Spectral Compression of Narrowband Single Photons with a Resonant Cavity

(Dated: May 30, 2019)

We compress the spectrum of narrowband heralded single photons generated by four-wave mixing in cold ^{87}Rb atoms using a near-resonant cavity as dispersion medium. and time-dependent phase modulation

Introduction – Efficient atom-light interactions at the single quantum level, the core of many proposals for storing, processing, and relaying quantum information [1, 2], requires single photons matching the spectrum of atomic transitions.

Single photon alley!

A widely adopted solution for generating spectral-matching single photons is passive filtering of bright, broadband sources [3, 4], with the unavoidable consequence of a drastic reduction of brightness. However, photon-atom interaction experiments require a high interaction rate and photon losses can compromise the feasibility of such experiments.

why alternative for atomic transitions

Inspired by techniques to compress ultra-fast pulses [5, 6] we developed a method to compress the bandwidth of already narrowband photons using an asymmetric cavity as dispersion medium. In principle, the photon rates are unaffected while the photon spectrum is narrowed. The compression mechanism relies on dispersion and a subsequent temporal phase manipulation. In previous works [ref] a long silica fiber provided sufficient non-linear dispersion to compress broadband photons. In the case of already narrowband photons, the necessary non-linear dispersion is several orders of magnitude larger, corresponding to an unpractical fiber length and the ~~associated unacceptable~~ losses. Here, for instance,

~~In our demonstration~~ we introduce the necessary non-linear dispersion with a highly reflective asymmetric cavity. Its dispersion is a function of the finesse and can be adjusted by tuning the resonance frequency. In principle this cavity does not introduce optical losses.

why fair, not dispersive medium

Theory – ~~Let's consider~~ a single photon with intensity time envelope $|\psi(t)|^2$ and its corresponding power spectrum $|\Psi(\omega;\,\omega_0,\Gamma_p)|^2$, connected by the Fourier transform F: $\Psi(\omega) = F[\psi(t)]$ and characterized by a spectral width Γ_p and central frequency ω_0. The first step is to spread out the wave packet in time with a dispersion medium. To introduce the dispersion necessary for stretching the pulse in time, we consider an asymmetric optical cavity. Choosing the output mirror to be fully reflective $R_{\mathrm{out}} = 1$, the cavity reflects any incident wavepacket without introducing losses, but adding a frequency dependent phase factor. Assuming a cavity linewidth Γ_c much smaller than the Free Spectral Range, the transfer function for frequencies around the resonance ω_c can be approximated with

$$C(\omega;\,\omega_c,\Gamma_c) \approx -\frac{\Gamma_c + i\,2(\omega-\omega_c)}{\Gamma_c - i\,2(\omega-\omega_c)}\,. \tag{1}$$

Multiplying the transfer function of Eq. (1) and the single photon state $\Psi(\omega;\,\omega_0,\Gamma_p)$ returns the dispersed state

$$\Psi'(\omega;\,\Delta\omega,\Gamma_c,\Gamma_p) = \Psi(\omega;\,\omega_0,\Gamma_p)\;C(\omega;\,\omega_c,\Gamma_c)\,, \tag{2}$$

where $\Delta\omega = \omega_0 - \omega_c$ is the detuning between the wavepacket and the cavity resonance. The state $\Psi'(\omega)$ has the same power spectrum as $\Psi(\omega)$because the cavity did not introduce any loss $|C(\omega;\,\omega_c,\Gamma_c)|^2 = 1$.

We now use the inverse Fourier transform F^{-1} to return to the time description

$$\psi'(t;\,\Delta\omega,\Gamma_c,\Gamma_p) = F^{-1}\left[\Psi'(\omega;\,\Delta\omega,\Gamma_c,\Gamma_p)\right]. \tag{3}$$

The new time envelope $\psi'(t;\,\Delta\omega,\Gamma_c,\Gamma_p)$ is broader in time and has acquired a time-dependent phase $\phi'(t;\,\Delta\omega,\Gamma_p,\Gamma_c)$ to?

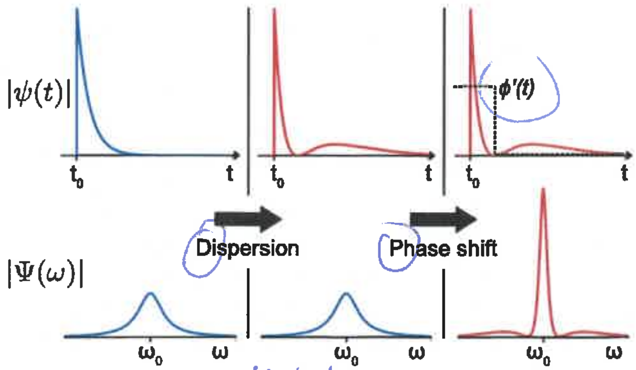
Similar to ~~what happens in the case~~ of Fourier-transform limited pulses, where the time-bandwidth product is minimized by a frequency-independent spectral phase, we expect to reduce the spectral bandwidth of the heralded single photon by removing any time-dependent phase.

To complete the compression, ~~we then apply~~ a time-varying phase shift $\phi_e(t)$ so that has to be the phase

$$\phi_e(t) = -\phi'(t;\,\Delta\omega,\Gamma_p,\Gamma_c)\,, \tag{4}$$

finally resulting in the spectrally-compressed

$$\psi''(t;\,\Delta\omega,\Gamma_p,\Gamma_c) = \psi'(t;\,\Delta\omega,\Gamma_p,\Gamma_c)\,e^{i\phi_e(t)}\,. \tag{5}$$



spectral

FIG. 1: Concept of compression. Top row is the temporal intensity profile of a photon, bottom row the respective power spectra. The initial pulse is dispersed by a cavity. The photon has now a new temporal shape, but the spectrum is unchanged. An EOM manipulates the phase of the pulse which leads to a narrower spectrum.

$\phi'(t)$

what does the color encode?

capitalization?

To quantify the compression we compare the spectral widths before and after the compression obtained from the respective power spectra. The power spectrum of the compressed photon is obtained through a Fourier Transform of Eq. 5.

We now consider the specific case of a signal and idler photon emerging from an atomic cascade decay, where we intend to compress the idler photon. The detection of the signal photon projects the idler mode into the heralded state

$$\psi(t) = \sqrt{\Gamma_p}\, e^{-\frac{\Gamma_p}{2}(t-t_0)}\Theta(t-t_0)\,, \tag{6}$$

where t_0 and t are the detection times of the signal and idler photons, respectively. The exponential decay with the constant Γ_p is a characteristic of the spontaneous process, while the Heaviside step function Θ is a consequence of the well-defined time order of the cascade decay process. For simplicity, we set $t_0 = 0\,s$.

Given this temporal profile, we expect a Lorentzian power spectrum for the idler photons. The bandwidth of a Lorentzian is described by the full-width half maximum Γ_p, which also corresponds to 50% of the total pulse energy. The compressed spectrum is a non-trivial distribution and the commonly used full width half maximum (FWHM) is not a good quantifier for bandwidth. Hence, we instead define bandwidth as the smallest spectral width containing 50% of the total pulse energy, as this definition of bandwidth is compatible for both a Lorentzian and a generic spectra.

To obtain the optimum cavity parameters, we numerically minimize the bandwidth of the compressed photon spectrum. The spectrum is obtained from the ~~Fast~~ Fourier transform of Eq.5. We find that the maximal compression is achieved by a resonant cavity $\Delta\omega = 0$ with a bandwidth of $\Gamma_c \approx \Gamma_p/4$. Under these conditions, the compressed single photon time envelope can be written as

$$\psi''(t) = e^{-i\phi'(t)}\sqrt{\Gamma_p}\,\frac{2\Gamma_c e^{-\frac{\Gamma_c}{2}t} - (\Gamma_p+\Gamma_c)\,e^{-\frac{\Gamma_p}{2}t}}{\Gamma_p - \Gamma_c}\,\Theta(t)\,, \tag{7}$$

with a

~~where the~~ phase function ~~is~~

$$\phi'(t) = \pi\,\Theta\left(t - 2\frac{\log\left(\frac{\Gamma_p+\Gamma_c}{2\Gamma_c}\right)}{\Gamma_p - \Gamma_c}\right)\,. \tag{8}$$

Comment that this is just a step!

Theoretically the narrowest bandwidth achievable with compression based on an asymmetric cavity is $\sim 0.3\Gamma_p$. The temporal photon envelope $|\psi(t)|^2$ and power spectra $|\Psi(\omega)|^2$ for an exponential decay are depicted in Fig.1.

Experiment – ~~We experimentally tested the spectral compression method.~~ The setup is shown in Fig. 2. We generate the time-ordered photon pairs by four-wave mixing in a cold ensemble of ^{87}Rb atoms in a cascade level scheme [7]. Pump beams at 780 nm and 776 nm excite atoms from the $5S_{1/2}, F = 2$ ground level to the

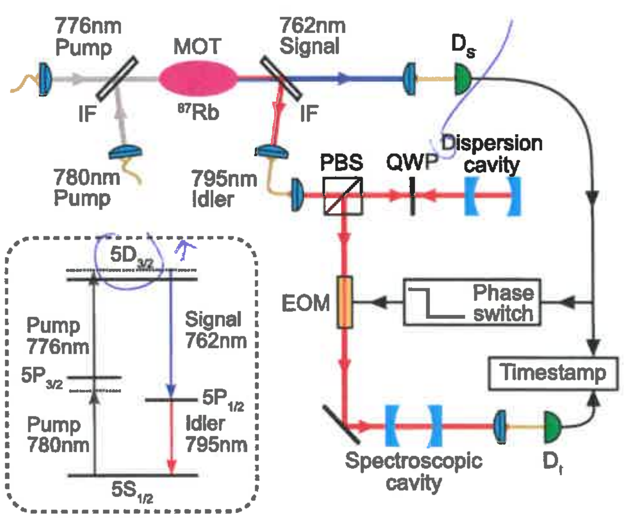


FIG. 2: ~~(top-right)~~ Schematic of the setup for generation and spectral compression of heralded single photons. Single-photon detectors $D_{S,I}$, Electro-optical modulator EOM, Polarization dependent beam splitter PBS, QWP Quarter-wave plate, IF Interference filter. ~~(bottom-left)~~ Energy level scheme for four-wave mixing in ^{87}Rb. (inset)

$5D_{3/2}, F = 3$ level via a two-photon transition. The 762 nm (signal) and 795 nm (idler) photon pairs emerge from a cascade decay back to the ground level and are coupled to single mode fibers. Phase matching is ensured with all four modes collinear and propagating in the same direction. The two pumps are focused in the cloud with a beam waist of about 400 μm. The 780 nm pump is 55 MHz blue-detuned from the $5S_{1/2}, F = 2$ to $5P_{3/2}, F = 3$ transition and has an optical power of 0.25 mW. The 776 nm pump shares the same optical mode, has an optical power of 11.4 mW, and is tuned such that the two-photon transition to the $5D_{3/2}, F = 3$ state is 5 MHz blue-detuned. When the excited atoms decay via the $5D_{1/2}, F = 2$ state back into the initial ground state, a 762 nm and 795 nm photon is emitted. After filtering the pump beams and separating the photons into different modes, we collect them in single mode fibers. The 762 nm signal photon is detected with an avalanche photo diode and heralds a 795 nm idler photon. The time correlation between the detection in the signal and idler modes, shown as blue circles in Fig. 3, corresponds to the intensity time envelope $|\psi(t)|^2$.

Ref to previous work

describe mechanism!

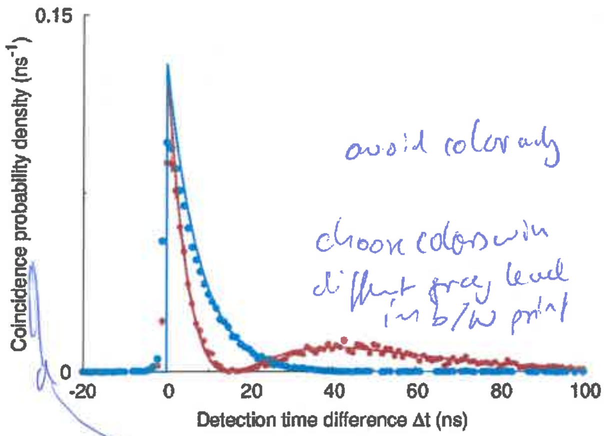
We measure the inital power spectrum of the wavepacket, shown in Fig. 4 blue dots, by measuring the photon transmission rate through a Fabry-Perot cavity (FP) with linewidth $\Gamma_{FP} \approx 2\pi * 2.6$ MHz. The transmission is recorded at different detunings corresponding to different parts of the photon spectrum. The observed photon spectrum is 20 ± 2 MHz, wider than the atomic line width of 6 MHz. We attribute this to collective emission effects in the cloud.

We then introduce the necessary dispersion by coupling the 795nm idler photon to a cavity. The highly reflective dispersion cavity has mirrors with nominal reflectivity $R_{\rm in} = 0.97$ and $R_{\rm out} = 0.9995$ separated by 10.1 cm, ~~resulting in an estimated~~ free spectral range of ≈ 1.48 GHz and a measured linewidth $\Gamma_c \approx 2\pi * 7.3$ MHz. A Pound-Drever-Hall frequency lock keeps the cavity resonant to the photons throughout the experiment. The measured time envelope of the single photon wavepacket after dispersion is shown as red circles in Fig. 3.

conversely

dots :)

The spectral compression is completed by applying the temporal phase of Eq. 8, in the form of a phase switch synchronized to the photon passage through a fiber connected electro-optical modulator (EOM). Since the idler photon is heralded, the location of the photon after some propagation time is known. The phase flip is applied, right after the first part of the dispersed photon exits the modulator and the second part starts to propagate through it. The right timing is indicated as dashed line in Fig.1. We measure the compressed photon spectrum by again recording the photon transmission rate through the Fabry-Perot cavity, shown as red dots in Fig. 4.



Circles

FIG. 3: Photon ~~detection~~ probability density before (blue dots) and after (red dots) the dispersion cavity. We fit an exponential decay Eq. 6 to the initial time correlation (blue solid line) , from which we infer the photon bandwidth Γ_p. From Eq. 2 we calculate the expected temporal profile after the photon passed through the dispersion cavity (red solid line).

the falling exponential

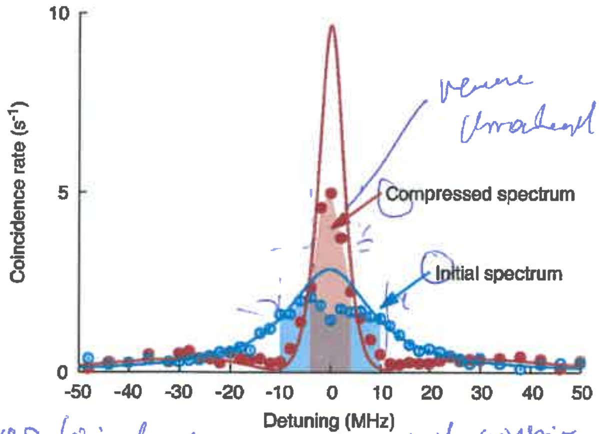
expectedly short

~~*Modeling the data*~~ – To obtain a initial photon bandwidth Γ_p, we fit Eq. 6 to the temporal envelope of the photons from our source; the blue dots in Fig. 3. The solid red line is the expected temporal envelope after the dispersion cavity, corresponding to Eq. 7, with Γ_p obtained from the fit of the initial photon shape, and Γ_c was experimentally determined. The measured temporal envelope after the dispersion cavity agrees well with the expected profile.

Circles

in Fig 3?

measured or calculated?



keep logical sequence: before and after compression

FIG. 4: Spectral profile of heralded photons with (red) and without (blue) compression measured by scanning fabry-perot cavity. The solid lines are calculated from Eq. 5, Γ_p is inferred from initial photon time correlation and Γ_c by experimentally characterizing the cavity bandwidth. The red and blue areas cover 50% of the total power.

The measured spectral profiles before and after compression is shown ~~as dots~~ in Fig 4. We observe a dip around the central frequency in the spectral profile of the uncompressed photons, and we attribute this to a reabsorption of the generated photons in our source. We model this by combining a Lorentzian with an absorption model

$$S(\omega, OD; \Gamma_p, \Gamma_a) = \frac{A}{\pi}\frac{2\Gamma_p}{4\omega^2+\Gamma_p^2}\, e^{-\mathrm{OD}\frac{\Gamma_a^2}{4\omega^2+\Gamma_a^2}}, \qquad (9)$$

the decay const

with OD ~~as the~~ an optical density of the cloud, and A a scaling factor as free fitting parameters. Γ_p determined by the previous fit, Γ_a is set to 6.06 MHz, the atomic line width of the $5S_{1/2} \rightarrow 5P_{1/2}$ transition. We fit this model to our data points and plot the Lorentizan part as the blue line in Fig. 4. We rescale the expected compressed power spectrum $|\Psi(\omega)|^2$ using the fitted value for the scaling factor A, shown as the red line in Fig. 4.

Discussion – A successful compression results in a narrower spectral width with an increased photon flux amplitude at the central photon frequency. In our experiment we measure a bandwidth of 20±2 MHz for the initial photon and 8±2 MHz for the compressed photon. This almost matches 6 MHz, the natural D transition linewidths of ^{87}Rb. The maximal photon flux through the spectroscopic cavity is increased by 239±4 percent. These two experimental observations demonstrate the successful spectral compression of narrowband photons. The compressions mechanism is in principle lossless since the photons are not spectrally filtered. However, we still suffer from photon loss due to the compression optics. In our experiment we have losses of >90%, where the main contribution of 70% comes from the fiber-based EOM.

← NEVER start a sentence with a symbol

This loss can be reduced signficantly by using a free-space EOM instead, which can have losses $< 10\%$.

for a The maximal compression is found ~~to be achieved when the~~ dispersion cavity bandwidth ~~is set to~~ $0.25\,\Gamma_p$. We believe that this compression method is a useful resource to relax the bandwidth requirements on narrowband single photon sources.

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$n(\omega)$ $C(\omega)$

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...ring in ...e shown ...hase manipulation ...he reversal

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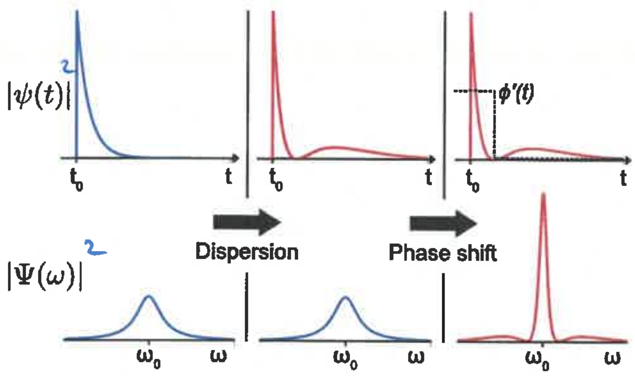

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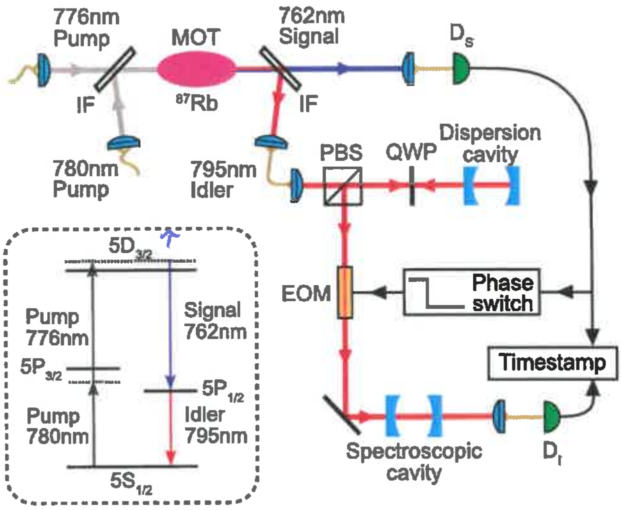

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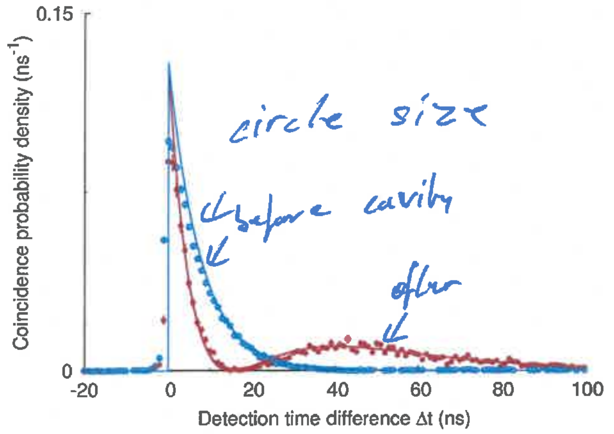

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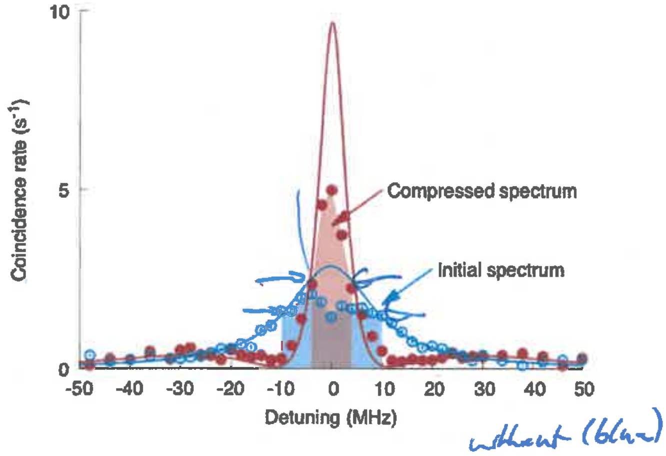
Modeling the data – To obtain a initial photon bandwidth Γ_p, we fit Eq. 6 to the temporal envelope of the photons from our source; the blue dots in Fig. 3. The solid red line is the ~~expected~~ temporal envelope after the dispersion cavity, ~~corresponding~~ calculated to Eq. 7, with Γ_p obtained from the fit of the initial photon shape, and Γ_c was experimentally determined. The measured temporal envelope after the dispersion cavity agrees well with the expected profile.



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The measured spectral profiles before and after compression is shown as dots in Fig 4. We observe a dip around the central frequency in the spectral profile of the uncompressed photons, and we attribute this to a reabsorption of the generated photons in our source. We model this by combining a Lorentzian with an absorption model

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an optical density OD

with OD as the optical density of the cloud, and A a scaling factor as free fitting parameters. Γ_p determined by the previous fit, Γ_a is set to 6.06 MHz, the atomic line width of the $5S_{1/2} \rightarrow 5P_{1/2}$ transition. We fit this model to our data points and plot the Lorentizan part as the blue line in Fig. 4. We rescale the expected compressed power spectrum $|\Psi(\omega)|^2$ using the fitted value for the scaling factor A, shown as the red line in Fig. 4. don't start with a symbol

Discussion – A successful compression results in a narrower spectral width with an increased photon flux amplitude* at the central photon frequency. In our experiment we measure a bandwidth of 20±2 MHz for the initial photon and 8±2 MHz for the compressed photon. This almost matches 6 MHz, the natural D transition linewidths of ^{87}Rb. The maximal photon flux through the spectroscopic cavity is increased by 239±4 ~~percent~~ 0.04. These two experimental observations demonstrate the successful spectral compression of narrowband photons. The compressions mechanism is in principle lossless since the photons are not spectrally filtered. However, we still suffer from photon loss due to the compression optics. In our experiment we have losses of >90%, where the main contribution of 70% comes from the fiber-based EOM.

* higher photon detect. probability

This loss can be reduced signficantly by using a free-space EOM instead, which can have losses $< 10\%$.

The maximal compression is found to be achieved when the dispersion cavity bandwidth is set to $0.25\,\Gamma_p$. We believe that this compression method is a useful resource to relax the bandwidth requirements on narrowband single photon sources.

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