Quantum Memory: A Review

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Abstract.
While Quantum Information Science has many conceptual parallels with classical computing and theory, some components need to be re-imagined from the ground up to effectively work with quantum information. The idea of "memory", and more specifically what constitutes storage of information is one of these concepts. Quantum memory systems are one of many that are crucial to the operation of NISQ devices and beyond. While the basic functionality expected of Quantum memory is analogous to classical memory, the nuances of the fragile information in a Quantum state require careful construction of a storage system. After addressing the basic functionality of Quantum memory, a simple implementation will be presented to further elaborate on essential points. Similarly to classical computing, multiple devices fall under the label "memory" due to similar functionality, but there are characteristic features one may pick to optimize over others to best fit the situation at hand. Finally, I will conclude this review with a quick mention of some interesting recent developments in Quantum memory protocols and applications. The interested reader will be pointed to references as appropriate.

1. Basic Principles and Functionality

As mentioned previously, Quantum memories are conceptually similar to classical memory in functionality. In general, both are responsible for recording desired information and allowing the user access at a specified later time. At a very simplified level, the reading and writing processes in classical computing are straightforward. To write, an external system outputs a binary value of zero or one, that value is sent to the classical memory and observed, and part of the memory system is changed to reflect the value that was passed in. Similarly, the reading operation can be thought of as the inverse; the read request is triggered at a designated time, the specified value in memory is observed, copied, and sent to the desired location.

In Quantum memory systems, although the central idea is similar, the challenges Quantum information presents (primarily due to the collapse postulate and the no-cloning theorem) requires the question of storage be approached carefully. Although the expectations are straightforward, the realization often is not; an unknown Quantum state has to be "recorded" without altering the system, and reproduced at a user defined time, all while avoiding directly disturbing the state. Due to the fragility of Quantum information, this is quite a feat to accomplish efficiently. However, just as Quantum mechanics presents a challenge, clever use of basic Quantum optics concepts provide multiple solutions. The intricacies of these solutions is best illustrated through an example.

2. Experimental Realization, Performance Parameters, and Additional Features

While they all have similar functionality, it is helpful to divide Quantum memory systems into categories to make the problem more tractable. Following (Simon et al. 2010), Quantum memory schemes can be broken down into four distinct categories: single photon memory, general state memory, memories that emit photons which can be measured directly, and memories that emit photons that are measured through retrieval. The type of memory to use depends on the needs of the experiment, namely the qualities of the photons that are to be stored. For instance, systems that fall under the single photon memory category are configured to record and “replicate” single photon states, such as the signal or idler photon from SPDC. If an experiment requires the storage of a more general multi-photon state, the general state memory would be best. For the sake of brevity, I will only describe a protocol that falls in the single photon and general state memory categories. The remaining two categories are more involved, and may distract from the fundamental principles I aim to emphasize. The interested reader is pointed to (Simon et al. 2010) for more details on the latter two categories.

Quantum memories involve the careful manipulation and control of light-matter interactions; as such, systems such as ultracold atoms and non-linear optics in materials are ideal. A simple implementation and protocol utilizes electromagnetic induced transparency, or EIT for short. While EIT puts central concepts on display with some “extra” features, it is by no means the best approach. EIT is a phenomenon that occurs in atoms with an energy level structure similar to that of figure one. It makes clever use of Raman coupling to allow the user control of the read/write process, while not directly disturbing the input state.

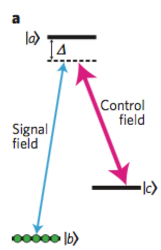

Figure One: Energy level diagram required for EIT. Note that the system starts purely in the ground state, and is excited by the input signal field.

With the control field on, the excitation caused by the signal field gets “stored” in state $|c\rangle$, and a photon similar to the input is emitted when the control field is applied a second time. If the control field is not on when a signal interacts with the system, the “storing” behavior will not occur. See figure two for the experimental data illustrating this process. While this sounds simple in practice, note that there are practical limitations that make the performance sub-optimal. The output state is often not a perfect copy of the input state. Instead, this protocol and others like it seek to create a system with unique behavior (dependent on the properties of the input state) that is transferred to a part of the system that can be accessed as needed.

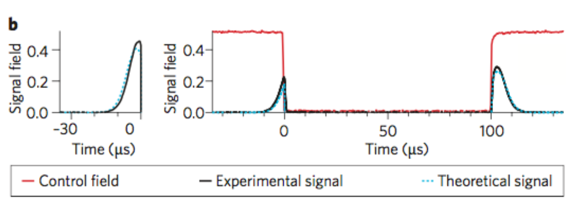

Figure Two: Experimental data describing an EIT protocol realized with a Rb vapor cell. Note the strong agreement between theory and experiment.

Mathematically, the system displayed in figure one beings with all atoms in the lower energy ground state, $|\psi_{initial}\rangle = |b_1 b_2 b_3 \dots b_N\rangle$, where N is the number of atoms in the system. With the control field on, the signal field is absorbed, exciting some of the atoms from the state $|b_i\rangle$ to the state$|c_i\rangle$, where i corresponds to the atom(s) that are excited. Since i can correspond to a singular atom (excited by a single photon) or a collection of atoms, note that this procedure allows for both single photon and general state storage. Now, $|\psi\rangle \; \alpha \; |b_1 b_2 \dots c_i \dots b_N\rangle$. The information from the input state is now stored in the atoms, and is "accessed" via decay back into the state $|b_i\rangle$, at the discretion of the control signal, resulting in $|\psi_{final}\rangle \; \alpha \; |b_1 b_2 b_3 \dots b_N\rangle$.

Although this implementation has its shortcomings, it gets to the core of what Quantum memory protocols aim to accomplish without a significant theoretical challenge (for more intricate Quantum memory schemes [that provide on-demand readout and are theoretically at the level of OPTI 544], see (Tittel et al. 2010) and (Tittel et al. 2009)). In principle, the idea is the same: there is a general input state that one wishes to hold on to for a designated period of time, and "reproduce" later on. This input state is "transferred" into the system as a separate excitation, and that excitation is later re-interpreted to achieve something that (ideally) resembles the original input state. While this has been an ideal description of EIT, in reality there are limitations both due to the protocol itself as well as experimental limitations (see (Simon et al. 2010) for more information). The performance of a Quantum memory can be quantified by considering quantities of interest such as the fidelity (overlap of the input state with the output state), conversion efficiency, bandwidth, operating wavelength, multi-mode capacity, etc. (Simon et al. 2010).

Finally, it is interesting to note that EIT has some unique benefits as well. Quantum memories implemented with schemes such as EIT are able to store photons that may come from a probabilistic event (such as SPDC). The memory retains the state until it is prompted to "re-emit" by a user. This converts a probabilistic distribution into an on-demand photon source (provided the window a signal input is obtained is sufficiently large). This may have use in various optical experiments. Further, as is the case with EIT, the nature of the protocol itself may have useful experimental qualities, such as pulse compression. The change in the absorption spectrum of the three level system at the resonant frequency corresponds to unique behavior in the index of refraction at that wavelength, resulting in pulse compression (Simon et al. 2010).

3. Current Areas of Study

The review presented above is a bird's eye view of the key goals in Quantum memory research. Quantum memory is an active field, with many groups working to improve the functionality of current memory schemes (see (Gröbracher et al. 2020) and (Jin et al. 2020), for example) as well as testing the limits of already verified memory schemes in practical scenarios such as entanglement distribution (Yu et al. 2020). The development of Quantum memory systems is far from over, and further research in the field is crucial to bringing more complicated Quantum devices to life.

Bibliography

1. Simon, Christoph et al. 2010. Quantum Memories: A Review based on the European Integrated Project “Qubit Applications (QAP)”. The European Physical Journal. D, Atomic, Molecular, and Optical Physics. 58(1): 1-22.
2. Tittel, Wolfgang et al. 2010. Prospective applications of optical quantum memories. Journal of Modern Optics. 00(00):1-21.
3. Lvovsky A., Sanders B., and Tittel W. 2009. Optical Quantum Memory. Nature Photonics. 3: 706-714.
4. Yu, Yong et al. 2020. Entanglement of two quantum memories via fibres over dozens of kilometres. Nature. 578: 240-245.
5. Gröblacher et al. 2020. A quantum memory at telecom wavelengths. Nature Physics. 16: 772-777.
6. Pang, Xiao-Ling et al. 2020. A hybrid quantum memory-enabled network at room temperature. Science Advances. 6(6).