre after frequency conversion. An electrical delay of 45 μs was utilised after detection of the signal photon to compensate for the idler’s storage time in the fibre. (b) and (c) The correlation between the heralding signal photon and the converted idler photon is shown directly after frequency conversion (blue) and at the end of the fibre spool (red). The electronic delay box processes only one pulse at a time, resulting in a decreased heralding photon event rate at the correlator. This causes a strong decrease of coincidence events after storage of the idler photon in the fibre. The temporal structure of the wave packet is in general conserved, but two processes increase the width of the individual peaks. On the one hand, the peaks are broadened by chromatic dispersion inside the fibre. On the other, the electronic delay and the preceding amplifier (AMP) introduce an additional timing jitter. The measured width is the convolution of IRF, chromatic dispersion and delay timing jitter. From the fit (black line), a peak width of 235 ± 4 ps is inferred. This is considerably larger than in the unconverted case.

3.3. Storage of a telecom photon wave packet

In a final experiment, we demonstrate a straightforward approach to store a converted photon for the time of about 45 μs in a 9.3 km long telecom fibre (SMF-28, Corning) furled on a spool (figure 4(a)). The frequency of the idler photon is converted to the telecom band as in the first experiment. Instead of detecting the idler photon directly after conversion, it is coupled into the 9.3 km fibre spool and detected by an SSPD at the end. Meanwhile, the signal photon is detected at the other SSPD. To accomplish almost simultaneous events at the correlator, i.e. to compensate for the optical time-of-flight delay of the idler photon in the long fibre, a 45 μs electrical delay (Highland Tech., T560) was applied to the detection voltage pulse from the SSPD of the unconverted signal photon. Both electrical detection signals are then correlated. The resulting histogram (figure 4(c)) demonstrates the general conservation of the idler photon’s wave packet.

Compared with the measurement directly after conversion (figure 4(b)), the temporal resolution in the correlation measurement is reduced after delaying the idler photon. A fit to the data (figure 4(c), black) — using the same parameters as in figure 2(c) except for the amplitude, temporal offset and IRF width — results in a FWHM of the peaks of 235 ± 4 ps. Two main factors from the additional equipment contribute to the broadening. The dispersion in SMF-28 fibre at 1550 nm is ≤18 ps/km nm. With the fibre length of 9.3 km and the width of the converted spectrum (≈100 GHz) at 1557 nm of ≈0.8 nm the temporal shape of the converted photon is broadened by ≈140 ps at the output of the fibre spool. Besides this, the timing jitter of the electronic delay is limited to 50 ps. Adding up these uncorrelated broadening effects quadratically points out a so far unaccounted impact to the data. We expect the timing jitter of the electronic amplifier (ZFL-500LN-BNC, Mini-Circuits) before the delay to be 155 ps to make up for the increase of the measured FWHM.

The strong decrease of coincidence events is dominantly caused by the electronic delay box. Each time one electrical pulse is delayed, no other signal will be processed within these 45 μs, which limits the detection rate of the idler photon to 1/45 μs, resulting in a reduction of the maximally achievable coincidence rate by a factor of 28. In comparison, the absorption of 1557 nm photons in the fibre at the order of ~0.23 dB/km, causing losses of 39 % in our experiment, is the far weaker influence on the coincidence rate. The limitation to the coincidence rate introduced by the electronic delay needs to be overcome, e.g. using digital delays or long analogue delay lines with buffers to store multiple pulses at a time, for the parallel synchronisation of huge numbers of correlated photon pairs in a quantum network. The fibre absorption loss, on the other side, implies a fundamental limit to the storage time of a photon. A fibre loop photon storage, consisting of a fast switchable four-port fibre Mach-Zehnder-interferometer and a fibre loop, is only reasonably used in a temporal delay range where its time-retrieval product, as defined in the introduction, excels those of other storage mechanisms. The optimum is found at 90 μs, which limits the maximum distance to establish quantum correlation to about said 18.9 km, or medium ranges of urban networks.
The dispersion of the wave packet in the long fibre reduces the temporal overlap between a photon just after frequency conversion and one at the end of the delay line. In Hong-Ou-Mandel type experiments where photon indistinguishability plays the major role this would utterly degrade the performance. This problem could be resolved with fibre optical links of all the same length and dispersion compensating fibres [48, 49] in the fibre loop storage.

4. Discussion

In this work, we have experimentally demonstrated the conservation of the complex temporal correlation during coherent frequency conversion between two pair photons which were generated by cavity–enhanced spontaneous parametric down-conversion. The idler photon wavelength was transferred from the atomic standard Cs D1-line at 894 nm to minimal absorption in telecommunication fibres at 1557 nm.

The maximum overall conversion efficiency of our setup $\eta_{QFC} = 13.1 \pm 0.2 \%$ is less than the 39 $\%$ [19], 32 $\%$ [39] or 22 $\%$ [20], which were achieved in other experiments. But our conversion efficiency can still be improved by using a telescope in front of the SM fibre coupler for the 1557 nm photons (up to $\eta_{QFC} = 70 \%$) and reducing the losses during spectral filtering in the fibre circulator system (up to $\eta_e \approx 100 \%$), resulting in a possible new maximum conversion efficiency $\eta_{QFC}^{\text{max}} \approx 40 \%$.

After completion of the experiments, the noise detection rate $N$ was further reduced to the dark count level of the SSPDs at the chosen operation mode with the help of a 2.0 $\mu$m longpass filter for the 2.1 $\mu$m pump laser. It now lies below $N < 100$ ps which would provide a SNR $> 1600$ under the same experimental conditions, apart from the added filter. Such a high signal-to-noise ratio enables subsequent conversion experiments with single-photon emitters with emission rates that are magnitudes lower than the photon-pair rates of this work.

A recent frequency conversion experiment with correlated photons from rubidium vapour was performed at a trade-off between conversion efficiency and noise detection rate [20]. Due to low excitation and collection efficiencies the detection count rate sank to 150ps at a conversion efficiency of $< 15 \%$, which made averaging times of up to 200 h necessary. With rates of about $10^7/s$ time–energy entangled photons from an InAs quantum dot [50] before frequency conversion and new SSPDs with a detection efficiency of $>40 \%$ at 1557 nm we could reach rates of entangled photons in the telecom band which are about one order of magnitude higher than in the above-mentioned study. This would equally reduce the integration time for a similar experiment to one day or less. Precise heralding of the signal photon and fast temporal modulation of the converted idler photon with commercial fibre telecommunication equipment allow for arbitrary shaping of single-photon wave packets. The temporal resolution of this process is only limited by the overall rise time of the function generator and the optical modulator. Combining fast temporal switching, as demonstrated here, with telecom ultra dense wavelength division multiplexing [51] would further enhance the attainable complexity of upcoming quantum networks.

Beyond that, the frequency-converted idler photon has been stored for more than 45 $\mu$s in a 9.3 km fibre spool and was heralded by the signal photon. With these premises a fibre loop storage was proposed that would in addition shape the single photon with a fast switchable electro-optic modulator at retrieval. Such a device would still outperform current atomic storages at room temperature by an order of magnitude [34, 35] and allow for immediate technical implementation of a simple storage of telecom single photons for medium distance urban networks. The bandwidth of atom-based quantum memories ranges from few megahertz [33], over about 100 MHz utilising electromagnetically induced transparency [52], to the order of gigahertz [34]. An optical fibre based memory for photons in the telecom C-band around 1557 nm would, in contrast, generally allow storage for a multitude of frequencies at the order of its own bandwidth, which makes frequency multiplexing possible over a width of a few terahertz. However, the exponential losses in a fibre loop limit storage times to below a millisecond and therefore necessitate other storage schemes for long-distance quantum communication protocols. For practical implementations the signal photon detection can also be used to add a classical telecom pulse to the transmitting fibre by wavelength division multiplexing and herald the following idler photon [53].

The fibre loop memory could be a node in the network, which merges storage and shaping, reducing the number of incorporated devices and, thus, the overall single-photon losses, bringing recent efforts a step closer to establishing quantum networks in real-world applications. One obstacle on that way is the still present insertion loss of 3 dB. In a fibre loop storage this would divide the retrieval probability in half for every round-trip. But in a proposal a new type of wavelength division multiplexer is designed that promises insertion loss down to 0.2 dB [54]. This would enhance the transmission per round-trip in the fibre loop to over 95 \%.
5. Conclusion

In conclusion, we have established the frequency conversion of photons generated at the atomic Cs D1 transition to 1557 nm in the telecom C-band. The overall efficiency lies in the range of other recent conversion experiments and still leaves room for realistic improvement. In this setup no detectable broadening was introduced to the fine temporal structure of the pair photon wave packet during conversion. Next, we have demonstrated the heralded arbitrary temporal tailoring of the converted photon on the timescale of nanoseconds. Such synchronised photon modulation will be of importance for optimal absorption in stationary solid state or atomic vapour quantum systems and essential for quantum protocols that rely on well-defined temporal photon states. We also investigated the influence of dispersion and an electrical delay on the heralded, converted photon that passed through a 9.3 km fibre. The temporal broadening in the correlation measurement has to be prevented by use of dispersion compensating fibres and low timing jitter of the synchronising electronics for applications requiring indistinguishable photons or the realisation of a basic fibre loop quantum memory. In the future our setup can be used to build long-distance quantum networks consisting of nodes at the Cs D1 transition and fibre based transfer channels in the telecom band. The current experiment could be extended by converting deterministically generated entangled photons from the pair source or a quantum dot [10, 50] to enable remote preparation of entangled states. Combining storage, heralding, arbitrary amplitude and phase modulation of single-photon wave packets, as well as remote state preparation will render more complex quantum networks possible.

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