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Project website Error! Bookmark not defined. **address:** http://quantumrepeaters.eu/

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QuReP

Quantum Repeaters for Long Distance Fibre-Based Quantum Communication

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QuReP: Executive Summary

A Quantum repeater is a compulsory tool for quantum communication. It is the equivalent of the fibre optical amplifiers used for classical communication. Without it, long range and high bandwidth optical communications is simply not possible. The first commercial application of quantum communication has been quantum key distribution and today systems run continuously in countries all around the world, however their range is limited to metropolitan network distances. Quantum repeaters provide a means to overcome the distance limitations for future quantum communication because it allows for the distribution of entanglement over arbitrarily long distances. Quantum repeater technologies will extend and facilitate the use of quantum key distribution in a wide variety of network infrastructures. Furthermore, they are other cryptographic primitives (e.g. bit commitment or database quantum query) that can be performed in a more secure way with quantum physics compare to classical physics or classical computation that will also profit from these advances.

The QuReP project set out in 2010 to study what was needed to bring quantum repeater technologies to a level where we can start to think about industrialising this technology. As the project comes to an end in 2013, we can look back on a highly successful project that has not only managed to advance all of the associated quantum technologies but also demonstrate key primitives for quantum repeaters, such as entangling distance quantum memories and teleportation between telecom regime photons and quantum memories.

Quantum repeaters are the primary target application in the QuReP project in order to have a clear objective for the development of frontier quantum photonic components. There is, however, a multitude of ways to exploit all those components for other applications ranging from computing, precision spectroscopy, biological imaging, metrology and many more. We have also worked to find and master the integration of multiple quantum photonics components in in increasingly complex quantum systems. The capacity of controlling basic quantum components like single photon detectors, pseudo single photon sources allowed the commercialisation of quantum key distribution systems. The ability to master this new generation of quantum components will lead to the commercialisation of new techniques in the near future.

The consortium competencies extend from fundamental aspects of spectroscopy, CNRS-LCMCP, to 3 groups working on quantum memory functionality in different systems: University of Geneva, CNRS-LAC and the University of Lund. The University of Paderborn is probably the leading applied physics groups in Europe working on integrated photonic sources based on nonlinear materials. The University of Geneva is also one of the few groups in Europe, and indeed the world, whose expertise covers all aspects of quantum communication, from single photon detectors, photon sources, and quantum memories to the theory of quantum communication architectures and security. The industrial partner IDQ, are the world leaders in the commercialisation of quantum communication. They have a proven experience in industrialising advanced quantum technologies and are ready to exploit the next generation of entanglement-enabled technologies arising from this project.

> There are already niche markets for quantum repeaters, should they exist, and the market is expected to grow significantly in the next 10 years. We expect that the results of QuReP will provide a solid foundation for this exciting future. We believe that QuReP has made an excellent start towards building a global quantum communication market, a quantum industry and the future Quantum Internet.

For more information visit the QuReP web site: QuantumRepeaters.eu

QuReP

Quantum Repeaters for Long Distance Fibre-Based Quantum Communication

The aim of QuReP is to develop a Quantum Repeater: the elementary building block required to overcome current distance limitations for long-distance quantum communication.

http://quantumrepeaters.eu

The goal of QuReP is to develop the technologies need for a Quantum Repeater - the elementary building block required to overcome current distance limitations for long-distance quantum communication. Quantum Repeaters are the analogue of classical optical amplifiers that permit the cascading of successive fibre optic communication links. Quantum Repeater technology is centred around quantum light-matter interactions at the quantum level in ensembles of rare earth ions frozen in a crystal that stores quantum information by coherent control of the quantum degrees of freedom. A clear and well-defined architecture and protocol for a complete Quantum Repeater can be realised with entangled photon pair sources that couple the quantum memories to fibre optic communication systems. The proof of principle has been shown for all aspects of this approach and QuReP now aims to bridge the gap between fundamental research and the specifications for an industrial project. The main technological result of the QuReP project will be a roadmap for the industrial realisation of quantum repeaters. The outcome of the QuReP project will serve as the basis for an industrial initiative, developing the first quantum repeater products. Considering the state of the art, potential difficulties and the chosen development approach, it is reasonable to assume that this technology could be translated into products in the next 10 years with spin-off technologies emerging in the interim period. We have brought together leading European groups in quantum communication, quantum memories, photonic sources and rare-earth ion spectroscopy and materials as well as the leading quantum communication technology SME to move what has been fundamental research towards commercial feasibility. There are already niche markets for quantum repeaters, should they exist, and the market is expected to grow significantly in the next 10 years.

A summary description of project context and objectives

Over the past twenty years, intense research has been advancing the field of quantum communication. The most mature application of this new field is quantum key distribution (QKD), which allows one to distribute cryptographic keys over an optical fibre. These keys can be used to encrypt data in order to guarantee its confidentiality and integrity. QKD replaces conventional key distribution techniques, which are based on mathematics and offer only limited strength. Their security is indeed based on unproven mathematical assumptions and vulnerable to increasing computing power. Consequently they are not appropriate to secure highly confidential data transmissions. On the contrary, the security of QKD is based on quantum physics and can be rigorously proven. It is the only technology that can offer such a high level of security. QKD is one of the key technologies that will be used to secure communication of the next generation Internet. The first commercial QKD products were brought to the market by two companies: Swiss based ID Quantique and US based MagiQ Technologies, 10 years ago. In 2007, ID Quantique announced that the IT department of the Geneva local government had decided to use QKD to secure the infrastructure used for ballot counting in elections, in what is considered as the first public application of QKD.

One of the technological limitations that prevent widespread deployment of QKD is the fact that its range is limited due to the optical attenuation of the fibre link. Commercial QKD systems work well over distances of 50km and can tolerate up to 80 – 100km in optical fibres. More recently, several research experiments have demonstrated key distribution over fibred links with distances exceeding 250km. One should note that attenuation also limits the range of classical communication systems but it can be corrected by signal amplification using optical amplifiers, usually spaced every 50 to 100 kilometres. In QKD, however, this optical amplification process doesn't work. We can expect - if the technological progress allows - that a direct QKD link will run up to a maximum distance of around 400 kilometres. Nonetheless, an equivalent of the optical amplifier exists in quantum communications and is called a Quantum Repeater.

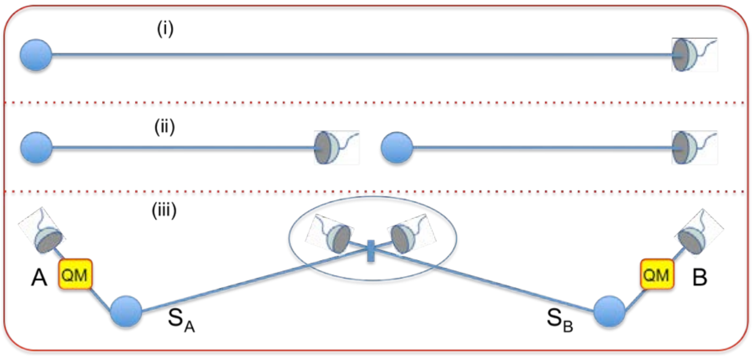

Figure 1: The Quantum Repeater solution: To avoid exponential transmission losses the link is broken up into smaller pieces (i→ii). However, without quantum memories this is not much better than direct transmission. (iii) Quantum Memories allow for each link to store entanglement until the next link is ready, thus allowing for the scalable concatenation of these links for quantum communication.

Quantum Repeaters are the analogue of classical optical amplifiers that permit the cascading of successive fibre optic communication links. The concept is illustrated in Figure 1, which shows how the problem of loss is overcome in the context of quantum communication channels. In QuReP the Quantum Repeater technology is centred around quantum light-matter interactions at the quantum level in ensembles of rare earth ions frozen in a crystal that store quantum information by coherent control of the quantum degrees of freedom. A clear and well-defined architecture and protocol for a complete Quantum Repeater can be realised with entangled photon pair sources that couple the Quantum memories to fibre optic communication systems.

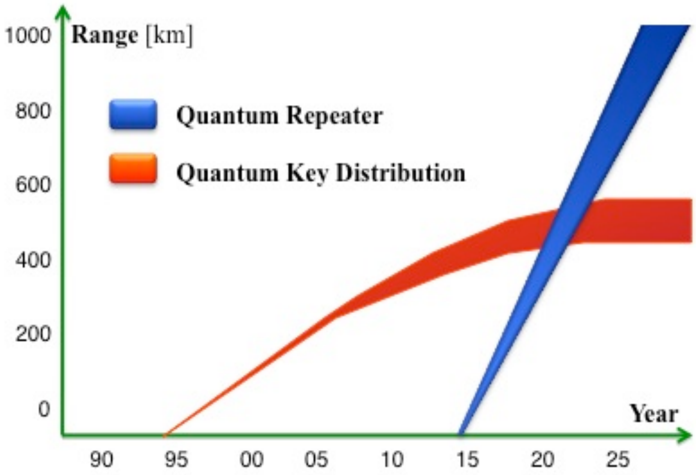

Figure 2: Comparison of achievable range for fibre-based QKD and quantum repeater technologies over time.

Quantum repeaters are currently the only solution to securely extend the reach of fibre-based QKD and make worldwide secure key distribution possible. The impact of this technology is illustrated in Figure 2. Since the first demonstration of a QKD system at the beginning of the 90's, this technology has made tremendous progress. As already explained, it can be expected that demonstration over distances of approximately 400 kilometres will be possible in the near future. However, without the development of quantum repeater technologies this progress will saturate. This technology offers extremely high security, but its application is currently restricted to metropolitan area networks. On the contrary, quantum repeater communication distances should advance more rapidly, as once initial elementary links for these repeaters start to be connected, say over a few hundred kilometres, then thousands of kilometres should follow rapidly.

> **The QuReP project targeted the development of the technologies and competencies necessary for the eventual industrialisation and commercialisation of Quantum Repeaters - the elementary building blocks required to overcome current distance limitations for long-distance quantum communication.**

The QuReP strategy is straightforward and has a clear vision for a Quantum Repeater architecture based on well-chosen materials and protocols. QuReP brought together leading European groups with competencies extending from fundamental aspects of spectroscopy by the CNRS (LCMCP), France, to 3 groups working on quantum memory functionality in different systems: The University of Geneva, Switzerland; CNRS (LAC), France, and The University of Lund, Sweden. The University of Paderborn, Germany, is probably the leading applied physics groups in Europe working on integrated photonic sources based on nonlinear materials and the University of Geneva is one of the few groups in Europe, and indeed the world, whose expertise covers all aspects of quantum communication, from single photon detectors, photon sources, and quantum memories to the theory of quantum communication architectures and security. The industrial partner ID Quantique, (Switzerland) are the world leaders in the commercialisation of quantum communication. They have a proven experience in industrialising advanced quantum technologies and are ready to exploit the next generation of entanglement-enabled technologies that should arise from this project.

To accomplish the objectives we broke the work effort down into four tasks:

1. Quantum Memories
2. Spectroscopy and growth of rare earth doped crystals
3. Sources & Interfaces
4. Quantum Repeaters

These focus on the refinement of component technologies (1 & 3), materials optimisation and fabrication (2), and integration of these towards a functional Quantum Repeater (4). The objectives and approach for each are briefly outlined in the following.

1. Quantum Memories

A mix of characterisation techniques using classical and quantum light as well as the many of the control techniques that are needed for a Quantum Repeater were studied in a selected range of rare-earth-ion doped materials. Close collaboration with efforts in spectroscopy was critical for improving the growth and optimisation of these materials for Quantum Repeaters. Quantum Memories are the last element for Quantum Repeaters to be experimentally realised and as such we have placed a heavy emphasis on bringing this work to the level of maturity needed.

2. Spectroscopy and growth of rare earth doped crystals

Prior to this project only one company in the USA was capable of supplying these quantum memory materials. During the project we refined these materials and their manufacturing process for the ions and the host crystals, as well as different isotopes that constitute the quantum memories.

3. Sources & Interfaces

Highly efficient narrow bandwidth (~100MHz) photon pair sources were a key enabling technology developed in QuReP. The realisation of high Fidelity (→100%) “Bell State” Measurements (BSM) between different sources was also a critical milestone for connecting multiple quantum repeater links. These photon pair sources were adapted to interface the quantum memories and the telecommunication fibre network. Sources target compact, stable and low loss integration of multiple components on-chip – Lithium niobate technologies were exploited for compatibility with standard telecom components.

4. Quantum Repeaters

This task focused on the high-fidelity integration of all component technologies developed in QuReP for their implementation in a functional quantum repeater architecture. Fundamental primitives in quantum communication such as entangling photons and multiple quantum memories were performed as well as the teleportation of information from a photon into a distant quantum memory were performed. These experiments demonstrated key aspects of the elementary building blocks for Quantum Repeaters and demonstrated their capabilities.

A key objective for QuReP was to demonstrate that quantum repeaters are advancing rapidly and that the industrialisation and commercialisation of these technologies needs to be addressed in the next 5-10 years.

A description of the main S&T results/foregrounds

As we already mentioned secure and private communication afforded by QKD is currently limited in the distance over which it can be utilised. Perhaps the simplest way of describing the principle challenge for the QuReP project and quantum repeaters in general is: - distributing quantum information securely over long distances. At a more fundamental level, we need to generate, distribute, manipulate and measure entanglement in complex networks that cover extended distances. This is the road towards building a Quantum Internet.

The QuReP project was a highly ambitious initiative, funded by the European Commission, to pave the way towards the industrialisation and commercialisation of quantum repeater technologies. It has been highly successful and in the following we break this down by each of the primary tasks before discussing some of the more general results of the project and the legacy that should lay the foundations for the future strengthening of a quantum information industry.

1. Quantum Memories

A quantum memory is a complex atomic system, which we are interested in interfacing with optical systems – typically those that are compatible with fibre optic networks. The memories themselves consist of hosting rare-earth ions in a crystal structure. Typical rare-earth ions that were used in the project include: Europium (Eu); Praseodymium (Pr); Neodymium (Nd), and Thulium (Th) and the crystals themselves were similar to those used in Lasers, YAG and YSO. A couple of typical crystals used in the quantum memory experiments are shown in Figure 3.

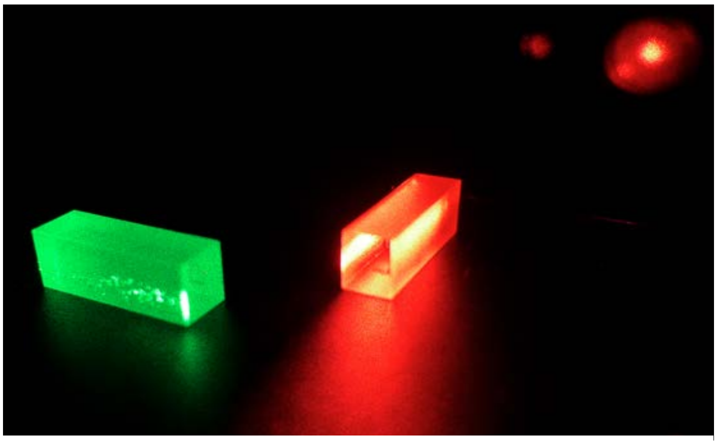

Figure 3: Picture of two Quantum memory crystals used in the Quantum Repeater experiments. Typical size is around 1cm in length.

In the following we go through some of the key characteristics for a quantum memory, elaborating on what is critical and what has been achieved in the project. Specifically the "Fidelity" – how well the quantum memory preserves the quantum state that it absorbed? The "Efficiency" – how probable is it that the photon, carrying the quantum state, is absorbed and re-emitted (read-out). The "memory storage time" defines how long we can store the quantum state in the memory, which is critical if we need to wait to verify entanglement in another link. The "memory bandwidth" is strongly related to the memories absorption properties but governs how fast the communication system can operate. The "multimode capacity" is a measure of how many quantum states can potentially be stored at any given time and this is a critical, perhaps the most critical, parameter for the scaling of quantum repeaters.

Memory fidelity

Each quantum state, each photon, is stored in an ensemble of around 10^9 ions. Dephasing processes mainly attenuate the signal while introducing very little noise. To illustrate with a simple example, we assume that each of these ions generates a field E_0 when the quantum state is read out. The total field would then be 10^9 E_0 and the intensity would be proportional to the square of this field. Let us now assume that $9*10^8$ of the ions above dephase randomly, while 10%, 10^8 ions, keep their phase. The total field would then be (10^8 ±$3*10^4$) E0, where the phase of the second term in the parenthesis will be random. However, it is clear that while the signal will decrease strongly due to the dephasing, the phase noise induced by the dephasing process will basically be negligible. Clearly this may be a somewhat naïve picture of the dephasing process, but the bottom line is that in these systems and with these techniques the optical quantum states are encoded into matter in a way that can be very robust against noise and in particular it can be extremely robust against random phase noise. Since the quantum memory storage fidelities are already typically well in the > 90% regime it has at the present stage not been a need to focus on this issue within QuReP.

Memory efficiency

When we talk of efficiency in this case, we are interested in knowing how well a quantum state can be absorbed, stored and then read-out again, from the quantum memory. In these systems the efficiency of the memory will be proportional to the square of the part of the input state energy that is absorbed by the memory. Hence much effort has been put into identifying highly absorbing systems and materials. In particular this has been regarded as necessary because the storage protocols (*e.g.* the atomic frequency comb (AFC) protocol [ASR-09] or the Coherent Reversible Inhomogeneous Broadening (CRIB) protocol [NK-05, KTG-06]), generally require that the absorption profile is restructured to optimise the rephasing and reemission of the stored information in such a way that the absorption coefficient is reduced by an order of magnitude. Thus even with large initial absorption the memory after reconstruction may still have non-negligible probability to just transmit and not at all absorb the input pulse. The other more fundamental issue is loss in efficiency due to decoherence. This clearly is directly connected to the storage time, such that high efficiency requires that the coherence time is much longer than the storage time and this issue will be further discussed in the paragraph on storage times below. However, in these techniques there is also a contribution to decoherence (*i.e.* having ions emitting radiation out of phase in a manner where this process can not be rephased) from the restructuring of the absorption profile. Taking the AFC storage protocol as an example, the storage efficiency is roughly proportional to *Exp*($-7/F^2$), where F is the finesse of the AFC structure. The effective absorption coefficient is defined as $d_{eff} = \alpha L/F$, where α is the absorption coefficient and L the length. From here it is clear that a high finesse gives a smaller dephasing, but on the other hand, it results in less absorption so there is clearly a trade off.

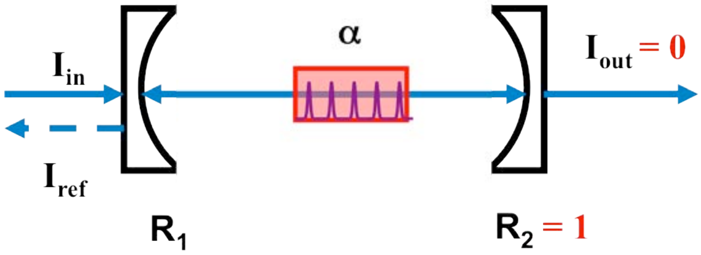

Figure 4: Impedance-matched cavity concept used for improving quantum memory efficiency.

At the start of the project these contradictory optimisation conditions seemed to be an inherent complication within the storage schemes used. However the possibility to insert the storage medium in a cavity [AC-10], between two mirrors with different reflectivities, distinctly changed the situation. The concept is illustrated in Figure 4 - By impedance matching the cavity with the memory inside, complete absorption of the input field can be obtained for an, in principle, arbitrarily weak absorber. This moves the efficiency problem into a new regime. Although the current maximum value for the efficiency within the project is 56% it is straightforward to identify the measures that need to be taken to reach above 80% efficiency. The upcoming issue will be to push the efficiency beyond 90% and during this process; it will also be relevant to more carefully start to investigate the fidelity.

Memory storage time

Although (on demand) spin storage and recall just had been demonstrated at the start of the project, it was more suitable to carry out many of the basic memory performance tests just storing information in the excited stage instead of the spin state. Because of the superior multi-mode capacity of the AFC technique [ASR-09] this was the technique chosen for most of the experiments. Although the excited state coherence times typically were in the 100 microsecond regime the storage time in excited state storage using the AFC technique is set by the inverse AFC mode spacing. This mode spacing may typically be close to a MHz leading to a time separation between input and output of the order of a microsecond.

However, as the project progressed, increasing efforts were invested in the development of on demand spin storage. The typical energy-level structure for these quantum memories is shown in Figure 5. Fundamental questions addressed included enhancing the spin coherence times using so called ZEro First Order Zeeman (ZEFOZ) splitting [FSL-04], where the amplitude and direction of an external magnetic field is adjusted such that the energy separation between the two spin states used for the storage is independent of small magnetic fields changes. In this configuration nuclear spin flips in the crystal host material do not dephase the phase information stored in the spin levels. In addition techniques have been developed and tested using radiofrequency pulse sequences (further) decoupling the spin levels from host (or external) changes. Using these techniques spin coherence times have been extended from hundreds of microseconds to hundreds of milliseconds and no doubt these improvements will continue.

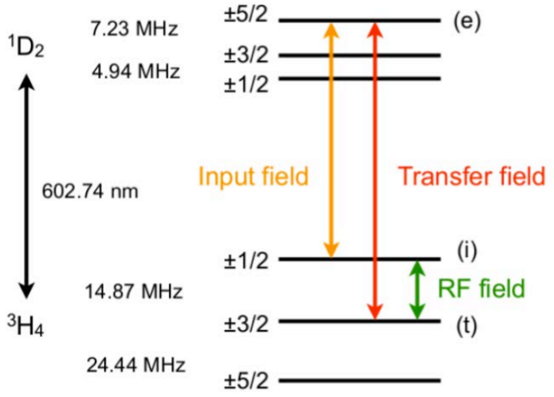

Figure 5: Energy level structure for Pr, showing the optical transition around 602nm, where a photon can be absorbed, the π-pulse for transfer to spin-wave storage and the RF fields needed to control dephasing.

In order to (efficiently) store information in the spin levels it is also necessary to have transfer fields (π-pulses) efficiently transferring the excited state probability amplitude down to the spin level (and back to the excited state at readout). It is also necessary to compensate for dephasing due to the inhomogeneous broadening on the spin transition. This can (also) be carried out using radiofrequency pulses. Storage times presently lag a little behind dephasing times, but also here the improvement is about three orders of magnitudes from a few microseconds to a few milliseconds. Again, we can expect a continued development here too. Most likely the storage times where development may stop will rather be regulated by what is practically needed rather than what will be possible to achieve and will also be closely connected to the storage efficiency development. A clear challenge will be to keep high efficiencies while continuously increasing storage times.

Memory bandwidth

QuReP has largely focused on multi-mode performance rather than bandwidth, as this is more critical for the scaling of quantum repeaters. Earlier experiments before QuReP had demonstrated bandwidths up to 100 MHz and within QuReP this has been extended to 1 GHz bandwidth using Tm:YAG [BLC-11] and around 350 MHz in Nd:YSO. However, it is presently unclear how well bandwidth requirements can be matched with storage time and storage efficiency requirements. The issue of combining bandwidth with other properties is still very open and there is not yet a clear-cut case for how to proceed. The issue of memory bandwidth appears to be an area where material development and new ideas can be quite important for the future development.

Memory multi-mode capacity

The multimode capacity for the rare-earth-ion doped crystals clearly is quite unique. The demonstration of storage and recall of >1000 modes, as was done in Tm:YAG [BLC-11], is certainly spectacular. So is the demonstration of storage and recall of a 64-bit sequence of weak coherent pulses [UAR-10] in Nd:YSO. This work clearly demonstrates the unique capacity of the rare-earth-ion doped crystal memories to store and recall complicated temporal sequences. There does not seem to be any clear indication that other quantum memory materials or quantum storage techniques will be able to be competitive regarding this aspect. Again it is here less evident to predict the coming development. On one hand we might anticipate a development focused on having a not very large number of modes, maybe 10-100 modes, and optimising storage efficiency and storage times, on the other hand there is a possibility that we also could in addition see a development in a different direction where focus could be on utilising the fact that it may be possible to carry out time or frequency domain operations directly on the data stored in the memory. Again this is a clear area for new ideas where it is not so easy to predict what the outcome may be.

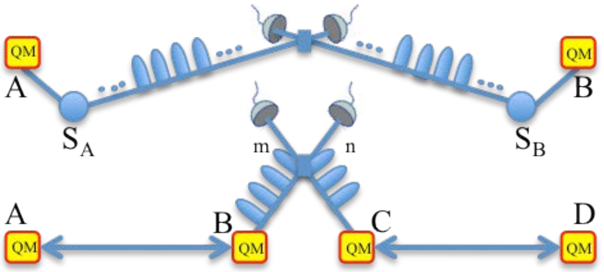

Figure 6: The Multi-Mode Quantum Repeater scheme using pair sources and multimode memories. (top) The sources S_A and S_B each emit a photon pairs into a sequence of time bins. The detection of a single photon behind the beam splitter at the central station projects the quantum memories (QM) at A & B into an entangled state for that temporal mode (time-bin). (bottom) If entangled states have been established between the m-th time bins in QM-A and –B and between the n-th time bins QM-C and –D, an entangled state between A and D can be created by reconverting these memory modes into photonic modes and combining the appropriate time bins on a beam splitter.

Light-matter entanglement via storage of entangled photons

The QuReP project has pushed the limits for light-matter and matter-matter entanglement, which is a central concept that will be elaborated upon momentarily. The project has demonstrated storage of one photon from an entangled pair in a Nd:YSO crystal [CUB-11] using the photon read out from the memory and the other photon in the entangled pair. This *tour-de-force* experiment was made possible through the high fidelity of the ensemble storage technique paired with the relatively high overall efficiency of the rare-earth-ion doped crystal storage techniques. Together with a subsequent still more demanding experiment demonstrating entanglement between two different crystals [UCB-12] these experiment have established storage in rare-earth-ion doped crystals as one, if not the, most competitive quantum state storage concept.

The main objectives here have been to develop quantum memories suitable for the quantum repeater technology. This includes memories capable of storing quantum states with excellent fidelity, high efficiency, extended storage times, reasonable bandwidth and multi-mode capacity. A key benchmark has also been to demonstrate light-matter entanglement via storage of entangled photons.

The improvements in the performance of quantum memories based on rare-earth-ion doped crystals have been significant, if not to say spectacular, during the course of the project. Storage times have moved from the few microseconds to the millisecond regime. The number of modes stored and recalled in the memory has increased from a handful to over a thousand. The material and experiments consistently show storage fidelities above 90% and commonly in the upper 90s. The bandwidths have also now reached the GHz regime. Storage efficiency has moved from the 1-10% region to over 50%, but more importantly, high efficiency memory performance has recently been demonstrated also for weakly absorbing samples by inserting them into cavities. Finally not only light-matter entanglement but also matter-matter entanglement has been demonstrated.

2. Spectroscopy and growth of rare earth doped crystals

Growing the high quality crystals that are needed for quantum memories is not so different from cooking – it is a delicate balance of the quality and quantity of ingredients AND how they're put together – the recipe. THE LCMCP group at the Ecole Nationale Supérieure de

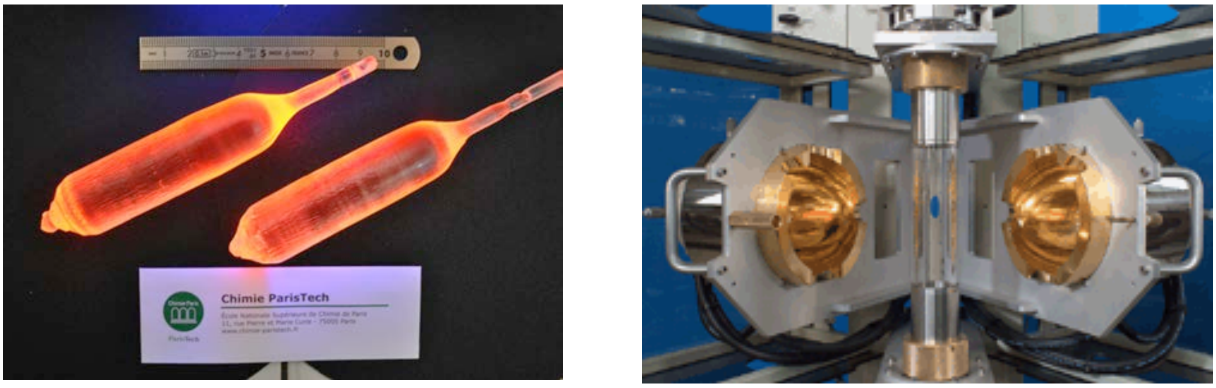

Figure 7: The crystals are grown (Left) from seed material in special ovens (Right).

Chimie de Paris (LCMCP) has been working on this with great success. Prior to the start of the project there was only one company in the USA capable of supplying high quality rare-earth ion doped crystals. In the following we highlight some of these advancements with different rare-earth ion and crystal combinations and explain how these crystals are characterised.

Optical and paramagnetic spectroscopy of Nd^{3+}:Y_2SiO_5

Several optical experiments were carried out in order to optimise the operating conditions for the quantum memory experiments. Let us emphasise that these are crucial for all quantum storage experiments like multimode storage and light matter entanglement. The quantum memory, based on the atomic frequency comb protocol, requires so-called "optical pumping" in order to shape the absorption into the desired frequency comb structure. In Figure 5 we see and example on the optical transition (602 nm). This in turn requires two spin state levels, which we could create via the magnetic Zeeman effect by applying an external magnetic field of 300 mT. A high-quality optical pumping requires a high ratio of the spin population relaxation time to the optically excited state lifetime. This was characterised using fluorescence spectroscopy and stimulated photon echoes techniques and an excited state lifetime of 300 microseconds was found (note that this parameter is not adjustable).

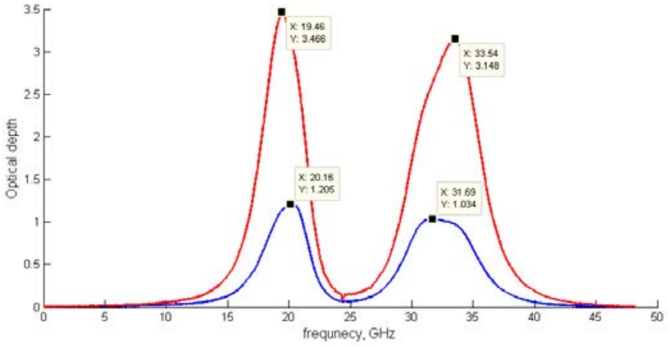

Figure 8: Absorption spectra in a 35ppm Nd:YSO sample at 3K and under a magnetic field. Light polarised along D1 (red) or D2 (blue) principal dielectric axes.

The spin population lifetime, however, was maximised by measuring it as a function of magnetic field strength and orientation, resulting in about 100 ms for 300 mT, when oriented 30 degrees relative to the crystal D2 axis. This configuration allowed us to reach 97% spin polarisation, which is crucial in order to create a high-quality atomic frequency comb. Samples were also produced to obtain a high absorption coefficient. It reaches 3.5 /cm in a 35 ppm crystal (Figure 8), which was crucial for improved memory storage efficiency, which was increased to 14 % in a single pass configuration.

For long storage times, additional ground state levels are needed to transfer the optical coherence to a long-lived transition. We investigated the hyperfine structure of ^{145}Nd:Y_2SiO_5 (nuclear spin I=7/2) for this purpose. CW electron paramagnetic resonance (EPR) spectroscopy allowed us to determine the spin Hamiltonian, including both Zeeman electronic and nuclear interactions as well as hyperfine interactions. This is important to predict the complex hyperfine structures under arbitrary magnetic fields. Using pulsed EPR and electron nuclear double resonance (ENDOR) experiments and in collaboration with Lille University (France) and University College London (UK), we also measured the hyperfine population relaxation time to be 34 ms at 6 K. The hyperfine coherence lifetime was 650 µs, which is the longest measured up to now for a paramagnetic rare earth ion. These results are very promising for using hyperfine transitions for quantum storage, especially since we expect even longer lifetimes at lower temperatures. Although these final samples could not be fully exploited during the project time it definitely seems that ^{145}Nd:Y_2SiO_5 is an attractive material for quantum memories with long storage time.

Optical and hyperfine spectroscopy of Eu^{3+}:Y_2SiO_5

Detailed optical spectroscopic studies of an isotopically pure ^{153}Eu:YSO sample were carried out. The goal was to determine parameters crucial to quantum memories, which were not previously known. In particular, we have determined the relative transition strengths of the nine possible transitions involving the three ground and excited state hyperfine levels. The spectroscopic data of these materials at this level is quite minimal – i.e. we are concerned about fluorescence emissions that would generate even a few photons that could destroy the memory capabilities. During this work we also successfully developed the necessary optical pumping schemes for manipulating the ions between the different hyperfine levels. Finally, we have measured Rabi frequencies, thus indirectly measuring absolute transition strengths for the three chosen transitions. We have also identified the absorption coefficient or Eu^{3+}:Y_2SiO_5 as the limiting factor in terms of the achievable memory storage efficiency. To address this question, a study was carried on samples grown within the project under various conditions and concentrations. We concluded that the oscillator strength of Eu^{3+} varies in these samples, which is an unexpected result for single crystals with well-defined structures and will require further investigation.

Using an improved process, we were able to grow samples with high absorption coefficients, up to 3.2 /cm, which is close to the best-published results and much larger than those obtained on commercial samples.

Hyperfine transitions are a key element of Eu:Y_2SiO_5 quantum memories as they are used to store the optical coherences. Measurements of hyperfine coherence lifetimes have been performed using optically detected magnetic resonance (coherent Raman scattering). Experiments were performed on the ±1/2 - ±3/2 transition of ^{151}Eu:Y_2SiO_5 ($I = 5/2$) at 34.5 MHz. We found inhomogeneous linewidths of 21 kHz and coherence lifetimes of 8.6 and 14 ms at zero and 14 G fields respectively, in agreement with spin-wave storage experiments (Figure 9). Hyperfine transitions of ^{153}Eu:Y_2SiO_5 were also investigated and have slightly longer coherence lifetimes. At zero field, we found T_2 of 9.9 and 10.4 ms for the ±1/2 - ±3/2 and ±3/2 - ±5/2 transitions respectively, whereas under a 18 G field, these values increased to 23.6 and 15.1 ms. The inhomogeneous linewidth was measured by spin wave storage and found to be 69 kHz for the ±3/2 - ±5/2 spin transition. To be useful for long storage, the spin coherence has to be refocused by radio-frequency (RF) pulses. To be efficient, their bandwidth has to be large

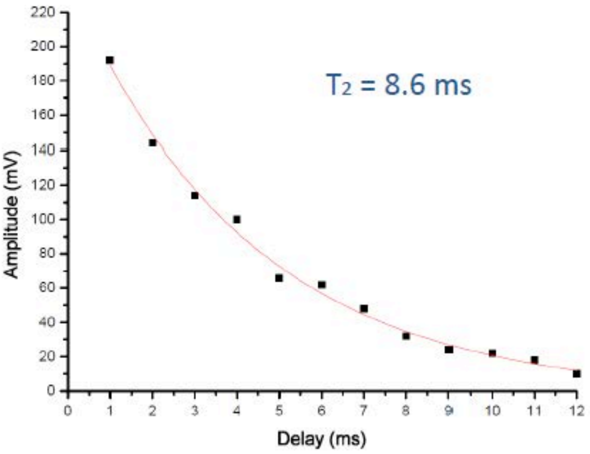

Figure 9: Optically detected spin echo amplitude as a function of pulse delay in $^{151}Eu^{3+}$:Y_2SiO_5 at zero magnetic field and 3 K.

compared to the transition inhomogeneous linewidth. Isotope 151 has a smaller inhomogeneous linewidth and is therefore advantageous in this respect. We chose it to grow the final isotopically pure crystal, using the improved process mentioned above. Samples extracted from the boule have been used to investigate high efficiency quantum storage experiments, by taking advantage of a large absorption coefficient. With this new material and recent developments in terms of laser frequency stability and cryostat vibration control, we believe that an efficient, long-lived and multimode quantum memory is within reach.

Optical to spin coherence transfer and refocusing

Spin refocusing is necessary to increase the quantum memory storage time beyond 10s of µs. The latter value corresponds to the typical hyperfine inhomogeneous linewidth. In collaboration with Dortmund University, we investigated RF pulse sequences to achieve optimal refocusing in Pr:$La_2(WO_4)_3$, which are taken as a model system. Although typical NMR sequences can greatly extend spin coherence lifetimes, they are generally not suited to quantum information processing, since they require a well-defined phase for the initial quantum state to be preserved.

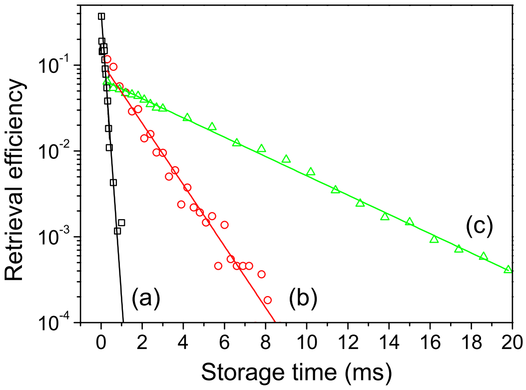

Figure 10: Storage efficiency as a function of the storage time for different RF dynamical decoupling sequences. (a) Two π-pulses, (b) KDD and (c) CPMG sequences.

In the storage protocols and implementations studied in QuReP, optical and RF sources have independent phases, so that it is necessary to find RF sequences which work equally well for any initial spin coherence. We were able to reach 1/e storage times of 4.2 ms with a "CPMG" sequence (Figure 10). Consisting of a series of RF π-pulses, it was compared to a KDD sequence, which uses π-pulses with complex phase cycling and is less sensitive to the initial spin state. As expected, the KDD sequence lead to higher efficiencies (a factor of 2) than CPMG at short storage times. However, it was preserving spin coherences for shorter storage times, which was not anticipated by theory. We finally performed an experiment in which two pulses are stored in the memory and interfered at the output - when the relative optical phase of the input pulses is varied, the output interference intensity varies in the same way. The corresponding visibility was close to 1, demonstrating the high fidelity of the memory. This is the first demonstration of a high fidelity optical memory in which dynamical decoupling is used to extend the storage time.

This technique of extending storage times seems very promising for Eu doped Y_2SiO_5 to obtain storage times well into the ms range. Indeed, we achieved a 33-fold increase in storage times compared to spin coherence lifetime in Pr:$La_2(WO_4)_3$, which would translate in 330 ms storage time for Eu: Y_2SiO_5. This is the kind of value necessary for the QuReP quantum repeater architectures.

Growth of rare earth doped materials

Crystals doped with naturally abundant Eu and Nd, as well as isotopically pure samples of $^{145}Nd^{3+}:Y_2SiO_5$, $^{151}Eu:Y_2SiO_5$ and $^{153}Eu:Y_2SiO_5$ were grown during the project to investigate specific properties for quantum memories – Figure 11 shows one particular example. Crystals grown by the Czochralski method were of excellent optical quality in terms of scattering, homogeneity and background absorption. Orientation of the samples was also accurate, providing excellent fidelity for storage of polarisation qubits. Spectroscopic properties were compatible with QuReP goals, and key parameters, like peak absorption, were at the level of the best-published results and better than commercially available materials. Moreover, these crystals allowed us to determine essential spectroscopic data. Samples of $Nd^{3+}:Y_2SiO_5$ and $^{151}Eu^{3+}:Y_2SiO_5$ have been used in quantum storage experiments.

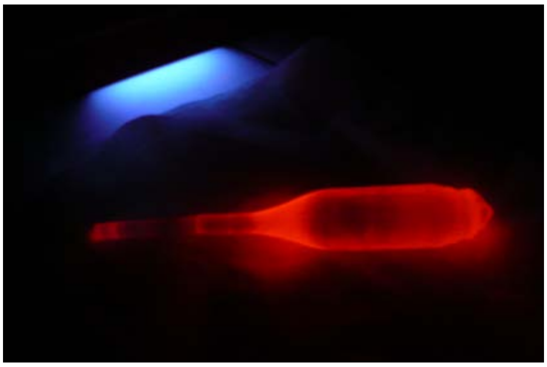

Figure 11: A 1000 ppm $Eu^{3+}:Y_2SiO_5$ crystal showing Eu fluorescence under UV excitation.

QuReP uses rare earth doped crystals as quantum memories. This work here is dedicated to the growth and optimisation of these materials with respect to the very particular and highly demanding properties required for quantum repeaters. This includes detailed spectroscopic studies to determine their materials key parameters.

In the QuReP quantum memory concept, the optical coherence is transferred to a spin coherence for long time storage. This involves many unknown or partially known spectroscopic parameters: hyperfine energy level structures, optical oscillators strengths between hyperfine levels, and transverse and longitudinal relaxation times of spin transitions. Moreover these data may have to be measured as a function of an external magnetic field. Spin coherence lifetime determines the memory storage time and has therefore to be as long as possible. Specific magnetic fields to obtain transition insensitive to magnetic fluctuations as well as trains of RF pulses to dynamically control coherence have also been studied. All these parameters are measured using a wide variety of techniques. This has also helped in the crystal growth and using spectroscopic studies to optimise these materials, as the properties of interest, like coherence lifetimes, are very sensitive to the rare earth environment at the nano-scale, crystals have to be produced at the highest quality. Beyond, quantum repeaters, it is expected that this understanding will find wide spread use in emerging applications where quality crystal growth is a necessity.

3. Sources and Interfaces

Typically the quantum memories do not operate at telecom wavelengths, however, this minor problem can be resolved through the use of nonlinear optics and frequency conversion. In particular we are interested in an interaction between a laser beam and a nonlinear crystal called spontaneous parametric down-conversion (SPDC). The idea is illustrated in Figure 12, where a laser (pump) photon spontaneously decays into two correlated photons (signal & idler). This interaction is governed by energy and momentum conservation laws, which determine what wavelengths and bandwidths can be realised. However, to make this approach practical, and to meet the constraints necessary for implementing quantum repeaters, we have to be clever about how we do this!

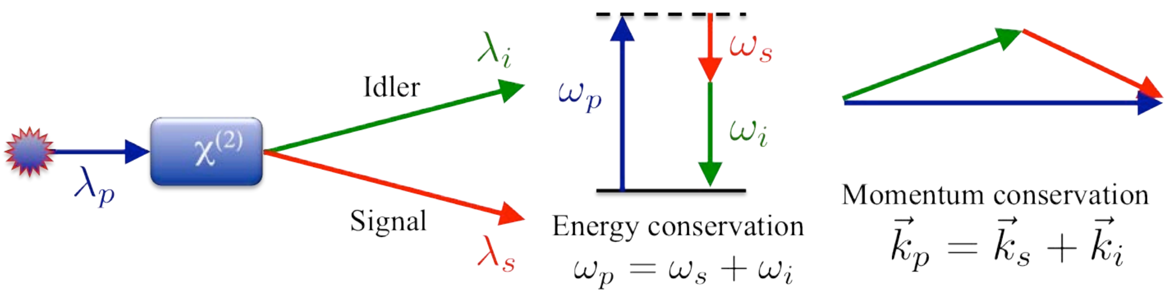

Figure 12: A ($\chi^{(2)}$) nonlinear crystal allows for the conversion of a pump photon into a pair of (signal and idler) photons. The energy and momentum conservation laws determine what wavelengths and bandwidths can be realised.

Besides improving the performance and functionality of nonlinear photonic sources, we also worked on developing better interfaces that allow for high fidelity measurements, as well as connecting the quantum memories to fibre optic networks, and advancing and integrating single photon detector technologies.

Photon Pair Sources

The development of integrated photon pair source exploited nonlinear optical SPDC in periodically poled lithium niobate (PPLN) waveguides - lithium niobate waveguides, similar to what is found in standard electro-optical modulators in telecommunication systems. Three generations of such integrated sources, shown in Figure 13, have been developed in QuReP.

The common challenge for the realisation of all three generations was the development of the proper fabrication technologies which essentially includes waveguide fabrication by Ti-indiffusion, field-assisted periodic poling, waveguide end-face preparation and dielectric coatings.

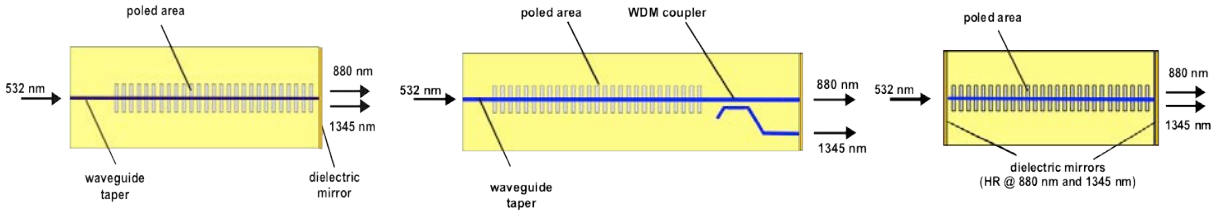

Figure 13: Three generations of integrated SPDC sources developed within the QuReP project.

In particular the periodic poling pointed out to be the most critical process. To obtain phase-matching (governing the momentum conservation in the crystals) for the SPDC, short poling periods of around 6.5 µm (type I phase-matching) or even only 4.5 µm (type II) are required. After optimising all the fabrication steps, we could finally succeed in the fabrication of waveguide samples with such short periods. In Figure 14 a micrograph of such a sample is shown. To visualise the 4.5 µm periodic domains, the sample was selectively etched.

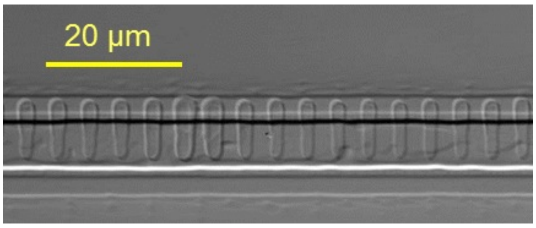

Figure 14: Micrograph of a selectively etched surface of a periodically poled Ti-diffused waveguide with a poling period of about 4.5 µm.

The target interaction for the sources consisted in a periodically poled waveguide for the generation of type I phase-matched photon pairs around 880 nm and 1345 nm, when pumped at 532 nm. At the input a waveguide “taper” enables an efficient coupling of the pump to the fundamental mode, by progressively adapting the mode of the waveguide to that of an optical fibre. At the output a dielectric mirror coating serves as pump blocking filter with high transmission for signal and idler photons.

In Figure 15 we see the measured SPDC spectrum for one of the photons in the pair. These measurements reveal that the spectral bandwidth is only about 0.5 nm, which is close to the theoretically predicted value. The photon pair generation rates of about 4…6 $*10^8$ photon pairs/(second mW) were determined confirming the efficient pair generation in the waveguide structure.

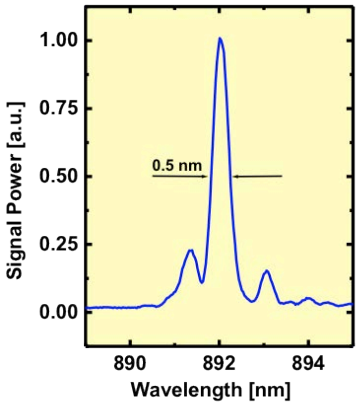

Figure 15: Measured SPDC spectra in a 7 µm wide waveguide with 6.4 µm poling period around the Nd quantum memory wavelength – the other photon is in the telecom regime.

The circuit for the 2nd generation source, in the middle of Figure 13, consists of a PPLN section for photon pair generation followed by a monolithically integrated directional coupler acting as wavelength division multiplexer, to separate the photon pairs directly on-chip. Various iteration cycles have been performed to optimise the device. This source has been operated as heralded single photon source [KHQ-13]. We identified an almost constant heralding efficiency as high as 60%, with pump powers less than 10 µW. The heralding efficiency defines the probability of finding the other photon of the pair, once the first photon has been detected – this is another critical parameter for scaling these technologies. This is the first time in a Ti:PPLN-based type-I SPDC source that such high heralding efficiencies have been reported.

The focus here is on the nonlinear crystal, however, the complete source of photon pairs is far more complicated. In particular we need to significantly reduce the 0.5 nm bandwidth – typically the Nd memory requires photons with around 100 MHz (a fraction of a pm), i.e. several order of magnitude narrower. In Figure 16 we see part of the optical setup used in engineering the desired characteristics of the photon pairs. As we see there are a lot of optical elements needed to control this, and many more still.

The basic idea of the third generation source was to exploit resonant enhancement for SPDC in a compact and rugged waveguide cavity to generate efficiently narrowband photon pairs – a greater level of integration. Such cavities are fabricated by directly depositing dielectric mirrors on the end-faces of the waveguide. This is a first step towards reducing the amount of bulk optics needed to operate these sources. The basic operation of this novel concept was studied theoretically and optimised design parameters determined [PSO-12]. It could be shown that a spectral narrowing down to a few (longitudinal) modes could be achieved, if the finesse of the cavity is large enough.

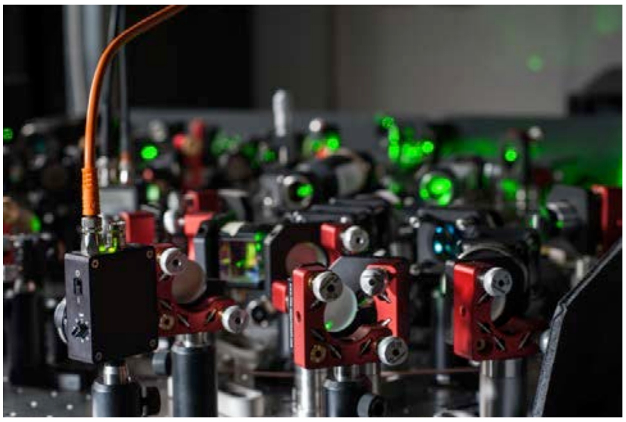

Figure 16: Part of the optical set-up used in generating the photon pairs.

Such resonant samples, as illustrated in Figure 17, with poling periods around 4.5 µm for type II phase-matching were fabricated. An asymmetric choice for the mirror reflectivities with high reflectivities (> 98%) for the front mirror and reflectivities of around 90 % for the (out-coupling) rear mirror have been chosen. The measured finesse of a 12.5 mm long resonator is around 25.

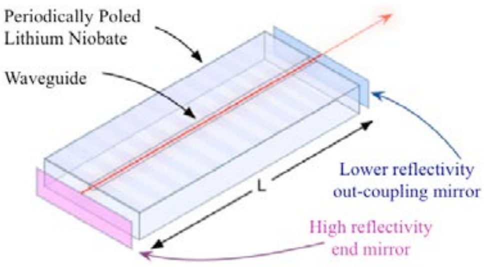

Figure 17: Concept for a resonant waveguide cavity photon pair source.

Detailed investigations [LHK-13] of the spectral structure of the resonant source strongly confirmed that the predicted clustering leads to a tremendous spectral narrowing compared to non-resonant devices. It could be shown that the photon-pair generation occurs within 3 “clusters”, three groups of cavity modes, which are spaced by about 160 GHz. Thus, a spectral filtering, to select a single cluster, is easily possible, even with standard DWDM technologies. Within a single cluster the pair generation is limited to 3 to 4 longitudinal modes as shown in Figure 18. The spectral linewidth of a single longitudinal mode could be resolved using coincidence measurements. From the measured correlation time τ_{coh}= 2.1 ns, a spectral bandwidth of about 150 MHz could be deduced which is in good accordance with the theoretically predicted width of the resonances calculated for the given cavity parameters and well suited to the quantum memories, without the need for further, and bulky, spectral filtering.

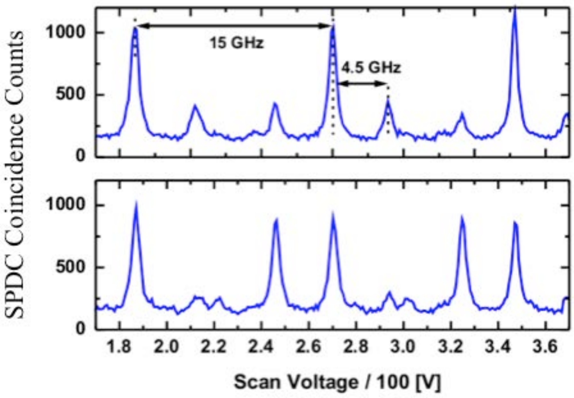

Figure 18: Photon spectra for the integrated OPO photon pair source. The two spectra vary in temperature by 6 mK around 161 °C.

High Fidelity Measurements & Interfaces

One of the principle challenges for the realisation of quantum repeaters is to interface multiple quantum systems, as illustrated in Figure 19. We already discussed the advantage of integrated sources to reduce the complexity of the photon pair sources, but we need to think about building many of these with sufficient control that they can be made "identical". One of the key measurements in a quantum repeater network is the so-called "Bell-State measurement" (BSM).

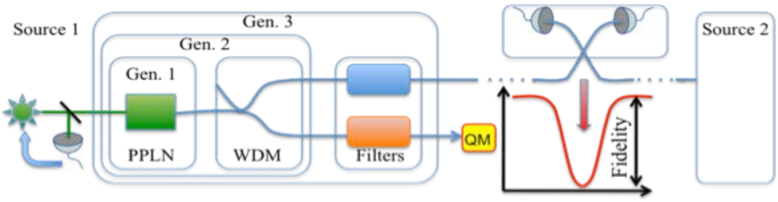

Figure 19: Concept image showing the reducing complexity of the different generation photon-pair sources and how these need to be connected via high fidelity "Bell-State Measurements" between different systems.

The BSM is away of measuring, for example, two photons from different sources. A typical Hong-Ou-Mandel interference measurement is shown in Figure 20. When two photons arrive at a beamsplitter (a coupler with two input and two output ports) they "bunch" and leave through the same output, such that the probability of finding one in each output goes to zero. This "dip" going to zero in the middle of Figure 20 is the signature that the photons from the different sources are indistinguishable – this lies at the heart of the BSM and again is a critical point for the Fidelity of the distributed quantum states. The narrow bandwidth of the photons, which implies a long coherent length, also helps ensure a robustness for the BSM against fibre length fluctuations on short time scales. This is because if one photon is slightly delayed with respect to the other, there is still a high probability of them arriving at the same time.

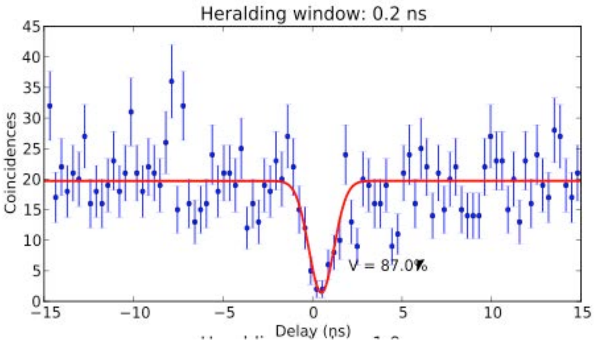

Figure 20: HOM interference measurement between quantum memory bandwidth photons.

Detection

Detectors are clearly a crucial element for quantum repeaters where the performance demands are paramount. The consortium did not initially plan to be directly involved in the development of detectors within QuReP project but used numerous collaborations with leading groups around the world to have access to cutting edge detection systems. In the end a combination of work on Solid state, InGaAs/InP avalanche photodiode schemes, and those based on superconducting technologies were exploited. The later being of particular interest on a commercial level as they spawned two new products for the project's industrial partner ID Quantique.

The first step of this task was to follow-up the research activity in single photon detection techniques in order to choose which technology was needed to fulfil the demanding requirements linked to the demonstration of a quantum repeater. Based on a review of quantum repeaters, by some of the University of Geneva group [SSR-11], high detection efficiencies (> 90%), low noise (< 1 Hz) and low timing jitter (< 100 ps) are needed for high-performance quantum repeaters. At the beginning of the project, the situation was very different for visible (around the quantum memory wavelengths) and near infrared (telecom) photons. Silicon (Si) avalanche photodiodes (APDs) having excellent performance (efficiency > 60%, noise < 100 Hz and jitter ~ 100 ps), for detecting the visible photons and these were already commercially available. The state of the art of near infrared single photon detection technologies was much less advanced than the Si APD-based detection techniques. At the beginning of QuReP, the most promising options were two emerging technologies based on superconducting detectors: TES (transition edge sensors) and SNSPD (superconducting nanowire single photon detectors). Before the project, the TES technology had already shown amazing performances in terms of efficiency versus noise, but with a quite poor timing jitter (~100 ns). This very large jitter value makes this technology unusable for quantum repeaters. The SNSPD had a low time jitter (<100 ps) with a relatively good efficiency versus noise value (~10% efficiency for ~ 10 Hz of noise).

Figure 21: Along with the excellent performance, the id220 has a simple packaging: fibre-optic input; sma (TTL) output; a USB interface for parameter selection and readout, and an external power supply.

Unfortunately, over the first three years of the project the performance of the SNSPDs did not improve markedly. Due to this lack of improvement, ID Quantique and the University of Geneva tried to improve the InGaAs APD-based techniques. The first achievement was the development of an InGaAs/InP diode that could operate in both Geiger modes: gated and free-running. This achievement was patented and the technology is already available as a commercial device - id210 [id210]. The ability to make the detection system in free-running mode is quite interesting for quantum repeaters because it allows the use of CW sources which reduces strongly the issues associated with synchronisation that can occur when working in gated mode. Based on the results obtained with the id210, UNIGE decided to makes a detection device optimised to work in the free-running mode. This led to a technology based on InGaAs APD, which was quite close to the SNSPD, at least in terms of efficiency versus noise. In one year the noise of InGaAs diode driven in free-running mode was reduced by a factor of 10 or more. This technology has been transferred by UNIGE to IDQ in order to make a product of it called id220 [id220] and the simple packaging of this device is illustrated in Figure 21. The best id220 devices have noise <250Hz for efficiency 10%. Nevertheless, this improvement is still too small to outperform the SNSPD so as to match the QuReP requirements.

It is only at the end of the third year of QuReP that a group at the National Institute of Standards and Technology (NIST) in the USA demonstrated a real breakthrough for the SNSPD technology [MVS-13]. This new technology is based on a superconducting material WSi, which had not been previously tested, but combined the best characteristics of TES and

SNSPD approaches. This US lab developed a detector capable to detect single photons at 1550nm with an efficiency value of 93%; a noise smaller than 1Hz and a timing jitter slightly larger than 100 ps.

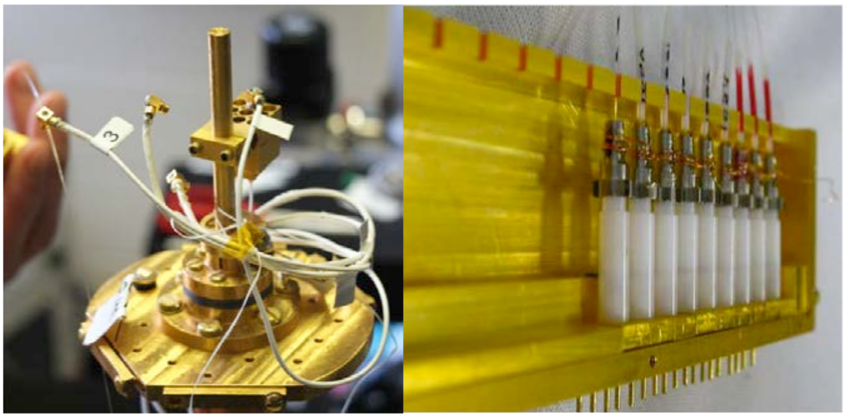

Figure 22: (Left) WSi SNSPD requires cryogenic cooling, however, (Right) many can be bundled in a compact array and are ideally adapted to standard fibre optic coupling. (Courtesy NIST)

The arrival of this detection technology has launched a flurry of activity from other groups striving to develop advanced single photon detectors. We expect that in the next couple of years that this will be reproduced by many labs throughout the world. This should also motivate research on looking at other, potentially higher temperature, superconducting materials. We expect that this will also lead to a rapid commercialisation of this technology.

The objective of this task were to focus on the development of photon pair sources and the integration of the diverse components and processes needed to interface quantum memories and optical fibres to extend current long distance telecommunication architectures. The work was broken down into: the development of compact integrated optical photon pair sources compatible with the QMs; high fidelity measurements and low-loss interfacing, and interfacing cutting-edge single photon detectors.

A high level of integration for telecom-compatible photonic devices has been demonstrated. Integrated photonics and low-loss optimisation of the sources saw orders of magnitude improvement in system performance. Key measurement primitives were successful demonstrated with high fidelity and a new generation of single photon detectors have all helped to open the way towards scalable quantum repeaters.

4. Quantum Repeaters

Entanglement is an essential ingredient of quantum communication [GT-07, GT-10]. Several applications of quantum communication are currently being developed and among these, quantum key distribution [GRT-02] is the most advanced and has already generated several commercial products [Q-IND]. The approach that we are interested in here is quantum key distribution that relies on the distribution of entanglement between two parties. In other words, pairs of entangled particles are sent – one particle to each communication party – through optical fibres and the two parties use this shared entanglement to exchange secret keys. Commercial applications, such as secure encryption in banking and government sectors, are emerging, but the current distances are a limiting factor for its broader acceptance. This distance limitation is due to absorption and scattering in optical fibres. Contrary to classical systems, one cannot amplify quantum bits as the no-cloning theorem [WZ-82] prevents one from perfectly copying a quantum state, and, consequently, perfectly amplifying it. Thus, we are left with a signal-to-noise ratio that decreases exponentially with distance. In 1998, the idea of a quantum repeater was proposed as a solution for distributing entanglement over arbitrarily long distances [BDC-98, DLC-01]. Since then, the concept of quantum repeaters has strongly evolved from theoretical and experimental points of view.

Quantum repeater architectures

Let's look at this idea in a little more detail. A simple procedure to distribute entanglement between remote locations *A* and *B* requires a quantum memory (QM) and a photon pair source (S_A and S_B) at each location, as shown in Figure 23. The two sources are triggered such that each has a small probability of creating a photon pair. If only one pair is created, one of the two photons is stored in the neighbouring quantum memory while the other is sent to a central station to be detected after a 50/50 fibre coupler. The fibre coupler erases the information about which source created the photon. Therefore, detection of a single photon at the central station heralds the entanglement of the two remote memories: only one memory contains a photon, but the state of both memories is in a quantum superposition of the two possibilities [DLC-01]. This system is called an elementary segment. One can repeat this procedure between several concatenated elementary segments and successively "teleport" the entanglement to two quantum memories that are even further apart. This constitutes the basic quantum repeater architecture.

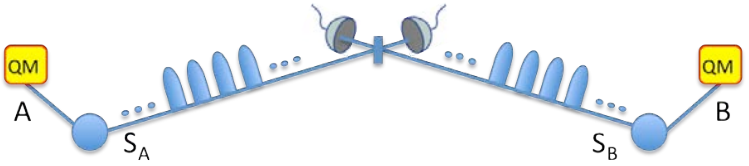

Figure 23: An elementary segment of a quantum repeater

The quantum memories are essential to improve the scaling of the entanglement distribution time (EDT) to long distances as they allow the synchronisation of neighbouring segments. As we have seen, another promising way to further lower the EDT is to use multimode quantum memories allowing simultaneous storage of multiple temporal modes. This effectively lowers the EDT by the number of modes that can be stored. Hence, this has the potential to dramatically improve quantum transmission rates by orders of magnitude over previous proposals [SRA-07].

Quantum repeater components and requirements

Quantum repeater architectures require three main components: quantum memories, sources of photon pairs and single photon detectors, which we have already discussed in some detail. A more comprehensive and technical report on the state of the art can be found on the QuantumRepeaters.eu web site of the project. A critical aspect of the QuReP project was that these component technologies were compatible with one another so that they could be brought together for quantum repeater demonstration experiments.

Quantum Memory – Photon Entanglement

There were several key demonstration experiments throughout the QuReP project that were performed as the component technologies improved and the complexity of the experiments could be increased. In Figure 24, we see the first of such experiments and also some of the complexity associated with this still simplified schematic.

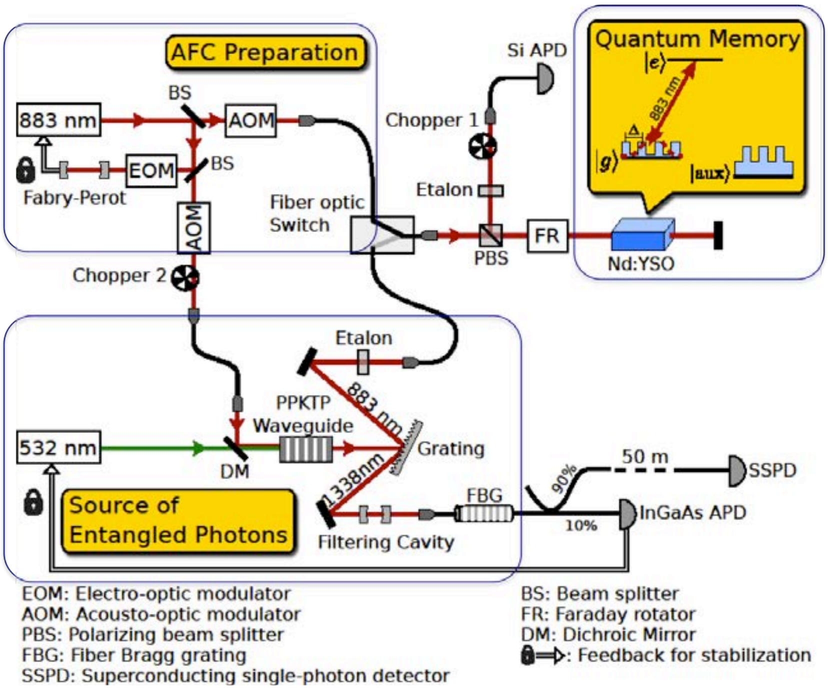

Figure 24: Schematic of the set-up entangling a telecom wavelength photon & a quantum memory.

In the lower section we see the generation and manipulation of the photon pairs. Both photons undergo extensive spectral filtering. The telecom photon is coupled into fibre, in this demonstration, only 50m long, and detected by a superconducting detector – the InGaAs APD is used for stabilisation. The 883 nm photon is sent to the Nd:YSO quantum memory. We also see the atomic frequency comb (AFC) preparation stage that is used to prepare the quantum memory for storage.

The quality of the final entangled state was characterised via interference experiments, yielding an 84 +/- 4% interference visibility, as well as a "Bell test", which provides a clear and definitive witness of the quality of the entanglement. A value of S = 2.64 +/- 0.23 was found, which is well above the bound of 2 needed to show entanglement.

Entangling Distributed Quantum Memories

In Figure 25 we see the scenario for entangling two remote quantum memories, which is another of the main characteristic of the elementary building blocks for quantum repeaters. In this first experiment, we only used one photon pair source, which greatly simplified this demonstration.

This experiment allowed us to also gain insight into the HOM interference DIP as well as the Fidelity of this critical measurement. As there is only one photon stored between the two quantum memories we cannot directly measure the HOM dip visibility (which requires two photons). However, by recombining the two output modes of the Quantum Memories we can perform a measurement that is analogous to the Bell state measurement (BSM). Furthermore, this measurement demonstrates how well we could concatenate elementary links. Therefore, this set-up was used to study the performance of this important measurement. Any characteristics associated with the Quantum Memories that could reduce the dip visibility measurement in this scenario would manifest itself consequently as a reduction in the observed interference visibility. We have shown that after storage of the entangled state between the two quantum memories, the two modes that are read out are then interfered and we observe an interference visibility of over 96%.

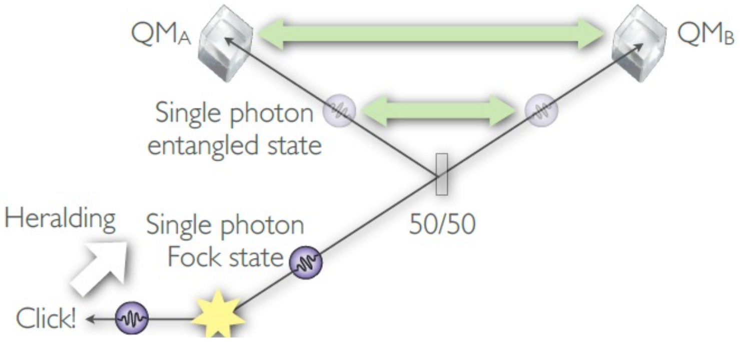

Figure 25: Experimental schematic for entangling two remote quantum memories.

We demonstrated **entanglement between two remote quantum memories** and the **high quality storage and release of entangled states** in those quantum memories.

This shows our capacity to implement high-performance elementary building blocks for quantum repeaters. We consider this work to be a significant highlight for the project and the results have been published in Nature Photonics [USB-12].

Teleportation

Teleportation is one of the most important primitives in quantum communication and underpins how information, and indeed entanglement itself, is distributed over extended quantum networks. Figure 26 illustrates a teleportation concept: firstly entanglement is distributed and then a BSM is performed between one of the entangled photons and another photon that is encoding some information, in our case a qubit. This state is then teleported onto the other photon, without ever passing in between.

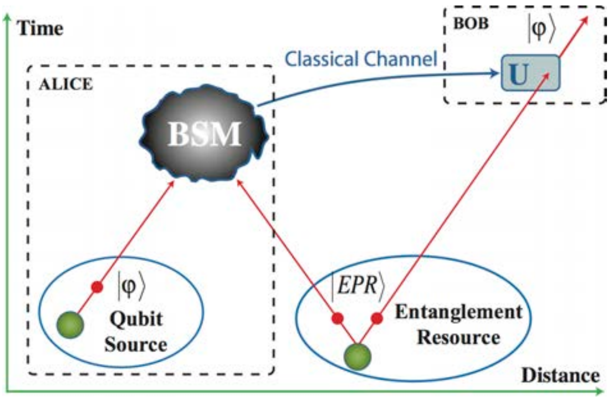

Figure 26: Concept of quantum teleportation

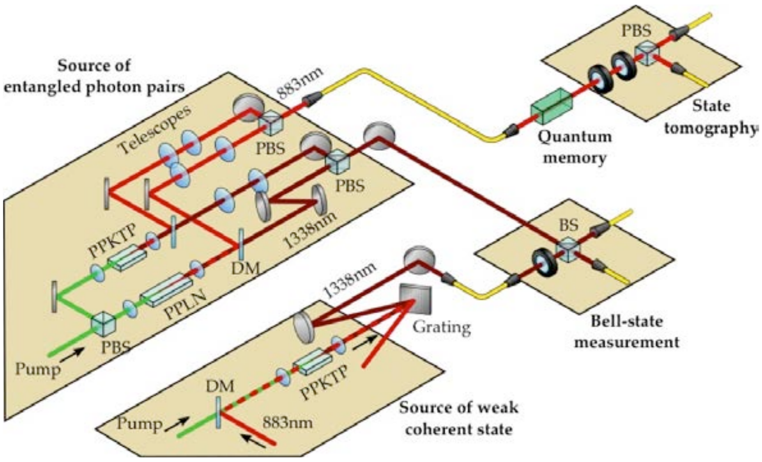

Figure 27: Experimental schematic for teleporting an unknown quantum state into a quantum memory.

In the final experiment in the QuReP project we made several significant changes, in particular we developed a polarisation entangled photon pair source along with a compatible quantum memory, i.e. capable of storing arbitrary polarisation states. Significant improvements concerning optical losses due to spectral filtering and improved fibre coupling systems were realised to make this step possible. This experiment allowed as to study the behaviour of polarisation in the context of quantum memories and repeaters, which was not initially considered when writing the project proposal, though is of great importance.

A schematic of the experimental set-up is shown in Figure 27. Several nonlinear crystals, 1 PPLN and 2 PPKTP, are used for generating the polarisation entangled state (on the left) and the qubit state that is to be teleported (on the right). One photon from the pair is combined on a coupler, or beam-splitter (BS), to perform the BSM. The other photon is sent to a quantum memory. The teleportation “channel” then maps the state of the initial qubit that is encoded on a telecom photon, into the quantum memory. Subsequently, when the quantum memory is read out, the emitted photon, at 882 nm will be in the desired qubit state. Extensive characterisation of this final state confirms that the teleportation protocol works with good fidelity.

The QuReP project had a clear vision for a Quantum Repeater architecture and what is required to implement it. We focused on refining the component technologies with the goal that these should be compatible for integration in complex demonstration experiments for quantum repeaters. All of these efforts will be utilised to promote Quantum Repeaters as a rapidly maturing technology.

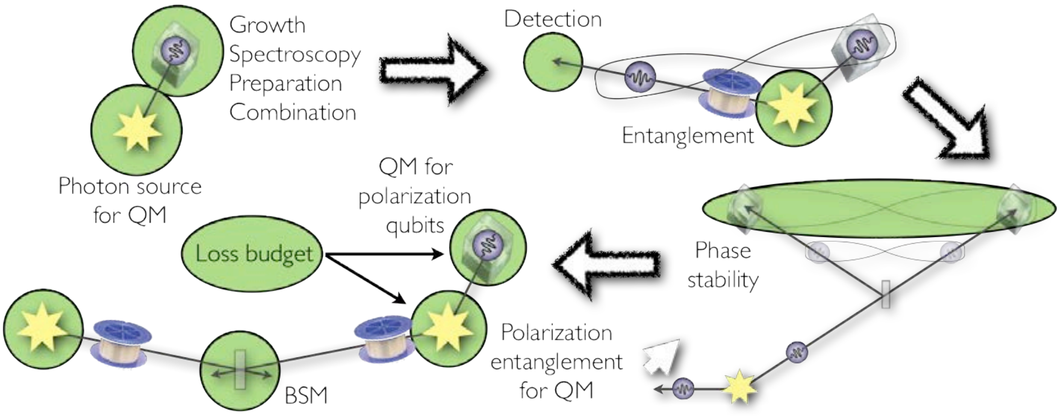

Figure 28: The QuReP development cycle illustrating the evolution from crystal growth and photon pair development, to improving detection and measurement systems for final Quantum Repeater demonstration experiments.

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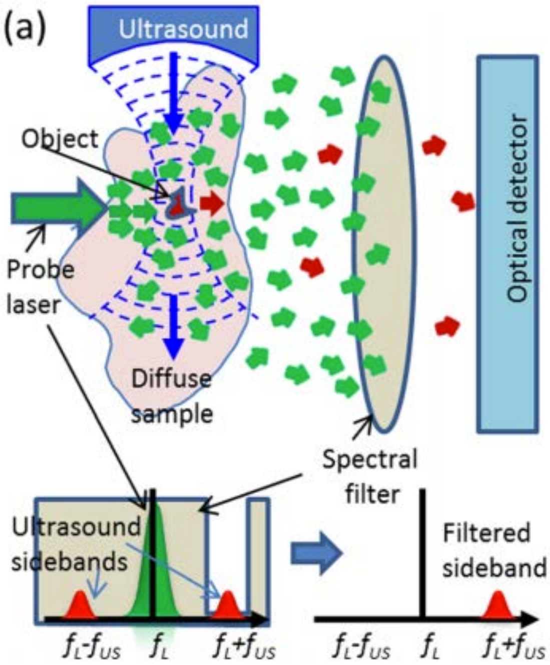
The potential impact and the main dissemination activities and exploitation of results

The focus of the QuReP project has been on the technologies associated with future applications of quantum repeaters. We have prepared several “Discussion” and “State of the Art” documents, which are available on the QuReP website QuantumRepeater.eu, that give a more detailed overview of what we have achieved concerning quantum repeaters. In the following we will focus on how some of the different technologies might be exploited beyond QuReP and beyond applications such as quantum repeaters.

Exploitation & Impact

The quantum memories developed within in QuReP are aimed for quantum repeaters. However, clearly high quality quantum memories will be immensely important for many other quantum information tasks and not least for quantum computing. Thus this work within QuReP is of particular significance for the field of quantum information. In a still wider context rare-earth-ion doped crystals have certain features that make them truly unique. They have very narrow homogeneous optical line width, G_h, and in comparison to the homogeneous line width, very broad inhomogeneous optical line widths, G_{ih}. This gives them exceptionally large ratios $G_{ih}/G_h > 10^6$, surpassed by very few materials (if any). In addition the spin levels can be extremely long-lived (several days) which will lead to spin offs also outside the quantum information area.



Optically detected ultrasound imaging inside a highly scattering medium. The probe light is modulated in the ultrasound region creating modulation sidebands on the probe light. Since the sideband power depends on the optical and acoustic properties of the object, the image includes both optical and acoustic contrast. The spectral filter passes only one sideband with high discrimination.

One direction that was an entirely unexpected spin-off was the discovery that the spectral filters, developed to more efficiently being able to create the Atomic Frequency Comb (AFC) structures, could be used to recover weak signals (such as a sideband) masked or swamped by the noise in spectrally very close lying, and many orders of magnitude stronger, carrier wave [LLG-11]. In particular we have shown that it is possible to more or less arbitrarily tailor the rare-earth-ion absorption profiles in the crystals. For example, narrow-band spectral filters can be made to transmit only one single very narrow frequency. Furthermore any spectral filter that is narrow in frequency will delay the signal transmitted through it. This is the case for *e.g.* electronic filters as well as for optical filters. For optical filters the delay can be described in terms of slow light caused by the steep refractive index dispersion across the narrow transmission window. Thus these filters can have a double effect in terms of, on one hand transmitting just a single frequency and, on the other hand, also delaying this single frequency in time temporally discriminating against light at other frequencies. These filters were subsequently used in ultrasound tomography, a relatively new medical diagnostic modality, but one in which a progressively larger number of hospitals are now investigating. It was possible to show that structures in tissue as far as 9 cm below the tissue surface could be detected using these filters [ZSR-12]. Other spin-off effects that have been demonstrated include increasing the Q-value of optical cavities by four orders of magnitude using such slow light effects [SQR-13].

The QuReP project has pushed the limits of linear filters operating near atomic resonances due to the extremely challenging retrieval efficiency demands. The AFC scheme, in particular, increased the efficiency upper limit to more than 50%, more than one order of magnitude higher than previously possible. The potential high efficiency of linear filtering in rare-earth ion doped materials should stimulate further investigations on the classical processing of optically-carried radio-frequency signals. For instance, temporal imaging applications could be strongly developed in those materials, with unprecedented dispersive power, since higher efficiency would permit filter combination or concatenation. This has been discussed recently and illustrated on the example of analogue time reversal of light in the microsecond range [LCL-13].

The quest for high transmission efficiency through an absorbing filter, at the origin of the AFC protocol, has stimulated in-depth investigation of optimal efficiency conditions in other signal processing applications of rare-earth ion doped crystals, such as the Rainbow Analyser, presently at the stage of demonstrator in the premises of THALES Company. This device is intended to perform the instantaneous spectral analysis of optically carried RADAR signals over a bandwidth of several tens of GHz. Based on the angular separation of spectral components, this equipment would benefit from the addition of a spatial dimension to the existing, spectral-only, optimised AFC scheme.

Another important point for potential economic development is that the crystals developed in QuReP for quantum memories and quantum information processing, can find applications in other fields, which are also taking advantage of small homogeneous line-widths. We have identified the following topics, which are currently studied by European research groups and industries:

- Ultra stable laser locking on spectral holes. Such lasers are of interest in metrology for developing time references at the highest precision. Locking a laser on a spectral hole in Eu:YSO (QuReP flagship crystal) could improve current setups accuracy by one order of magnitude.
- Analysis of radar signals on optical carriers. This technology is also based on spectral hole burning in rare earth crystals and is investigated by the French company Thales in collaboration with QuReP partner CNRS-LAC.
- Ultra sound optical tomography. A rare earth crystal is used as a narrow spectral filter to select light, which has interacted with ultra sounds. This technique aims at real-time biomedical imaging with high spatial resolution.

The crystals and the spectroscopic properties developed in QuReP have potential applications beyond their use as quantum memories. Indeed, the YSO crystals produced within the project are currently being studied in several groups for:

- Superconducting qubits/ Nd:YSO hybrid quantum systems (Uni. Chalmers, Sweden)
- Ultra long spin coherence lifetimes in Eu:YSO (Uni. LUND)
- Laser locking on spectral holes for metrology in Eu:YSO (Observ. de Paris, France)

In these applications, the crystal's optical quality (scattering, polishing, orientation) is crucial, and so are the spectroscopic properties (optical depth, coherence lifetimes). The growth and processing techniques optimised in QuReP can therefore be exploited in these applications. Moreover, the spectroscopic data determined in QuReP, like hole burning schemes or relative oscillator strengths, are likely to enable rapid progress. Concerning commercial exploitation, ultra stable laser locking on spectral holes [TRF-11] seems to be very promising and has been already strongly funded in France. Indeed, this technique has the potential to exceed the performances of the best Fabry-Pérot cavities used in time metrology, because of the exceptionally narrow holes, which can be burnt in Eu:YSO. This is exactly what was used in QuReP to design AFC structures with long delays. Given the importance of time definition in many applications, commercial spin-offs could be significant.

Crystals grown by QuReP partners at CNRS-LCMCP at Chimie Tech, Paris.

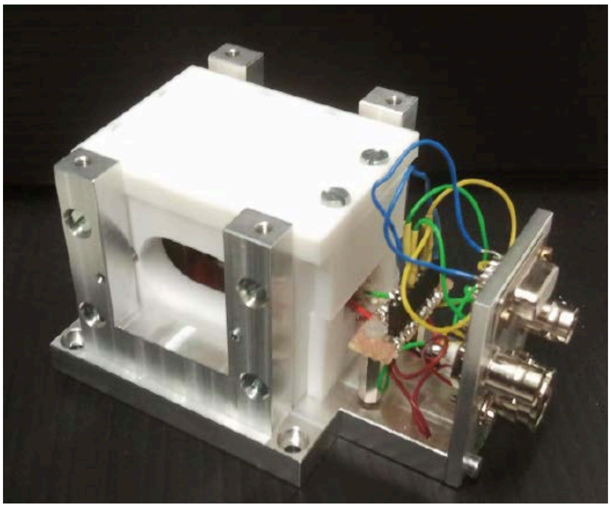
The efforts dedicated to crystal growth and spectroscopy have allowed us to deepen our expertise on materials specifically developed for quantum memories. Indeed, we were able to grow samples whose performance are unmatched by commercially available crystals. To the best of our knowledge, this expertise is unique in the world as the very few groups outside QuReP with comparable knowledge (groups of Pr. Cone, Montana State University (USA) and of Dr Matthew Sellars, Australian National University) are focused on spectroscopy and have no, or very limited growth activities. On the other hand, the only company (Scientific Materials, USA) able to provide crystals for quantum information processing is now nearly entirely dedicated to the production of laser crystals for defence applications. This, in itself is an incredibly important for Europe as a leader in advanced quantum technologies.

Considering the range of applications involving rare earth doped crystals combined with coherent light-matter interactions, it can be hoped that a European commercial production of high quality samples will be launched in the future.

In the prospect of industrial development, this expertise could be transferred to several European crystal growth companies like FEE (http://www.fee-io.de, Germany) specialised in laser crystals, Cristal Laser (http://www.cristal-laser.fr, France) that produces nonlinear crystals or RSA le Rubis (http://www.rubisrsa.com, France) offering aluminium oxide and spinel single crystals. These companies could all potentially grow the high melting temperature crystals used in QuReP. One of the QuReP partner (CNRS-LCMCP) is already in contact with them for other projects. For example, FEE is already selling a crystal discovered at CNRS-LCMCP: Yb:CaGdAlO$_4$.

It is reasonable to believe that we have not at all seen the full impact of these materials. We have seen it neither what regards quantum repeater technology, nor what regards other areas of the quantum information field and we also have not seen the full impact in other areas of technology. In this sense projects like QuReP, exploring new avenues and materials, are of significant importance for science and society and promise a high potential impact on the development of new, highly innovative technologies in Europe.

While the crystals for the quantum memory effort have wide potential, the nonlinear crystals for the photon pair sources have chosen to work with technology that is widely used in the telecommunication sector – waveguides in lithium niobate (LiNbO$_3$). **Lithium niobate waveguides** are utilised extensively, for example, in optical amplitude and phase modulators. In the quantum regime, we need to introduce an extra degree of complexity for generating photon pairs – periodic poling. In this case the temperature also plays a role in the phase-matching, as previously discussed. An intense development programme has pushed these capabilities into new operation regimes. In particular "short" (4.5 micrometre) poling periods increase enormously the range of wavelengths for which we can generate photon pairs. The generation of photon pairs is closely related to other frequency conversion such as second harmonic, sum-frequency and difference-frequency, which play a role in a wide range of applications.



Test set-up and housing for temperature controlling the PPLN photon pair source.

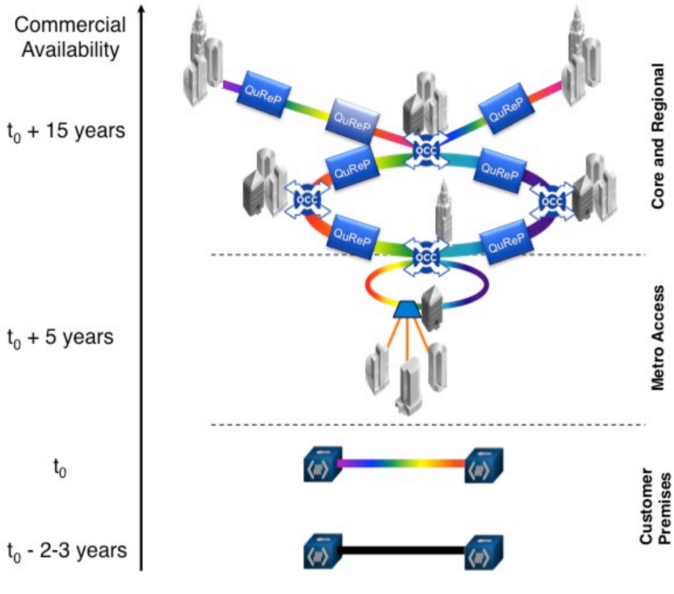
Integrated quantum photonics is a growth area for quantum technologies, for example in in communication and metrology. During the QuReP project, the group of Applied Physics at the University of Paderborn, have been able demonstrate increasing levels of complexity for these integrated periodically poled lithium niobate (PPLN) devices. These include on-chip wavelength division multiplexing (WDM), precision reflection (and anti-reflection) coatings – either used to reduce reflection losses, or to create optical cavities at the end-faces of the waveguide. The flexibility in wavelength, high efficiency, low loss and compatibility with standard telecom components holds great promise for these devices. It is expected, in the next year, devices like this will be commercially available, from QuReP partner IDQ, for turnkey photon pair generation.

Single photon detectors are an enabling technology for a wide variety of fields, especially where weak optical signals are either needed or all that there is. Recently, we have seen more and more research groups in biology and chemistry have started fluorescence experiments at near-infrared wavelengths, thus opening up another potentially large market. For example, singlet oxygen luminescence detection is a very important experiment that could lead to breakthroughs in life sciences. Indeed, single oxygen is a crucial intermediate in many biological processes. This luminescence occurs at 1270 nm. The first demonstration of single oxygen luminescence detection has been performed with superconducting detectors (SNSPD). Several groups around the world are attempting to repeat this experiment with the id220 detectors developed during the QuReP project.

All the partners of the consortium have been made aware about the potential of innovation produced within the framework of QuReP project and have been strongly motivated to submit patents. The two **patents** have been filed. The first patent has been filed by IDQ in April, 2012. This patent deals with the capacity of being able to drive APDs-based single photon detectors in both, gated and free-running modes. Its title is: 'Apparatus and method for allowing avalanche photodiode based single-photon detectors to be driven by the same electrical circuit in gated and in free-running modes'. The Provisional US patent application is No.: 61/638,609. The other patent has been filed by CNRS-LAC in April 2012. It deals with the description of the ROSE protocol, which allows quantum memory implementation with an efficiency of 100% in theory. Its title is: Photon echo quantum memory and method.

Within the second year, a technology transfer has been done between UNIGE and IDQ. UNIGE developed a new single photon detection platform dedicated to the free-running working mode of InGaAs avalanche diodes. This technology has been licensed to IDQ and has been on sale now for over a year. The product based on this technology transfer is called the id220. This product is a kind of breakthrough in the single photon technology because it allows the user to work in conditions that were not achievable before except with SNSPDs. The SNSPD technologies can typically outperform the id220 devices, but at a much higher (~ factor x4) cost and with significant maintenance overheads (cryostat equipment installation and maintenance). The id220 facilitates the access to free-running mode detection for near-infrared photons.

A **Quantum repeater** is a compulsory tool for quantum communications. It is the equivalent of fibre optical amplifiers for classical communications. Without it, long range and high bandwidth optical communications are not possible. The first commercial application of quantum communications is quantum key distribution. Quantum repeater technology will extend and facilitate the use of quantum key distribution. Furthermore, they are other cryptographic primitives (e.g. bit commitment or database quantum query) that can be performed in a more secure way with quantum physics compare to classical physics or classical computation. The



Forecasted evolution of the network complexity in which QKD can be integrated and build on Quantum Repeater technologies.

implementations of these primitives are at an initial stage, but they should reach an industrial level within the next 5 years. Quantum communication is based on the distribution of entangled particles. The entanglement is then processed in different ways depending on the application. That is why the future cryptographic applications will experience the same distance limitation than quantum key distribution. Quantum repeaters are a general concept that will overcome the distance limitation of all future quantum communications because it allows the distribution of entanglement over arbitrary long distances.

Quantum repeaters are the primary target application in the QuReP project in order to have a clear objective for the development of frontier quantum photonic components. There is a multitude of ways to exploit all those components for other applications. Moreover, we have also worked to find and master the integration of multiple quantum photonics components in in increasingly complex quantum systems. The capacity of controlling basic quantum components like single photon detectors, pseudo single photon sources allowed the commercialisation of quantum key distribution systems. The ability to master this new generation of quantum components will lead to the commercialisation of new techniques in the near future.

Some useful references for future exploitation

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The Industrial partner ID Quantique will be actively pursuing several of these technologies in the near future. For more information visit: ID Quantique.

Dissemination

Throughout the QuReP project, the partners have presented their work at over 80 conferences, and made over 20 exhibitions or presentations to industry every year. The consortium has published over 40 scientific publications in high impact journals, all of which are available, open access, on the project web site. We have also made a significant effort in training, in conjunction with yearly Winter Schools organised by the industrial partner IDQ. On the QuReP website one can also find:

- A short introductory (YouTube) film on quantum communication and quantum repeaters:- The Qubit Lab: Quantum Repeaters
- A short introductory book on quantum communication and quantum repeaters.
- State of the Art and Discussion documents
- Quantum communication FAQ
- The project website can be found at: http://quantumrepeaters.eu

We plan for the web site to remain available as an information resource for quantum repeater technologies as the work continues towards building the quantum Internet.

QuReP in Geneva 2013 for the final project revue.
(L-to-R) Fabio Sciarrino (Reviewer), Corin Gawath (Reviewer), Christoph Clausen (Geneva), Bart Van Caenegem (EC), Grégoire Ribordy (IDQ), Harald Herrmann (Paderborn), Matthieu Legré (IDQ), Nicolas Gisin (Geneva), Philippe Goldner (CNRS-LCMPC Paris), Alban Ferrier (UPMC Paris), Félix Bussières (Geneva), Mikael Afzerlius (Geneva), Jean-Louis Le Gouët (CNRS-LAC Paris), Rob Thew (Geneva), Stefan Kröll (Lund).

For more info on Quantum Repeaters and Quantum Communication:

QuantumRepeaters.eu

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QuReP
Quantum Repeaters for Long Distance Fibre-Based Quantum Communication

Section A (public)

Scientific Publications

2013

1. High-bandwidth quantum memory protocol for storing single photons in rare-earth doped crystals, V. Caprara Vivoli, N. Sangouard, M. Afzelius, N. Gisin, arxiv:1305.1863 (2013)
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5. Efficient Quantum Memory Using a Weakly Absorbing Sample, M. Sabooni, Q. Li, S. Kroll, and L. Rippe, Phys. Rev. Lett. 110, 133604 (2013)
6. Two-color narrowband photon pair source with high brightness based on clustering in a monolithic waveguide resonator, K-H. Luo, H. Herrmann, S. Krapick, R. Ricken, V. Quiring, H. Suche, W. Sohler, and C. Silberhorn, arxiv:1306.1756 (2013)
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15. Adiabatic passage with spin locking in Tm3+:YAG, M. F. Pascual-Winter, R. C. Tongning, R. Lauro, A. Louchet-Chauvet, T. Chanelière and J.-L. Le Gouët, Phys. Rev. B. 86 064301 (2012)
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24. Long-term performance of the swissquantum quantum key distribution network in a field environment, D Stucki, M Legré, F Buntschu, B Clausen, N Felber, N Gisin, L Henzen, P Junod, G Litzistorf, P Monbaron, L Monat, J-B Page, D Perroud, G Ribordy, A Rochas, S Robyr, J Tavares, R Thew, P Trinkler, S Ventura, R Voirol, N Walenta, H Zbinden, New J. Phys. 13, 123001 (2011)
25. Efficient solid state memories for quantum cryptography, F. Beaudoux, R. Marino, J. Lejay, A. Ferrier, B.Tumino, O. Guillot-Noel, P. Goldner, J. Luminescence 131 469 (2011)
26. Hyperfine characterization and coherence lifetime extension in $Pr^{3+}:La_2(WO_4)_3$, M. Lovric, P. Glasenapp, D. Suter, B. Tumino, A. Ferrier, P. Goldner, M. Sabooni, L. Rippe, & S. Kröll, Phys. Rev. B, 84, 104417 (2011)
27. Revival of Silenced Echo and Quantum Memory for Light, V. Damon, M. Bonarota, A. Louchet-Chauvet, T. Chanelière, J.-L. Le Gouët, New J. Phys., 13 093031 (2011)
28. Absorption of a pulse by an optically dense medium: An argument for field quantization, P. R. Berman, J.-L. Le Gouët, Am. J. Phys., 79 5 (2011)
29. Phase-matched emission from a medium following one-photon pulse excitation: energy considerations, P. R. Berman and J.-L. Le Gouët, Phys. Rev. A. 83 035804(2011)
30. Quantum storage of photonic entanglement in a crystal, C. Clausen, *et al.*, Nature 469, 508 (2011)
31. Adiabatic refocusing of nuclear spins in Tm^{3+}:YAG, R. Lauro, T. Chanelière and J.- L. Le Gouët, Phys. Rev. B, 83 035124 (2011)
32. Emission of photon echoes in a strongly scattering medium, F. Beaudoux, B. Tumino, A. Ferrier, R. Marino, J. Lejay, O. Guillot-Noël, T. Chanelière, J.-L. Le Gouët and Ph. Goldner, Opt. Exp., 19 15236 (2011)
33. Highly multimode memory in a crystal, M. Bonarota, J.-L. Le Gouët, T. Chanelière, New J. Phys. 13 013013 (2011)

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34. Efficient optical pumping of Zeeman spin levels in Nd^{3+}: YVO_4, Mikael Afzelius, Matthias U. Staudt, Hugues de Riedmattena, Nicolas Gisin, Olivier Guillot-Noël, Philippe Goldner, Robert Marino, Pierre Porcher, Enrico Cavalli, Marco Bettinelli, J. Luminescence, 130 1566 (2010)
35. Light storage protocols in Tm:YAG, T. Chanelière, M. Bonarota, M. Afzelius & J.L. Le Gouët, J. Luminescence, 130 1572 (2010)
36. Efficient optical pumping of Zeeman spin levels in Nd^{3+}: YVO_4, Mikael Afzelius, Matthias U. Staudt, Hugues de Riedmattena, Nicolas Gisin, Olivier Guillot-Noël, Philippe Goldner, Robert Marino, Pierre Porcher, Enrico Cavalli, Marco Bettinelli, J. Luminescence, 130 1566 (2010)
37. Efficient light storage in a crystal using an Atomic Frequency Comb, T. Chanelière, J. Ruggiero, M. Bonarota, M. Afzelius, and J.-L. Le Gouët, New J. Phys.12 023025(2010)
38. Spin-wave storage using chirped control fields in atomic frequency comb-based quantum memory, J. Minar, N. Sangouard, M. Afzelius, H. De Riedmatten, & N. Gisin, Phys. Rev. A, 82, 042309 (2010)
39. Coherent response to optical excitation in a strongly absorbing rare-earth ion doped crystal, J. Ruggiero, T. Chanelière, J.-L. Le Gouët, J. Opt. Soc. Am. B 27 32 (2010)
40. Impossibility of faithfully storing single photons with the three-pulse photon echo, N. Sangouard, C. Simon, J. Minar, M. Afzelius, T. Chanelière, N. Gisin, J-L. Le Gouët, H. De Riedmatten, & W. Tittel, Phys. Rev. A, 81, 062333 (2010)
41. Impedance-matched cavity quantum memory, Mikael Afzelius and Christoph Simon, Phys. Rev. A, 82, 022310 (2010)
42. Efficiency optimization for Atomic Frequency Comb storage, M. Bonarota, J. Ruggiero, J.-L. Le Gouët, T. Chanelière, Phys. Rev. A, 81 033803 (2010)
43. Quantum communication technology, Nicolas Gisin & Rob Thew, Electronic Letters, 46 995 (2010)
44. Storage and recall of weak coherent optical pulses with an efficiency of 25%, M. Sabooni, F. Beaudoin, A. Walther, Lin Nan, A. Amari, M. Huang, S. Kröll, Phys. Rev. Lett. 105, 060501 (2010)

Presentations

No.	Title	Authors	Type	Event	Location	Date
135	Solid state quantum memories, teleportation and large entanglement	Nicolas Gisin	Invited	QIPC 2013	Florence, Italie	June – July 2013
134		Alban Ferrièr	Invited		Cherbourg France	June 2013
133	A highly efficient integrated two-color source for heralded single-photons	H. Herrmann, V. Quiring, B. Brecht, H. Suche C. Silberhorn	Talk	CLEO-Europe	Munich, Germany	May 2013
132	An efficient integrated two-color source for heralded single-photons	S. Krapick, H. Herrmann, V. Quiring, B. Brecht, H. Suche C. Silberhorn	Invited	DPG Spring Meeting	Regensburg Germany	March 2013
131	Engineering Quantum Photonic Systems	Robert Thew	Invited	University of Bern, Colloque	Bern, Switzerland	March 2013
130		Philippe Goldner	Invited	Seminar	Tsukuba Japan	February 2013
129		Philippe Goldner	Invited	Seminar	Okazaki Japan	February 2013
128	Spin coherence lifetime extension through dynamical decoupling : coping with the spin inhomogeneous broadening in Tm^{3+}:YAG	M. F. Pascual-Winter, R. C. Tongning, T. Chanelière, and J.-L. Le Gouët	Invited	Physics of Quantum Electronics	Snowbird, Utah, USA	January 2013
127	Quantum Repeater Architectures	Nicolas Gisin	Tutorial	IDQ Winter School	Les Diablerets, Switzerland	January 2013
126	Quantum Memories	Mikael Afzelius	Tutorial	IDQ Winter School	Les Diablerets,	January

					Switzerland	2013
125	Components for Quantum Repeaters	Robert Thew	Tutorial	IDQ Winter School	Les Diablerets, Switzerland	January 2013
124	QKD	Gregoire Ribordy	Tutorial	2012 IEEE Conference on Homeland Security Technologies	Waltham, MA, USA	November 2012
123	Quantum Memories for Long Distance Quantum Communication	Nicolas Gisin	Invited	OSA's 96th Annual Meeting, Frontiers in Optics 2012, Laser Science XXVIII, APS/DLS 28th annual meeting	Rochester, USA	October 2012
122	Quantum Memories for quantum networks and device-independent QKD	Nicolas Gisin	Invited	Quantum Africa 2	Kwazulu-Natal South Africa	September 2012
121		A. Arcangeli	Talk	International Conference on Optical Materials	Belgrade Serbia	September 2012
120	Revival of silenced echo for optical quantum memory in rare-earth crystals	M. Bonarota, V. Damon, T. Chanelière, J.-L. Le Gouët, A. Louchet-Chauvet, M. F. Pascual Winter	Invited	11th International Conference on Hole Burning, Single Molecule and Related Spectroscopies: Science and Applications	Tübingen Germany	August, 2012
119	Rare earth doped crystal quantum memory	Imam Usmani	Talk	11th International Conference on Hole Burning, Single Molecule and Related Spectroscopies: Science and Applications	Tübingen Germany	August, 2012
118		Philippe Goldner	Talk	11th International Conference on Hole Burning, Single Molecule and Related Spectroscopies: Science and	Tübingen Germany	August, 2012

				Applications		
117	A long lived AFC quantum memory in a rare earth doped crystal	Nuala Timoney	Talk	11th Intl. Conference on Quantum Communication, Measurement and Computing	Vienna, Austria	July - August 2012
116	Heralded entanglement between two crystals	By Imam Usmani	Poster	11th Intl. Conference on Quantum Communication, Measurement and Computing	Vienna, Austria	July - August 2012
115	Quantum Communication, repeaters and macro-entanglement	Nicolas Gisin	Invited	11th Intl. Conference on Quantum Communication, Measurement and Computing	Vienna, Austria	July - August 2012
114	Non-locality	Nicolas Gisin	Tutorial	5th International Summer School of the SFB/TRR21 "Control of Quantum Correlations in Tailored Matter	Heinrich-Fabri-Haus, Blaubeuren, Germany,	July – August 2012
113	Quantum Communication	Nicolas Gisin	Invited	5th International Summer School of the SFB/TRR21 "Control of Quantum Correlations in Tailored Matter	Heinrich-Fabri-Haus, Blaubeuren, Germany,	July – August 2012
112		Philippe Goldner	Invited	International conference on laser physics	Calgary Canada	July 2012
111	Quantum memories for quantum networks and device-independent QKD	Nicolas Gisin	Invited	Central European Workshop on Quantum Optics	Sinaia, Romania	July 2012
110	Atomic Frequency Combs	Mikael Afzelius	Invited	Coherent Information Processing in Rare-Earth Ion Doped Solids	Mainz Germany	June 2012
109	Coherent information processing in Rare-Earth Ion Doped Solids	Pierre Jobez	Talk	Coherent Information Processing in Rare-Earth Ion Doped Solids	Mainz Germany	June 2012

108	Heralded entanglement between two crystals	Imam Usmani	Talk	Coherent Information Processing in Rare-Earth Ion Doped Solids	Mainz Germany	June 2012
107	Quantum entanglement and real world communications	Nicolas Gisin	Invited	Photonics without Frontiers	Lausanne, Switzerland	June 2012
106	Quantum Storage of Heralded Polarization Qubits in Birefringent and Anisotropically Absorbing Materials	Christoph Clausen	Poster	Photonics without Frontiers	Lausanne, Switzerland	June 2012
105		Philippe Goldner	Invited	Workshop on advanced processes in optical sensing and photonics applications	Miraflores Spain	May 2012
104	What are single photons good for?”	Hugo Zbinden	Invited	DSS	Baltimore, USA,	April 2012
103	Solid state quantum memory for quantum repeaters	Mikael Afzelius		European Cluster Review Meeting	Bingen, Germany	April 2012
102	Revival of silenced echo for optical quantum memories: efficiency and noise level	M. Bonarota, V. Damon, T. Chanelière, J.-L. Le Gouët, and M. F. Pascual-Winter	Talk	Quantum Information and Measurement,	Berlin, Germany	March 2012
101	Heralded quantum entanglement between two crystals	Christoph Clausen	Talk	Quantum Information and Measurement,	Berlin, Germany	March 2012
100	Entanglement Swapping & Heralded Photon Amplification for Device Independent QKD”	Rob Thew	Invited	Quantum Information and Measurement,	Berlin, Germany	March 2012

	Quantum Information and Measurement					
99	Quantum communication: real-world applications and academic research	Nicolas Gisin	Invited	Symposium From Atoms to Photonic Circuits: Integrating Quantum Optics and Optical Communication,	Stuttgart, Germany	March 2012,
98	Heralded quantum entanglement between two crystals	Christoph Clausen	Talk	Symposium From Atoms to Photonic Circuits: Integrating Quantum Optics and Optical Communication,	Stuttgart, Germany	March 2012,
97		Philippe Goldner	Invited	International Conference on luminescence and applications	Hyderabad India	February 2012
96	Quantum nonlocality based on finite-speed influences leads to signaling	Nicolas Gisin	Invited	Workshop I –"Quantum Mechanics: from Foundations to Quantum Information Science	Bielefeld Germany	February 2012
95	La Téléportation Quantique (grand public)	Nicolas Gisin	Invited Pulic	HES de Sion	Sion, Switzerland	February 2012
94	Quantum non-locality: how does nature do it?	Nicolas Gisin	Invited	Colloque	Helsinki, Sweden	January 2012
93						
92	High speed single photon detectors for high speed QKD	Nino Walenta	Poster	2nd General Meeting of the NCCR QSIT	Arosa, Switzerland	January 2012
91	Doubly-resonant narrowband photon pair source based on parametric down-conversion in	K.H. Luo, H.Herrmann, W. Sohler, C. Silberhorn	Invited	DPG Spring Meeting	Stuttgart, Germany	March 2012

	Ti:PPLN waveguide cavity					
90	Efficiency and capacity of an Atomic Frequency Comb based quantum memory	M. Bonarota, T. Chanelière, J. Ruggiero, J.-L. Le Gouët	Invited	PQE	Snowbird, USA	January 2011
89	Quantum storage in atomic samples	T. Chanelière	Invited	Qupa	Paris	February 2011
88	Spin refocusing through double Rapid Adiabatic Passage (RAP)	M F. Pascual-Winter, R.-C. Tongning, A. Louchet-Chauvet, T. Chanelière, J.-L. Le Gouët	Invited	Quantum Information Processing with Rare-Earth doped Solids 2011	Barcelona Spain	May, 2011
87	Revival of Silenced Echo for quantum memory	T. Chanelière	Invited	Quantum Information Processing with Rare-Earth doped Solids 2011	Barcelona Spain	May, 2011
86	Rephasage de coherences atomiques par passages adiabatiques rapides pour la mémorisation quantique	M.F. Pascual-Winter, R.-C. Tongning, M. Bonarota, V. Damon, T. Chanelière, A. Louchet-Chauvet et J.-L. Le Gouët	Invited	Optique Marseille 2011 COLOQ'12	Marseille France	July, 2011
85	Revival of silenced echo and quantum memory for light	V. Damon, M. Bonarota, A. Louchet-Chauvet, T. Chanelière, and J.-L. Le Gouët	Invited	LPHYS'11	Sarajevo, Bosnia-Herzegovina	July 2011
84	MAFC photon echo quantum memory	S. A. Moiseev & J.-L. Le Gouët	Invited	LPHYS'11	Sarajevo, Bosnia-Herzegovina	July 2011
83	Quantum memory for light	M. Bonarota,	Invited	OCS 2011	Marseille	September

	in rare earth ion doped crystals	V. Damon, R.C. Tongning, M. F. Pascual Winter, A. Louchet-Chauvet, T.Chanelière, J.-L. Le Gouët			France	2011
82	Quantum Communication: from quantum engineering to future quantum networks	N. Gisin	Invited	Quantum Optical Information Technology	Barcelona, Spain	October, 2011
81	Quantum Communication	N. Gisin	Invited	ECOC 2011	Geneva, Switzerland	September, 2011
80	Quantum Memories for Quantum Networks and Device-Independent QKD	N. Gisin	Invited	QCRYPT 2011	Zurich, Switzerland	September, 2011
79	Quantum Communication	N. Gisin	Invited	Quantum Information Processing and Communication – QIPC 2011	Zurich, Switzerland	September, 2011
78	Atomic frequency comb memory with spin wave storage in 153 Eu3+ :Y2 Si05	N. Timoney	Talk	Quantum Information Processing and Communication – QIPC 2011	Zurich, Switzerland	September, 2011
77	A solid-state quantum memory for entangled photons	F. Bussières	Talk	Quantum Information Processing and Communication – QIPC 2011	Zurich, Switzerland	September, 2011
76	History of Quantum Communication: Enabling Quantum Communication	R. Thew	Invited	IEEE Photonics Society Summer Topical Meeting on Entanglement Distribution in Quantum Communication and Beyond	Montreal, Canada,	July, 2011

75	Quantum Memory in Neodymium and Europium doped Crystals	N. Timoney	Invited	Quantum Information Processing in Rare-earth doped Solids 2011	Barcelona, Spain	May, 2011
74	Quantum Memory in Neodymium and Europium doped Crystals	M.Afzelius	Invited	Quantum Information Processing in Rare-earth doped Solids 2011	Barcelona, Spain	May, 2011
73	Quantum networks with atomic ensembles and photon	N. Sangouard	Invited	Colloqium - ICFO	Barcelona, Spain	May, 2011
72	Solid-state storage device for entangled photons	M.Afzelius	Invited	Quantum Science and Technologies	Rovereto, Italy	May, 2011
71	Futures of quantum communication : quantum memories for quantum networks and device-independent QKD	N. Gisin	Invited	International Conference on Quantum Technologies in the 21st century	Munich, Germany	May, 2011
70	Quantum storage of photonic entanglement in a crystal	F. Bussières	Invited	QSIT lunch seminar	Zurich, Switzerland	May, 2011
69	Quantum storage of photonic entanglement in a crystal	F. Bussières	Talk	Great lakes symposium on very large scale integration 2011	Lausanne, Switzerland	May, 2011
68	The continuous dialog between applied and fundamental physics	N. Gisin	Invited	Quantum Repeater Workshop	Hannover, Germany	March 2011
67	A solid-state photon pair source with controllable delay based on shaped inhomogeneous broadening	N. Sangouard	Invited	Colloque LMU, Munich	Munich, Germany	March 2011
66	Enabling Technologies for Quantum Communication	R. Thew	Invited	Gdr - Information Quantique, Fondements & Applications	Nice, France	March 2011

				Colloquium		
65	Quantum storage of photonic entanglement in a crystal	F. Bussières	Talk	Photonics West 2011	San Francisco, USA	January 2011
64	Towards quantum networks	N. Gisin	Training	2011, Winter School on Quantum Key Distribution	Les Diablerets Switzerland	January 2011
63	Quantum repeaters for communication	N. Gisin	Invited	NCCR - QSIT	Arosa, Switzerland	January 2011
62	Towards an AFC memory for light 3+ with Spin-Wave storage in Eu :Y2Si05	N. Timoney	Talk	NCCR - QSIT	Arosa, Switzerland	January 2011
61	Fascinating entanglement	N. Gisin	Invited	Colloque de l'Université de Constance	Constance, Germany	January 2011
60	Storage of Photonic Entanglement in a Crystal	M. Afzelius	Invited	Swiss-Swedish Meeting on Quantum Materials and Devices	Les Diablerets, Switzerland	January 2011
59	Hyperfine coherence lifetime increase in a rare earth doped crystal using static magnetic field decoupling	B. Tumino, M. Lovrić, P. Glasenapp, D. Suter, M. Sabooni, L. Rippe, S. Kröll, A. Ferrier, P. Goldner	Poster	International Workshop on Quantum Information and Applications	Paris, France	September 2011
58	Long coherence lifetimes for Zeeman and hyperfine transitions in Nd3+:y2sio5 measured by pulsed EPR	R. Marino, R. E. George, J. J. L. Morton, A. Ferrier, P. Goldner, H. Vezin	Poster	International Workshop on Quantum Information and Applications	Paris, France	September 2011
57	Hyperfine coherence lifetime increase in a rare earth doped crystal using static magnetic field decoupling	B. Tumino, M. Lovrić, P. Glasenapp, D. Suter, M. Sabooni, L. Rippe, S. Kröll,A. Ferrier, P.	Invited	Laser Physics	Sarajevo, Bosnia	July 2011

		Goldner				
56	Materials for Solid State Quantum Information Processing	Ph. Goldner and A. Ferrier	Invited key lecture	International Workshop on Advanced Spectroscopy and Optical Materials	Gdansk, Poland	July 2011
55	Long coherence lifetimes for Zeeman and hyperfine transitions in Nd^{3+}:y_2sio_5 measured by pulsed EPR	Robert Marino, A. Ferrier, O. Guillot-Noël, P. Goldner, H. Vezin	Poster	Euromar	Frankfurt, Germany	August 2011
54	Quantum Cryptography applications	IDQ	Talk	Institute for Quantum Computing	Waterloo, Canada	June 2011
53	Quantum Cryptography	IDQ	Talk	Information security MBA	Geneva, Switzerland	June 2011
52	Photon Echoes in Strongly Scattering Media	Ph. Goldner , J.-L. Le Gouët, T. Chanelière, A. Ferrier	Talk	International Conference on Luminescence 2011	Ann Arbor	June 2011
51	Hyperfine Coherence Lifetime Increase in Pr:La2(WO4)3 using static magnetic field decoupling	A. Ferrier, M. Lovric P. Glasenapp, D. Suter, M. Sabooni, L. Rippe, S. Kroll, B. Tumino, P. Goldner	Talk	International Conference on Luminescence 2011	Ann Arbor	June 2011
50	High Resolution and Coherent Spectroscopy of Eu doped crystals and ceramics	A. Ferrier, B. Tumino, J. Lejay, P. Goldner	Talk	Quantum Information Processing in Rare Earth Doped Solids	Barcelona	April 2011
49	Coherence lifetimes of zeeman and hyperfine transitions in Nd:YSO measured by ESR spectroscopy	R. Marino, O. Guillot-Noël, J.J.L. Morton, R. George, A. Ferrier, P. Goldner, H. Vezin	Talk	Quantum Information Processing in Rare Earth Doped Solids	Barcelona	April 2011

48	Quantum Cryptography	? IDQ ?	Talk	DC 4420 Defcon	London	March 2011
47	Rare Earth Doped Materials for Quantum Information Processing	Ph. Goldner, A. Ferrier and J. Lejay	Invited	Phosphor Global Summit 2011	San Antonio	March 2011
46	Photon echoes in scattering media	Ph. Goldner , J.-L. Le Gouët, T. Chanelière, A. Ferrier	Invited	SPIE Photonics West	San Francisco	January 2011
45	Rare earth doped crystals for quantum memories and slow light	A Amari, F Beaudoin, S Kröll, H Maomao, Lin Nan, L Rippe, M Sabooni & A Walther	Poster	International Conference on Quantum Information and Computation (ICQIC)	Stockholm	October 2010
44	Quantum communication	N Gisin	Invited	Colloquia,	Vienna, Austria	Dec 2010
43	10 Years of Quantum Information Activities	G. Ribordy	Invited	European Workshop “From Quantum Foundations to Quantum Technologies - Challenges for Europe”	Vienna, Austria	Dec 2010
42	Commercial applications of QKD	G. Ribordy	Invited	Updating Quantum Cryptography and Communication (UQCC 2010)	Tokyo, Japan	Oct 2010
41	Rare earth doped crystals for quantum memories and slow light	A Amari, F Beaudoin, S Kröll, H Maomao, Lin Nan, L Rippe, M Sabooni & A Walther	Poster	International Conference on Quantum Information and Computation (ICQIC)	Stockholm	Oct 2010
40	Control at the quantum level	S. Kröll	Invited	Albanova and Nordita Colloquium, organized jointly by the physics departments of KTH, Stockholm, University,	Stockholm	Oct 2010

				and Nordita theoretical physics institute,		
39	Qurep: Quantum Repeaters for Long Distance Fibre-Based Quantum Communication	R.T.Thew + qurep	Invited	Photonics (area 'communication networks') Concertation meeting	Brussels	Oct 2010
38	Integrated quantum memory for sub-nanosecond non-classical light	E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, D. Oblak, F. Bussières, W. Tittel, M. George, R. Ricken and W. Sohler	Invited	Updating Quantum Cryptography and Communication (UQCC 2010)	Toyko, Japan	Oct 201
37	Quantum communication	N. Gisin	Invited	Updating Quantum Cryptography and Communication (UQCC 2010)	Toyko, Japan	Oct 2010
36	Quantum processing in rare earth doped crystals: an overview and recent results	L Rippe	Invited	Solid state quantum information technology	Copenhagen	Sept 2010
35	Coherent collective emission in random media	F. Beaudoux, J.-L. Le Gouët, T. Chanelière, A. Ferrier, R. Marino, B. Tumino, O. Guillot-Noël and P. Goldner	Invited	Excited states of transition elements	Wroclaw, Poland	Sep 2010
34	Quantum storage of photonic entanglement in a crystal	H de Riedmatten	Invited	EMALI 2010 conference	Barcelona, Spain	Sept 2010
33	Quantum Memories based on Rare Earth Ion Doped Solids	B. Lauritzen	Invited	Colloquium at University of Otago	Dunedin, New Zealand	Aug 2010

32	Rare earth doped crystals for quantum memories and slow light	A Amari, F Beaudoin, S Kröll, H Maomao, Lin Nan, L Rippe, M Sabooni, & A Walther,	Invited	International conference on coherence and Nonlinear Optics (ICONO)	Kazan	Aug 2010
31	Photon echo measurement in scattering media	F. Beaudoux, P. Goldner, J.-L. Le Gouët, T. Chanelière, A. Ferrier, R. Marino, B. Tumino and O. Guillot-Noël	Invited	19th International Laser Physics Workshop	Iguacu, Brazil	July 2010
30	Integrated quantum memory for quantum communication	E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, F. Bussières, W. Tittel, M. George, R. Ricken and W. Sohler	Invited	19th International Laser Physics Workshop 2010	Iguacu, Brazi	July 2010
29	Atomic Frequency Comb Memory for Light with Spin Wave Storage	B. Lauritzen	Invited	QCMC 2010	Brisbane, Australia	July 2010
28	QM experiments in Er3+:y2sio5 and Eu3+:y2sio	B. Lauritzen	Invited	Colloquium at the Australian National University	Canberra, Australia	July 2010
27	Quantum memories with solid state atomic ensembles	H de Riedmatten	Invited	Colloquium	Nice, France	June 2010
26	Solid state quantum memory for photons at telecommunication wavelengths	B. Lauritzen	Invited	E-MRS 2010 Spring Meeting	Strasbourg, France	June, 2010
25	Today's and tomorrow's challenges for quantum communication	N. Gisin	Invited Plenary	International Scenario Workshop – Use Case for QKD Application	Vienna, Austria	June 2010

24	Efficient Solid State Memories for Quantum Cryptography	F. Beaudoux, R. Marino, J. Lejay, A. Ferrier, O. Guillot-Noël and Ph. Goldner	Invited Talk	Dynamical Processes in Excited States of Solids	Argonne, USA	June 2010
23	Rare earth doped materials for quantum information hardware	S Kröll, A Amari, F Beaudoin, H Maomao, Lin Nan, L Rippe, M Sabooni, A Walther, Ying Yan, M Afzelius, I Usmani, B Lauritzen, C Simon, N Sangouard, J Minár, H de Riedmatten, N Gisin & A Kalachev	Invited Talk	E-MRS 2010	Strasbourg, France	June 2010
22	Quantum light storage in rare-earth doped crystals: recent progress toward efficient and large-capacity single photon storage	T. Chanelière	Invited Talk	DPC2010	Argonne, Illinois, USA	June 2010
21	Development of quantum information hardware based on rare earth ion doped crystals	A Amari, F Beaudoin, M Huang, J Karlsson, S Kometa, Lin Nan, L Rippe, M Sabooni, A Walther, Y Yan, S Kröll	Talk	International Symposium on Optical Manipulation of Quantum Information in Solids	Paris, France	May 2010
20	Towards an AFC Memory for Light with Spin-Wave Storage in Eu3+:y2sio5	B. Lauritzen	Poster	ISOMQIS	Paris, France	May 2010
19	Photon echo measurement in scattering media	P. Goldner, J.-L. Le Gouët, T. Chanelière, A. Ferrier, R. Marino, B.	Poster	International Symposium on Optical Manipulation of Quantum Information in Solids	Paris, France	May 2010

		Tumino and O. Guillot-Noël				
18	Raman Heterodyne Characterization of the Pr^{3+}:La$_2$(WO$_4$)$_3$ Hyperfine Interaction	Marko Lovrić, Philipp Glasenapp, Dieter Suter, B. Tumino, F. Beaudoux, A. Ferrier, J. Lejay, O. Guillot-Noël and Philippe Goldner	Poster	International Symposium on Optical Manipulation of Quantum Information in Solids	Paris, France	May 2010
17	Long coherence lifetimes for Zeeman transitions in Nd^{3+}:y$_2$sio$_5$ measured by pulsed EPR	Robert Marino, F. Beaudoux , A. Ferrier, B. Tumino, O. Guillot-Noël, P. Goldner, H. Vezin,	Poster	International Symposium on Optical Manipulation of Quantum Information in Solids	Paris, France	May 2010
16	Towards quantum repeaters using photon echo based quantum memories	H. De Riedmatten	Talk	International Symposium on Optical Manipulation of Quantum Information in Solids	Paris, France	May 2010
15	Solid state quantum memories for quantum repeaters	H. De Riedmatten	Talk	CLEO/QELS 2010	California, USA	May 2010
14	Quantum memories based on solid state atomic ensembles	H. De Riedmatten	Talk	California Institute of Technology	California, USA	May 2010
13	Integrated quantum memory for quantum communication	E. Saglamyurek, N. Sinclair, C. La Mela, W. Tittel, M. George, R. Ricken and W. Sohler	Invited	International Symposium on Optical Manipulation of Quantum Information in Solids	Paris, france	May 2010
12	Memoire quantique intégrée	W. Tittel, C. La Mela, M. George, R. Ricken, E. Saglamyurek, N. Sinclair and W. Sohler	Invited	78 congrès de l'Association francophone pour la savoir	Montréal, Québec	May 2010

11	Novel Source of Polarization Entangled Photon Pairs Using a PPLN Waveguide with Interlaced Domains	A. Thomas, H. Herrmann, W. Sohler	Talk	ECIO 2010	Cambridge, UK	April 2010
10	Locally poled ridge waveguide on X-cut linbo$_3$ for nonlinear wavelength conversion	L. Gui, H. Hu, R. Nouroozi, W. Sohler	Talk	ECIO 2010	Cambridge, UK	April 2010
9	Tm:Ti:linbo3 waveguide for quantum memory applications	M. George, R. Ricken, W. Sohler, and E. Saglamyurek, N. Sinclair, C. La Mela, and W. Tittel	Post deadline	ECIO 2010	Cambridge, UK	April 2010
8	Integrated quantum memory for quantum communication	E. Saglamyurek, N. Sinclair, C. La Mela, W. Tittel, M. George, R. Ricken and W. Sohler		OFC/NFOEC2010	San Diego, California	Mar 2010
7	Integrated quantum memory for quantum communication	E. Saglamyurek, N. Sinclair, C. La Mela, W. Tittel, M. George, R. Ricken and W. Sohler	Invited	Workshop on Crytography from Storage Imperfections	Pasadena, California	Mar 2010
6	Towards Integrated Quantum Optics in Lithium Niobate	W. Sohler, H. Herrmann, A. Thomas, M. George, H. Hu, H. Suche, R. Ricken, and V. Quiring	Talk	Quantum Communication based on Integrated Optics	Physikzentrum Bad Honnef, Germany	Mar 2010
5	Solid state quantum memories for quantum repeaters	H. De Riedmatten	Invited Talk	Annual meeting of the spanish Consolider Ingenio 2010 project: QOIT, Quantum Optics and Information	Valencia, Spain	Feb 2010

				Technologies		
4	Coherent Collective Emission in a Random Medium	F. Beaudoux, J.-L. Le Gouët, T. Chanelière, A. Ferrier, R. Marino, O. Guillot-Noël and P. Goldner	Invited Talk	40th Winter Colloquium on The Physics of Quantum Electronics	Utah, USA	Jan 2010
3	Few photons storage in thulium doped crystals	T. Chanelière, M. Bonarota, R. Lauro, J. Rugierro, J.-L. Le Gouët	Invited Talk	40th Winter Colloquium on The Physics of Quantum Electronics	Utah, USA	Jan 2010
2	Coherent interactions in rare earth ion doped crystals for quantum memory and quantum computer development	S Kröll	Invited Plenary	40th Winter Colloquium on The Physics of Quantum Electronics	Utah, USA	Jan 2010
1	Multi-mode solid-state storage device for photons	M. Afzelius	Talk	QSIT Meeting,	Arosa, Switzerland	Jan 2010

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

No.	Type of activities[2]	Main leader	Title	Date/ Period	Place	Type of audience[3]	Size of audience	Countries addressed
117	Conference	CNRS- LCMCP P. Goldner	Workshop on Quantum Information Processing in Rare earth doped crystals	June 2012	Mainz, Germany	Scientific Community	50	EU
116	Conference	CNRS- LCMCP P. Goldner	International conference on Hole burning and single molecule spectroscopy	August 2012	Tuebingen, Germany	Scientific Community	150	International
115	Conference (invited)	CNRS- LCMCP P. Goldner	International Conference on luminescence and applications	February 2012	Hyderabad (India)	Scientific Community	150	International
114	Conference	CNRS- LCMCP A. Arcangeli	International Conference on Optical Materials	September 2012	Belgrade (Serbia)	Scientific Community	150	International
113	Conference (invited)	CNRS- LCMCP P. Goldner	International conference on laser physics	July 2012	Calgary (Canada)	Scientific Community	300	International
112	Conference (invited)	CNRS- LCMCP P. Goldner	Workshop on advanced processes in optical sensing and photonics applications	May 2012	Miraflores (Spain)	Scientific Community	50	EU
111	Seminar	CNRS- LCMCP P. Goldner		February 2013	Okazaki (Japan)	Scientific Community	20	Japan
110	Seminar	CNRS- LCMCP P. Goldner		February 2013	Tsukuba (Japan)	Scientific Community	20	Japan
109	Conference	UPMC A. Ferrier		June 2013	Cherbourg (France)	Scientific Community/	50	France

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[2] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[3] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

						Industry		
108	Plenary Conference talk	ULUND Stefan Kröll	Central European Workshop on Quantum Optics	June 2013	Stockholm, Sweden	International Quantum Optics and Quantum Information Scientists	150	International
107	Contributed conference talk	ULUND Qian Li	Nordic Physics Conference	June 2013	Lund, Sweden	Solid state physicists	50	Mainly Nordic and Baltic countries
106	Invited seminar	ULUND Stefan Kröll	Dept of Physics Université Nice	February 2013	Nice	Physicists	30	France
105	Invited seminar	ULUND Stefan Kröll	Dept of Physics, Oxford University	November 2012	Oxford	Physicists	40	England
104	Public exhibition	ULUND Mahmood Sabooni	Day of Culture, Lund	September 2012	Lund, Sweden	Public citizens in Lund	100	Sweden
103	Contributed Conference talk	ULUND Lars Rippe	11th International Conference on Hole Burning, Single Molecule and Related Spectroscopies:Science and Applications (HBSM2012)	August 2012	Tübingen, Germany	International scientists on holeburning and single molecule spectroscopy	50	International
102	Invited conference talk	ULUND Stefan Kröll	LPHYS12	July 2012	Calgary, Canada	International scientists, Laser Physics Quantum optics etc.	150	International
101	Conference Talk	UPB K.H. Luo, H.Herrmann, W. Sohler, C. Silberhorn	DPG Spring Meeting	March 2012	Stuttgart, Germany	Scientific		European

99	Conference Poster	UPB S.Krapick, B. Brecht, V. Quiring, H. Herrmann, W. Sohler, C. Silberhorn	DPG Spring Meeting	March 2011	Dresden, Germany	Scientific		European
98	Conference Talk	UPB S. Krapick, H. Herrmann, V. Quiring, B. Brecht, H. Suche C. Silberhorn	DPG Spring Meeting	March 2013	DPG Spring Meeting	Scientific		European
97	Conference Talk	UPB S. Krapick, H. Herrmann, V. Quiring, B. Brecht, H. Suche C. Silberhorn	CLEO-Europe	May 2013	Munich, Germany	Scientific		International
96	Invited	CNRS-LAC M. F. Pascual-Winter, R. C. Tongning, T. Chanelière, and J.-L. Le Gouët	Physics of Quantum Electronics	January 2013	Snowbird USA	Scientific		International
95	Talk	CNRS-LAC M. Bonarota, V. Damon, T. Chanelière, J.-L. Le Gouët, A. Louchet-Chauvet, M. F. Pascual Winter	Hole Burning, Single Molecule and Related Spectroscopies: Science and Applications	August 2012	Tübingen Germany	Scientific		International
94	Talk	CNRS-LAC M. Bonarota, V. Damon, T. Chanelière, J.-L. Le Gouët, and M. F. Pascual-Winter	Quantum Information Measurement	March 2012	Berlin, Germany	Scientific		International
93	Workshop	IDQ	QKD: A Workshop For It Professionals	August 22-23 2012	Hosted by Battelle & IDQ in Columbus, Ohio, USA	Security and telecom Engineers	20	USA
92	Training course	IDQ	5th Winter School On Quantum Communications	January 21-24 2013	Les Diablerets, Switzerland	Security and telecom Engineers, and Researchers	22	International

91	Conference	IDQ	‘Industry Panel, QCRYPT 2012,	September 2012	Singapore	Researchers in quantum optics		International
90	Invited	CNRS-LAC M. Bonarota, T. Chanelière, J. Ruggiero, J.-L. Le Gouët	Physics of Quantum Electronics	January 2013	Snowbird USA	Scientific		International
89	Invited	CNRS-LAC T. Chanelière	Quantum information in Paris	February 2011	Paris, France			French
88	Invited	CNRS-LAC M F. Pascual-Winter, R.-C. Tongning, A. Louchet-Chauvet, T. Chanelière, J.-L. Le Gouët	Quantum Information Processing with Rare-Earth doped Solids	May, 2011	Barcelona Spain	Scientific		International
87	Invited	CNRS-LAC T. Chanelière	Quantum Information Processing with Rare-Earth doped Solids	May, 2011	Barcelona Spain	Scientific		International
86	Invited	CNRS-LAC M.F. Pascual-Winter, R.-C. Tongning, M. Bonarota, V. Damon, T. Chanelière, A. Louchet-Chauvet & J.-L. Le Gouët	Optique Marseille 2011 COLOQ’12	July, 2011	Optique Marseille 2011 COLOQ’12	R&D		French
85	Invited	CNRS-LAC V. Damon, M. Bonarota, A. Louchet-Chauvet, T. Chanelière, & J.-L. Le Gouët	LPHYS’11	July 2011	Sarajevo, Bosnia-Herzegovina	Scientific		International
84	Invited	CNRS-LAC S. A. Moiseev & J.-L. Le Gouët	LPHYS’11	July 2011	Sarajevo, Bosnia-Herzegovina	Scientific		International
83	Invited	CNRS-LAC M. Bonarota, V. Damon, R.C. Tongning, M. F. Pascual Winter, A. Louchet-Chauvet, T. Chanelière, J.-L. Le Gouët	Optical Complex Systems	September 2011	Marseille France	Scientific		European

82	Invited	UNIGE N. Gisin	Quantum Communication: from quantum engineering to future quantum networks	October, 2011	Quantum Optical Information Technology			Barcelona, Spain
81	Invited	UNIGE N. Gisin	Quantum Communication	September, 2011	ECOC 2011			Geneva, Switzerland
80	Invited	UNIGE N. Gisin	Quantum Memories for Quantum Networks and Device-Independent QKD	September, 2011	QCRYPT 2011			Zurich, Switzerland
79	Invited	UNIGE N. Gisin	Quantum Communication	September, 2011	Quantum Information Processing and Communication – QIPC 2011			Zurich, Switzerland
78	Talk	UNIGE N. Timoney	Atomic frequency comb memory with spin wave storage in 153 Eu3+ :Y2 Si05	September, 2011	Quantum Information Processing and Communication – QIPC 2011			Zurich, Switzerland
77	Talk	UNIGE F. Bussières	A solid-state quantum memory for entangled photons	September, 2011	Quantum Information Processing and Communication – QIPC 2011			Zurich, Switzerland
76	Invited	UNIGE R. Thew	History of Quantum Communication: Enabling Quantum Communication	July, 2011	IEEE Photonics Society Summer Topical Meeting on Entanglement Distribution in Quantum Communication and Beyond			Montreal, Canada,
75	Invited	UNIGE	Quantum Memory in	May,	Quantum			Barcelona,

		N. Timoney	Neodymium and Europium doped Crystals	2011	Information Processing in Rare-earth doped Solids 2011			Spain
74	Invited	UNIGE M.Afzelius	Quantum Memory in Neodymium and Europium doped Crystals	May, 2011	Quantum Information Processing in Rare-earth doped Solids 2011			Barcelona, Spain
73	Invited	UNIGE N. Sangouard	Quantum networks with atomic ensembles and photon	May, 2011	Colloqium - ICFO			Barcelona, Spain
72	Invited	UNIGE M. Afzelius	Solid-state storage device for entangled photons	May, 2011	Quantum Science and Technologies			Rovereto, Italy
71	Invited	UNIGE N. Gisin	Futures of quantum communication : quantum memories for quantum networks and device-independent QKD	May, 2011	International Conference on Quantum Technologies in the 21st century			Munich, Germany
70	Invited	UNIGE F. Bussières	Quantum storage of photonic entanglement in a crystal	May, 2011	QSIT lunch seminar			Zurich, Switzerland
69	Talk	UNIGE F. Bussières	Quantum storage of photonic entanglement in a crystal	May, 2011	Great lakes symposium on very large scale integration 2011			Lausanne, Switzerland
68	Invited	UNIGE N. Gisin	The continuous dialog between applied and fundamental physics	March 2011	Quantum Repeater Workshop			Hannover, Germany
67	Invited	UNIGE N. Sangouard	A solid-state photon pair source with controllable delay based on shaped inhomogeneous broadening	March 2011	Colloque LMU, Munich			Munich, Germany

66	Invited	UNIGE R. Thew	Enabling Technologies for Quantum Communication	March 2011	Gdr - Information Quantique, Fondements & Applications Colloquium			Nice, France
65	Talk	UNIGE F. Bussières	Quantum storage of photonic entanglement in a crystal	January 2011	Photonics West 2011			San Francisco, USA
64	Training	UNIGE N. Gisin	Towards quantum networks	January 2011	2011, Winter School on Quantum Key Distribution			Les Diablerets Switzerland
63	Invited	UNIGE N. Gisin	Quantum repeaters for communication	January 2011	NCCR - QSIT			Arosa, Switzerland
62	Talk	UNIGE N. Timoney	Towards an AFC memory for light 3+ with Spin-Wave storage in Eu :Y2Si05	January 2011	NCCR - QSIT			Arosa, Switzerland
61	Invited	UNIGE N. Gisin	Fascinating entanglement	January 2011	Colloque de l'Université de Constance			Constance, Germany
60	Invited	UNIGE M. Afzelius	Storage of Photonic Entanglement in a Crystal	January 2011	Swiss-Swedish Meeting on Quantum Materials and Devices			Les Diablerets, Switzerland
59	Poster	CNRS-LCMCP / ULUND / UPMC B. Tumino, M. Lovrić, P. Glasenapp, D. Suter, M. Sabooni, L. Rippe, S. Kröll, A. Ferrier, P. Goldner	Hyperfine coherence lifetime increase in a rare earth doped crystal using static magnetic field decoupling	September 2011	International Workshop on Quantum Information and Applications			Paris, France
58	Poster	CNRS-LCMCP / UPMC R. Marino, R. E. George, J. J.	Long coherence lifetimes for Zeeman and	September 2011	International Workshop on			Paris, France

		L. Morton, A. Ferrier, P. Goldner, H. Vezin	hyperfine transitions in Nd3+:y2sio5 measured by pulsed EPR		Quantum Information and Applications			
57	Invited	CNRS-LCMCP / ULUND / UPMC B. Tumino, M. Lovrić, P. Glasenapp, D. Suter, M. Sabooni, L. Rippe, S. Kröll, A. Ferrier, P. Goldner	Hyperfine coherence lifetime increase in a rare earth doped crystal using static magnetic field decoupling	July 2011	Laser Physics			Sarajevo, Bosnia
56	Invited key lecture	CNRS-LCMCP / UPMC Ph. Goldner and A. Ferrier	Materials for Solid State Quantum Information Processing	July 2011	International Workshop on Advanced Spectroscopy and Optical Materials			Gdansk, Poland
55	Poster	CNRS-LCMCP/CNRS-LAC/UPMC Robert Marino, A. Ferrier, O. Guillot-Noël, P. Goldner, H. Vezin	Long coherence lifetimes for Zeeman and hyperfine transitions in Nd^{3+}:y_2sio_5 measured by pulsed EPR	August 2011	Euromar			Frankfurt, Germany
54	Talk	IDQ	Quantum Cryptography applications	June 2011	Institute for Quantum Computing			Waterloo, Canada
53	Talk	IDQ	Quantum Cryptography	June 2011	Information security MBA			Geneva, Switzerland
52	Talk	CNRS-LCMCP/CNRS-LAC/UPMC Ph. Goldner , J.-L. Le Gouët, T. Chanelière, A. Ferrier	Photon Echoes in Strongly Scattering Media	June 2011	International Conference on Luminescence 2011			Ann Arbor
51	Talk	CNRS-LCMCP/CNRS-LAC/UPMC A. Ferrier, M. Lovric P. Glasenapp, D. Suter, M. Sabooni, L. Rippe, S. Kroll, B.	Hyperfine Coherence Lifetime Increase in Pr:La2(WO4)3 using static magnetic field decoupling	June 2011	International Conference on Luminescence 2011			Ann Arbor

		Tumino, P. Goldner						
50	Talk	CNRS-LCMCP / UPMC A. Ferrier, B. Tumino, J. Lejay, P. Goldner	High Resolution and Coherent Spectroscopy of Eu doped crystals and ceramics	April 2011	Quantum Information Processing in Rare Earth Doped Solids			Barcelona
49	Talk	CNRS-LCMCP R. Marino, O. Guillot-Noël, J.J.L. Morton, R. George, A. Ferrier, P. Goldner, H. Vezin	Coherence lifetimes of zeeman and hyperfine transitions in Nd:YSO measured by ESR spectroscopy	April 2011	Quantum Information Processing in Rare Earth Doped Solids			Barcelona
48	Talk	IDQ	Quantum Cryptography	March 2011	DC 4420 Defcon			London
47	Invited	CNRS-LCMCP / UPMC Ph. Goldner, A. Ferrier and J. Lejay	Rare Earth Doped Materials for Quantum Information Processing	March 2011	Phosphor Global Summit 2011			San Antonio
46	Invited	CNRS-LCMCP/CNRS-LAC/UPMC Ph. Goldner ,J.-L. Le Gouët, T. Chanelière, A. Ferrier	Photon echoes in scattering media	January 2011	SPIE Photonics West			San Francisco
45	Poster	ULUND A Amari, F Beaudoin, S Kröll, H Maomao, Lin Nan, L Rippe, M Sabooni & A Walther	Rare earth doped crystals for quantum memories and slow light	October 2010	International Conference on Quantum Information and Computation (ICQIC)			Stockholm
44	Invited	UNIGE N Gisin	Quantum communication	Dec 2010	Colloquia			Vienna, Austria
43	Invited	IDQ G. Ribordy	10 Years of Quantum Information Activities	Dec 2010	European Workshop “From Quantum Foundations to Quantum Technologies -			Vienna, Austria

					Challenges for Europe”			
42	Invited	IDQ G. Ribordy	Commercial applications of QKD	Oct 2010	Updating Quantum Cryptography and Communication (UQCC 2010)			Tokyo, Japan
41	Poster	ULUND A Amari, F Beaudoin, S Kröll, H Maomao, Lin Nan, L Rippe, M Sabooni & A Walther	Rare earth doped crystals for quantum memories and slow light	Oct 2010	International Conference on Quantum Information and Computation (ICQIC)			Stockholm
40	Invited	ULUND S. Kröll	Control at the quantum level	Oct 2010	Albanova and Nordita Colloquium, organized jointly by the physics departments of KTH, Stockholm, University, and Nordita theoretical physics institute,			Stockholm
39	Invited	UNGIE R.T.Thew + qurep	Qurep: Quantum Repeaters for Long Distance Fibre-Based Quantum Communication	Oct 2010	Photonics (area 'communication networks') Concertation meeting			Brussels
38	Invited	UPB E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, D. Oblak, F.	Integrated quantum memory for sub-nanosecond non-classical light	Oct 201	Updating Quantum Cryptography			Toyko, Japan

		Bussières, W. Tittel, M. George, R. Ricken and W. Sohler			and Communication (UQCC 2010)			
37	Invited	UNIGE N. Gisin	Quantum communication	Oct 2010	Updating Quantum Cryptography and Communication (UQCC 2010)			Toyko, Japan
36	Invited	ULUND L Rippe	Quantum processing in rare earth doped crystals: an overview and recent results	Sept 2010	Solid state quantum information technology			Copenhagen
35	Invited	CNRS-LCMCP/CNRS-LAC/UPMC F. Beaudoux, J.-L. Le Gouët, T. Chanelière, A. Ferrier, R. Marino, B. Tumino, O. Guillot-Noël & P. Goldner	Coherent collective emission in random media	Sep 2010	Excited states of transition elements			Wroclaw, Poland
34	Invited	UNIGE H de Riedmatten	Quantum storage of photonic entanglement in a crystal	Sept 2010	EMALI 2010 conference			Barcelona, Spain
33	Invited	UNIGE B. Lauritzen	Quantum Memories based on Rare Earth Ion Doped Solids	Aug 2010	Colloquium at University of Otago			Dunedin, New Zealand
32	Invited	ULUND A Amari, F Beaudoin, S Kröll, H Maomao, Lin Nan, L Rippe, M Sabooni, & A Walther,	Rare earth doped crystals for quantum memories and slow light	Aug 2010	International conference on coherence and Nonlinear Optics (ICONO)			Kazan
31	Invited	CNRS-LCMCP/CNRS-LAC/UPMC F. Beaudoux, P. Goldner, J.-L. Le Gouët, T. Chanelière, A. Ferrier, R. Marino, B. Tumino	Photon echo measurement in scattering media	July 2010	19th International Laser Physics Workshop			Iguacu, Brazil

		and O. Guillot-Noël						
30	Invited	UNIGE E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, F. Bussières, W. Tittel, M. George, R. Ricken & W. Sohler	Integrated quantum memory for quantum communication	July 2010	19th International Laser Physics Workshop 2010			Iguacu, Brazi
29	Invited	UNIGE B. Lauritzen	Atomic Frequency Comb Memory for Light with Spin Wave Storage	July 2010	QCMC 2010			Brisbane, Australia
28	Invited	UNIGE B. Lauritzen	QM experiments in Er3+:y2sio5 and Eu3+:y2sio	July 2010	Colloquium at the Australian National University			Canberra, Australia
27	Invited	UNIGE H de Riedmatten	Quantum memories with solid state atomic ensembles	June 2010	Colloquium			Nice, France
26	Invited	UNIGE B. Lauritzen	Solid state quantum memory for photons at telecommunication wavelengths	June, 2010	E-MRS 2010 Spring Meeting			Strasbourg, France
25	Invited Plenary	UNIGE N. Gisin	Today's and tomorrow's challenges for quantum communication	June 2010	International Scenario Workshop – Use Case for QKD Application			Vienna, Austria
24	Invited Talk	CNRS-LCMCP / UPMC F. Beaudoux, R. Marino, J. Lejay, A. Ferrier, O. Guillot-Noël & Ph. Goldner	Efficient Solid State Memories for Quantum Cryptography	June 2010	Dynamical Processes in Excited States of Solids			Argonne, USA
23	Invited Talk	ULUND / UNIGE S Kröll, A Amari, F Beaudoin, H Maomao, Lin Nan, L Rippe, M Sabooni, A Walther, Ying Yan, M Afzelius, I Usmani, B Lauritzen, C Simon, N Sangouard, J Minár, H de	Rare earth doped materials for quantum information hardware	June 2010	E-MRS 2010			Strasbourg, France

		Riedmatten, N Gisin & A Kalachev						
22	Invited Talk	CNRS-LAC T. Chanelière	Quantum light storage in rare-earth doped crystals: recent progress toward efficient and large-capacity single photon storage	June 2010	DPC2010			Argonne, Illinois, USA
21	Talk	ULUND A Amari, F Beaudoin, M Huang, J Karlsson, S Kometa, Lin Nan, L Rippe, M Sabooni, A Walther, Y Yan, S Kröll	Development of quantum information hardware based on rare earth ion doped crystals	May 2010	International Symposium on Optical Manipulation of Quantum Information in Solids			Paris, France
20	Poster	UNIGE B. Lauritzen	Towards an AFC Memory for Light with Spin-Wave Storage in Eu3+:y2sio5	May 2010	ISOMQIS			Paris, France
19	Poster	CNRS-LCMCP/CNRS-LAC/UPMC P. Goldner, J.-L. Le Gouët, T. Chanelière, A. Ferrier, R. Marino, B. Tumino and O. Guillot-Noël	Photon echo measurement in scattering media	May 2010	International Symposium on Optical Manipulation of Quantum Information in Solids			Paris, France
18	Poster	CNRS-LCMCP / UPMC Marko Lovrić, Philipp Glasenapp, Dieter Suter, B. Tumino, F. Beaudoux, A. Ferrier, J. Lejay, O. Guillot-Noël and Philippe Goldner	Raman Heterodyne Characterization of the Pr^{3+}:$La_2(WO_4)_3$ Hyperfine Interaction	May 2010	International Symposium on Optical Manipulation of Quantum Information in Solids			Paris, France
17	Poster	CNRS-LCMCP / UPMC Robert Marino, F. Beaudoux , A. Ferrier, B. Tumino, O.	Long coherence lifetimes for Zeeman transitions in Nd^{3+}:y_2sio_5 measured by pulsed	May 2010	International Symposium on Optical			Paris, France

		Guillot-Noël, P. Goldner, H. Vezin,	EPR		Manipulation of Quantum Information in Solids			
16	Talk	UNIGE H. De Riedmatten	Towards quantum repeaters using photon echo based quantum memories	May 2010	International Symposium on Optical Manipulation of Quantum Information in Solids			Paris, France
15	Talk	UNGE H. De Riedmatten	Solid state quantum memories for quantum repeaters	May 2010	CLEO/QELS 2010			California, USA
14	Talk	UNIGE H. De Riedmatten	Quantum memories based on solid state atomic ensembles	May 2010	California Institute of Technology			California, USA
13	Invited	UPB E. Saglamyurek, N. Sinclair, C. La Mela, W. Tittel, M. George, R. Ricken and W. Sohler	Integrated quantum memory for quantum communication	May 2010	International Symposium on Optical Manipulation of Quantum Information in Solids			Paris, france
12	Invited	UPB W. Tittel, C. La Mela, M. George, R. Ricken, E. Saglamyurek, N. Sinclair & W. Sohler	Memoire quantique intégrée	May 2010	78 congrès de l'Association francophone pour la savoir			Montréal, Québec
11	Talk	UPB A. Thomas, H. Herrmann, W. Sohler	Novel Source of Polarization Entangled Photon Pairs Using a PPLN Waveguide with Interlaced Domains	April 2010	ECIO 2010			Cambridge, UK
10	Talk	UPB L. Gui, H. Hu, R. Nouroozi, W.	Locally poled ridge waveguide on X-cut linbo$_3$ for nonlinear	April 2010	ECIO 2010			Cambridge, UK

		Sohler	wavelength conversion					
9	Post deadline	UPB M. George, R. Ricken, W. Sohler, and E. Saglamyurek, N. Sinclair, C. La Mela, and W. Tittel	Tm:Ti:linbo3 waveguide for quantum memory applications	April 2010	ECIO 2010			Cambridge, UK
8		UPB E. Saglamyurek, N. Sinclair, C. La Mela, W. Tittel, M. George, R. Ricken and W. Sohler	Integrated quantum memory for quantum communication	Mar 2010	OFC/NFOEC2010			San Diego, California
7	Invited	UPB E. Saglamyurek, N. Sinclair, C. La Mela, W. Tittel, M. George, R. Ricken and W. Sohler	Integrated quantum memory for quantum communication	Mar 2010	Workshop on Crytography from Storage Imperfections			Pasadena, California
6	Talk	UPB W. Sohler, H. Herrmann, A. Thomas, M. George, H. Hu, H. Suche, R. Ricken, and V. Quiring	Towards Integrated Quantum Optics in Lithium Niobate	Mar 2010	Quantum Communication based on Integrated Optics			Physikzentrum Bad Honnef, Germany
5	Invited Talk	UNIGE H. De Riedmatten	Solid state quantum memories for quantum repeaters	Feb 2010	Annual meeting of the spanish Consolider Ingenio 2010 project: QOIT, Quantum Optics and Information Technologies			Valencia, Spain
4	Invited Talk	CNRS-LCMCP/CNRS-LAC/UPMC F. Beaudoux, J.-L. Le Gouët, T. Chanelière, A. Ferrier, R. Marino, O. Guillot-Noël and P. Goldner	Coherent Collective Emission in a Random Medium	Jan 2010	40th Winter Colloquium on The Physics of Quantum Electronics			Utah, USA
3	Invited Talk	CNRS-LAC	Few photons storage in thulium	Jan 2010	40th Winter			Utah, USA

		T. Chanelière, M. Bonarota, R. Lauro, J. Rugierro, J.-L. Le Gouët	doped crystals		Colloquium on The Physics of Quantum Electronics			
2	Invited Plenary	ULUND S Kröll	Coherent interactions in rare earth ion doped crystals for quantum memory and quantum computer development	Jan 2010	40th Winter Colloquium on The Physics of Quantum Electronics			Utah, USA
1	Talk	UNIGE M. Afzelius	Multi-mode solid-state storage device for photons	Jan 2010	QSIT Meeting,			Arosa, Switzerland
27	Exhibition	IDQ	PHOTONICS WEST 2012	January 24-26 2012	San Francisco	Industries and researchers in optics	20’000	USA
26	Exhibition	IDQ	LASER WORLD OF PHOTONICS CHINA	March 20-22 2012	Shanghai New International Expo Centre	Industries and researchers in optics	36’000	CHINA
25	Exhibition	IDQ	SPIE PHOTONICS EUROPE	April 16-18 2012	Brussels	Industries and researchers in optics	2’000	Belgium
24	Exhibition	IDQ	CLEO 2012	May 8-10 2012	San Jose Convention Center	Industries and researchers in optics		USA
23	Exhibition	IDQ	QCMC 2012	July 30 - August 3 2012	Vienna	Researchers in quantum optics		Austria
22	Exhibition	IDQ	QCRYPT 2012	September 10-14 2012	Singapore	Researchers in quantum optics		Singapore

21	Exhibition	IDQ	ECOC 2012	September 16-20 2012	Amsterdam	Industries and researchers in optics	5’500	Netherlands
20	Exhibition	IDQ	PHOTONICS WEST 2013	February 5-7 2013	San Francisco	Industries and researchers in optics	20’000	USA
19	Presentation	IDQ	QKD Tutorial 2012 IEEE Conference on Homeland Security Technologies	Tuesday November 13, 2012	Waltham, MA	Industries and researchers in security		USA
18	Technical publication	IDQ	‘Quantum Communication is ready for its close-up’, Photonics Spectra	February 2012.		Engineers		
17	Technical publication	IDQ, UNIGE	‘Quantum cryptography: yesterday, today, and tomorrow’, ARS Technica	September 2012		Engineers		
16	Articles published in the popular press	IDQ, UNIGE	‘Licht aus für Hacker’, Sonntagszeitung	February 2012		Public		Switzerland
15	Media briefings	IDQ	‘Battelle Installing First Quantum Key Distribution in US’, Reuters	June 2012	Columbus, Ohio	Engineers & Policy makers		USA
14	Exhibition	IDQ	Quantum Information Processing	October 2011	Singapore			International
13	Exhibition	IDQ	Photonic West & bios	January 2011	USA	R&D		International
12	Exhibition	IDQ	Defense, Security and Sensing	April 2011	Orlando, USA	R&D		International
11	Exhibition	IDQ	CLEO	June 2011	Baltimore, USA	R&D		International
10	Exhibition	IDQ	Laser World exhibition	May 2011	Munich, Germany	R&D		Europe
9	Exhibition	IDQ	International Workshop biophotonics	June 2011	Parma, Italy	R&D		Europe

8	Exhibition	IDQ	Single Photon Workshop	July 2011	Braunschweig, Germany	Scientific		International
7	Exhibition	IDQ	New Developments In Photodetection	July 2011	Lyon, France	Scientific		International
6	Exhibition	IDQ	OPTIQUE Marseille / coloq'12 (LASER et Optique Quantique)	July 2011	Marseille, France	R&D		European
5	Exhibition	IDQ	2011 IQEC / CLEO Pacific Rim Conference	August 2011	Sydney, Australia	Scientific		International
4	Exhibition	IDQ	QIPC 2011	September 2011	Zurich, Switzerland	Scientific		International
3	Exhibition	IDQ	QCRYPT 2011	September 2011	Zurich, Switzerland	Scientific		International
2	Exhibition	IDQ	ECOC 2011	September 2011	Geneva, Switzerland	R&D		International
1	Exhibition	IDQ	SPIE Security + defense	September 2011	Prague, Czech republic	Scientific		International

Part B2: Main results from QuReP

Scientific activities

Quantum memories

General specifications

- Solid-state based on rare-earth ions doped crystals
- Atomic frequency comb protocol
- Implementation of methods for enhancement of the performances

Demonstrated performances[4]

- Efficiency > 50% (using impedance-matching cavity method)
- Multimode capacity > 64 modes
- Storage time > 1ms (using spin wave storage technique)

Entangled photon pair sources

General specifications

- Narrow spectral bandwidth
- High quality polarisation entanglement

Demonstrated performances

- Spectral bandwidth several hundreds of Mhz with low transmission loss
- Entanglement visibility > 95%

Quantum measurement devices

General specifications

- High quality of the measurement
- High measurement success probability

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[4] Note that all these performance values have been obtained in different experiments, but that the techniques used to optimise one parameter are all compatible together.

Demonstrated performances

- HOM dip ~85% (limited by multi-photons)
- Acquisition time reduced by more than a factor of 12 during the project

Dissemination and exploitation activities

- 21 scientific publications (amongst them 1 Nature, 1 Nature Photonics and 2 PRL)
- 2 patents
- 2 commercially available products

Key result from each qurep partner

- University of Geneva (CH): Integration of all qurep components for a quantum teleportation experiment (fidelity > 76%)
- Lund Universitet (S): Demonstration of impedance-matching cavity enhancement method (storage-&-release efficiency > 50%)
- CNRS-Ecole Nationale Supérieure de Chimie de Paris (F): Fabrication of high quality Eu:YSO crystals (the unique manufacturer in the EU - 1 of only 2 in the world)
- CNRS-Laboratoire Aimé Cotton (F): Creation and implementation of a new protocol for quantum memories called ROSE
- University of Paderborn (D): Fabrication capacity of short poling periods in Lithium niobate (down to 4.5um) and integration of several optical functions on the same chip.
- ID Quantique SA (CH): Development of several techniques for photon counting (2 already commercially available products)

Type of Exploitable Foreground[5]	Description Of exploitable foreground	Confidential Click on YES /NO	Foreseen embargo date Dd/mm /yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[6]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
General advancement of knowledge	Integration of all qurep components for a quantum teleportation experiment (fidelity > 76%)	No	-		1. Communication 2. Security		-	Concepts advanced by the QuReP consortium, but implemented by the University of Geneva. These are published results and are exploitable by anyone.
General advancement of knowledge	Demonstration of impedance-matching cavity enhancement method (storage-&-release efficiency > 50%)	No	-		1. Communication 2. Security		-	Concepts advanced by the QuReP consortium, but implemented by the Universities of Lund (Sweden) & Geneva (Switzerland). These are published results and are exploitable by anyone.
General advancement of knowledge	Fabrication of high quality Eu:YSO crystals (the unique manufacturer in the EU - 1 of only 2 in the world)	No	-		1. Communication 2. Security 3. Materials 4. Lasers	Discussions underway. Near future.	-	LCMCP (materials for photonics group) at Ecole Nationale Supérieure de Chimie de Paris, France (Owner).
General advancement of knowledge	Creation and implementation of a new protocol for quantum memories called ROSE	No	-		1. Communication 2. Security		-	Laboratoire Aimé Cotton (LAC) Paris, France (Owner).
General advancement of knowledge	Fabrication capacity of short poling periods in Lithium niobate (down to 4.5um) and integration of several optical functions on	No	-		1. Communication 2. Security 3. Photonics 4. Frequency conversion		-	The Applied Physics group At University of Paderborn, Germany (Owner).

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[19] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[6] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

Type of Exploitable Foreground[5]	Description Of exploitable foreground	Confidential Click on YES /NO	Foreseen embargo date Dd/mm /yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[6]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
	the same chip.							
General advancement of knowledge & Commercial exploitation of R&D results	Development of several techniques for photon counting (2 already commercially available products)	No	-	Two single photon counting detector modules are commercially available.	1. Communication 2. Security 3. Fluorescence imaging 4. Metrology 4. Lidar / range - finding	Immediately	-	ID Quantique.SA, Switzerland (Owner).

In addition to the table, please provide a text to explain the exploitable foreground, in particular:

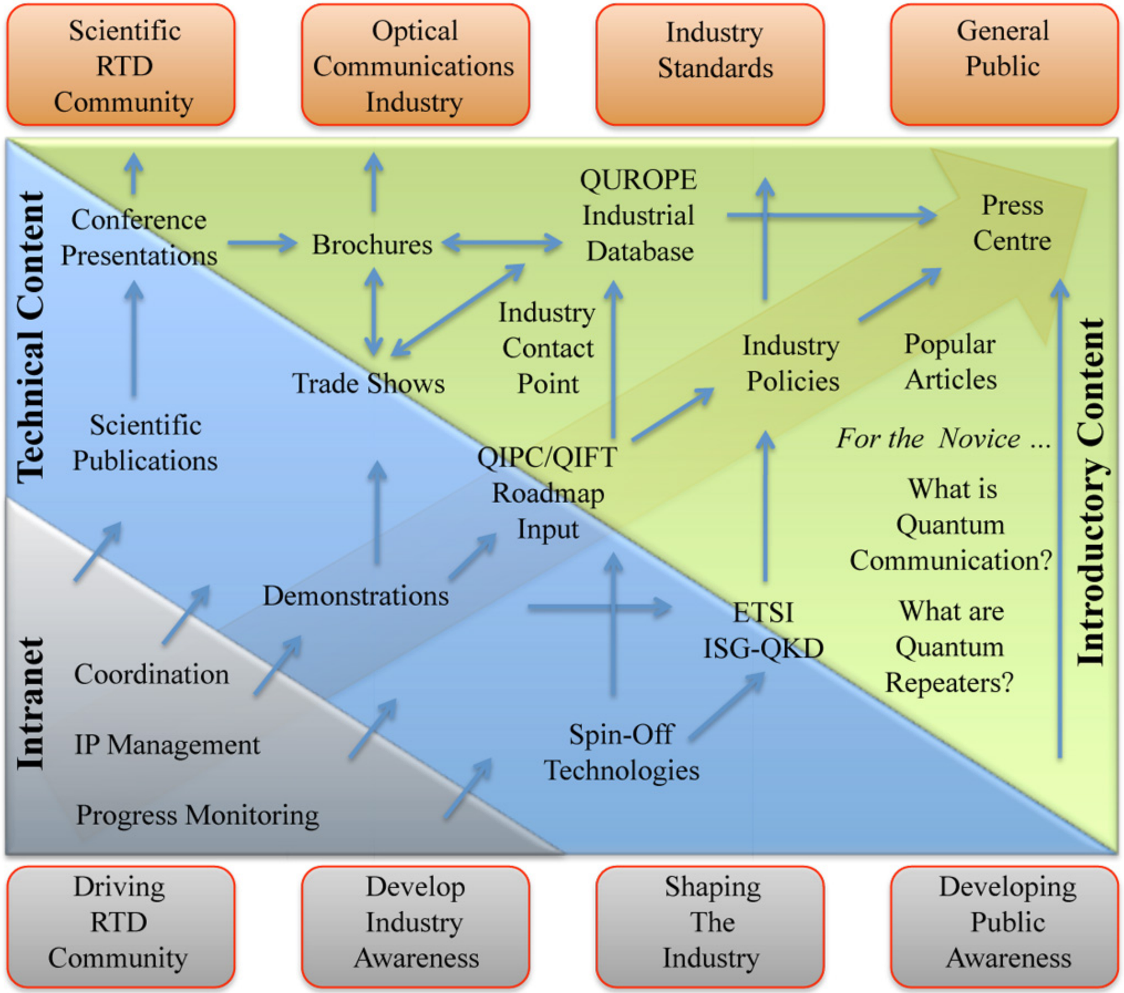
- Its purpose
    - The QuReP project's goal was to advance our understanding of what is required for the industrial development of quantum repeater technologies. The implementation of quantum repeaters is still some years away but many of the enabling technologies are rapidly advancing. Several of the key advances are listed in the previous table, however, more information can be found on the project website (http://quantumrepeaters.eu/) that will be maintained as an information service to those interested in these emerging technologies.
- How the foreground might be exploited, when and by whom
    - The majority of the exploitable foreground associated with the project is already published in scientific journals and as such is in the public domain. The development of quantum repeater technologies is an enormous undertaking and cannot be realised by such a small project and by so few partners. It is hoped that the growing number of groups working in this direction can exploit the foundational results of the QuReP project to further, and more quickly, advance towards real world quantum repeater networks. Some of the spin-off technologies and know-how are open for discussion with the different partners, for example the crystal growth methods could have wide spread interest for laser systems and beyond. The work on PPLN crystals will also have significant impact on emerging integrated quantum photonics systems.

- IPR exploitable measures taken or intended
  - Two patents have been applied for although these remain confidential at this point in time.
- Further research necessary, if any
  - The QuReP project has made significant advances towards the understanding of what is needed to industrial quantum repeater technologies – both in the context of implementing a quantum repeater as well as potential spin-off technologies. The development of two single photon counting products arising from some of this work is already testifies to this.
- Potential/expected impact (quantify where possible).
  - Quantum repeaters hold the potential for connecting a future Quantum Internet, where the "quantum" is there to ensure security. The QuReP industrial partner IDQ is already well established in the $20 billion encrypted communication market and is one of the few to provide quantum-enabled security – quantum key distribution. As recent revelations about spying and encryption being weakened by governments, a means of providing provably secure communication is of paramount importance. We expect that the QuReP project will have laid the foundations for some of the first quantum repeater based demonstrations and identified key steps towards a Quantum Internet.

To highlight the exploitable foreground generated by the QuReP project a wide range of dissemination activities, have again taken place addressing primarily the scientific community and industrial interest. Highlights include continued high profile talks, across all partners and around the world. Several partners again assisted in the organisation of, and participation in, a symposium in Mainz. This is the annual rare-earth ion symposium meeting, which was started in Geneva and laid the foundations for this project, which continues to grow, to the point where it will be taken over by a new Marie Curie ITN (CIPRIS) and has expanded to include a summer school as well as the scientific conference itself. Several members of the current project, Geneva, Lund, Paris are involved.

IDQ organised the 5th Winter School on practical quantum cryptography. This winter school allows people from different backgrounds to familiarise themselves with quantum cryptography. The number of participants continues to increase with over 20 people this year getting hands-on training as well as a series of lectures on all aspects of quantum communication. Similarly to previous years a significant proportion of these are coming from outside of the quantum communication community, including many from industry. This year one day was dedicated to Quantum Repeater technologies with lectures given by QuReP Partners N. Gisin, M. Afzelius and R. T. Thew.

Projects such as QuReP, have also been pivotal in providing the motivation for related technologies such as single photon detectors. We have also consolidated collaborations with: The Technical University of Eindhoven; The Moscow State Pedagogical University, The Technical University of Delft, the Russian company Scontel, as well as NICT in Japan and UNIGE have recently launched a new collaboration with the University of Basel in Switzerland.



All Partners worked collaboratively with numerous groups throughout the world and are actively involved in many European and National research programmes. ID Quantique has been participating in multiple commercial and scientific events and exhibitions as listed above. During most of them, ID Quantique has exhibited its products on a booth. There, ID Quantique presented quantum cryptography and described the QuReP project whenever people were looking for a solution to the distance limitation of QKD. Some of the brochures that were distributed are available via the QuReP website.

As the industrial partner, ID Quantique is continuously in contact with potential customers concerning today and tomorrow's quantum cryptography solutions and continue to see increasing interest in quantum repeaters. IDQ presents its encryption products to about one hundred groups each year. For privacy reasons, only few details can be disclosed about them. They are distributed in three main categories: governmental institutions (40%); banking sector (40%), and large companies (20%). About half of ID Quantique's potential customers are interested in quantum cryptography. A large proportion of these are interested in relatively long distance applications, i.e. solution like quantum repeaters that overcome the actual distance limitation of current QKD systems. This has also motivated a spin-off initiative with the US company Battelle to develop a so called "trusted-node" long distance QKD link over around 800km in the USA. This will be a first step in developing long distance quantum networks before implementing fully quantum, i.e. quantum repeater, networks.

At the start of the project, we set out a dissemination plan that looked at the different target groups and how we wanted to address them – how to inform them of what we are doing. The graphic here illustrates this. The QuReP website (http://quantumrepeaters.eu/) will remain as a service to these groups. There is information that ranges from a level suitable for the expert to the general public, including a FAQ page targeting these different levels of expertise. A short book also introduces some of the key concepts in a simple way and we also made a short film to better explain what quantum repeaters are and what the QuReP project has been doing. All of the projects publications are also available via the project website. There are also links to and from the key quantum information dissemination hubs, such as – QUROPE (Quantum Information Processing and Communication in Europe - http://qurope.eu).

Many of the popular articles, roadmaps brochures and some presentations can be found either on the QuReP website or linked from there.