The QScale Project
09/2011 to 03/2015

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Madrid, Final review meeting, March 2015
The General Content of QScale

**Quantum node**
generate, process, store quantum information locally

**Quantum channel**
transport / distribute quantum information over the entire network

Scalable Q. Communication
Distributed Q. computing
Quantum resource sharing
Quantum simulation
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**One example: ‘Quantum Repeater’**

Entanglement Distribution on distances larger than set by the attenuation length of fibers

→ Long-distance Q. cryptography, Q. state transmission
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**Enters into Topic 3 of the QIFT call**
- focus on “Long distance quantum communications”

**Overall objective**
- experimentally demonstrate *photonic and atomic components*
- enabling the development of quantum repeaters and their integration into *quantum communication and processing networks*
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Implementation?

- Physical processes for reliable generation, processing, & transport of quantum states (including novel architectures)
  - Quantum interfaces between matter and light
- Networks will be heterogeneous: Various kind of photonic carriers, of encodings and of material systems
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Discrete/continuous encodings
- Single photons, Squeezed light, Non-gaussian states, ...
- Doped crystals, cold and ultra-cold atoms, ion strings
The Tools of QScale

Bose-Einstein Condensate on chip

Cold atoms in 2D-MOT and dipole trap

Rare-earth ion doped crystals

Trapped ion strings
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Discrete degrees of freedom

Polarization qubits
Single-photon entanglement
Involve photon counting

Continuous degrees of freedom

Quadrature measurements
Involve homodyne detection

Single photons

Gaussian Squeezed light and Entanglement

Non-Gaussian states Hybrid operations
The QScale Consortium

- 5 academic partners
- 1 industrial partner
- 5 countries
- Funding: ~1 M€
- 400 person months

Quantum technologies for extending the range of quantum communications
The QScale Consortium

5 academic partners
1 industrial partner
5 countries
Funding: ~1 M€
400 person months

Barcelona, Spain
Institute of Photonic Sciences
PI: H. de Riedmatten
(Q. memory in solids)

Saarbrucken, Germany
Universitat des Saarlandes
PI: J. Eschner
(Trapped ion strings)

Firenze, Italy
Istituto Nazionale di Ottica
PI: M. Bellini
(Q. memory in BEC, Non-gaussian)

Milano, Italy
Quanta System
PI: A. Raspa
(Tools: locking, detection)

Geneva, Switzerland
Group of Applied Physics
PI: N. Sangouard
(Theory of quantum networks)

Paris, France
Laboratoire Kastler Brossel
PI: J. Laurat
(Q. memory in MOT, Non-gaussian)
QScale WorkPackages

WP1: Photonic components for quantum architecture
Developing sources of non-classical light compatible with memories and the ability to perform non-Gaussian operations.

WP2: Controlling light-matter interfaces
Implementing long-lived and efficient quantum memories in ensembles (cold atoms, BEC on AtomChip, and rare-earth doped solid) and the synchronous control of photon emission by trapped ion strings leading to light-ion entanglement.
QScale WorkPackages

WP1: Photonic components for quantum architecture
Non-classical light and non-Gaussian operations.

WP2: Controlling light-matter interfaces
Memories in ensembles and control of ion strings.

WP3: Demonstration of Q. repeaters building blocks
On-demand matter-matter entanglement, long-lived light-solid entanglement, local ion string processing and teleportation between strings
QScale WorkPackages

**WP1: Photonic components for quantum architecture**
Non-classical light and non-Gaussian operations.

**WP2: Controlling light-matter interfaces**
Memories in ensembles and control of ion strings.

**WP3: Demonstration of Q. repeaters building blocks**
Light-matter, matter-matter entanglement, node processing

**WP4: Novel architectures and tools for repeaters**
Investigating new architectures and characterization for operational repeaters (e.g. hybrid schemes, heralded qubit amplifier, deterministic operations, witnesses)
QScale Website

A website
www.chistera-qscale.eu
Partners, Workpackages
Workshop programs
Papers from the consortium
General audience page
Kick-off Meeting in 2011

Kick-off, Paris, October 2011
25 researchers, 9 talks
2 discussion sessions
Presentation of the groups
Consortium agreement validated
Mid-term meeting January 2013

Paris
January 30, 31 and February 1st 2013
Hipercom and QScale together
70 researchers
27 talks + administrative session
9 invited speakers from outside the consortiums
New collaborations emerged
Focus meeting in November 2013

Paris
November 5 and 6, 2013
“Informal Workshop on Atomic Ensembles”
30 researchers
Including 13 researchers from Qscale groups
A focus workshop on a hot topic of Qscale
Different approaches compared
Last meeting: June 2014
Brussels, during CEWQO 2014
23-27 June 2014
Hipercom and QScale together again
One afternoon session for each project
+ two invited speakers from Qscale
in the plenary sessions
Dissemination towards the whole QIP community
QScale ‘Metrics’

46 papers in international peer-reviewed journals
  5 ‘common’ papers between QSCALE partners
117 contributions in international meetings and workshops
  3 book chapters, 3 popularization articles, General audience conf

WP1: Photonic components for quantum architecture → 18 papers

WP2: Controlling light-matter interfaces → 17 papers

WP3: Q. repeaters building blocks → 4 papers

WP4: Novel architectures and tools for repeaters → 7 papers
**QScale WorkPackages**

**WP1:** Photonic components for quantum architecture – All delivered, additional works
Non-classical light and non-Gaussian operations.

**WP2:** Controlling light-matter interfaces
Most of deliverables, two delayed
Memories in ensembles and control of ion strings.

**WP3:** Demonstration of Q. repeaters
building blocks **Results presented today**

**WP4:** Novel architectures and tools for repeaters
– All deliverables done, new results not initially expected in the project, large collaboration
New architectures and characterization for operational repeaters
INO and QuantaS: industrial developments

WP1: Collaboration INO and Italian industrial partner – Development of electronics board

Ultrafast, time-domain, homodyne detectors

Will enable more efficient quantum state generation and characterization

WP4: Non-gaussian tasks and criteria for networks operations

Industry-standard, purpose-driven development and engineering of advanced devices for quantum optics experiments

Initially delayed, not reported before

Pulsed UV pump enhancement in a cavity
LKB and INO: A novel form of entanglement

Hybrid Entanglement
A novel form of entanglement following two different strategies

Alice and Bob working with different encodings, i.e. CV or DV

\[ |0\rangle_A |\alpha\rangle_B + |1\rangle_A | - \alpha\rangle_B \]

Hybrid entanglement between particle-like and wave-like optical qubits

A heterogeneous network

Opens the way to heterogeneous networks and computational basis mapping

WP1 and WP4: Non-gaussian toolbox and Hybrid approach for network operations and architectures
LKB and INO: A novel form of entanglement

Nature Photonics 8, 564 (2014)
Nature Photonics 8, 570 (2014)

Press release by ANR and MIUR

Covered by many medias, newspapers, La Repubblica, websites...
Cited among the 10 best Italian science achievements of 2014 by Citta della Scienza

An example of work not fully planned at the beginning of the project but that emerges from the first developed capabilities

WP1 and WP4: Non-gaussian toolbox and Hybrid approach for network operations and architectures
ICFO: Storage in doped crystal

Storage of the single-photons into Pr doped crystal

Quantum Storage of Heralded Single Photons in a Praseodymium-Doped Crystal

We report on experiments demonstrating the reversible mapping of heralded single photons to long-lived collective optical atomic excitations stored in a Pr³⁺:Y₂SiO₅ crystal. A cavity-enhanced spontaneous down-conversion source is employed to produce widely nondegenerate narrow-band (≈2 MHz) photon pairs. The idler photons, whose frequency is compatible with telecommunication optical fibers, are used to herald the creation of the signal photons, compatible with the Pr³⁺ transition. The signal photons are stored and retrieved using the atomic frequency comb protocol. We demonstrate storage times up to 4.5 µs while preserving nonclassical correlations between the heralding and the retrieved photon. This is more than 20 times longer than in previous realizations in solid state devices, and implemented in a system ideally suited for the extension to spin-wave storage.

Phys. Rev. Lett. 112, 040504

A quantum node compatible with telecom photons
Storage of the single-photons into Pr doped crystal

Telecom frequency → QMemory

Frequency converter Noise free

Storage of up-converted telecom photons

We report on an experiment that demonstrates the frequency up-conversion of telecommunication wavelength single-photon-level pulses to be resonant with a Pr$^{3+}$:Y$_2$SiO$_5$ crystal. We convert the telecom photons at 1570 nm to 606 nm using a periodically-poled potassium titanyl phosphate nonlinear waveguide. The maximum device efficiency (which includes all optical loss) is inferred to be $\eta_{\text{max}} = 22 \pm 1\%$ (internal efficiency $\eta_{\text{int}} = 75 \pm 8\%$) with a signal to noise ratio exceeding 1 for single-photon-level pulses with durations of up to 560 ns. The converted light is then stored in the crystal using the atomic frequency comb scheme with storage and retrieval efficiencies exceeding $\eta_{\text{AFC}} = 20\%$ for predetermined storage times of up to 5 $\mu$s. The retrieved light is time delayed from the noisy conversion process allowing us to measure a signal to noise ratio exceeding 100 with telecom single-photon-level inputs. These results represent the first demonstration of single-photon-level optical storage interfaced with frequency up-conversion.

New Journal of Physics 16, 113021 (2014)

Outperforms (efficiency, storage time) the previous absorptive telecom memory at the single photon level

A quantum node compatible with telecom photons
Quantum information encoded in vector beams of light
A multiple-degree-of-freedom quantum memory

Storage and retrieval of vector beams of light in a multiple-degree-of-freedom quantum memory

The full structuration of light in the transverse plane, including intensity, phase and polarization, holds the promise of unprecedented capabilities for applications in classical optics as well as in quantum optics and information sciences. Harnessing special topologies can lead to enhanced focusing, data multiplexing or advanced sensing and metrology. Here we experimentally demonstrate the storage of such spatio-polarization-patterned beams into an optical memory. A set of vectorial vortex modes is generated via liquid crystal cell with topological charge in the optic axis distribution, and preservation of the phase and polarization singularities is demonstrated after retrieval, at the single-photon level. The realized multiple-degree-of-freedom memory can find applications in classical data processing but also in quantum network scenarios where structured states have been shown to provide promising attributes, such as rotational invariance.

Storage ~ 30%
Offers a universal quantum memory for structured light and rotationally-invariant qubits

Enters into WP3: Multiplexed quantum memories in a network
Quantum state conversion from a polarization-encoded photon to an ion

- Fidelity of the mapping above 95%
- Heralded process

High-fidelity heralded photon-to-atom quantum state transfer

Quantum network combines the benefits of quantum systems regarding secure information transmission and calculational speed-up by employing quantum coherence and entanglement to store, transmit, and process information. A promising platform for implementing such a network are atom-based quantum memories and processors, interconnected by photonic quantum channels. A crucial building block in this scenario is the conversion of quantum states between single photons and single atoms through controlled emission and absorption. Here we present an interface for photon-to-atom quantum state conversion, whereby the polarization state of an absorbed single photon is mapped onto the spin state of a single absorbing atom with >95% fidelity, while successful conversion is heralded by a single emitted photon. Heralding high-fidelity conversion without affecting the converted state is a main experimental challenge, in order to make the transferred information reliably available for further operations. Other approaches employ optical resonators or a deep parabolic mirror, but results so far have been inherently probabilistic with overall fidelities below 10%. We circumvent this limitation by our heralding protocol. We record >80/s successful quantum state transfer events out of 18,000/s repetitions.

Nature Communications 5, 5527 (2014)
The other way round atom-to-photon state conversion

We realized a flexible, programmable interface for quantum state conversion between photons and atoms. Depending on its mode of operation, it serves as photon-to-atom quantum state converter or for its inverse, i.e. atom-to-photon state conversion, as well as for the generation of entangled atom-photon pairs, or for single-photon frequency conversion. The interface comprises single-ion gate operations conditioned on an absorbed or emitted photon.

A close-to-unity fidelity quantum state transfer from atom-to-photon

A very flexible interface ion-light interface for bi-directional state transfer
Absorption a telecom photon into a single-ion

**Telecom heralded single-photon absorption by a single ion**

We present, characterize, and apply a photonic quantum interface between the near infrared and telecom spectral regions. A singly resonant optical parametric oscillator (OPO) operated below threshold generates high-rate narrowband photon pairs; the signal photons are tuned to resonance with an atomic transition in Ca⁺, while the idler photons are at telecom wavelength. Quantum interface operation is demonstrated through the absorption of a single photon by a single trapped ion, heralded by a telecom photon.

**In preparation**

Telecom-heralded single photon are absorbed by the single-trapped ion

**Enters into WP3: coupling ion to a telecom network**
A witness for single-photon entanglement using only local homodyne measurements

Witnessing single-photon entanglement with local homodyne measurements: analytical bounds and robustness to losses

Single-photon entanglement is one of the primary resources for quantum networks, including quantum repeater architectures. Such entanglement can be revealed with only local homodyne measurements through the entanglement witness presented in [Morin et al. Phys. Rev. Lett. 110, 130401 (2013)]. Here, we provide an extended analysis of this witness by introducing analytical bounds and by reporting measurements confirming its great robustness with regard to losses. This study highlights the potential of optical hybrid methods, where discrete entanglement is characterized through continuous-variable measurements.

Physical Review Letters 100, 130401 (2013)
New Journal of Physics 16, 103035 (2014)

Robustness demonstrated up to 80 km of telecom fibers

Well-suited for a large-scale networks

Enters into WP4: Verifying the functionality of a quantum network
GAP: NL Interactions between single-photons

Sum-frequency generation between heralded single-photons at telecom frequencies

Non-linear interactions between two heralded single-photons

Detailed study with doped crystals led to an alternative implementation

⇒ First demonstration with waveguide

Enters into WP4: Towards more deterministic operations in a network
QScale

A variety of results, from novel tools to complex implementations

Advances in the development of functional quantum networks

Look for new joint efforts...
Quantum technologies for extending the range of quantum communications

www.chistera-qsacle.eu