Broadband Waveguide
Quantum Memory for Entangled Photons

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Motivation for Quantum Memory

A Synchronization Device for Quantum Data

On-Demand Single Photon Sources from Probabilistic Sources

Essential for Quantum Repeaters

Briegel et al., Phys. Rev. Lett (1998); Hammerer et al., Rev. Mod. Phys (2010); Simon et al., Eur. Phys. J. D (2010); Sangouard et al. Rev. Mod. Phys. (2011)
State-of-the-Art Quantum Memory

| Property                | Desired | State-of-the-art | Approach                                                                 |
|-------------------------|---------|------------------|--------------------------------------------------------------------------|
| Efficiency              | ≈ 1     | 0.87             | Photon-echo QM in room-temp gas\(^1\)                                    |
| Fidelity                | ≈ 1     | 0.92 - 0.98      | Photon-echo, EIT, Raman…                                                  |
| Multi-mode capacity     | high    | 64 modes         | Photon-echo QM in RE crystal\(^2\)                                      |
| Pulse duration          | ≤ ns    | < 100 ps         | Photon-echo QM in RE crystal\(^3\)                                      |
| Storage time            | > sec   | > 2 sec          | EIT based QM in a RE crystal\(^4\)                                      |
| Entanglement preservation| Yes    | Demonstrated     | EIT based QM in trapped atoms\(^5\) Photon-echo QM in RE crystal\(^3,6\) |
| Complexity              | Simple  | …                | …                                                                         |

- Electromagnetically induced transparency (EIT)
- Off / On resonant Raman
- Photon-echo: Time reversal of absorption in a controlled way

*Our approach:* Atomic Frequency Comb (AFC) in rare-earth (RE) doped crystals

1. Hosseini et al, Nature Phys. (2011); 2. Usmani et al, Nature Comm. (2010); 3. Saglamyurek, N.S., et al, Nature (2011); 4. Longdell et al, PRL (2005); 5. Choi et al, Nature (2008); 6. Clausen et al, Nature (2011)
Outline

- AFC Memory and Rare-Earth Crystals
- Experimental Setup for Entanglement Storage
- Results & Conclusions
AFC Photon-Echo Quantum Memory Protocol

1. Preparation of Atomic Frequency Comb

2. Absorption of Photon → Fast Dephasing

3. Wait, Repetitive Rephasing → Emission of Photon

\[ t = \frac{1}{\Delta_{\text{comb}}} \]

+ Recall on demand through reversibly mapping optical coherence onto spin coherence
+ Emission in backwards direction: \( \phi(z) = -2kz \)

100% efficiency & fidelity, Large Bandwidth potential, High multi-mode capacity

Experiments: Geneva, Lund, Paris, Calgary

Hesselink et al., PRL (1979); Afzelius et al., PRA (2009); De Riedmatten et al., Nature (2008); Afzelius et al., PRL (2010); Usmani et al., Nature Comm. (2010).
Rare-Earth-Ion Doped Crystals (Lanthanides)

Stresses & Strains  \rightarrow \text{Inhomogeneous Broadening}

- Large inhomogeneous broadening, 0.5 – 500 GHz
- Long optical coherence, 4 ms at 4 K
- Long spin coherence, up to 30 s at 4 K
- Transitions available in visible and telecom wavelengths

Tittel et al., Laser Phot. Rev. (2010)
**Ti:Tm:LiNbO$_3$ Waveguide**

**Thulium:**
- 795 nm zero-phonon line ($\Gamma_{\text{hom}} \sim 200$ kHz, $T = 3K$)
- Off-the-shelf Si single photon detectors available
- Large optical depth (alpha~2.2/cm @ 3K & 795.5 nm)
- Long-lived magnetic sublevels ($T_1$~sec @ B = 150G, T = 3K)

**LiNbO$_3$:**
- Standard telecom material waveguide fabrication mastered
- Control atomic phase evolution via DC Stark effect (a possibility for on-demand recall with AFC)

**Waveguide:**
- Small mode diameter -> large Rabi frequencies
- Fast switching electric fields
- Simplified integration with fibre optic components into networks

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N.S. et al, J. Lumin. (2010); Thiel et al, J. Lumin (2010)
Experimental Setup – The Waveguide
Quantum Memory Setup

- 5 GHz wide AFC, Generated via laser sideband chirping
  - stores < 100 ps photons
- 142 MHz tooth separation = 7 ns storage time
- Waveguide coupling efficiency = 10%
- Memory retrieval efficiency = 2%
  (limited by: Finesse = 2, non-uniform AFC)

50-fold efficiency increase “readily” achievable
• Generate “individual” entangled photon pairs in state:

• Photon wavelengths coincide with free-space and telecom transmission windows
  • 1532 nm suitable for long-distance fibre transmission
  • 795 nm on resonance with Tm transition

Measurements with and without memory
• Qubit Analyzers allow projection measurements onto and other superposition bases i.e. $\sigma_x$, $\sigma_y$

• Measurements allow one to **reconstruct the two-qubit density matrix** (with & without storage)

i.e. $\sigma_x \otimes \sigma_x$, $\sigma_x \otimes \sigma_y$, $\sigma_x \otimes \sigma_z$, …
Density matrices allow for a quantitative comparison of the quantum state with and without storage.

(all imaginary components are < 0.04 and are not shown)
## Results

|                          | Entanglement of formation | With-Without Fidelity | Purity       | Fidelity with $|\varphi^+\rangle$ | CHSH-Bell Parameter S (measured) |
|--------------------------|---------------------------|-----------------------|--------------|-----------------------------------|----------------------------------|
| $\rho_{\text{without}}$ | 0.644±0.042               | 0.954±0.029           | 0.757±0.024  | 0.862±0.015                       | 2.379±0.034                     |
| $\rho_{\text{with}}$    | 0.65±0.11                 |                       | 0.763±0.059  | 0.866±0.039                       | 2.25±0.06                       |

- No measurable degradation of (post-selected) entanglement during storage

- State with and without storage has limited purity and fidelity with target

- Independently measured: experimental violation of CHSH Bell inequality ($S_{\text{LHV}} \leq 2$)
Conclusions

First demonstration of a reversible mapping of an entangled photon into and out of a solid-state device (see also work by N. Gisin)

Integrated approach, for ~100 ps photons
Simple interfacing with sources of non-classical light
Limited efficiency and preset, short storage time

Photon-Crystal
CHSH = 2.64 ± 0.23

C. Clausen et al., Nature (2011).

E. Saglamyurek, N.S. et al., Nature (2011).

Next: teleportation and entanglement swapping into memory

Saglamyurek, N.S. et al, Nature (2011); Clausen et al, Nature (2011)
Thank you

And Collaborators

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M. George
R. Ricken
F. Bussières
