Solid-state quantum memories for quantum repeaters

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N. Sangouard, M. Afzelius, N. Gisin

11 September 2012

Quantum communication at a distance

State of the art from **field** experiments

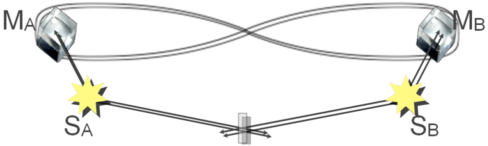
- Fibre length $\sim$ 150 km *
  (250 km in the lab)
- Losses of 43 dB (0.29 dB/km)
- Base frequency $>$ 300 MBits/s
- Secret bit key rate of 2.5 bits/s

Longer distances require new technologies : quantum repeaters and quantum networks

Stucki et al, Optics Express, **17**, 13326 (2009)

Quantum repeater

Creating entanglement



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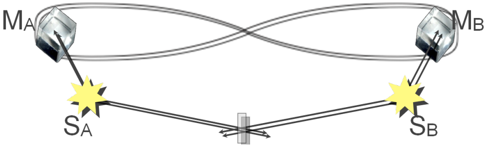
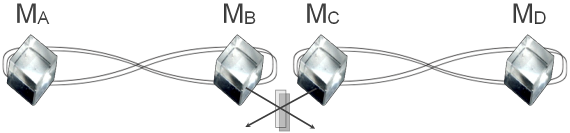


Entanglement swapping



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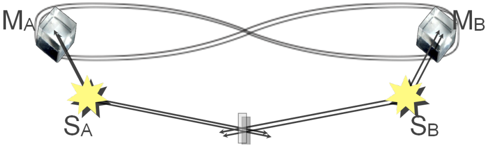

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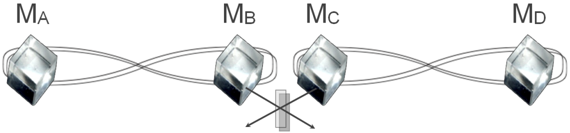
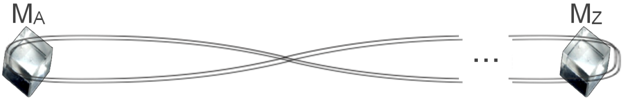


Increasing the distance.



Quantum repeater:ingredients

- Efficient, long lived and multimode quantum memories
- Efficient quantum sources adapted to the memory bandwidth
- Efficient single photon detectors

Quantum memories in rare earth doped crystals

- Weak interaction with crystal environment.
    - "Atom" like energy structure on the 4f-4f transitions
    - "Frozen gas" of ions, no motional decoherence
- High number of stationary ions $(10^7 - 10^{10})$
- Long optical coherence times (T$<$ 4K), T_2^{opt} from μs-ms
- Long hyperfine coherence times (T$<$ 4K), T_2^{hyp} from ms-s
- Large optical inhomogeneous broadening 100 MHz $-$ 10 GHz
- Light storage times great than 1 s *

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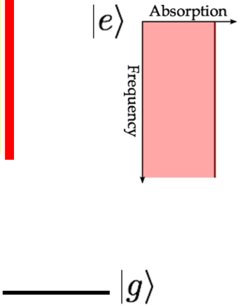
As quantum memories:

- 69 % storage efficiency**

* Longdell et al, PRL, 95, 06301 (2005), **Hedges et al, Nature 465, 1052 (2010)

Quantum memory: AFC technique



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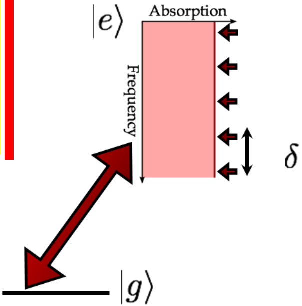

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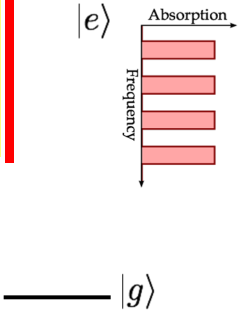
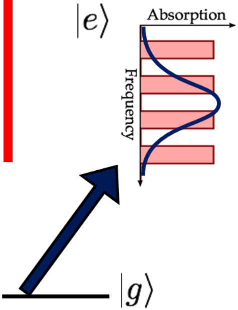


Quantum memory: AFC technique

State after absorption

$$\sum_{k=1}^{N} c_k |g_1 g_2 .... e_k ... g_N\rangle$$



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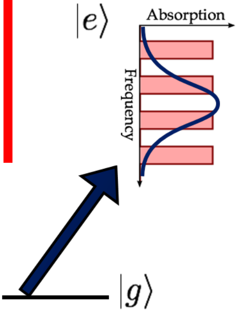

State after absorption

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Dephasing occurs:

$$\sum_{k=1}^{N} c_k e^{-\delta_k t} |g_1 g_2 .... e_k ... g_N\rangle$$

$$\delta_k = m_k \Delta$$

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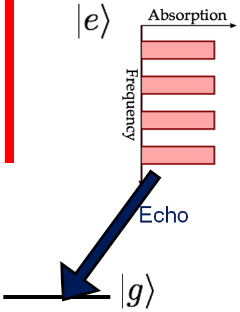

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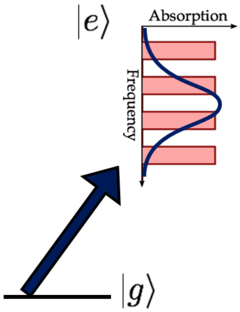
Rephasing after a time $t_e = \frac{2\pi}{\Delta}$
Collective emission in the forward mode. Photon echo like emission.

Afzelius et al, PRA, **79**,052329 (2009)

Full AFC scheme



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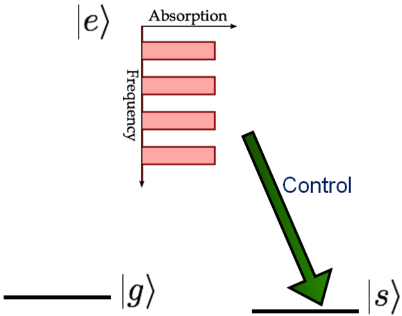

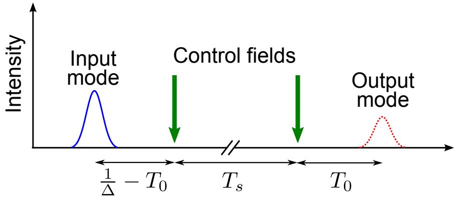

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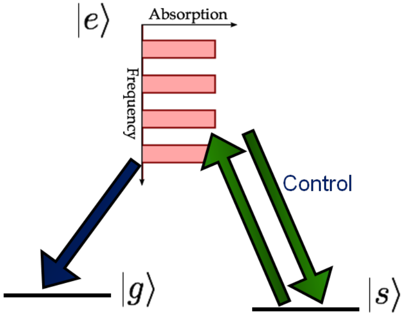

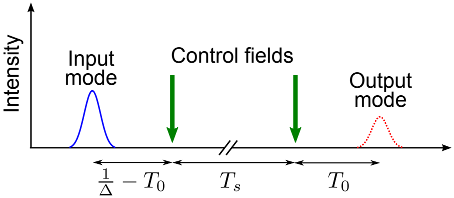

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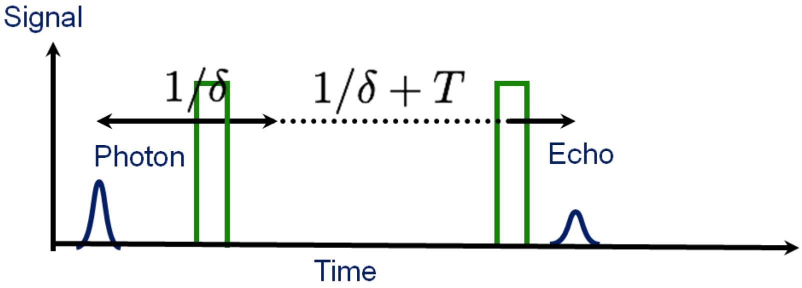
Multimode memory



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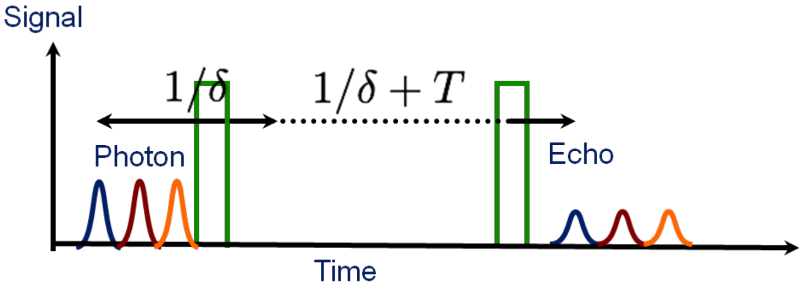
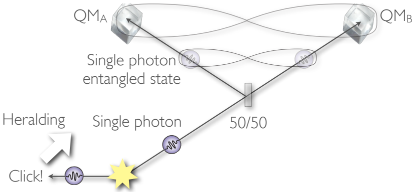


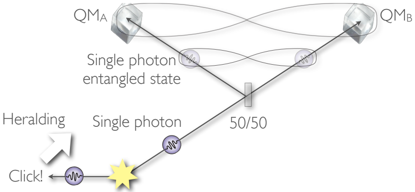
Outline

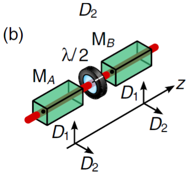
- Heralded entanglement of two crystals



Outline

- Heralded entanglement of two crystals
- Storing polarization entanglement





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- Heralded entanglement of two crystals
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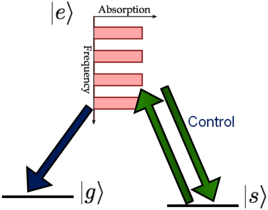
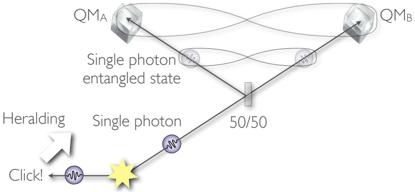
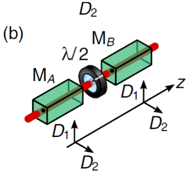
- Long storage times in an on demand memory.







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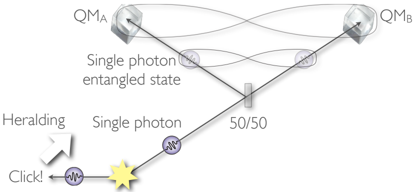
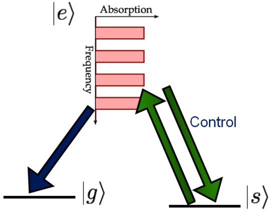
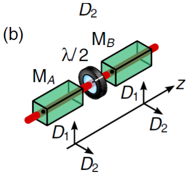
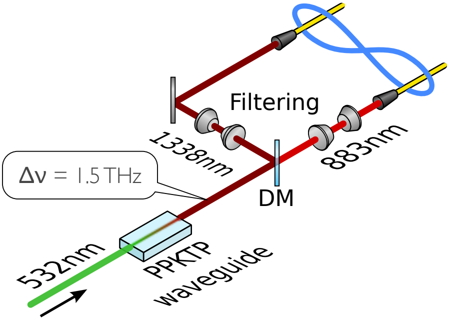
- **Heralded entanglement of two crystals**
- Storing polarization entanglement
- Long storage times in an on demand memory.

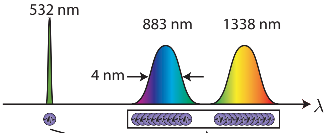






Photon pair source





Clausen et al, Nature, **469**,508 (2011)

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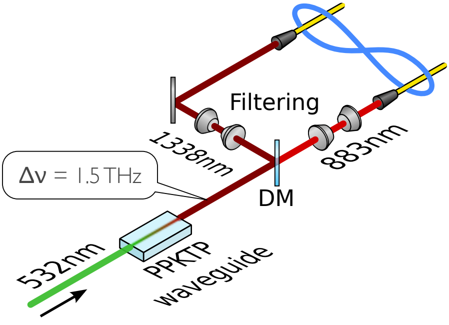

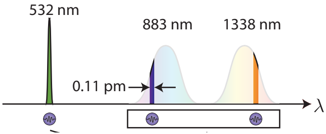

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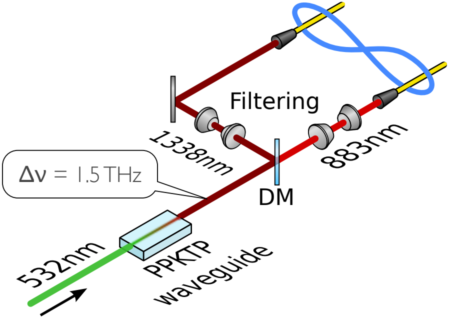

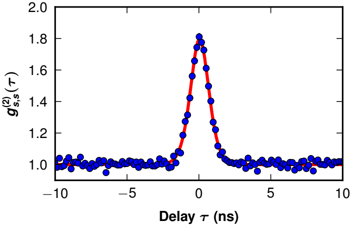

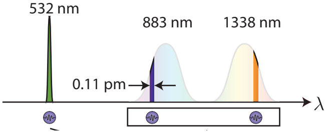

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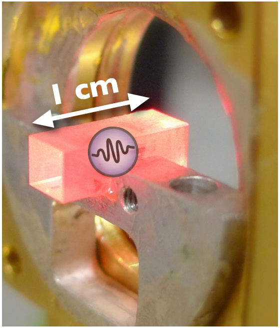
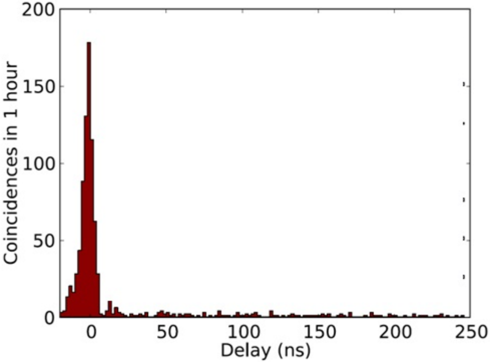
The memory

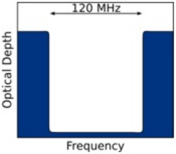


- Crystal : Nd^{3+}:Y_2SiO_5 (@ 3 K)
- $^4I_{9/2} \rightarrow {}^4F_{3/2}$ (883 nm, $\Gamma_{inh} = 6$ GHz)
- $B_{ext} = 300$ mT (Zeeman split)
- AFC $1/\Delta$ from 30 ns to 1 μs

Clausen et al, Nature, **469**,508 (2011)

Heralding stored photon in the memory





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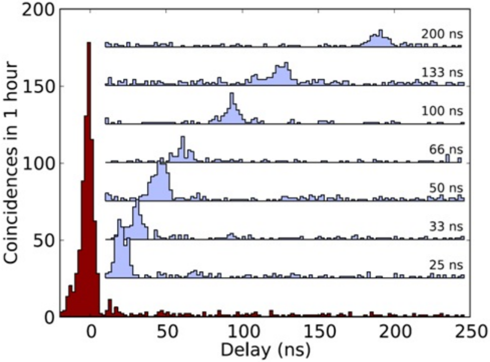

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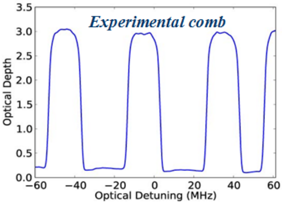
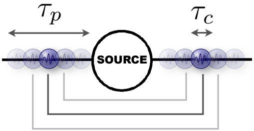


Storing photonic entanglement



Energy time entanglement

- Both photons are created simultaneously (τ_c)
- Creation time is uncertain (τ_p)

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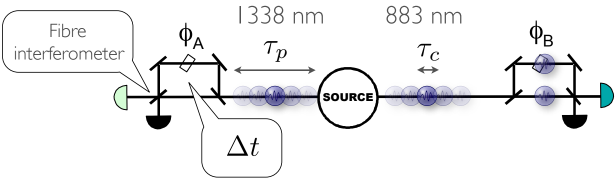

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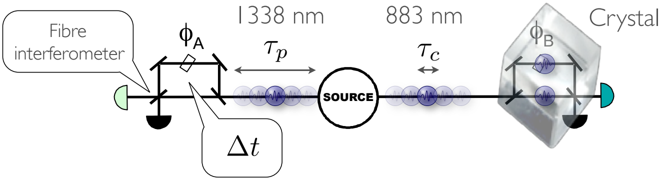

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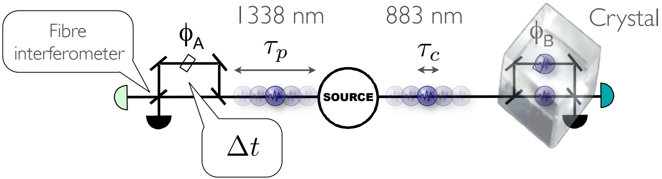
Bell- CHSH inequality

- $S_{CHSH} \leq 2$ (Local bound)
- $S_Q = 2\sqrt{2}$ (Quantum bound)
- $S_{exp} = 2.64 \pm 0.23$

Storing photonic entanglement



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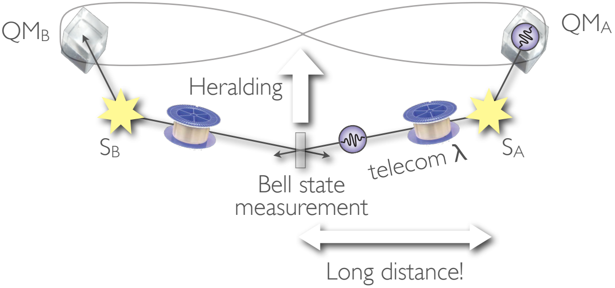
Similar work in: Saglamyurek et al, Nature, **469**, 512 (2011)

Entangling two crystals

$$|\Psi\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|1\rangle_A|0\rangle_B + e^{i\phi_{AB}}|0\rangle_A|1\rangle_B\right)$$



QM$_B$

QM$_A$

Heralding

S$_B$

S$_A$

telecom λ

Bell state measurement

Long distance!

Entangling two crystals

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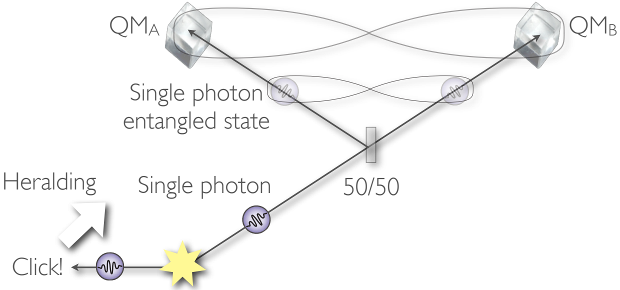

- **Prior work** Nature **438**, 828 (2005), PRL **99**, 180504 (2007), Nature **452** 67 (2008), Polzik group (2001), Vuletic group (2007)
- **Related work** Science **334** 1253, (2011)

Entanglement?

- Ideal state : $\frac{1}{\sqrt{2}}(|1\rangle_A|0\rangle_B + |0\rangle_A|1\rangle_B)$
- Actual state:

$$\begin{pmatrix} p_{00} & 0 & 0 & 0 \\ 0 & p_{01} & d & 0 \\ 0 & d^* & p_{10} & 0 \\ 0 & 0 & 0 & p_{11} \end{pmatrix}$$

- $C \geq \max(0, V(p_{01} + p_{10})) - 2(p_{11} p_{00})^{\frac{1}{2}})$

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✓ Single excitation terms

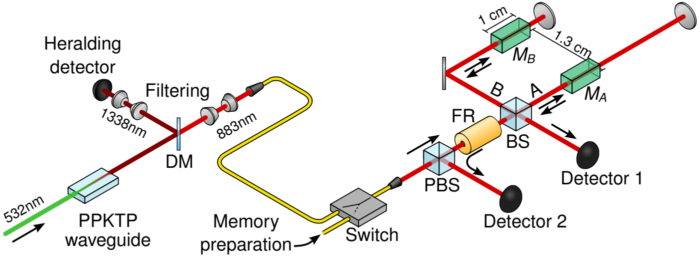
✓ Single excitation coherence

x Loss

x Two-photon term

Chou et al, Nature, **438**, 828 (2005)

Experiment to entangle two crystals

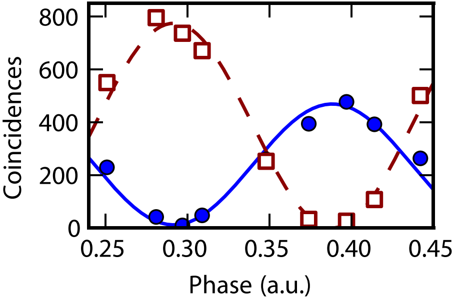


I Usmani et al, Nature Photonics, **6**, 234 (2012)

State tomography

$$C \geq \max(0, V(p_{01} + p_{10}) - 2\sqrt{p_{11} p_{00}})$$

- Lock and scan the interferometer to measure the visibility



- $V = 96.5 \pm 1.2\%$.
- Not enough to demonstrate entanglement.

I Usmani et al, Nature Photonics, **6**, 234 (2012)

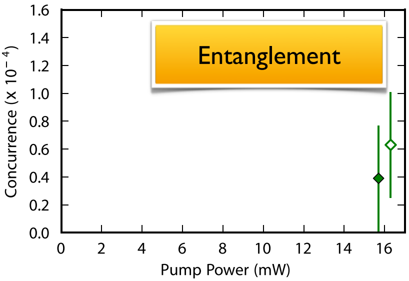
State tomography

$$C \geq \max(0, V(p_{01} + p_{10})) - 2(p_{11} p_{00})^{\frac{1}{2}})$$

- The interferometer was let drift over 166 hours, where 2 threefold coincidences were measured

Results:

- $p_{01} + p_{10} = 1.7777(34) \times 10^{-4}$
- $p_{00} = 0.999822$
- $p_{11} = (2.9 \pm 2.1) \times 10^{-9}$
- $V = 96.5 \pm 1.2\%$
- $C \geq (6.3 \pm 3.8) \times 10^{-5}$



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State tomography

Conservative assumption two-mode squeezed state → p_{11}

Results:

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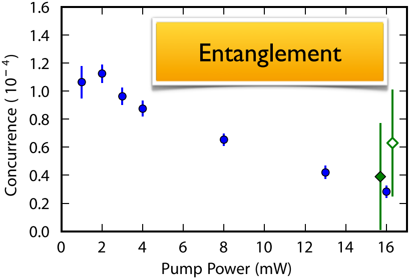
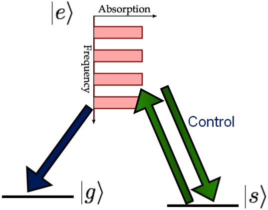


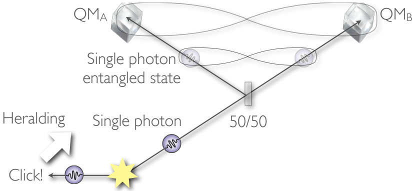
10^6 faster to get some statistics!

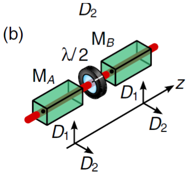
I Usmani et al, Nature Photonics, **6**, 234 (2012)

Outline

- Heralded entanglement of two crystals
- **Storing polarization entanglement**
- Long storage times in an on demand memory.



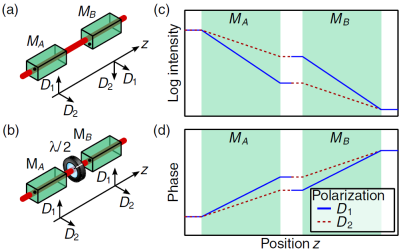




Storing polarization entanglement

- Crystals have two different indices of refraction in xy (d_1, d_2)
- Crystals have two absorption coefficients in xy (d_1, d_2)

It is necessary to compensate for these effects



C Clausen et al, PRL, **108**, 190503 (2012)

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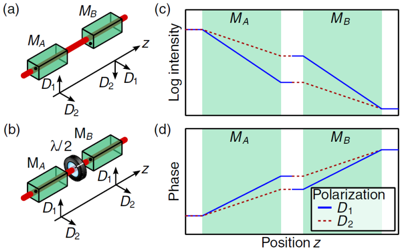

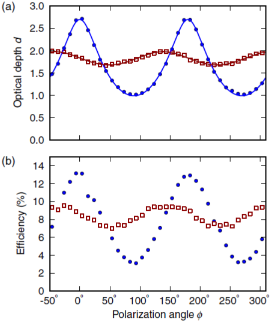

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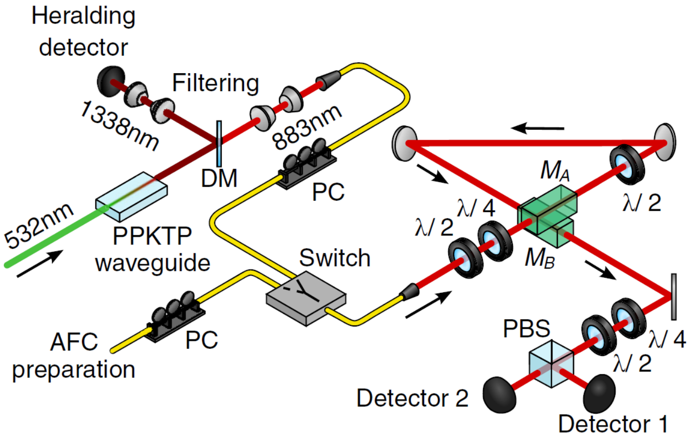

Auto correlation before storage $g^{(2)}_{s|i} < 0.06$

C Clausen et al, PRL, **108**, 190503 (2012)

Storing polarization entanglement

Input state	Fidelity	$\bar{g}_{si}^{(2)}$
$\vert H\rangle$	99.3(6)%	7.6(3)
$\vert V\rangle$	97(1)%	6.0(3)
$\vert L\rangle$	97.7(6)%	9.4(3)
$\frac{1}{\sqrt{2}}(\vert H\rangle + \vert V\rangle)$	95(1)%	8.0(3)
$\alpha\vert H\rangle + \beta\vert V\rangle$	98.7(9)%	9.2(3)

Similar work with weak coherent states in:

- Gündogan et al et al, PRL, **108**, 190504 (2012)
- Zhou et al, PRL, **108**, 190505 (2012)

C Clausen et al, PRL, **108**, 190503 (2012)

Outline

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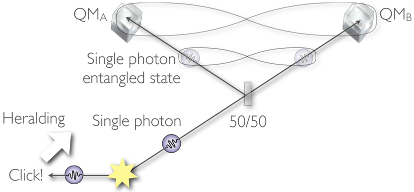
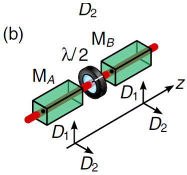
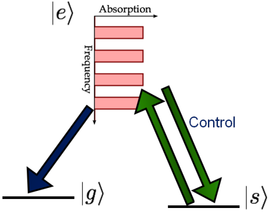
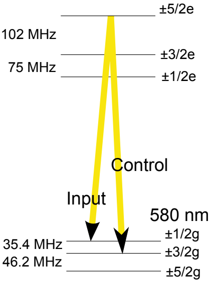






Candidate: Europium

- Our sample (10 ppm) has an optical depth of 1.5 cm^{-1} and an inhomogeneous linewidth of 500 MHz
- The spin coherence time for ^{151}Eu $\sim$ 15 ms ($B = 0$)



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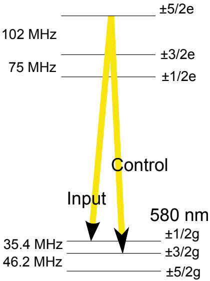
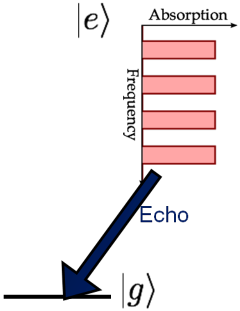
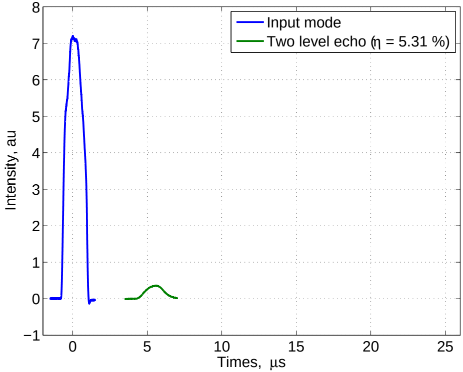


- Optical depth of the input transition is 1 cm^{-1}
- Really good for a longlived multimode memory!

Two level echo



Two level echo efficiency



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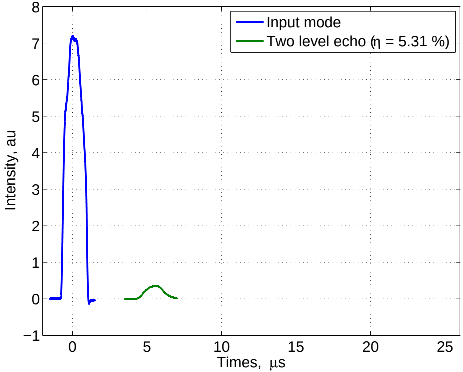
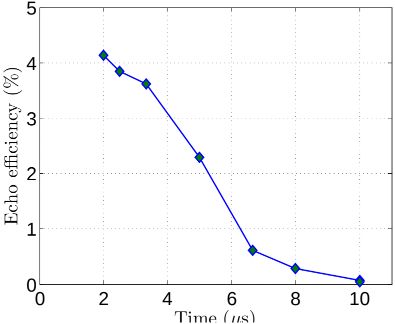


Comb spacing of 200 kHz → 5 μs AFC

Laser linewidth limitation



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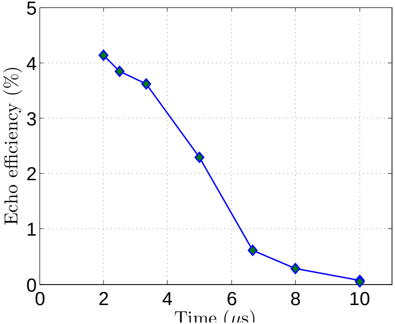
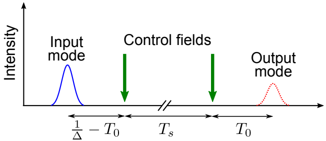
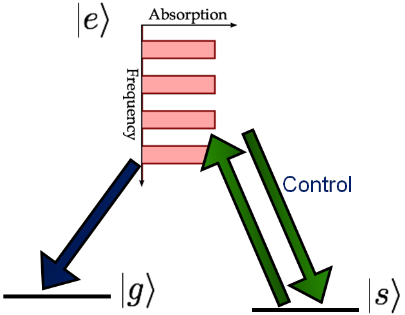




Afzelius et al, PRA, **79**,052329 (2009)

Spin wave storage



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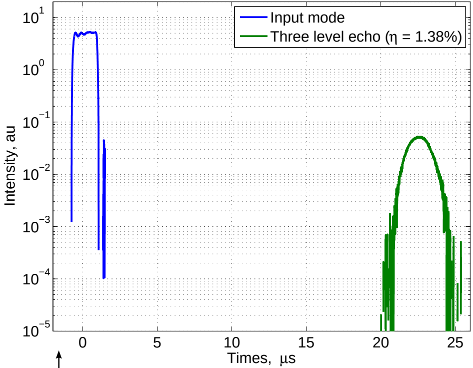

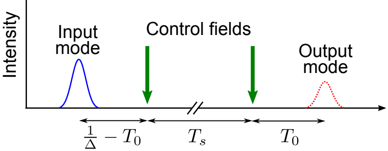

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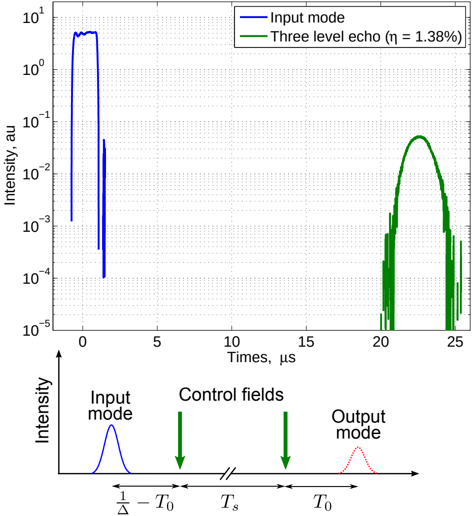
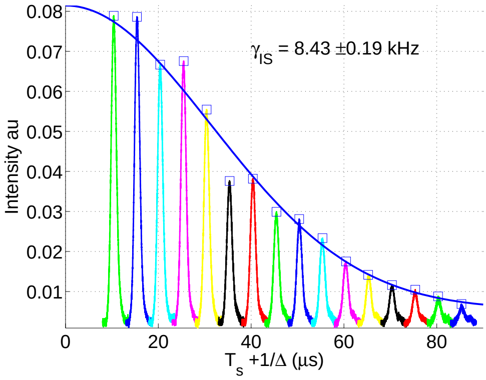


- Using square non chirped pulses estimate transfer efficiencies to be almost 50 %

Inhomogeneous spin linewidth



$$\text{Echo height} = Ae^{\left(\frac{-t^2\gamma_{IS}^2\pi^2}{2ln2}\right)}$$

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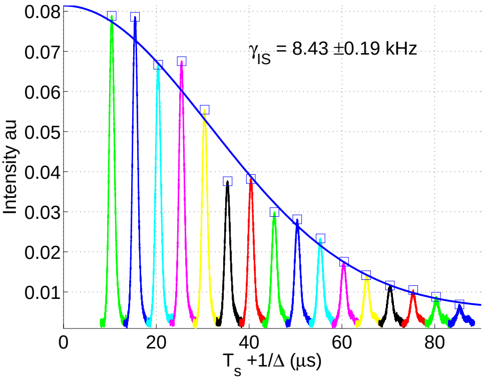

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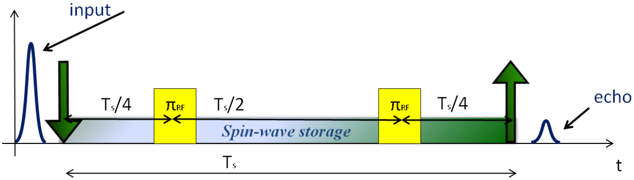
- Possible to use spin echo techniques to increase the lifetime *

* Longdell et al, PRL, **95**, 063601 (2005)

Overcoming inhomogeneous spin linewidth



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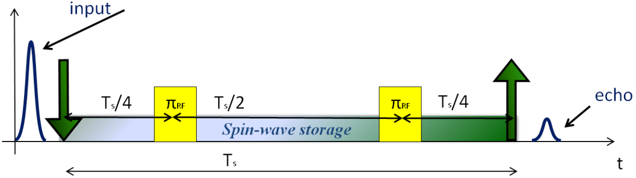

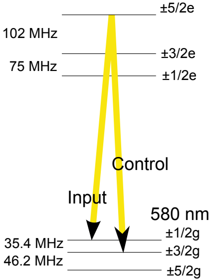

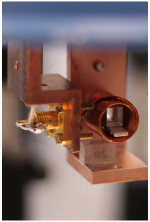

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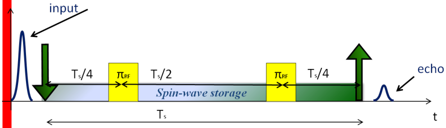
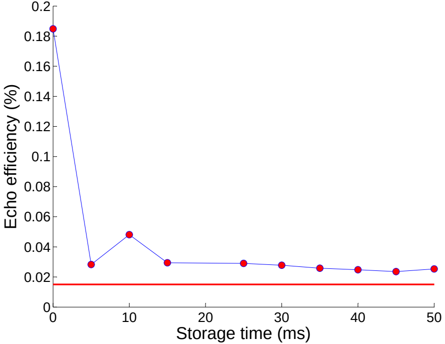


- Preliminary results
- Storage time of optical pulse for 50 ms!



- Oscillation a quantum beat phenomenon?

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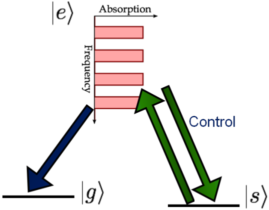

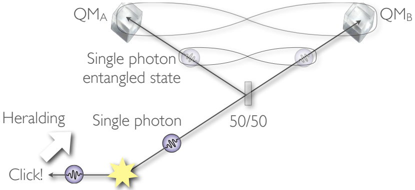

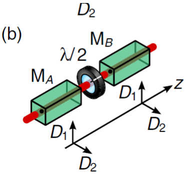

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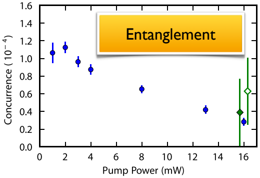

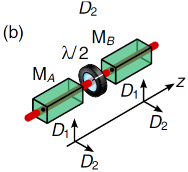

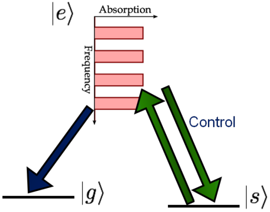

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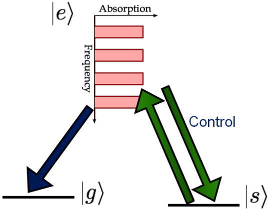

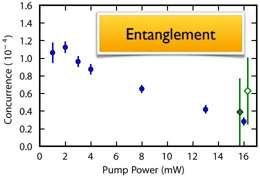

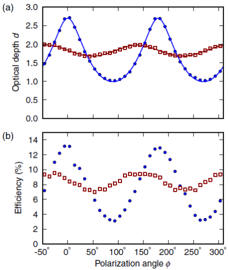

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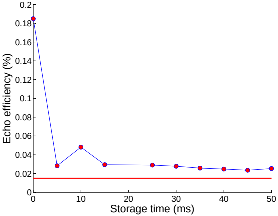

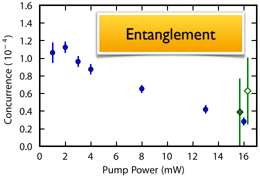

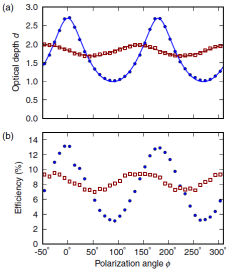

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- Our long term goal is to make and elementary quantum repeater link as a long a distance as we can!

Thank you

QuReP

QSIT Quantum Science and Technology

MARIE CURIE ACTIONS

Marie Curie Initial Training Network
Coherent Information Processing
in Rare-Earth Ion Doped Solids

QESSENCE

erc

We are grateful to Y Sun, R L Cone and RM Macfarlane for kindly lending us the $^{151}Eu^{3+}$ doped Y_2SiO_5crystal.