Broadband Waveguide Quantum Memory for Entangled Photons

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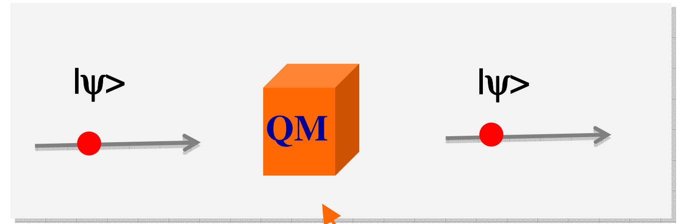
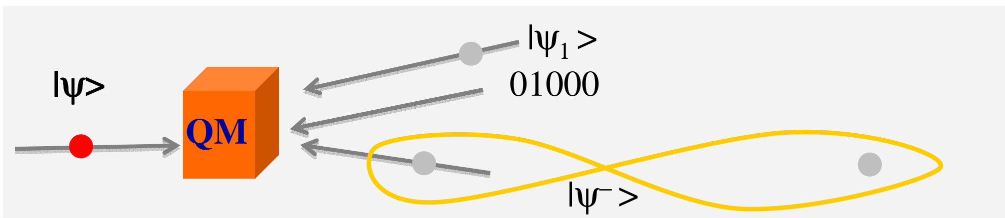
Motivation for Quantum Memory



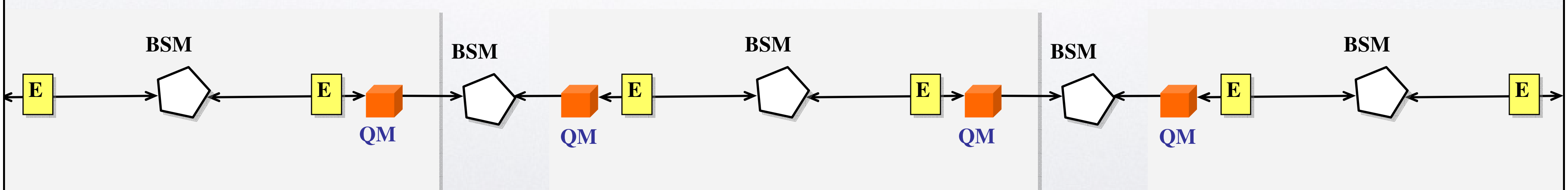
Want to store externally provided photons

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: **A**tomic **F**requency **C**omb **(AFC)** in rare-earth (RE) doped crystals

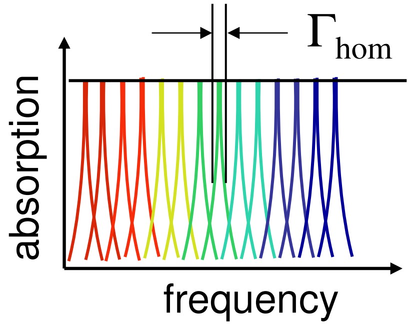
1. Hosseini et al, Nature Phys. (2011); 2. Usmani et al, Nature Comm. (2010); 3. Saglamyurek, N.S., et al, Nature (2011);
4. Longdell et al, PRL (2005); 5. Choi et al Nature (2008); 6. Clausen et al, Nature (2011)

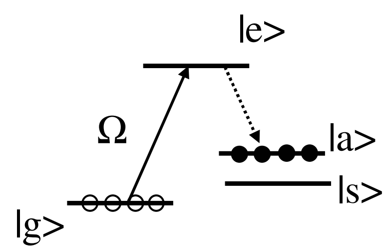
Outline

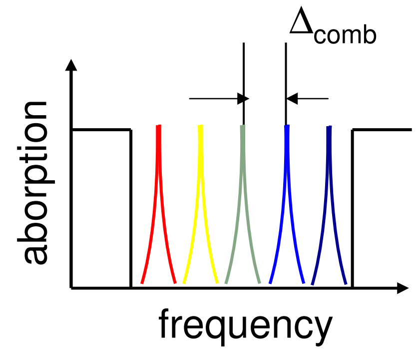
- AFC Memory and Rare-Earth Crystals
- Experimental Setup for Entanglement Storage
- Results & Conclusions

AFC Photon-Echo Quantum Memory Protocol

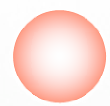
1. Preparation of Atomic Frequency Comb







2. Absorption of Photon → Fast Dephasing



3. Wait, Repetitive Rephasing → Emission of Photon

$$t = 1/\Delta_{comb}$$

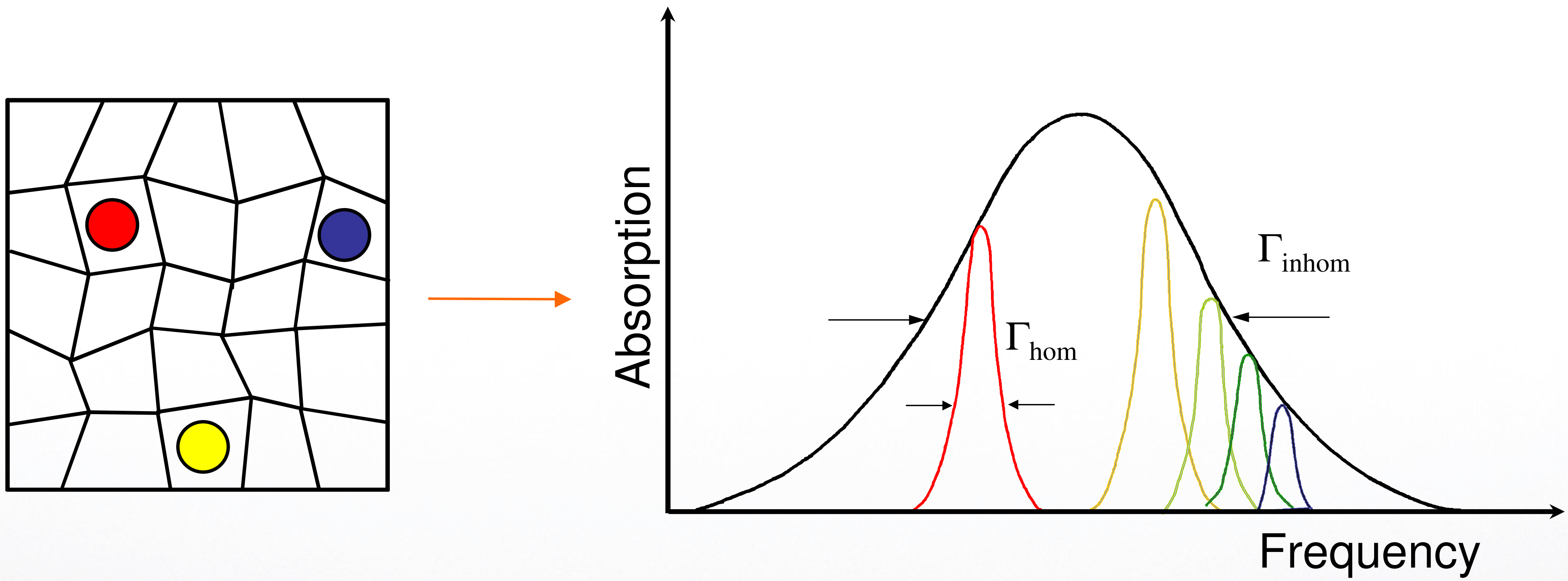
Experiments: Geneva, Lund, Paris, Calgary

+ 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

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)

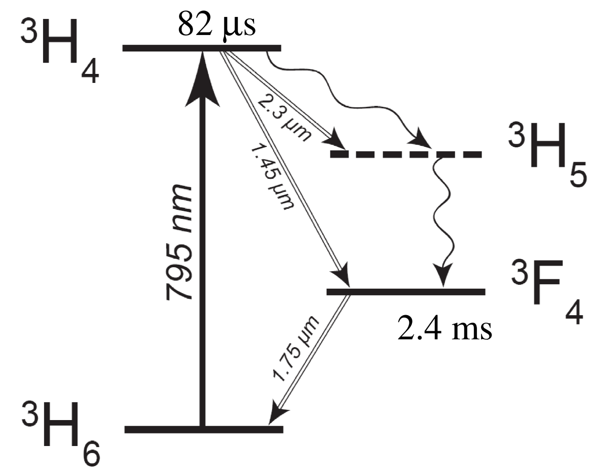


Stresses & Strains → Inhomogeneous Broadening

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

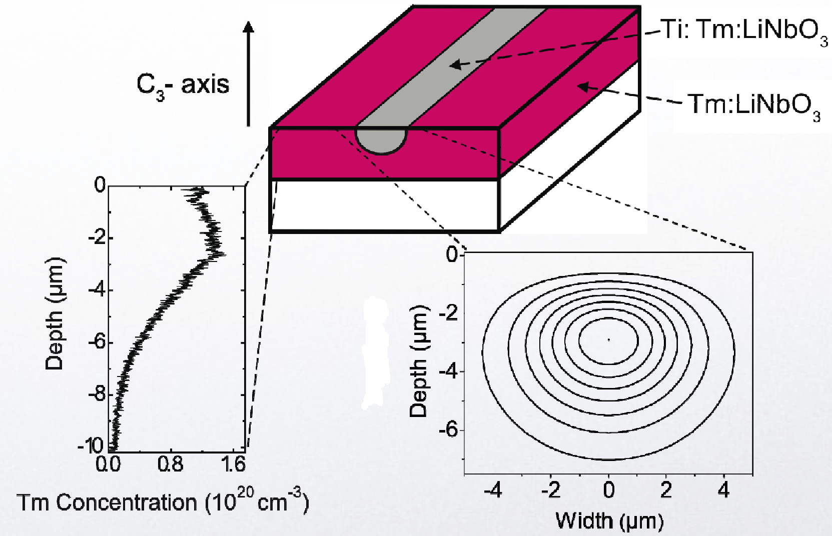


Thulium:

- 795 nm zero-phonon line (Γ_{hom} ~ 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)

$LiNbO_3$:

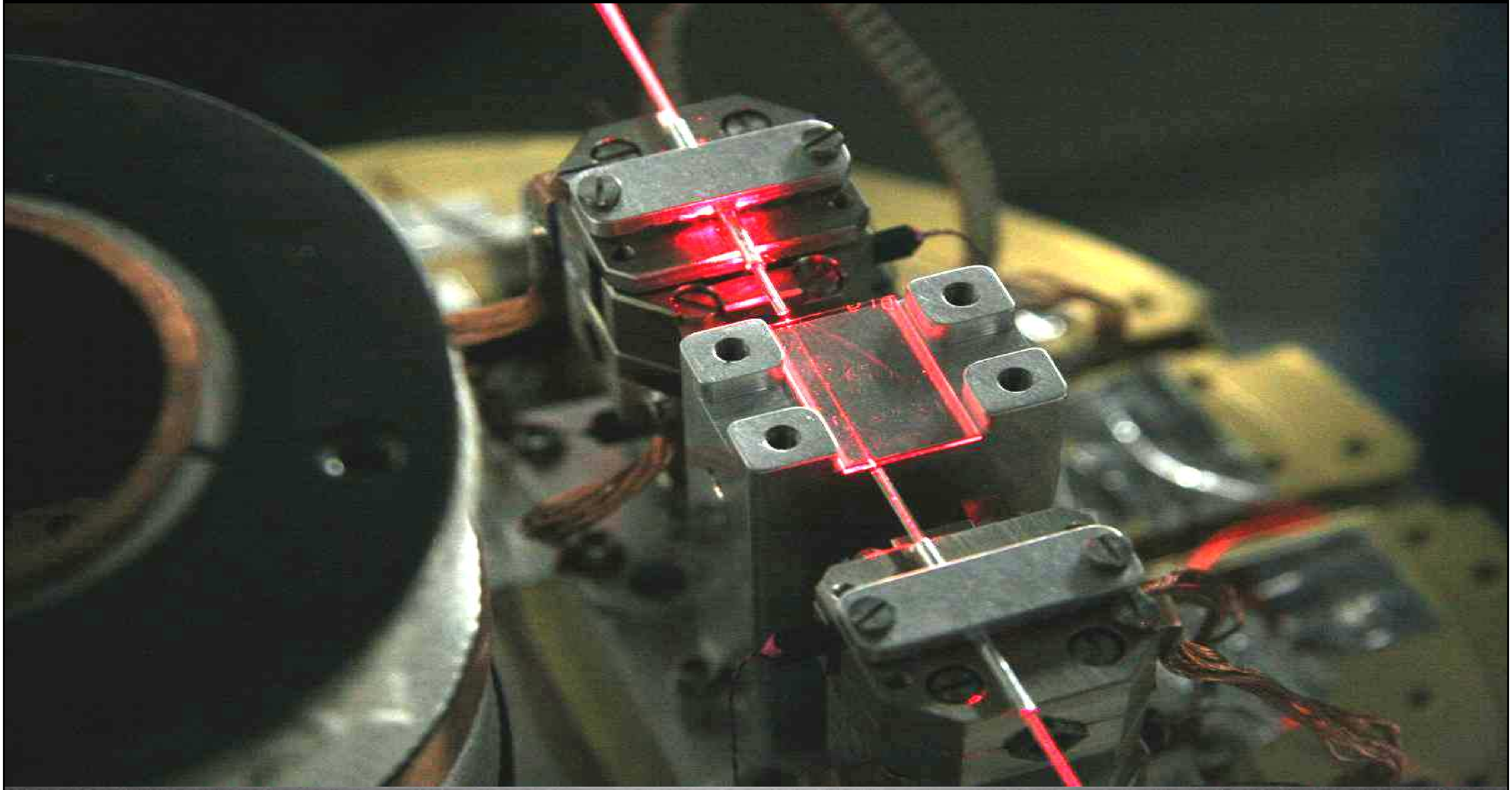
- Standard telecom material → waveguide fabrication mastered
- Control atomic phase evolution via DC Stark effect (a possibility for on-demand recall with AFC)



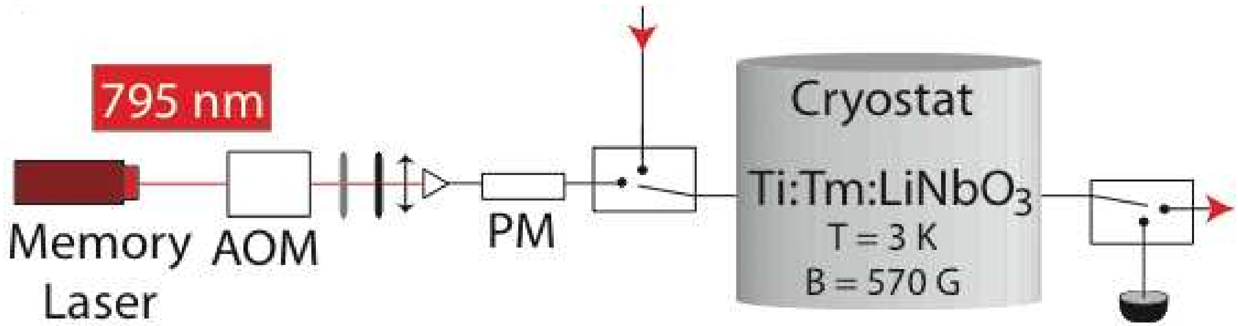
Waveguide:

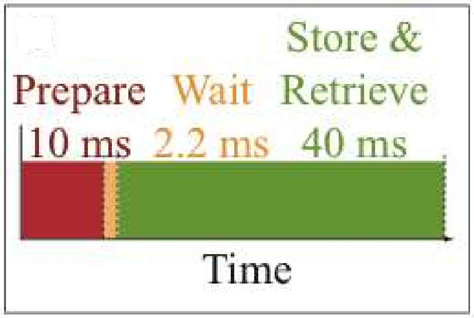
- Small mode diameter → large Rabi frequencies
- Fast switching electric fields
- Simplified integration with fibre optic components into networks

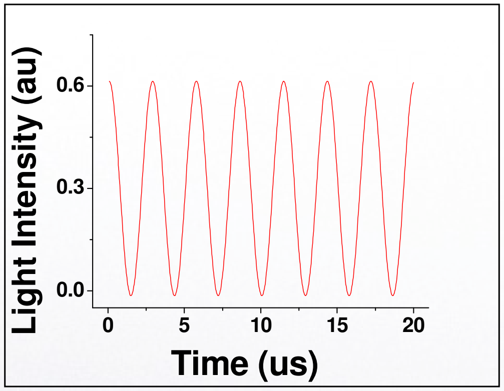
Experimental Setup – The Waveguide



Quantum Memory Setup







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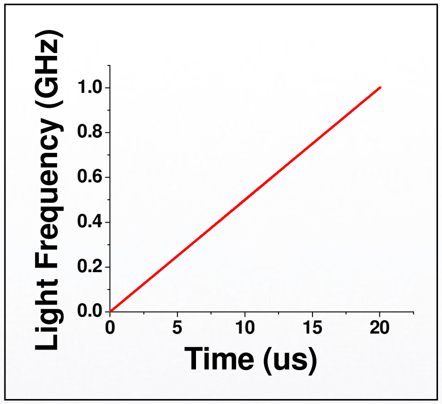

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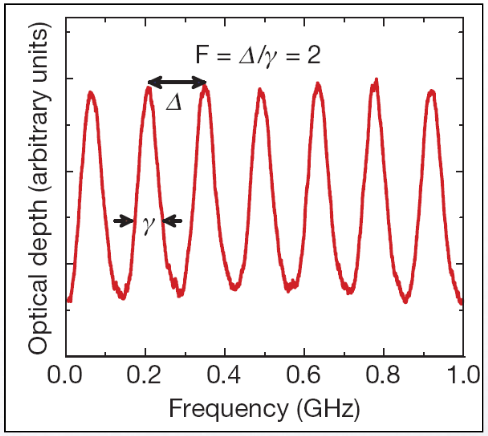
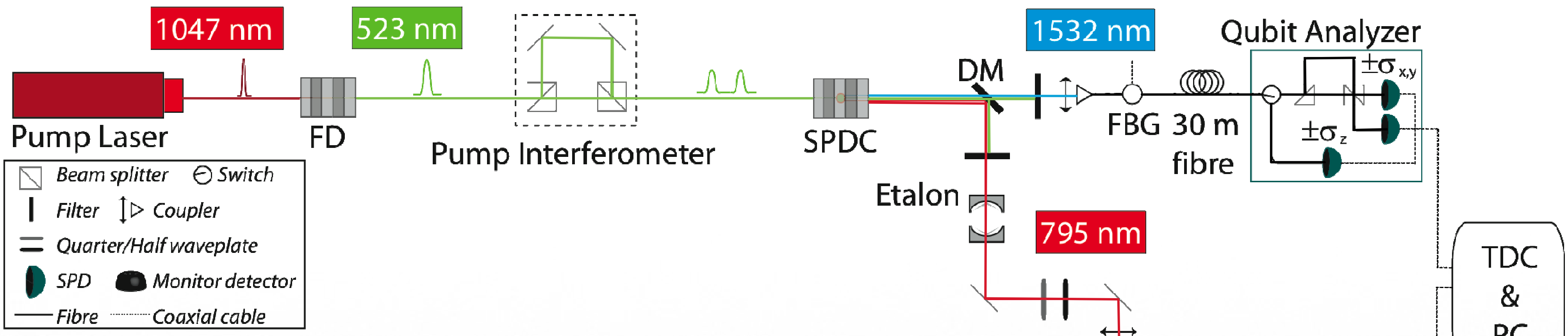


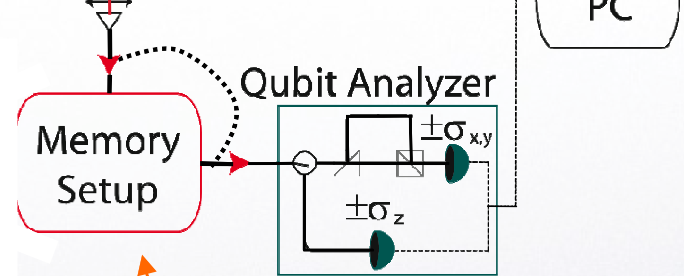
- 5 GHz wide AFC, Generated via laser sideband chirping → stores < 100 ps photons
- 142 MHz tooth separation = 7 ns storage time
- Waveguide coupling efficiency = 10%
- Memory retrieval efficiency = 2% (limited by: Finesse = 2, non-uniform AFC)

50-fold efficiency increase “readily” achievable

Generating and Storing Entanglement



• Generate "individual" entangled photon pairs in state:

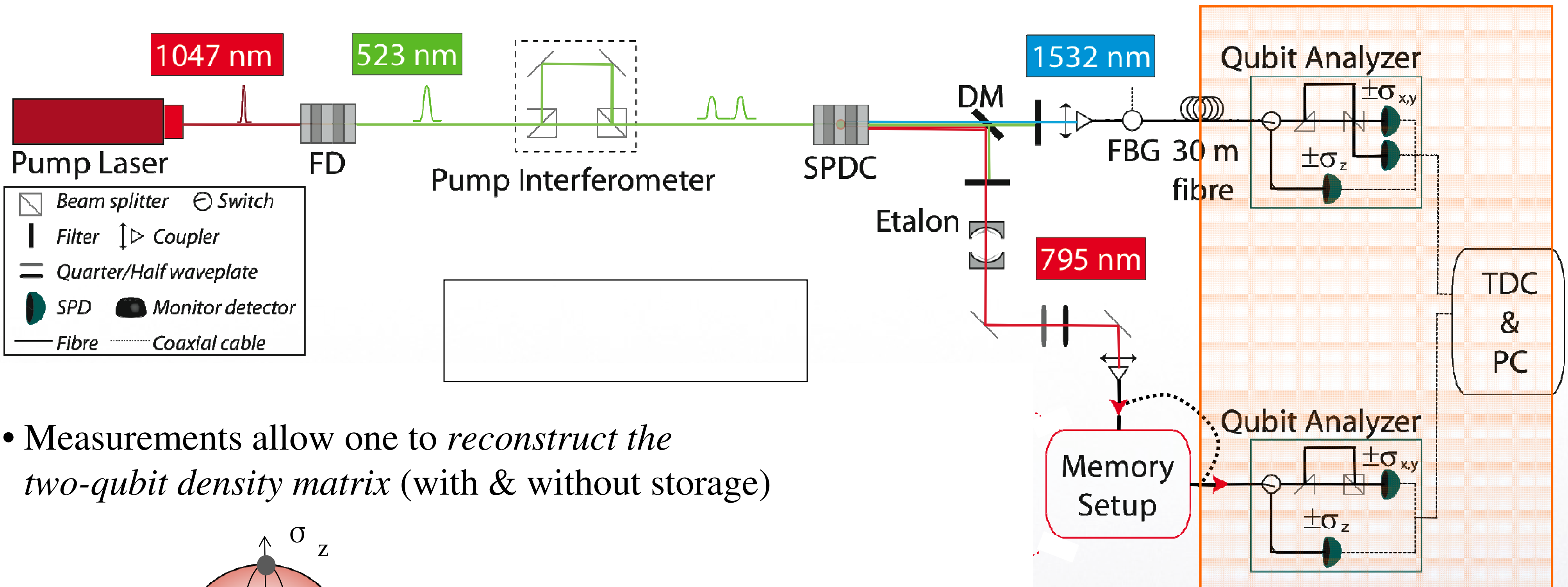


795 nm 1532 nm

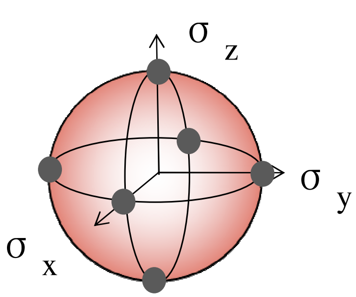
• Photon wavelengths coincide with free-space and telecom transmission windows
• 1532 nm suitable for long-distance fibre transmission
• 795 nm on resonance with Tm transition

Measurements with and without memory

Measurement and Analysis



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

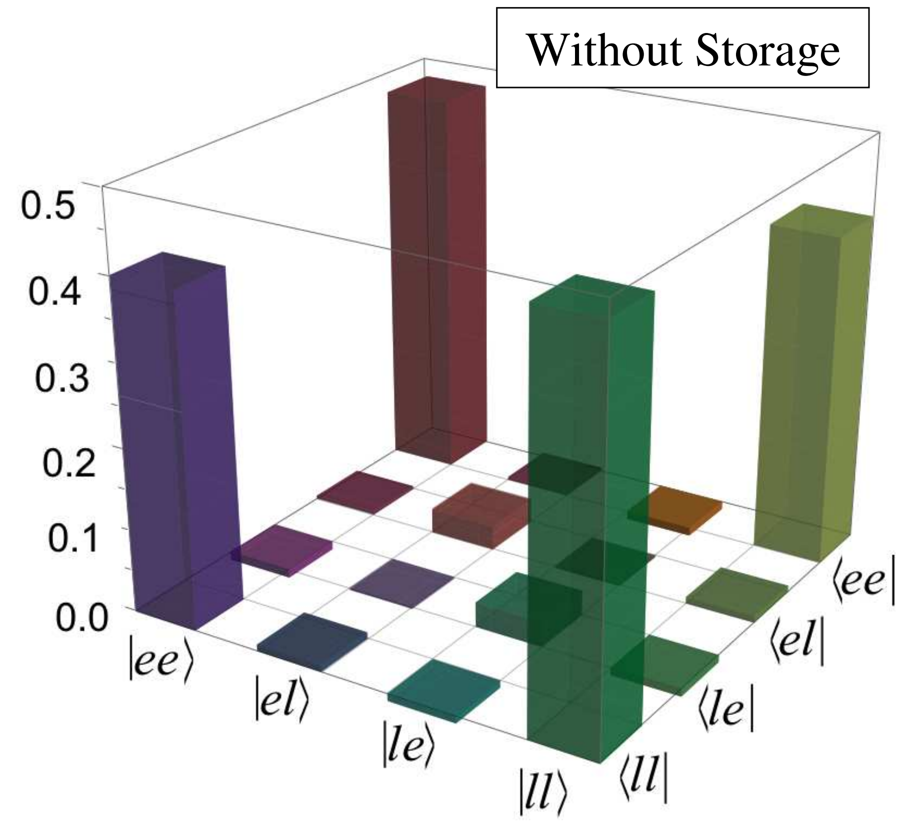


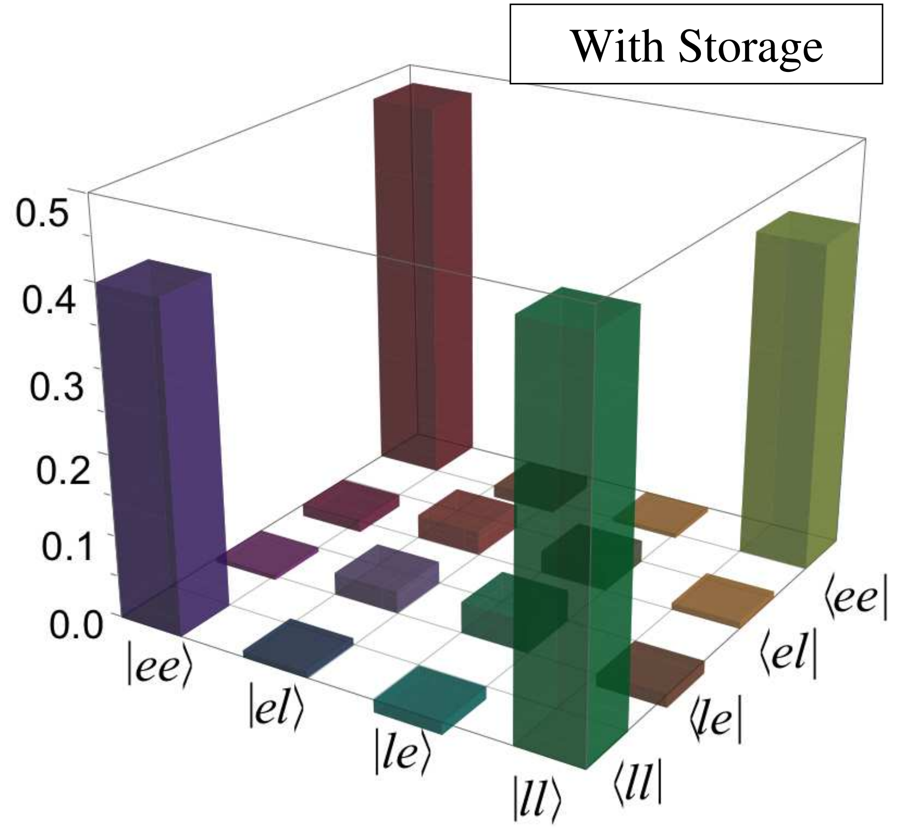
i.e. $\sigma_x \otimes \sigma_x,\ \sigma_x \otimes \sigma_y,\ \sigma_x \otimes \sigma_z, \ldots$

- Qubit Analyzers allow projection measurements onto , i.e. σ_z

 and other superposition bases i.e. σ_x, σ_y

Density Matrices





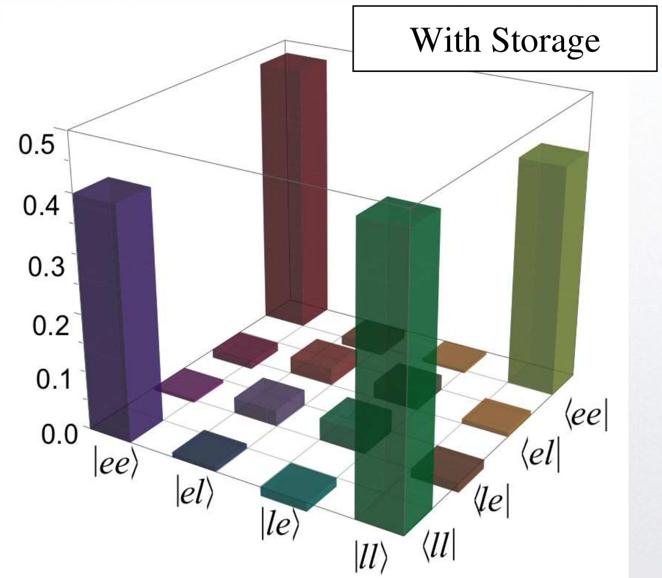
(all imaginary components are < 0.04 and are not shown)

Density matrices allow for a quantitative comparison of the quantum state with and without storage

Results

	Entanglement of formation	With-Without Fidelity	Purity	Fidelity with $\|\varphi^+>$	CHSH-Bell Parameter S (measured)
$\rho_{without}$	0.644±0.042	0.954±0.029	0.757±0.024	0.862±0.015	2.379±0.034
ρ_{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 ($S_{LHV} \leqslant 2$)

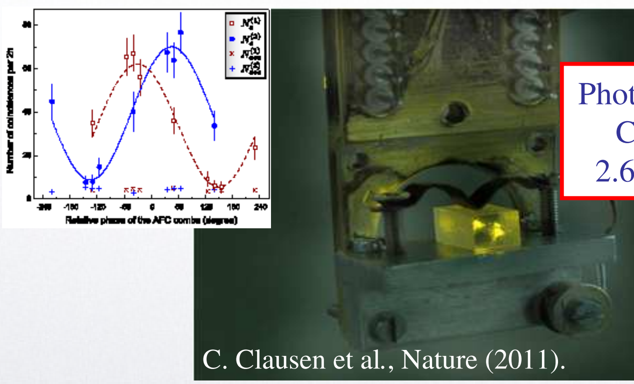


Saglamyurek, N.S. et al, Nature (2011)

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

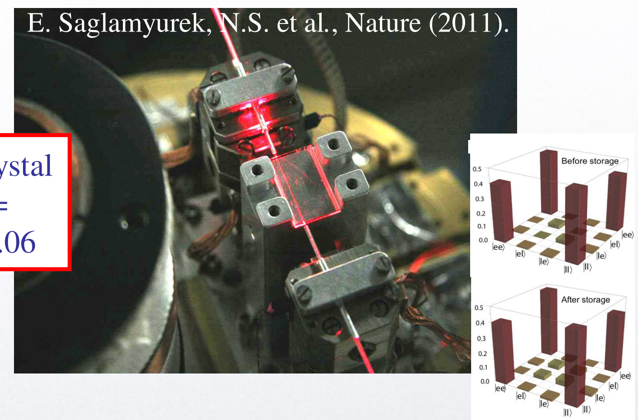


C. Clausen et al., Nature (2011).

Photon-Crystal
CHSH =
2.64 ± 0.23

Photon-Crystal
CHSH =
2.25 ± 0.06

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


Wolfgang Tittel
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Jeongwan Jin
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CRSNG
CORE
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Thank you

Félix Bussières

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Neil Sinclair

Erhan Saglamyurek

Jeongwan Jin

Wolfgang Tittel

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