Quantum Memory

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1 Introduction

Since the birth of quantum computing, the concept of a device capable of preserving quantum states for an arbitrary amount of time and retrieving them on demand, referred to as *quantum memory*, has featured both implicitly and explicitly in a wide range of research papers. Despite its frequent appearance, the existence of such a device is often taken for granted, without a comprehensive analysis of its practical requirements or a realistic account of how such a system might be physically implemented. As a result, quantum memory has sometimes been treated more as an abstract ideal than as a concrete technological goal, leaving open critical questions about its design, feasibility and consequences for quantum computing.

The purpose of this technical report is to theoretically formalize the concept of quantum memory and explain the state of the current research in practical implementations. Section 2 begins by presenting an abstract characterization of quantum memory. Section 3 examines some of the different physical implementations proposed and developed to date, analyzing the capabilities, limitations, and trade-offs inherent to each technological approach. Finally, in Section 4, a critical assessment of recent progress is provided, together with the discussion of persistent challenges that the , and future directions in the development of scalable and reliable quantum memory systems.

2 Theoretical Quantum Memory

The concept of quantum memory is not new within the field of theoretical quantum computing. Early works, such as [3], implicitly assume the existence of such a device in the context of an early quantum cryptography model. Similarly, in [15], quantum memory is introduced naturally in the discussion of quantum search algorithms. However, it was not until 2009 that Vittorio Giovannetti, Seth Lloyd, and Lorenzo Maccone published *Quantum Random Access Memory* [6], an article in which they addressed the functional requirements of a quantum memory and introduced the bucket brigade architecture, which has since become one of the most extensively studied models in the theoretical exploration of quantum memory systems.

Abstractly, a Quantum Random Access Memory (QRAM) comprises three main components: an address register, a memory array, and an output register. The primary difference from classical RAM lies in the fact that both the address and output registers in a QRAM are quantum, that is, they are composed of qubits rather than classical bits. The memory array itself may be either quantum or classical, depending on the specific application, thus enabling the storage of arbitrary quantum states or classical data. A key feature of QRAM is that, due to the quantum nature of the input and output registers, memory can be accessed in superposition, allowing the output register to contain the corresponding superposition of the contents of the addressed memory cells. An abstract representation of the operation of a quantum memory is shown in Figure 1.

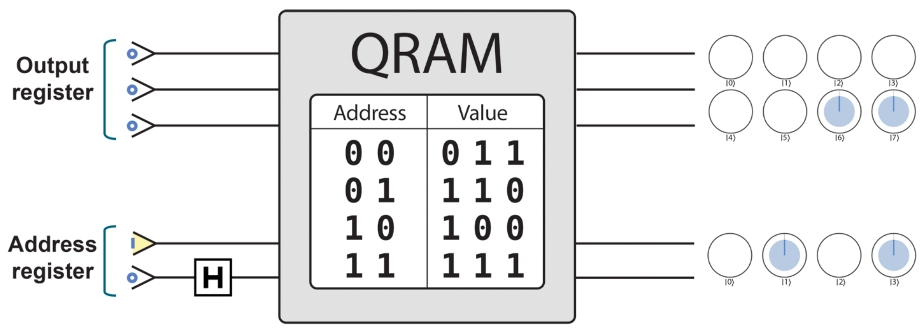

Figure 1: Example of an abstract quantum memory that stores classical information. In this case, the memory is accessed in an equal superposition of the states $|01\rangle$ and $|11\rangle$ created by applying a Hadamard gate to the most significant bit, thus obtaining an also equal superposition of the values stored at those addresses: $|110\rangle$ and $|111\rangle$. From the book *Programming Quantum Computers* [10].

In the article, the authors introduce an architecture known as *bucket brigade*. It is based on a perfect binary tree structure, where the memory array is located at the leaf nodes and the internal and root nodes function as the signal routing network. These routing nodes are three-level quantum systems called qutrits. The three possible states are $|wait\rangle, |left\rangle$ and $|right\rangle$. Initially, all qutrits are in the $|wait\rangle$ state, awaiting input. When a $|0\rangle$ is received by the qutrit, it changes its state from $|wait\rangle$ to $|left\rangle$, and will now redirect all subsequent traffic to its left child. The same process, but with the transition $|wait\rangle \rightarrow |right\rangle$ occurs when receiving a $|1\rangle$. In this manner, the address register can be sent to the root node one qubit at a time, guiding the configuration of the routing path in superposition.

Once the addressing phase is complete, a bus qubit is sent through the tree. It traverses the superposed paths defined by the states of the qutrits and interacts with the memory contents, encoding the result. On its return, the bus qubit resets each qutrit encountered in the $|left\rangle$ or $|right\rangle$ state back to $|wait\rangle$, restoring the system to its initial configuration. An illustrative example from [16] is shown in Figure 2.

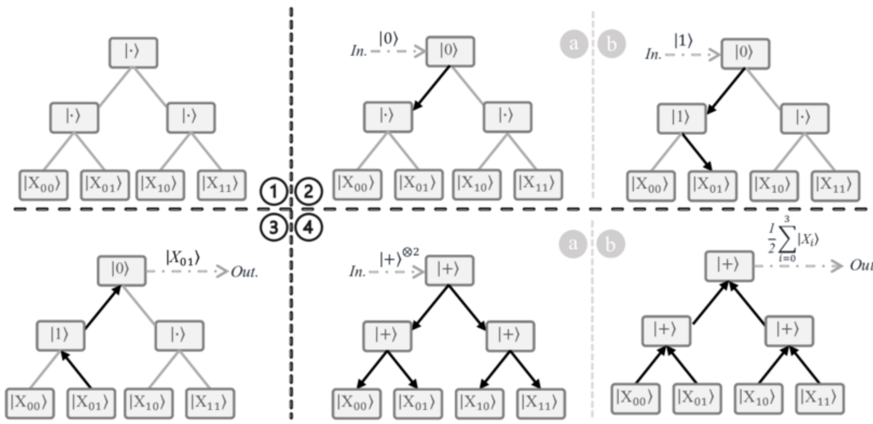

Figure 2: A bucket brigade QRAM. Note that, in this picture, $|wait\rangle = |\cdot\rangle$, $|left\rangle = |0\rangle$ and $|right\rangle = |1\rangle$. In **2** and **3**, we access the address 01 of the memory, and the change of the qutrits is shown. In **4**, an access in superposition is shown (two $|+\rangle$ states are the input), and we get as output an equiprobable state of the contents of addresses 00, 01, 10 and 11. Taken from [16].

3 Physical realizations

The physical realization of a fully functional quantum memory, as envisioned in [6], remains a significant scientific and engineering challenge. The current state of the art in the field is still far from achieving this goal. One of the main theoretical obstacles is the No Cloning Theorem [17], which prohibits the copying of arbitrary quantum states, thus preventing direct storage without disturbing the original state. Similarly, directly measuring a qubit to extract and store its information is not useful, as measurement collapses the quantum state and destroys any entanglement it may possess, eliminating the advantages of quantum computing. Despite these limitations, substantial progress has been made in the last decades toward the storage of photonic qubits, which serve as the primary carriers of information in quantum communication systems. Several of the leading technological approaches to photonic quantum memory are discussed in the following sections.

3.1 Electromagnetically Induced Transparency (EIT)

EIT is a technique that, intuitively speaking, allows an otherwise opaque medium to become transparent to light, significantly slowing down the speed of light within it. This effect enables us to temporarily store photonic qubits in the said medium. EIT involves the use of an additional control light pulse, distinct from the photonic signal that carries the quantum information, tuned to a specific frequency that enables the signal photons to propagate through the medium without being absorbed, effectively rendering the material transparent. When the control field is switched off, the quantum state of the incoming light is coherently mapped onto a collective atomic excitation, effectively halting the propagation of the signal field. To retrieve the stored information, the control beam is reapplied, converting the atomic excitation back into light, as illustrated in Figure 3 [13] [5].

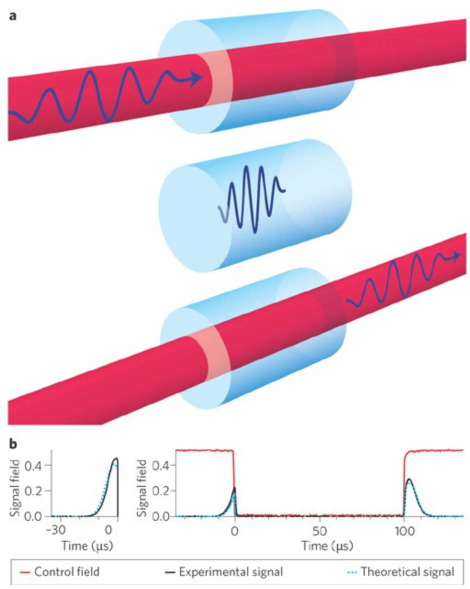

Figure 3: Image of an Electromagnetically Induced Transparency quantum memory. The state to store, codified in the blue photon beam, can pass through the medium while the control signal (red laser) is active. Figure taken from [12]

Different storage mediums have been used in EIT memories. In cold atomic ensembles, storage times on the order of microseconds with high fidelity have been routinely demonstrated, such as in [8]. More recently, much longer storage times have been realized in solid-state systems, particularly rare-earth ion-doped crystals under cryogenic conditions. A notable example is [7], reporting storage times up to one minute in a crystal, a significant breakthrough in the field. Other EIT quantum memories, specially those using warm or cold atomic vapors are more susceptible to external perturbations, thus limiting their storage durations as previously stated.

Research on EIT-based quantum memories is conducted by several institutions worldwide, most notably by the Quantum Optics Lab at the University of Basel, the National Institute of Standards and Technology (NIST) and the University of Science and Technology of China.

3.2 Atomic Frequency Comb (AFC)

Another studied approach for photonic quantum memory is the Atomic Frequency Comb (AFC) technique, which utilizes solid-state systems doped with rare-earth ions as the storage medium [1]. These ions exhibit inhomogeneously broadened absorption spectra, enabling them to absorb light at discrete frequency intervals that correspond to energy level transitions within the dopant atoms. A periodic absorption structure (that resembles a comb, hence the name) is engineered into the inhomogeneous profile of the medium. This structured absorption profile acts as a quantum memory capable of storing and later re-emitting photonic quantum states.

To prepare this comb structure, a technique known as optical pumping is used. This involves selectively redistributing the population of ions among their internal energy levels by applying a laser pulse, effectively ”emptying” certain frequency intervals and enhancing absorption at others. The result is a series of narrow absorption peaks, regularly spaced in frequency, which form the atomic frequency comb. When a photon enters the medium, its energy is coherently absorbed across the ensemble of ions within the comb peaks. Due to the regular spacing of these peaks, the ions re-emit the photon collectively after a fixed time, an effect known as a photon echo. One important limitation of basic AFC memories is that the re-emission time is fixed by the comb spacing and cannot be chosen freely, unlike in EIT-based memories where retrieval can be triggered by reapplying the control field.

To overcome this constraint and enable on-demand readout, the excitation can be transferred to long-lived auxiliary spin states within the rare-earth ions. These spin states offer enhanced protection against decoherence and allow for controlled retrieval of the stored information. Using such spin-wave storage techniques, researchers have achieved storage times significantly longer than those obtainable with EIT-based memories. Notably, storage durations of up to one hour have been demonstrated under cryogenic conditions [14].

It is worth noting that one of the world’s leading groups in AFC quantum memories is located in Spain at the Institute of Photonic Sciences in Barcelona, led by professor Hugues de Riedmatten, a pioneer in solid-state quantum memory. Another major center of research in AFC-based memories is the Quantum Information and Communication group of the University of Geneva, which has focused its efforts in the implementation of quantum repeaters.

4 Conclusions

While there has been significant advancements towards quantum memory devices in recent years, they remain in the early developmental stage, far from the theoretical requisites described in [6], and are not yet ready for widespread practical applications due to their limitations in storage duration, efficiency, and scalability. Some authors have even argued that the realization of cheap and scalable quantum memory might be unlikely due to fundamental challenges associated with maintaining coherence and the need for error control [9].

Nonetheless, research in this field is of critical importance to both quantum computing and foundational physics. Quantum memories serve as indispensable components in quantum networks, particularly in the construction of quantum repeaters (though recently some researchers have explored the usage of all-photonic quantum repeaters, which do not need quantum memories [2] [11]), and have already been tested in various experiments such as [4], where a four-fold improvement in secret key generation rates for QKD was shown thanks to a quantum memory.

References

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