Room temperature atomic frequency comb storage for light: supplement

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Supplement DOI: https://doi.org/10.6084/m9.figshare.14608131

Parent Article DOI: https://doi.org/10.1364/OL.426753
Supplement: Room Temperature Atomic Frequency Comb Memory for Light

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1 Experimental Setup

Figure 1 shows a schematic of the experimental setup. Our memory is a paraffin-coated Cs cell of length 25 mm and diameter 10 mm. Three independent narrowband continuous-wave (CW) lasers are utilised. One laser is tuned to the \( F = 4 \rightarrow F' = 4 \) transition in the \( D_2 \) line (852 nm - Sacher Lasertechnik ECDL) and is used to perform the initialisation of the ground states. A second laser is tuned to the \( F = 3 \rightarrow F' = 4 \) transition in the \( D_1 \) line (895 nm - Toptica DFB) and is used to perform the velocity-selective optical pumping - see below for more details. The final laser acts to probe the system both in frequency (absorption spectra) and time (AFC echoes) on the \( F = 4 \rightarrow F' = 3, 4, 5 \) transitions in the \( D_2 \) line (Toptica DL Pro). Each pump mode has an acousto-optic modulator (AOM) for temporal control of the pumping, while the probe mode has an AOM in a double-pass configuration in the detection. The role of the AOM is two-fold: For the spectroscopy the detection AOM turns on only at the appropriate time (more information below) for a duration of 100 ns; For the echo experiment the detection AOM serves to protect the single photon detector (more information below) from the AFC preparation. For the creation of the pulses for the echo experiments, a fiber-based electro-optic modulator is used (driven by two arbitrary waveform generators - RF1 and RF2) to create near Gaussian pulses of 2 ns duration. For more details on this pulse carving setup see [1]. We note that this EOM is bypassed when measuring the atomic spectra. The pump modes are combined using a dichroic mirror (DM), and then expanded to a beam radius size of 2.7 mm (1.9 mm) for the hyperfine (velocity selective) pump mode before the cell.

![Experimental Setup Diagram](image)

Figure 1: Experimental setup. See text for details.

We arrange the probe mode (of beam radius 290 mm at the cell) to be counter-propagating the pump modes and a polarising beam splitter (PBS) is used after the cell to separate this mode toward the detection. A bandpass filter (BPF - Thorlabs FL850-10) centered on the \( D_2 \) laser is placed in the detection mode to effectively filter the velocity selective pump laser. A silicon avalanche photodetector (Thorlabs PDA120) is used for the spectroscopy and a single-photon avalanche photo-detector (Perkin Elmer SPCM-AQR series) together with a time-tagger module (Swabian Instruments Time Tagger 20) for the echo experiments. For the echo experiments, several neutral density (ND) filters are placed in the pulsed signal mode before the cell to reduce the number of photons per pulse to the few hundreds level, and additional ND is placed in the detection mode to reduce the signal and any leakage to the single photon level.

The atoms physically move out of the probe mode much faster that the laser can be scanned in a mode-hop free manner, therefore it is not possible to probe the entire AFC spectrum after a given velocity-selective pumping procedure. We instead piece together a full spectrum with around a thousand individual probe measurements. The sequence begins with the pump mode open for approximately 998 \( \mu s \) and power of about 20 mW, emptying the \( F = 4 \) hyperfine level. The role of the paraffin coating becomes apparent here, assisting in this initialisation by redistributing the velocity classes of the atoms with spin-preserving collisions with the paraffin allowing to use a narrowband laser for efficient pumping. This is followed by a velocity-selective optical pump for a duration of around \( \tau_p \) and a varying power level. Then, the probe mode is detected precisely after the velocity-selective pump has turned off for a duration of around 100 ns. The total sequence duration is 1 ms. The probe laser is scanned over about a GHz at a rate of 5 Hz and is done asynchronously with the AFC preparation, such that a
Figure 2: Velocity selective optical pumping. A single velocity class is pumped back into the $F = 4$ hyperfine ground state of a cesium vapour. The zero of the frequency axis represents the $F = 4$ to $F' = 5$ transition. The unpumped case is included for comparison. A fit is made to the features giving a width of about 45 MHz.

different part of the AFC spectrum is probed after each preparation round. Repeating this procedure we piece together 1000 probe measurements to complete the full spectrum.

2 Velocity Selective Pumping

Figure 2 shows an example of preparing a single velocity class in the $F = 4$ ground state. The velocity-selective pump power and time are 0.86 mW and 1.2 $\mu$s respectively. We see three distinct peaks in the spectrum, corresponding to the three allowed transitions between the ground and excited states associated with the narrow velocity class. The spectral width of the velocity class is determined to be 45 MHz by fitting using Gaussian functions centered at the absorption peaks. The dependence of the width on pump duration and power is described in a separate publication [2].

3 AFC Preparation

As outlined above, the velocity selective pump mode is applied by a single laser tuned to the D1 transition for a duration around 100 ns. To prepare the various atomic frequency combs, it is necessary to address multiple frequency classes. This is done with direct modulation of the laser current via the bias-T with an RF Arbitrary Waveform Generator (Keysight 33600A). Our approach was to use integer divisions of the $F' = 4$, $F' = 5$ hyperfine excited state splitting of 251 MHz in order to utilise both transitions for a broader band AFC implementation. Modulation on the bias-T of the laser has the effect of inducing frequency sidebands on the spectrum of the laser at plus and minus the modulation frequency, resulting in two additional velocity classes being addressed per applied modulation frequency.

Table 1 outlines the AFC comb spacings $\Delta$ we prepared, the resulting rephasing times $\tau$, and the required RF modulation frequencies necessary to create the AFC. Given the maximum analogue output of our waveform generator (80 MHz), it was necessary in some instances to use a half the frequency needed and then to double-amplify-filter the AWG output with mini-circuits electronics. In the instances where two frequencies are required, these where provided by the 2-channel AWG and were combined using a simple coaxial T-piece. The authors note that this approach is far from an ideal implementation involving the use of an RF power splitter, however was sufficient to demonstrate the particular AFC. The RF power of the modulation was optimised for each AFC and was generally not exceeding 6 dBm.

| $\Delta$ [MHz] | $\tau$ [ns] | Mod Freq. [MHz] |
|----------------|-------------|-----------------|
| 125.5          | 7.97        | 125.5           |
| 83.67          | 11.95       | 83.67           |
| 62.75          | 15.94       | 62.75, 125.5    |
| 50.2           | 19.92       | 50.2, 100.4     |

Table 1: AFC tooth separation $\Delta$, corresponding rephasing time $\tau$ and the modulation frequencies needed. To create the * frequencies (i.e. frequencies that exceeded the maximum analogue frequency of the AWG), the AWG was set to half the required frequency and a mini-circuits frequency doubler and amplifier were used.
Figure 3: Different implementations of the AFC. Velocity classes are pumped back into the $F = 4$ hyperfine ground state using the VSP pump laser with modulation frequencies outlined in Table 1. The zero of the frequency axis represents the $F = 4$ to $F' = 5$ transition. The unpumped $F = 4$ spectrum is included for reference.

Figure 3 shows the spectra for four separate AFC implementations. Two of these are exactly the combs from the main text with rephasing times of around 8 ns and 12 ns, the additional two showing the case for rephasing times of around 16 ns and 20 ns. This showcases the flexibility of our system and our approach being able to create arbitrary-spaced many-toothed atomic structures within a timescale of a $\mu$s. It is clearly seen that as we decrease the tooth separation $\Delta$, the effective background absorption of the AFC is increasing. This is an expected observation given the minimum velocity class width that we can prepare, limited by the laser linewidth, power broadening and ultimately the atomic linewidth of the transition [2]. We note that we were not able to observe the time response for the 16 ns and 20 ns rephasing time AFCs, the increased absorption background for these AFCs inducing too much loss to enable efficient read out.

References

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