B1 - Research and Technological Quality

Research and technological quality

During the last decade, quantum computing and quantum communication have become one of the new scientific subjects in the front pages of our newspapers. Indeed these topics have brought together scientists from a wide range of disciplines from physics to mathematics or computer science and engineering. It has been a striking demonstration of the use of fundamental quantum properties of light and matter to address engineering problems such as random number generation or secure key distribution. Moreover, we have seen during recent years the development of various bridges between science and industry and the rise of companies selling *quantum devices* (see for example www.idquantique.com or www.magiqtech.com). The multiple aspects of Quantum Information make this a highly exciting area to work in, and provide an excellent framework for the training of young research scientists.
This proposal is deeply involved in several aspects of this innovative and multidisciplinary area. In the following we give the details of the project during the outgoing phase at the National Institute of Standards and Technology (referred as to NIST) and Australian National University (ANU) and the returning phase in the Group of Applied Physics of Geneva University (GAP-Optique).

Quantum communication aims to transmit quantum states between distant locations[1]. The distribution of quantum states over long distances is essential for future potential applications, in particular for quantum key distribution (allowing secure communication through public channels). Entanglement is a key resource to achieve this goal. Experimentally, photons will almost certainly be used to distribute this entanglement between distant locations. However, the quantum channels are affected by losses during the transmission either in free space or in optical fiber. For the realistic implementation of a quantum network[2], the use of optical fibers is required. The quality of optical fiber at the optimal wavelength (1.5 μm, known as the telecom wavelength) is really impressive, typically 0.2 dB/km of loss which means 95% transmission over 1 km. However, the losses become significant when you start considering distances larger than a few hundred km. Moreover the transmission rate drops exponentially with the distance : for example in the regime of photon counting, if you have a source which can give you a rate of 1 bit (1 photon) per second at 500 km, this rate falls to 1 photon every 300 years at 1000 km !

In classical communication this problem can be overcome using amplifiers. Unfortunately, noiseless amplification is not allowed for quantum states unless you limit yourself to a set of orthogonal states or to one single quadrature of the field. As the advantage of quantum communication relies on the quantum superposition, such an approach is obviously irrelevant. Nevertheless, the concept of **quantum repeaters**, a more sophisticated method based on entanglement sharing, offers the possibility to solve this problem[3]. The key idea of this approach is that entanglement over a given distance can be created by entanglement swapping starting from two entangled pairs, each of which covers only half the distance. This method implies the ability of storing a quantum state at each of the quantum repeater stations, and thus quantum repeaters require the availability of **quantum memories**.

While photons are the best carrier for the quantum state, the choice of the best medium for quantum state storage is not as obvious. From this starting point the proposal aims at deepening the study of the most promising media and protocols for the realization and the practical implementation of quantum repeaters. The final far-reaching goal in the field is **exceeding the direct-transmission rate in the distribution of quantum states, defined as the exponential decay with the distance, as discussed earlier**.

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[1] Gisin, N. et al. *Quantum cryptography*, Rev. Mod. Phys. **74**, (2002).
[2] Kimble, H J, *The quantum internet*, Nature **453**, (2008).
[3] Sangouard N. et al. *Quantum repeaters based on atomic ensembles and linear optics*, Rev. Mod. Phys. **83**, (2011).

To advance towards this goal during the returning phase, several concepts will be studied during the outgoing phase of this proposal. The common approach developed during this project is centered around the theme of **multiplexing the communication channels in time and/or in space.**

State of the art

Multiple media and various protocols have been considered for the realization of a quantum memory both in the single photon and continuous variable regimes[4], including optical delay lines, high-Q cavities, electromagnetically induced transparency[5], off-resonant Faraday interaction[6] or photon echo.
In 2001, an innovative approach for the implementation of quantum repeaters was proposed by Duan, Lukin, Cirac and Zoller (DLCZ)[7]. This highly scalable protocol employs atomic ensembles addressed by weak laser pulses and single photon detection. The use of atomic ensembles significantly increases the interaction between light and matter via collective enhancement effects. The key process of the DLCZ protocol is the spontaneous Raman emission of one photon, which induces a collective spin excitation in the atomic ensemble. This proposal has been followed by numerous very successful experiments showing that this approach of using atomic ensembles, linear optics, and photon counting is indeed perfectly relevant on the experimental side[8],[9].

Since then, multiple variations of this protocol have been proposed and demonstrated. For example DLCZ-type atomic ensemble can be replaced by a photon-pair source and a quantum memory that can store and reemit photons[10]. Such an approach has several advantages, especially greater wavelength flexibility (compared to DLCZ where the Stokes photon must be emitted at the telecom wavelength) and the capacity of **multiplexing in time and in space.** These two ways of multiplexing have different impact on the quantum state distribution rate with quantum repeaters. On one side, the use of temporal multimode memories could obviously reduce the entanglement distribution time. On the other side, it has been demonstrated that a multi-spatial mode approach for quantum memories can reduce the necessary memory storage time[11]. These two methods of multiplexing will be tackled during this project both in the outgoing and returning phase.

Recent results show efficient storage, high fidelity, multimode capacities and long storage time. However, these performances have not been demonstrated using the same medium and protocol, and more efforts are required to combine these characteristics in a single experimental set-up. To give an overview of the state-of-the-art we have listed the main characteristics in Table 1.

Criteria	Required	State of the art	Reference
Retrieval efficiency	100%	87 %	Nature Com. 2,174 (2011)
Fidelity	1	0.93	Nature 473, 190 (2011)
Storage time	> tens of ms	>2 s (crystal) and 240 ms (cold atoms)	PRL 95, 063601 (2005), PRL 103, 033003 (2009)
Number of spatial modes	maximum	1	
Time Bandwidht product	maximum	2500	PRL 107, 053603 (2011)

Table 1: State of the art and requirements for quantum communication applications.

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[4] Lvovsky, A. et al. *Optical Quantum Memory*, Nature Photonics **3**, 231, (2009).
[5] Fleischhauer, M. and Lukin, M. *Dark state polaritons in electromagnetically induced transparency.*, Phys. Rev. Lett. **84**, 5094 (2000).
[6] Julsgaard, B. et al. *Experimental demonstration of quantum memory for light*, Nature **432**, (2004).
[7] Duan, L. et al. *Long-distance quantum communication with atomic ensembles and linear optics*, Nature **414**, (2001).
[8] Choi, K. et al. *Mapping photonic entanglement into and out of a quantum memory*, Nature **452**, (2008).
[9] Kuzmich, A. et al. *Generation of nonclassical photon pairs for scalable quantum communication with atomic ensembles*, Nature **423** (2003).
[10] Simon, C et al. *Quantum Repeaters with Photon Pair Sources and Multimode Memories*, Phys. Rev. Lett. **98**, 190503, (2007).
[11] Collins, O. et al. *Multiplexed Memory-Insensitive Quantum Repeaters*, Phys. Rev. Lett. **98**, 060502, (2007).

Research methodology

This proposal focuses on **photon echo type memories**, which are excellent candidates for high efficiency coherent optical memory[12],[13]. In principle, they are capable of high fidelity and high-bandwidth storage, time multiplexing as well as multi-spatial mode storage. During the outgoing phase we will focus our attention on a very promising protocol : the Gradient Echo Memory (GEM).

The GEM is based on the reversible decay of macroscopic coherence of an atomic ensemble. A pulse of light is sent into a storage medium which is considered (for sake of simplicity) as a collection of two-level systems. A spatially dependent Zeeman shift (respectively Stark shift) is obtained by applying a linearly varying magnetic field (respectively electric field) to the medium. For a shift larger than the pulse frequency bandwidth and a high optical density, each frequency component of the pulse can be absorbed. Similarly to nuclear magnetic resonance the spectral components of the signal are mapped linearly along the length of the sample. After the excitation, the collective dipole dephases due to the inhomogenous magnetic (electric) field. It is however possible to recover the ensemble macroscopic coherence by reversing the magnetic field gradient (respectively the electric field). When all the dipoles have rephased, the input light pulse can emerge in the forward direction.
Extension of this oversimplified description of the GEM allows the use of a colection of three level Λ system, and therefore dramatically increases the coherence time by storing the excitation in the long-lived ground state coherences of an atomic medium. The ANU group has proposed theoretically and demonstrated the GEM for the first time in 2008 in a hot rubidium vapor. To date, they have achieved impressive experimental results leading to 87% quantum efficiency, and time multiplexing of pulses[14],[15]. They have also demonstrated the quantum behavior of this memory with very weak pulses[16]. The present state of the art of the ANU experiment testifies to the high quality of the work and the expertise of the group.

During the initial period of 6 months at NIST, the goal will be to reproduce this experiment in rubidium 85 in order to **investigate the multi-spatial mode properties** of this highly efficient quantum memory. Indeed, the NIST group has a broad expertise in the experimental multi-spatial mode squeezing generation. A four-wave-mixing (FWM) source of quantum correlated beams with multi-spatial character has been demonstrated[17] and used for quantum imaging both in the regime of bright beams and squeezed vacuum[18]. The key advantage of this kind of source, besides the multispatial modes, is its intrinsic matching with an atomic transition (D1 line of the rubidium 85 in our case) which can be used to interact with an atomic quantum memory.

The collaboration between the ANU group and the NIST group is therefore highly synergistic, leading to sharing of knowledge and skills on two complementary systems : a source of multimode squeezed light and a potentially multimode quantum memory at the same wavelength.

After this initial period, I will stay 6 months in ANU where I will benefit from their knowledges about GEM. The goal during this period will be the improvement of the storage time of the GEM. Indeed, to improve the coherence time of the ground state coherence and therefore the storage time of the memory, one solution is to use a cold atomic medium (e.g. cold atomic gas in a dipole trap or an optical lattice) instead of the hot atomic vapor. **The aim is to implement GEM in a dipole trap with both magnetic gradient and an AC Stark gradient.** Through the optimization of this memory, we can expect a high fidelity and a longer storage time. Pulse squeezing generated by a FWM source could then be succesfully stored in this memory. My expertise regarding these sources will therefore be highly beneficial to the group.

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[12] Gisin, N. et al. *Storage and retrieval of time-bin qubits with photon-echo-based quantum memories*, Phys Rev A. **76**, 014302, (2007).
[13] Hetet, G. et al. *Photon echoes generated by reversing magnetic field gradients in a rubidium vapor* Optics Letters, **33**, 20, (2008).
[14] Hosseini, M. et al. *High efficiency coherent optical memory with warm rubidium vapour*, Nature Comm **2-174**, (2011)
[15] Hosseini, M. et al. *Coherent optical pulse sequencer for quantum applications*, Nature **461**, (2009)
[16] Hosseini, M. et al. *Unconditional room-temperature quantumămemory*, Nature Physics **10**-1038, (2011)
[17] Boyer, V. et al. *Entangled Images from Four-Wave Mixing*, Science **321**, 544, (2008).
[18] Marino, A. et al. *Tunable delay of Einstein-Podolsky-Rosen entanglement*, Nature **457**, 07751, (2009)

During the second period at NIST, the final goal will be **the storage and the retrieval of two quantum correlated images from hot atomic vapor GEM**. The principle of this experiment is relatively simple. A FWM source of pulse squeezed light will be tuned to generate two images with relative-intensity squeezing (quantum correlations) at the wavelength of the quantum memory, and each of these two images will be stored into two identical high efficiency GEMs (to minimize the losses). After a given time the two images will be released from the memories and we will proceed to a measurement of the remaining quantum correlations. **It is expected to be the first demonstration of the storage of a quantum image in a quantum memory.**

The experience gained in the route towards this goal will be applied in the returning institution GAP-Optique. The far-reaching long-term goal in the field is **to surpass the limit of direct transmission rate with a reasonable number of links and quantum repeaters.** When this limit will be broken, this will open the way to practical implementation of quantum communication protocols and technology transfer with industry. The medium used by the group in Geneva is rare-earth-metal ions doped into optical crystal. These are highly interesting quantum memory materials since they have very good coherence properties when cooled down to below 4 Kelvin. The group has recently reported the demonstration of entanglement between a photon at a telecommunication wavelength and a single collective atomic excitation stored in such a crystal[19] and is therefore well positionned for the long-term goal of implementing a "quantum network". Depending of the experiemental progress of the group, I will be involved in the current experiments to advance towards this goal.

The protocol proposed and used by the group is based on spectral shaping of an inhomogeneously broadened optical transition into an atomic frequency comb (AFC) and allows the storage of multiple temporal modes. The idea of the AFC is to tailor the absorption profile with a series of periodic and narrow absorbing peaks. A single photon can then be absorbed by all the atoms in the comb, and its state is transferred to the collective atomic excitations at the optical transition frequencies. Due to the periodic structure of the absorption profile, the atoms will be able to rephase after the absorption. When all the atoms are in phase, light is reemitted in the forward direction as a consequence of a collective interference.

It is worth noting that a key advantage of the present proposal relies on the diversity of the approaches. This will ensure a high probability of achieving the expected goals and provide me a broad understanding of the field as we will study two regimes : continuous variable and single photon, three different media: hot atomic vapor, cold atomic sample and crystals, and two way of multiplexing : in time and in space.

Originality and innovative nature of the project

The GEM proposed theoretically for a three-level Λ-system only three years ago has already led to one of the most impressive quantum memories demonstrated to date. In particular the very high efficiency of retrieval turns this scheme into a very promising solution for quantum repeater applications. One key focus of this project is the **multi-spatial mode behavior of the GEM**. As described earlier, the spatial multiplexing for a quantum memory allows a reduction of the needed storage time. However, the multimode behavior of the GEM has not been investigated yet and is an innovative approach for quantum memory. The expected goal of storing an image in a quantum memory is indeed considered as a milestone in the field. The collaboration between ANU and NIST will play a key role in this achievement by sharing the respective expertise about GEM and multi-spatial mode squeezing.

The second approach (developed at ANU) is to increase the storage time of the memory by replacing hot atomic vapor with a cold atomic sample. As the main source of ground state decoherence in hot atomic vapor is related to the atoms time of flight inside the field, we can expect a dramatic improvement of the storage time. The idea of combining this enhancement with the multi-spatial mode properties is a novel

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[19] C. Clausen et al., *Quantum storage of photonic entanglement in a crystal*, Nature **469**, 508 (2011)

and very attractive approach for quantum repeater applications.

As stated in Table 1, none of the current memory media combines all the requirements, and therefore the choice of the ideal medium is not yet determined. An important part of the innovative nature of this proposal resides therefore in the multiple perspectives that we will consider. After the hot atomic vapor and the cold atomic sample during the outgoing phase, this project will focus on the use of rare-earth-ions doped crystals during the returning phase at GAP-Optique. In this medium, we will investigate temporal multiplexing with the aim of practical implementation of a quantum repeater and the long-term goal of improving over direct transmission distribution rate.

Two aspects are therefore innovational in this proposal : I will address **multiple media with multiple memory protocols** and I will investigate the **multi mode properties** of the memories (spatial and temporal multiplexing). This is the reason why the acronym **MULTI-MEM** has been choosen for the proposal.

Timeliness and relevance of the project

As we will see in the section B5 of this proposal, the interest in quantum memory has been rising very quickly over the past decade. The demonstration of the very promising GEM protocol by the ANU group has been achieved only three years ago and this group remains the only one, to our knowledge, with an available working GEM. According to the potentiality of this memory scheme, building a GEM experiment at NIST is therefore highly relevant and within the appropriate timing. On the other side, the expected demonstration of a GEM in a cold atomic sample at ANU is also of great interest for potential applications of this memory.

The storage of single-mode quantum states in quantum memories has now been achieved in several laboratories in Europe and abroad. A major direction for the research in the field is multimode memories. The experience gained during the fellowship on this subject will be highly beneficial to the European Research Area (ERA) during the returning phase. Indeed, the long term goal of winning over direct transmission in quantum states distribution rate is a highly competitive field, where the GAP-Optique group is one of the main front-runners. Nevertheless, the ability to use complementary approaches (spatial and temporal multiplexing) is a clear advantage that will contribute to enhancing the ERA research excellence.

At the same time, this multidisciplinary approach will enable me to develop and apply skills of considerable value for the reintegration as a researcher in the ERA.

It is worth noting that the theme of quantum memory is a major motivation for the EU Integrated Project Qubit Applications (QAP) started in 2005 and for the QUIE2T Coordination Action, two programs funded by the European Commission under the 7th framework programme. The host institution (GAP-Optique) is one of the academic partners of the QAP project and Nicolas Gisin is a Roadmap committee member of the QUIE2T.
This proposal is therefore highly relevant according to the scientific priorities of the European Commission and the returning host is an ideal location to achieve this project.