# Quantum Memory using $Pr^{3+}$:$Y_2SiO_5$

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**Abstract**

Quantum memory to be used in quantum repeater schemes appears to be essential to the development of long distance quantum communication and quantum networks. The realization of long distance quantum network capability has not yet been achieved and the presented research makes headway towards this goal. We report progress towards the implementation of a quantum memory in $Pr^{3+}$:$Y_2SiO_5$ that has read-write capability. Specifically, this research successfully implemented a narrowband spectral filter into the memory scheme.

# 1 Motivation

A correlative to the development of quantum computing devices is the need for the communication of quantum states between separate devices that is efficient and fault-tolerant over long distances. An elementary quantum network can be constructed by sharing entangled states over large distances and can then be used for quantum teleportation, quantum cryptography, and Bell inequality detection. Creating long-distance quantum communication is hampered by the fact that photonic channels have loss and decoherence that renders information to be lost exponentially with the distance traveled.[1] These losses are due to optical absorption and channel noise and make it impossible to create entangled states over distances of thousands of miles using traditional fiber networks.[2] It is not possible to compensate for these losses with signal amplification due to the no-cloning theorem. [3] Therefore, it is desirable to find a means by which high fidelity quantum communication can be achieved that avoids exponential loss. A scheme was proposed in 2001 by Lu-Ming Duan, Mikhail Lukin, J. Ignacio Cirac and Peter Zoller (DLCZ) to use quantum repeaters to achieve long-distance quantum communication. [1]

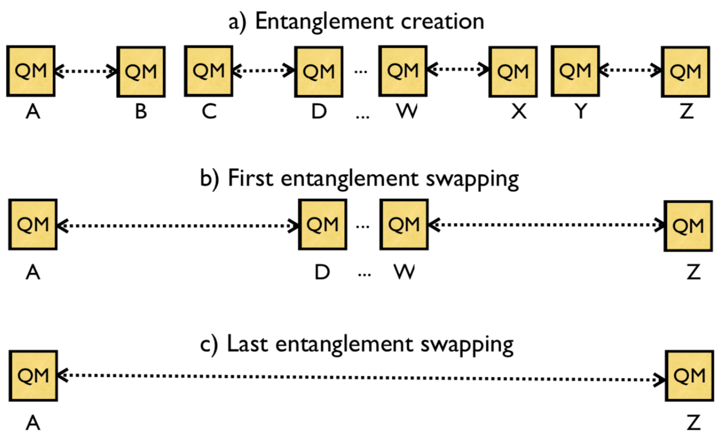


Figure 1: Entanglement swapping allows entangled states to be created over long distances without the entangled pair having ever directly interacted. (Image from [4])

## 1.1 DLCZ Protocol

The quantum repeater protocol consists of three steps: entanglement generation, connection and application. Entanglement is generated by simultaneously exciting two ensembles of atoms and combining the forward scattered Stokes light at a beam splitter. The success of creating entanglement in this process is inherently probabilistic and may require several tries. On average one will need to repeat the process $1/p$ times to achieve entanglement where $p$ is the probability of getting a click at the photodetector. [4] For this reason, it is necessary to not lose the quantum information in the case of a failed entanglement. Quantum repeaters are used to store the quantum information in an excited state of matter which can then be accessed using a *read* pulse. By storing the quantum information in a memory device for a sufficiently long time, it may be re-accessed until a successful entanglement is accomplished.[2]

Also key to the DLCZ protocol is the process of entanglement swapping that connects quantum repeaters. (Figure 1) Entanglement swapping allows for the transmission of information between adjacent quantum repeaters by entangling two states that have never interacted. Consider four quantum states encoded in photons A, B, C and D where A-B are entangled and C-D are entangled. A joint measurement on A and C in the Bell basis causes photons B and D to be projected onto an entangled state and effective entanglement swapping has occurred. Entanglement swapping has been throroughly demonstrated experimentally and was achieved with continuous light for the first time in 2007.[5]

If entanglement can be created over a short distance, L, and entanglement swapping can be successfully employed, then creating entanglement independently in adjacent systems each

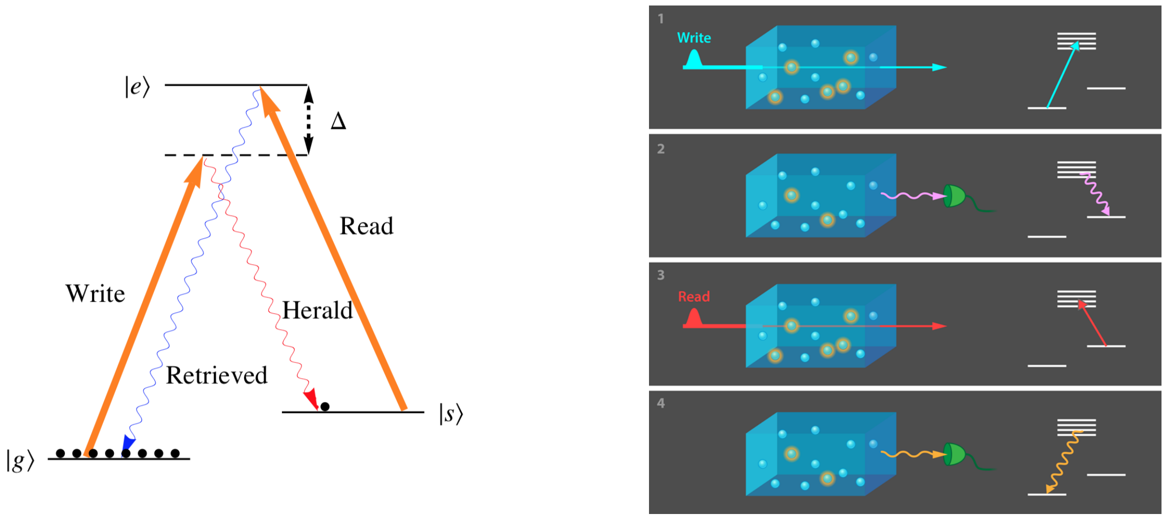


Figure 2: a) DLCZ memory scheme in which quantum information is stored in the $|s\rangle$ state and can be accessed at a later time using "read" pulse of light tuned to a frequency corresponding to the energy difference of $|e\rangle$ and $|s\rangle$ (Image from [7]) b) DLCZ memory scheme in a REIDS. A write pulse excites the atomic ensemble which then relaxes to state $|s\rangle$ in (2). At a later time the information is retrieved when a read pulse re-excites the atomic ensemble and a photon is emitted in the transition back to $|g\rangle$ (4).(Image from [6])

with length L and performing an entanglement swapping operation will provide entanglement over a distance 2L without the newly entangled state every having directly interacted.[4] This can be repetitively employed to allow entanglement over arbitrary distance within the confines of the experimental constraints such as the decoherence time of the quantum memory being used. Quantum memory provides the means by which entanglement may be stably stored at regular intervals and entanglement swapping can be performed.[6]

Quantum memory is also essential due to the fact that, during entanglement, there is photon loss via channel attenuation, spontaneous emissions, coupling inefficiencies and photon detector inefficiency. These problems can be intractable in the case of single photon-to-single atom interfacing. To mitigate these losses, collective excitations of atomic ensembles are used to achieve reasonable coupling. [7]

The DLCZ scheme in an atomic ensemble is best visualized through the three-level energy spacing diagram seen in Figure 2a. A properly configured atomic system will be initialized to have all effective absorbers in the ground state $|g\rangle$. The quantum information is stored in *write* pulse and will excite an absorber to a higher energy state.[11] Upon application of the *write* field, a Stokes photon heralds a spin wave excitation in the ensemble. The *heralded* photon that is emitted as the ensemble relaxes to the state $|s\rangle$ is critical to the the scheme as it provides evidence that the desired transition has occurred. If the heralded photon is not emitted or is not detected, the *write* pulse is readministered until it is. Once in the state $|s\rangle$, the quantum information is effectively stored in memory with a time-scale of order seconds [10] and can be accessed when desired through an appropriate *read* pulse. (Figure 2)

It is important to note that what is being stored is not a single photon but rather a probabilistically generated, heralded collective excitation in the atomic ensemble. The doping ions in the solid are identical particles so the collective state of the atomic ensemble is no more complex than that of a single particle.[7] The implication of having identical particles in the atomic ensemble is that the excited state is not linked to a specific doping site but exists as a superposition over all of the accesible ion locations. So while the physics is essentially the same as that of a single particle excited state, it is spread out over the crsytal and this provides robustness that is not present for single particle excitations. [7] The use of collective excitations rather than single particle excitations leads to much greater efficiency due to collectively enhanced coupling. Once coupled, the state becomes an effective maximally entangled state [1] and can be used for quantum teleportation of unknown quantum states.

Quantum memories must be capable of efficiently storing quantum information for time lengths orders of magnitude larger than the computational time, must be high efficiency in their read and write processes and must be high fidelity in retaining and delivering the desired quantum information. There are several candidate systems to be used as quantum memory devices. Cooled clouds of trapped alkali atoms have shown success as have rare-earth ion doped solids (REIDS). [12][11] An advantage of using REIDS is that the unfilled electronic orbitals lie inside of filled outer shells. The filled exterior shells provide shielding against environmental electromagnetic noise that could interfere with the band structure of low energy linewidths that are being used as the effective three level system for the DLCZ protocol. In our research we use a REIDS memory, $Pr^{3+}$:$Y_2SiO_5$. The overall goal of this research is to demonstrate that $Pr^{3+}$:$Y_2SiO_5$ crystals can be used as quantum repeaters in the DLCZ protocol.

## 1.2 Spectral Hole-Burning

The ability to use rare-earth ion doped solids as quantum memory was first demonstrated by Mattias Nilsson, Lars Rippe, Stefan Kroll, Robert Klieber and Dieter Suter in 2004.[10] The key to using rare-earth ion doped solids as quantum memory devices is to isolate specific bandwidths to be used for collective excitations.[11] At low temperature, rare-earth ions in inorganic crystals have narrow homogenous linewidths that makes them effective for use in coherent quantum optics.[7] There also exists a wide inhomogenous line that buries the narrow homogenous lines. The homogeneous lines can be accessed by using a process called hole-burning. [13]

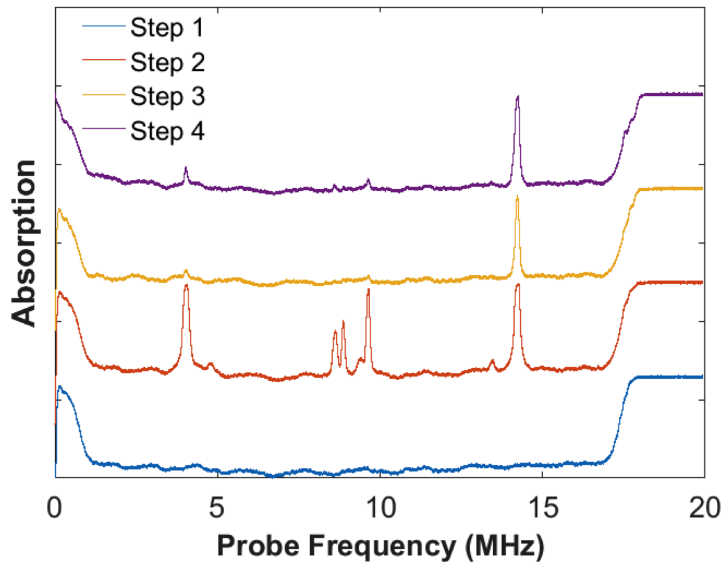


Figure 3: Spectral hole-burning and preparation of the $\pm 3/2$g state in our crystal.

The initial step in spectral hole-burning is to perform repeated frequency sweeps in order to excite all absorbers in the REIDS ensemble out of the ground state. This removes the absorbers within the inhomogeneous absorption line to create an optical "pit" where there is essentially no absorption or fluorescence.

Two factors limit how pure of a background may be prepared: the spectral purity of light and the relaxation rate of the hyperfine level. [10] If there is a large impurity of light, energy outside of the pumped spectral region can be absorbed or cause excitations away from the desired level. If the relaxation rate is too fast then the pit will constantly be refilled faster than optical pumping can clear it.

Once a pit is created, it is possible to create a spectrally narrow peak of absorbers. This can be done by optically pumping with one laser to excite a broad spectral interval and using a second laser to de-excite a narrow region within this interval. Alternately, this can be achieved by completely emptying the absorbers and then shifting the frequency by an amount equal to one hyperfine level separation to excite a narrow frequency interval. There is a large signal-to-noise ratio due to the collective mode.

The process of spectral hole burning can be observed from data taken from the probe beam of our experiment in Figure 3. The first step entails an optical sweep that removes all absorbers and creates the "pit" or "spectral trench". A repump beam is now applied that selectively repopulates the absorbers. These will naturally decay and cause side-bands to occur. In step 3, these side-bands are removed by burning at their specific frequencies. Step 4 includes a further sweep to clean up the trench and spectral peak.

Spectral hole-burning is a necessary step in the preparation of REIDS systems to be used as quantum repeaters. It creates the spectral backdrop in which *read* and *write* operations can be performed and *heralded* and *retrieved* photons may be observed. Here we have demonstrated this process in $Pr^{3+}:Y_2SiO_5$.

# 2 Experiment

The essential nature of this experiment is to utilize our ability to control light in order to manipulate the electronic structure of a special type of crystal that is held at very low temperature. By operating at a few degrees above absolute freezing, most thermodynamic behavior, in the form of phonons, has been frozen out and the electronic band structure of the crystal is stable and free of perturbations on the time-scale needed to achieve quantum memory. A single frequency laser can be sieved into many beams using beam-splitters at the cost of power reduction in each beam. Individual beams can then be controlled using acousto-optic modulators. These devices are voltage controlled and use sound waves to shift the frequency of light that passes through them. They can also act as a switch since they will not allow light through when a voltage is not applied. By driving acousto-optic modulators with complex voltage sequences, we have the ability to modulate the single frequency laser beam into frequency sweeps and pulses. The beams naturally diverge so it is essential to place focusing lens throughout the experiment such that the "optical quench" occurs at places of significance such as the AOM, fiber coupling and crystal location. Taking advantage of the numerous beams that can be individually controlled for frequency, power, location and beam size, we gain much control over access and manipulation of the electronic structure of the rare-earth ion doped crystal.

The optical setup is shown in Figure 4. A Toptica diode laser is used at 1212 nm which is frequency doubled to 606 nm by a MPB photonics visible Raman fiber amplifier. The power given by this laser is up to 2W although we require only 100 mW. This is further divided up into the probe, burn, repump, and filter beams. These powers are 10 $\mu$W, 400 $\mu$W, 90 $\mu$W, and 650 $\mu$W, respectively. It is frequency locked to a stable frequency that deviates $\pm$ 50 MHz. Each beam is passed through an IntraAction acousto-optic modulator (AOM) with a center frequency of 110 MHz, and bandwidth 50 Mhz. The first mode is isolated using a pin-hole and is reflected with a ThorLabs labs mirror back through the AOM for a double-pass. The beams are now coupled into fiber optic cables. Control over which beam is being coupled into a fiber and the complex pulse sequence of the beam is achieved by driving the AOMs with a wave-form generator (Spincore PulseBlasterUSB-300).

The beams emerge downstream and are reflected off of several mirrors before entering

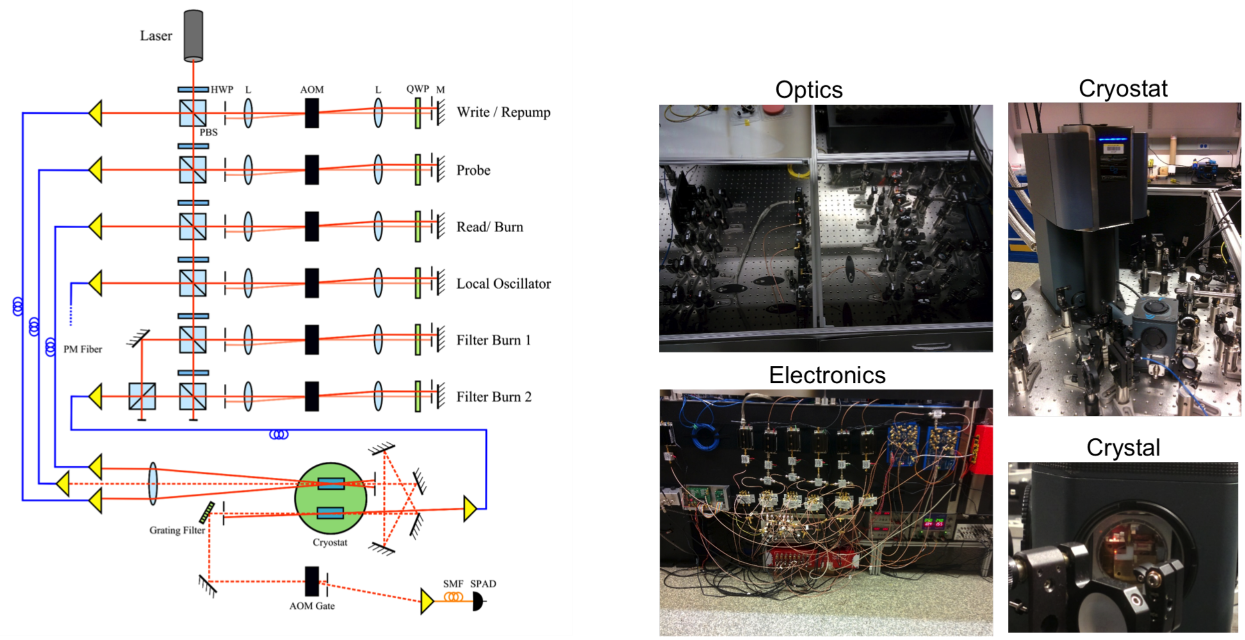


Figure 4: Arrangement and images of optical apparatus for quantum memory experiment (Courtesy of K. Kagalwala)

the cryostat where the $Pr^{3+}$:$Y_2SiO_5$ crystal is held at 3.4 K. The size of the crystal is 5x5x10 mm and the doping is 0.05%. The beam diameters for the read/write and filter are both approximately 530 $\mu$m.

To maximize efficiency, the beam power must be measured at each stage of passing through optical apparatus and slight tweaking of alignment is performed. Optimization begins with the first arm and continues methodically to the last until a satisfactory power is delivered from each branch to the point of fiber coupling. Once aligned up to the position of coupling, power is measured downstream at the output of fiber optical cabling and further tweaking is performed.

Once alignment is satisfactorily accomplished, an automated pulse sequence is performed. First, a narrow ensemble of ions is prepared in the ground state via an optimized spectral-hole burning and re-pump sequence. Next, *write* and *read* pulses are applied for a duration of 10 $\mu$s and a separation of 20 $\mu$s between their centers. This process produces the *herald* and *retrieved* photons through spontaneous Raman scattering. For $Pr^{3+}$:$Y_2SiO_5$, the hyperfine levels of the $^3H_4$-$^1D_2$ transition (for the $Pr^{3+}$ ions) are used for the states $|g\rangle$,$|s\rangle$ and $|e\rangle$ in the three-level scheme (Figure 2). The $|g\rangle$-$|e\rangle$ transition occurs at 605.977 nm and is addressed with a frequency-stabilized laser. The state $|g\rangle$ corresponds to $\pm 3/2$g and $|s\rangle$ corresponds to the $\pm 1/2$g state. The *herald* and *retrieved* photons are emitted along a path that bisects the paths of the *write* and *read* pulses due to phase-matching. The frequency

sweep sequence used is:
probe: 105 to 115 MHz
burn: 105.5 to 113.6 MHz
repump: 125.45 MHz
filter: 107 and 114.4 MHz

The goal of the present work is to implement the filter beam incident upon a lower portion of the crystal than where the quantum memory process is occurring. Photons used in the quantum memory traverse this path and are selectively allowed through the filter. As this is the same path that the read/write pulses travel, the filter is intended to block light that is not *herald* or *retrieved* photons. It also enables the simultaneous purification of herald and retrieved photons in a one-way co-propagating geometry, thereby considerably reducing the complexity of the experimental setup.

# 3 Results

When joining the lab, successful spectral hole-burning and re-population had been accomplished and this work has been extended to include an optical filter into the experiment. Optically pumping across a frequency spectrum upon crystal created a spectral trench that could then be selectively refilled at a specific frequency window to create the desired initial atomic energy spectrum to be used for quantum memory.

In this work we have introduced several more AOM's and beam paths to the optical setup and successfully implemented a filter beam. (Figure 5a) The information beam is passed back through a lower section of the crystal where the filter beam is targeted and selectively allows through the desired *heralded* and *retrieved* photons. This work is a positive step in the direction of demonstrating the capabilities of REIDS to be used as quantum repeaters in the DLCZ scheme in order to achieve long-distance quantum communication.

The initial results of implementing a filter into our optical setup are displayed in Figures 5b-10. Figure 5b shows the effective on-off switching capability of the filter. When turned off, the probe beam is completely absorbed by the crystal and we see no transmission (blue and red). When the filter is turned on, it creates a spectral hole that allows the probe beam to pass through the crystal (yellow).

Figure 6a displays the spectral hole burning as the probe beam passes through the spectral trench as well as the filter. We observe the large "pit" that is desired as the starting zero background and we see that the filter performs better with a larger number of sweeps but saturates to its optimal performance at approximately 400 sweeps. This pit spans an

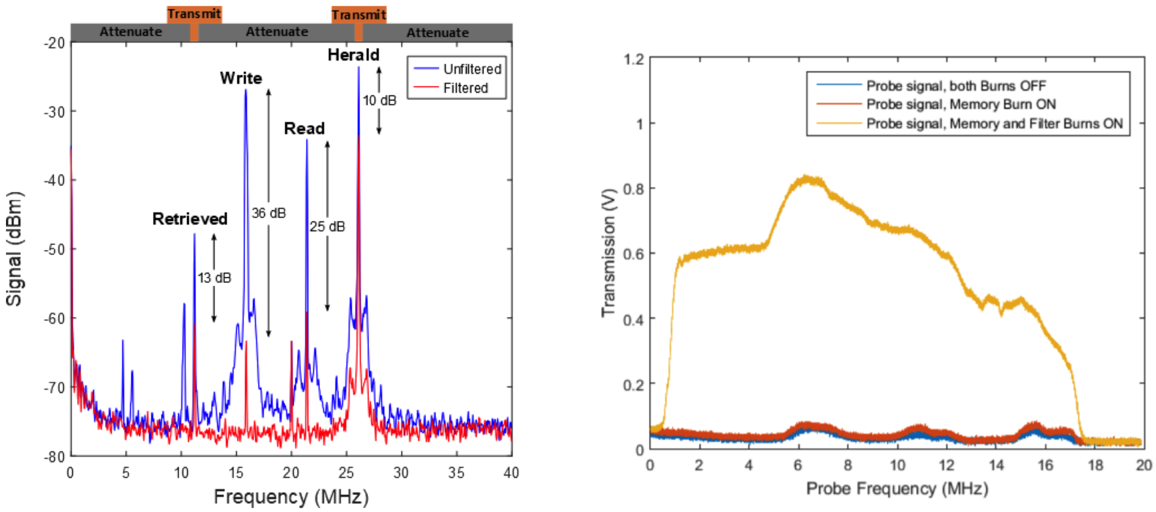


Figure 5: a)Filter performance. With the filter implemented we see a marked decrease in the *read* and *write* beams that is transmitted. b)Probe signal when 16.2 MHz wide trenches are burnt in both the memory and filter crystals. When the filter is off, there is some burning caused by the memory beam. The baseline is when both the burns are off, due to self burning by the probe.

approximately 14 MHz frequency range from 2 MHz to 16 MHz.

In Figure 6b we have re-excited the crystal at a specific frequency to repopulate the 3/2g linewidth that occurs at 14 MHz. The signal is measured after both the first pass through the crystal (blue) and the second pass through the crystal where the filter beam has been focused (red). We see an expected drop in the overall amplitude of the signal that is due to inherent losses in the signal caused by the filter pass. Beam alignment is critical at this stage in order to overlap the probe and filter beams. Slight deviations and misalignment cause the probe signal to be absorbed and we lose 3/2g linewidth trench. Observation of the peak at 14 MHz after a filter pass confirms that proper alignment has been accomplished.

The overall success of the filter can be seen from heterodyne measurements taken with and without the filter beam (Figure 5a). With the filter implemented, we obtain a suppression of 36 dB for the *write* frequency and 25 dB for the *read* frequency. The filter also unintentionally blocks some of the *herald* and *retrieved* frequencies of 10 dB and 13 dB, respectively. It is observed that some leakage still passes through and further work remains to fine-tune the performance of the filter. The percentile impact that the filter has on the transmission rates is:

*Retrieved*: 43% ±5% reduction
*Write*: 72% ±5% reduction
*Read*: 45% ±5% reduction
*Herald*: 10% ±5% reduction

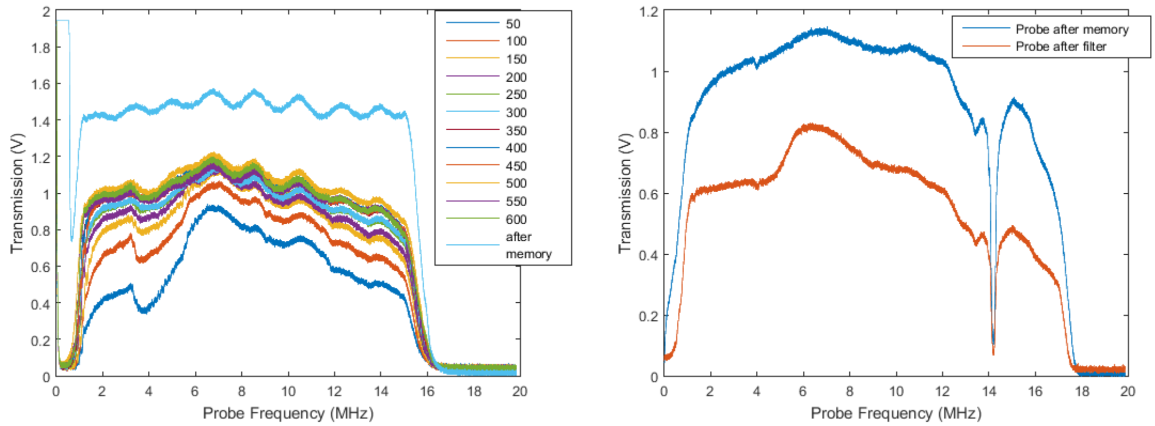


Figure 6: a) Probe signal as the number of filter burns is varied from 50 to 600. The signal through the filter can be compared the signal obtained in the Memory crystal. b) This plot shows the probe signal before and after the filter, and the state is prepared with the population in $\pm 3/2$g

Our filter performs well in significantly reducing the amount of *write* beam transmitted and allows through most of the *herald* photons. The performance relative to the *read* and *retrieved* beams is moderately successful.

The narrowband spectral filter is a key component to the experiment as it suppresses spontaneous emission noise and leakage from the *write* and *read* beams. Its implementation into our optical setup is an important step forward towards the goal of using rare-earth ion doped solids as quantum repeaters in the DLCZ protocol.

# 4 Future Work

At the time that this research was being done in 2017, Kutlu Kutluer, Margherita Mazzera, and Hugues de Riedmatten demonstrated correlated photon pairs with embedded spin-wave quantum memory using $Pr^{3+}$:$Y_2SiO_5$.[9] This result is the goal of our current work and provides evidence that this is a promising path towards the realization of quantum communication and quantum networks.

Now that it is established that doped crystals are a successful candidate to be a quantum repeater, it remains to be shown that adjacent crystals can efficiently communicate between each other. This will be done by implementing a second crystal into the optical setup that receives the output pulse that is generated by a read pulse upon the first crystal. This output signal contains the quantum information and now acts as the write pulse for the second crystal.

## 5 Conclusions

In this work, we have successfully implemented a filter in a $Pr^{3+}$:$Y_2SiO_5$ crystal. This is a crucial step forward in the application of rare earth-ion doped solids to be used as memory devices in a quantum repeater scheme for long distance quantum communication. There is further work to be done reducing losses in the system, improving phase matching, and filter performance. Once sufficiently efficient photon correlation with a single crystal is achieved, a second $Pr^{3+}$:$Y_2SiO_5$ crystal can be implemented into the optical setup and photonic communication between adjacent crystals can be attempted. If this is accomplished and entanglement swapping is used to connect adjacent segments, it will be clear that rare-earth ion doped solids can be used to effectively achieve long-distance quantum networks.

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