

Electromagnetically Induced Transparency as a Memory for Quantum Entanglement Distribution

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ABSTRACT

Effective quantum communication is the transfer of quantum states over long distances. Optical fibres are effective for classical communications, where amplification is possible, but the no-cloning theorem and the very nature of quantum information, quantum states encoded in single photons, means there is no way to make a “quantum” amplifier. For this reason, free space transmission is almost certainly important for developing a quantum information network based on quantum repeaters. In particular, satellite communications allow for maximum single jumps between repeaters, at the cost of size, weight, and power restrictions, and all the other requirements of optical systems in space.

In order to make these quantum repeaters, a method of storing and retrieving the quantum states is needed: a quantum memory. One form of quantum memory is to use three levels in an atomic system: in particular, using electromagnetically-induced transparency (EIT) in a Λ system in rubidium atomic vapour to slow, stop, and release photons.

This Λ system requires laser locking and conditioning, as well as very effective optical coupling and filtering. Moreover, a magneto-optical trap (MOT) can be used to cool and compact the atom cloud, at the difficulty of requiring further laser conditioning and magnetic field control. As a start toward satellite-based optical quantum state exchange, we have begun creating a ground-scale optical quantum memory with Rb atoms, and have shown modest storage and retrieval efficiencies and times. We will show these results, and our proposed steps towards improving them and making the entire system smaller and more light-weight.

Keywords: Quantum Networks, Quantum Communications, Electromagnetically-Induced Transparency

1. INTRODUCTION

Quantum networks, allowing the interaction of quantum systems over long distances, are of great interest.¹ However, the quantum states are fragile (often single photons), the losses in transmission are high (whether in waveguides such as fibre, or in free space), and amplification is not possible^{2,3} (because of the no-cloning theorem). However, it is not necessarily the quantum state itself that is of interest, but the entanglement between two quantum states. By implementing a chain of entanglement swapping,⁴ it is possible for entanglement to be distributed over great distances, far beyond the range of a single pair of photons, using a network of quantum repeaters. An important practical consideration for entanglement swapping is ensuring the quantum states, encoded in photons, arrive at the correct place at the same time.

To this end, quantum memories are an essential component of a quantum repeater network, obviating the problem of timing differences. The prototypical optical quantum memory will take in a photon, store it for a time, and on demand release it unchanged. There are many possible technologies for quantum memories, including rare-earth-ion doped crystals,⁵ nitrogen vacancy (NV) centres in diamond,^{6,7} and gradient echo memories,⁸ Raman scattering,⁹ and electromagnetically-induced transparency (EIT)^{10,11} in neutral atoms.

One way to avoid losses in transmission channels, as well as increasing the destinations a single repeater can address, is to operate in free space rather than a waveguide.¹² By mounting the repeater nodes on satellites, the

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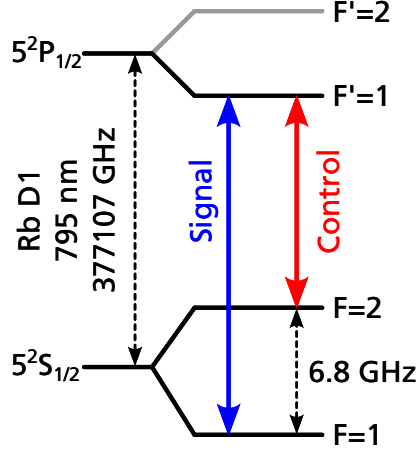


Figure 1: The energy levels used here for EIT in ^{87}Rb atoms.

maximum distance for a single link in the entanglement chain can be obtained, at the cost of the stringent size, weight, and power (SWaP) restrictions of satellite technologies. EIT in neutral atoms has promising properties for use in satellites: it requires no moving parts or cryogenics, the laser powers required are relatively low, and with careful design the systems can be miniaturised into small, self-contained, systems. In particular, it is possible to make small magneto-optical traps with grating chips,^{13,14} so called grating MOTs or gMOTs, that increase coherence and thus could increase storage times and efficiencies. These gMOTs are also suitable for satellite use.

EIT is a procedure where the absorption of an atomic transition is reduced, perhaps to zero, as a result of destructive quantum interference, which shows as the increased transmission of a weak probe beam. The interference occurs when a second, coupled, transition is driven very strongly,^{15,16} and has the overall effect of changing the refractive index of the material, thus changing the speed of light in the material. This is perhaps an intuitive way to think of EIT for memories: the light is captured and slowed down to zero speed for a time, then released on demand.

There are several different systems that are available to induce transparency.^{10,15} Of these, the Λ system shown in Figure 1 has the possibility of complete (100%) transparency,¹⁰ which implies the maximum storage and retrieval efficiency, as well as being compatible with our ultimate goal of using cold atoms trapped in a magneto-optical trap (MOT), which allows for high optical densities and low decoherence. The Λ scheme used is shown in Figure 1, where the photons to be stored (the “signal”) are close to resonant with one transition ($F = 1 \leftrightarrow F' = 1$), while a “control” transition ($F = 2 \leftrightarrow F' = 1$) which shares one energy level with the signal transition is also driven. The $F = 1 \leftrightarrow F = 2$ transition between the energy levels that are not common to these transitions is electric-dipole forbidden, so that we can imagine the incoming photons being stored in a non-emitting state until later recalled.

Here we show preliminary measurements of EIT in a warm vapour cell, as a means to easily demonstrate the procedure, and to understand some of the requirements and possibilities of the system, with the intention of future integration with a grating MOT.

2. ELECTROMAGNETICALLY INDUCED TRANSPARENCY

Our system is based on the use of electromagnetically-induced transparency (EIT), and so it naturally is useful to determine that EIT is present, and to characterise the degree of transparency. This is both a proof of the concept, and a way to ensure that our optical system is configured correctly, with suitable beams, overlaps, and laser locking.

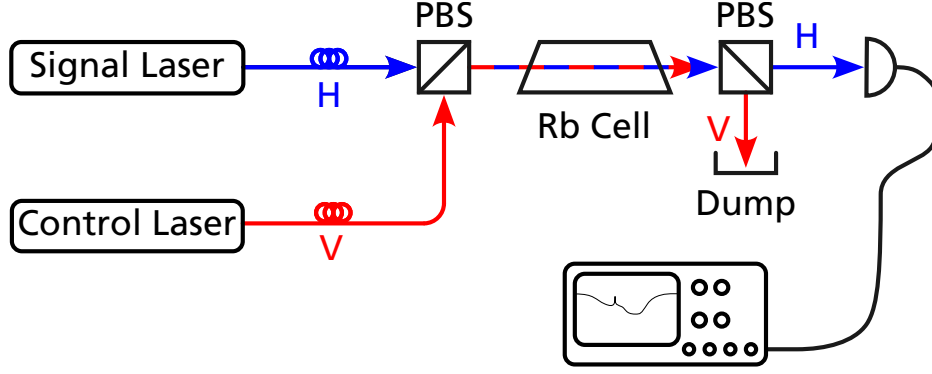


Figure 2: The experimental configuration for EIT measurements. The two lasers, one fixed to the control transition frequency, one scanning approximately 4.5 GHz over the signal transition, are polarised horizontally (H) and vertically (V) with respect to the optical table, and are combined on a polarising beam splitter cube (PBS). The two beams pass through the cell together, then are separated on another PBS cube. The control laser is dumped, and the signal transmission is measured on an amplified photodetector which is connected to an oscilloscope for data recording.

2.1 Methods

The configuration for the first measurement, of EIT, is shown in Figure 2. A control laser (Toptica DLC pro diode laser) is locked to the “control” transition in Figure 1 with Doppler-free saturated absorption spectroscopy (SAS) of a separate Rb vapour cell, and is coupled to a polarisation maintaining fibre. A second laser, of the same type, is swept with a saw-tooth function over the signal transition by approximately 4.5 GHz. The two laser beams are coupled out into free space with orthogonal polarisation, and are combined and overlapped on a polarising beam splitter cube. After the cell, the control beam is separated from the signal beam with another polarising beam splitter and the control beam dumped. The transmitted signal is measured by a photo detector, and resulting voltage recorded with an oscilloscope. Because the polarising beam splitters only have an extinction ratio of around 1000, it is also necessary to take a measurement with the signal laser blocked to determine the true zero level of the detector.

In order to calibrate the frequency scale, the output of a separate SAS system attached to the signal laser is recorded at the same time as the transmission, and the Doppler-free peaks of the absorption features are located. The frequency between these peaks is well known, and so a polynomial giving the optical frequency as a function of the time axis on the oscilloscope can be fitted.

2.2 Results

A representative measurement of the observed EIT can be seen in Figure 3. With the control laser locked to the desired transition, the signal laser is scanned and the Doppler-broadened absorption spectrum is seen as a broad decrease in transmission. However, when the signal laser is resonant with the three-level system shown in Figure 1, the transmission increases back to the background level. The depth of this change, the difference between the background transmission, the complete transmission, and the EIT peak transmission is a measure of the completeness of EIT. For the purposes of photon storage, the higher the EIT the better, and in principle with this particular system we can reach complete transparency.¹⁰ The relative intensities of the two beams affect the depth of EIT: this can be easily adjusted by changing the laser power of each beam, and changed with more difficulty by altering the beam size. In the image shown, the control laser was approximately 14.9 mW with a diameter of approximately $450\text{ }\mu\text{m}$ at the centre of the cell, and the signal laser was approximately $420\text{ }\mu\text{m}$ in diameter with power of 1.32 mW.

To determine the degree of transmission, a Lorentzian curve, modified with a linear background term, was

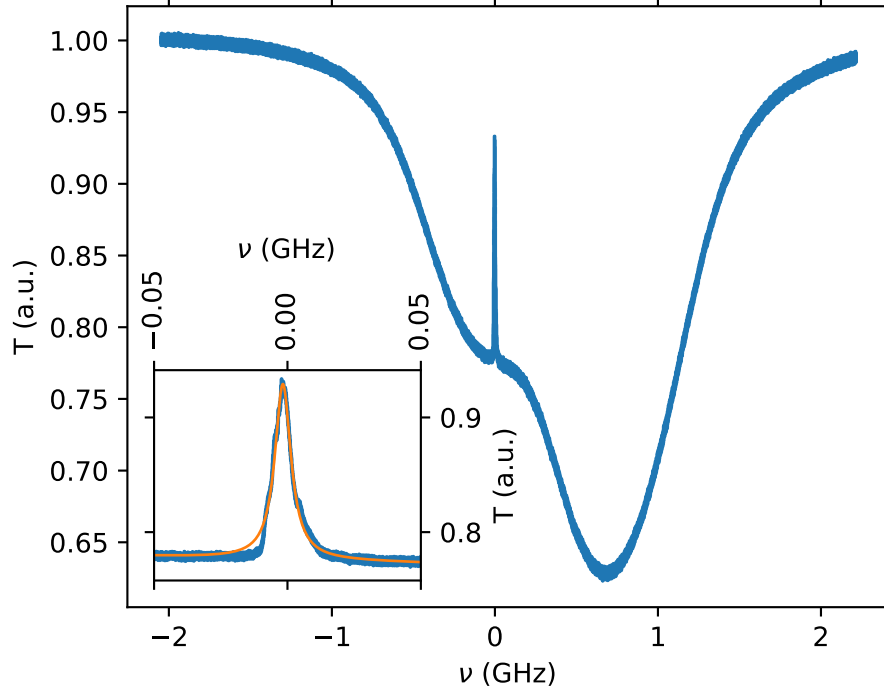


Figure 3: Measured transmission using the configuration in Figure 2. The induced transparency is clear at 0 Hz. The inset shows the fit to the EIT, as described in the text.

fitted to the EIT peak, as shown in the inset to Figure 3. This expression has the form

$$T(\nu) = A \cdot \frac{\frac{1}{2}\Gamma}{(\nu - \nu_0)^2 + \left(\frac{1}{2}\Gamma\right)^2} + C + D \cdot \nu, \quad (1)$$

where C and D are empirical values describing the background shape of the Doppler-broadened spectrum, A is an empirical scaling factor, ν_0 accounts for the line shift, and Γ is the usual Lorentzian full-width at half-maximum (FWHM). For the data shown, $\Gamma = 7.29$ MHz. Using these parameters, we can determine the degree of induced transparency. If 100% is complete transmission, and 0% is the background of the feature, the data in Figure 3 show a induced transparency of 68.4%.

3. STORAGE AND RETRIEVAL

After confirming that we see induced transparency, we can then show it is possible to store and retrieve photons in the warm vapour.

3.1 Methods

We measure the storage and retrieval of photons using the system shown in Figure 4a with the pulse sequence in Figure 4b. We use the same two lasers, vapour cell, and beam-splitters as for the EIT measurements above.

The lasers now are locked to their respective transitions in Figure 1, and instead of CW beams into the vapour cell, the output is modulated with acousto-optic modulators (AOMs, A.A. Opto-Electronic MT110-NIR20-Fio, 110 MHz) driven by an arbitrary waveform generator (AWG, Keysight 33622A) that is programmed with the desired envelope function over the 110 MHz driving frequency to generate the pulses.

While the output of the control laser is kept as high as possible, the power of the signal laser is attenuated to better approximate the eventual single photon source. Typical levels for the powers, as well as other parameters,

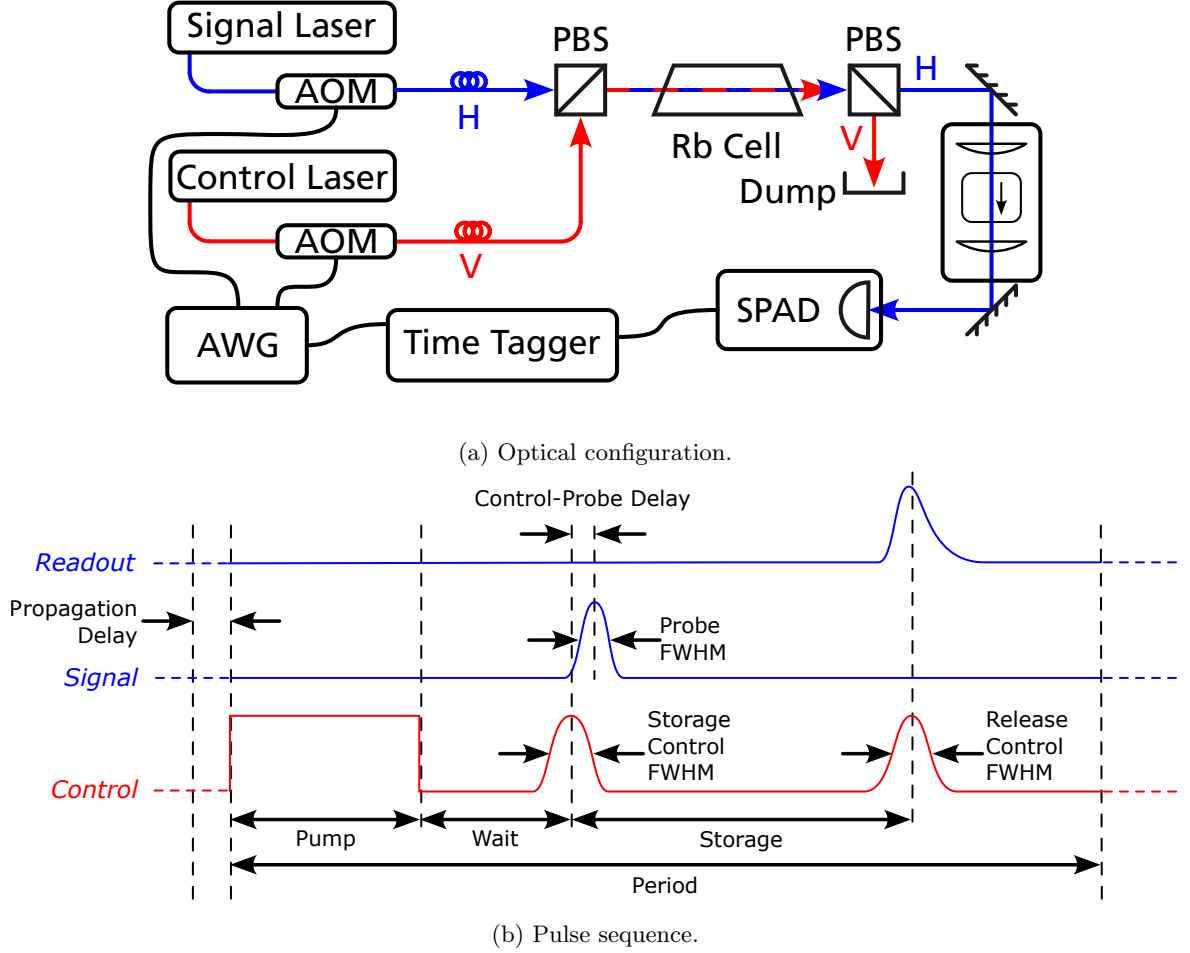


Figure 4: Measurements of storage and retrieval. (a) The same polarised lasers as for the EIT measurements are used, both locked to their respective transitions. Their output is pulsed with acousto-optic modulators (AOMs) controlled with an arbitrary waveform generator (AWG), as described in the text. A filter module of two étalons and an optical diode suppresses residual control laser power, and the signal photons, both leakage through the atoms and stored and released photons, are detected on a single-photon avalanche photodiode (SPAD) module. (b) The pulse sequence incident on the vapour cell, with named parameters. Example parameters are given in Table 1. The signal and readout are the same wavelength, but are separated here for clarity of description. This shows an ideal case, where all of the signal photons are absorbed by the atoms, and all are released on the readout.

Table 1: Typical parameters for the pulses in Figure 4b, and the actual parameters for Figures 5 and 6.

Parameter	Unit	Typical	Figure 5	Figure 6
Period	ms	32	32.0	32.0
Pump Time	ns	0–10	10000.0	10000.0
Wait Time	ns	100	1000.0	400.0
Storage Time	ns	100	2000.0	350.0
Pulse-Control Delay	ns	± 100	0	0
Control FWHM	ns	30–200	350.0	50.0
Readout FWHM	ns	30–200	350.0	50.0
Probe FWHM	ns	30–200	140.0	20.0
Control Peak Power	mW	~ 10	10	12.5
Signal Peak Power	nW	10–200	130	100
Repetitions		10^6	937500	937500
Counts: Leakage			4712347.3	605990.5
Counts: Retrieved			25956.7	39015.5
Efficiency η		0–10%	0.05%	6.0%

are given in Table 1, along with the actual parameters used for the two measurements reported here. The signal is ~ 100 nW, while the pump is as large as practical, here ~ 10 mW. This disparity of powers means that the polarising beam splitter, with extinction ratio of merely 1000:1, is not enough to avoid saturating the single photon avalanche diode (SPAD) module, and so additional filtering is required.

A particular difficulty of this filtering is that the signal in the pass-band is small ($\sim$ nW), while a mere 6.8 GHz away the undesired laser in the stop band is much stronger even after polarisation separation (~ 100 μ W). The entire filter module, including the polarisation filtering, must pass approximately all of the signal ($\sim$ nW) while also reducing the control (~ 10 mW) to less than the signal, that is to say, more than seven orders of magnitude, or >70 dB. Even under ideal circumstances, the polarising beam splitters are only able to suppress three orders of magnitude, so there are still more than five orders or 50 dB required. The additional filtering is implemented as a pair of temperature-controlled cascaded Fabry-Pérot étalons (Thorlabs FPQSA-5) separated with an optical diode to prevent interference between the étalons (Toptica SSR 780). These étalons have a FSR of around 30 GHz, and a finesse of >300 , and can be tuned over several FSRs by controlling the temperature (and thus length) of the étalon. The finesse means that at 6.8 GHz from the pass line, there is approximately 30 dB of suppression for one étalon, which is why two in series are required. As will be seen with the measured results, this is sufficient to reduce the control laser power incident on the SPAD module to less than the signal level.

The filtered signal beam is then passed into the SPAD module (Excelitas SPCM-AQRH-16), which has a protective shutter and broadband dielectric filter (Thorlabs FBH789-10) as a final protection against over-saturation, as the beam path after the cell is entirely in open space. The output of the SPAD is fed to a time-resolving pulse counting device (Swabian Instruments TimeTagger Ultra) which is also connected to the AWG.

To store and retrieve photons, the pulse sequence in Figure 4b is used. First, a square pump pulse is used to drive the atoms to a known state. Then, after a short wait time, a “storage” pulse on the control laser is used to open transparency in the atoms, which overlaps with a pulse of light from the signal laser, to give a “probe” bundle of photons. Typically the number of photons per signal pulse is around 10^6 , and the delay between probe and control is zero. After some predetermined storage time, a second pulse of the control laser (a “release” pulse) is used to retrieve the photons from the atomic cloud. These released photons show as pulse of light at the same wavelength as the signal laser but delayed by the storage time. This diagram shows the ideal case, where all of the probe pulse is absorbed by the atoms and all of the absorbed photons are released. In actual fact, because the EIT is not complete, there is some “leakage” of photons through the atoms which shows as a pulse synchronous with the control pulse. Similarly, the actual storage efficiency is less than one, so that the background noise of the SPAD is as large as the signal. Therefore, the sequence shown is repeated a great number of times in order

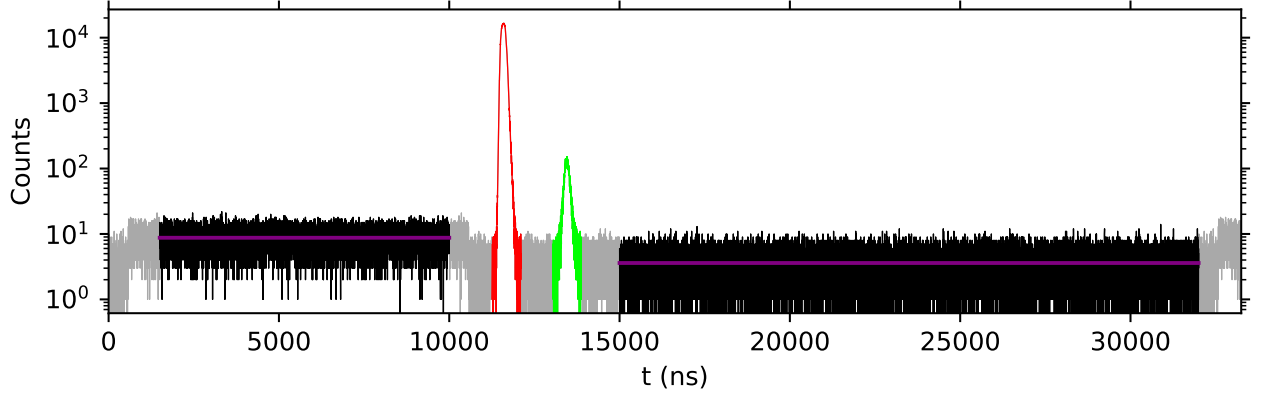


Figure 5: An example dataset, showing that there is significant leakage through the cloud of atoms (first peak, red), as well as a moderate number of retrieved photons (second peak, green). The leakage of the control beam through the filter can also be seen during the pump portion ($t < 10000$ ns). This, along with the dark counts, are fitted with horizontal lines (shown in purple) and are subtracted before analysing the data. The coloured peaks show the range over which the counts are integrated for each peak.

to improve the signal to noise ratio. Because there is no preparation time for this system, the 32 ms sequence can be repeated immediately, so that over the course of a minute approximately 10^6 repetitions occur.

In order to ensure that the storage and retrieval is real, the AWG is programmed so that the same sequence is repeated the same number of times without the “probe” pulse and also without the control laser pulses, so that any leakage through or around the filter is shown separately, as well as any other processes that might happen. These other data are used for the moment only as a pass/fail confirmation, because instability of the étalon filters make quantitative comparisons between runs difficult.

3.2 Results

A great number of measurements have been made with a great number of parameters varied: for the sake of convenience we show only two of them: one to show the procedure, and one to show the performance so far obtained.

The first is shown in Figure 5 and was collected with the parameters in Table 1. It shows the sum over 1 minute (or 937500 repetitions) of the sequence, for a storage time of $2\ \mu\text{s}$, with relatively long pulses. Storage and retrieval is clearly evident, if not large, and moreover this plot shows two other important features: the leakage of the pump pulse through the filter module ($1000\ \text{ns} < t < 11000\ \text{ns}$), and an offset from dark counts on the detector ($15000\ \text{ns} < t < 32000\ \text{ns}$). The control leakage can be averaged to give a background level for the leakage of the “storage” and “release” pulses, which can be subtracted from the measured pulses to give a more correct count. Similarly, the long dead time after the pulses gives a measure of false counts that also can be removed.

Once these false counts have been removed from each bin, the counts can be integrated over each of the pulses, to give a count of the total photons. The assumption is made that the detector efficiency is the same for both pulses, and the integration range is set to 1.2 times the programmed pulse full-width at half-maximum (FWHM). Each of the leaking storage pulses and the retrieved pulses is integrated. The efficiency is approximated by dividing the retrieved sum by the sum of the leakage pulses and the retrieved pulses, which while not a complete measurement gives an approximate efficiency.

In this case, the storage efficiency after $2\ \mu\text{s}$ is around 0.055%, or 550 parts per million.

The second results are shown in Figure 6, with parameters as shown in Table 1. This shows a much higher storage efficiency, with much shorter pulses and for a much shorter storage time, collected over the same number of cycles. In this case, the efficiency is approximately 6%. There is also a tail evident on the first pulse, suggesting

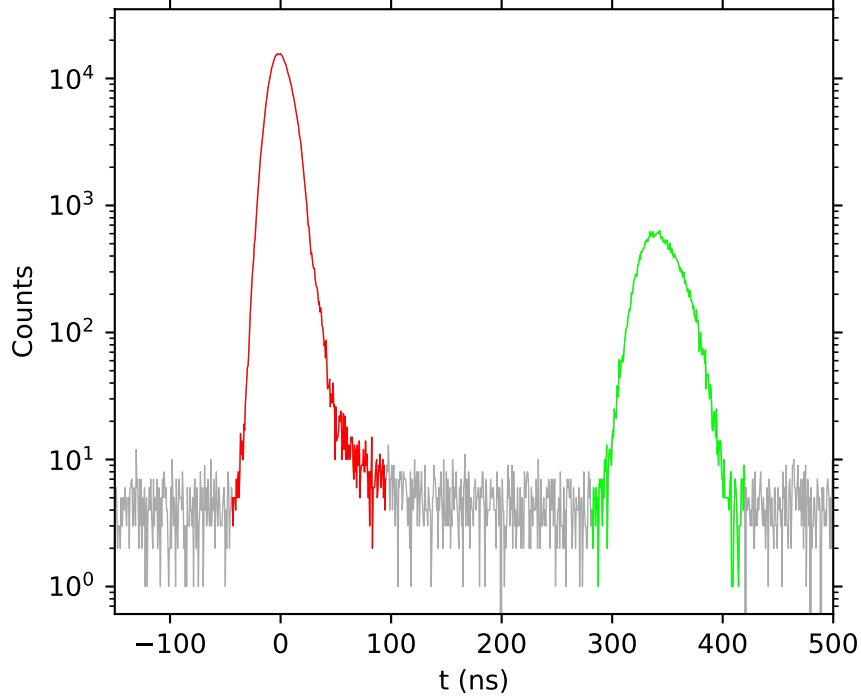


Figure 6: An example of higher efficiency storage and retrieval. Note how there is still significant leakage through the warm vapour, and also that the Gaussian input pulses have a changed shape after passing through the vapour. In spite of this, the measured efficiency is approximately 6%.

that the “storage” pulse was not of the optimal length, shape, or offset, and allowed some of the stored photons to escape before the EIT window closed completely.

4. DISCUSSION

The transparency seen in Figure 3 is not the complete transparency that the theory predicts. This can be attributed ultimately to practical reasons: these measurements were taken in order to confirm we had the correct equipment and sequence of operations to show EIT in a cloud of cold atoms that is being developed separately, rather than seeking the best possible storage and retrieval in warm atoms. Therefore, the optical power available and the beam shapes were not optimised for this warm vapour cell. In particular, the control laser power was set to the maximum available, which is evidently not enough. While it could be possible to increase the power with amplification, this was not deemed necessary once EIT and storage was seen.

In a similar vein, the storage efficiency seen is modest, merely showing that we have the correct approach to store and retrieve photons.

It is also important to note that the calculated efficiency here is only an approximation of the true efficiency, ignoring as it does any other loss of photons from, for example, scattering off the atoms or spontaneous emission. When the efficiency is seen to be larger it will be necessary to make a more complete measurement.

While for these proof-of-concept measurements the leakage of the control signal through the filter module were useful as a check on the detector operation, the extinction ratio as well as the stability of these étalon filters is not particularly good, the transmission band moving by more than a line width over the course of seconds, seemingly in response to environmental changes and the intensity of the incident light. This did not affect the suppression of the control beam, but did mean that the transmission of the signal varied from around 70% to much less than 10% over the course of seconds, making comparisons of different data sets difficult. Furthermore, even with better stabilisation, the expected transmission is not at high as might be desired for single photons,

and the extinction ratio still allows leakage of the control beam of a similar amplitude as the signal we are measuring. Because we require filtering of the light a mere 6.8 GHz from the pass band, the options are limited. There are, for example, fibre Bragg grating filters for 1550 nm band light,¹⁷ but they are not yet shown to work at the 795 nm we require.

Notwithstanding the movement of the pass-band, the filter module suppression is in fact slightly better than the data in Figure 5 suggest. It turned out that there was significant scattering off the warm atoms inside the vapour cell, and this light was able to make its way through free space around the filters to the SPAD, increasing the apparent noise levels. With better enclosures and shielding, the amount of leakage past the filters has been reduced by more than a factor of 10.

5. CONCLUSION

We have replicated the well known phenomenon of electromagnetically induced transparency in a vapour of ^{87}Rb atoms at around 50°C. While it is theoretically possible to get complete transparency using this system of atoms, the main purpose of these measurements is to show that the procedure and equipment are capable of measuring the transparency and of storing and retrieving photons from ^{87}Rb atoms, which it successfully did. The system is now being integrated with a grating MOT of ^{87}Rb , with the expectation of decreased decoherence and increased storage time and efficiency.

ACKNOWLEDGMENTS

The authors thank Carlos Sandchidrián Vaca for his valuable assistance in experimental and measurement preparations.

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