

Storage of entangled telecom-wavelength photons in an Er-doped optical fiber

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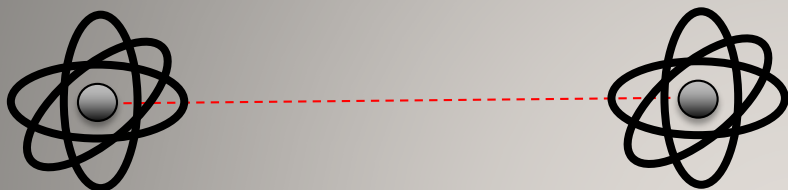
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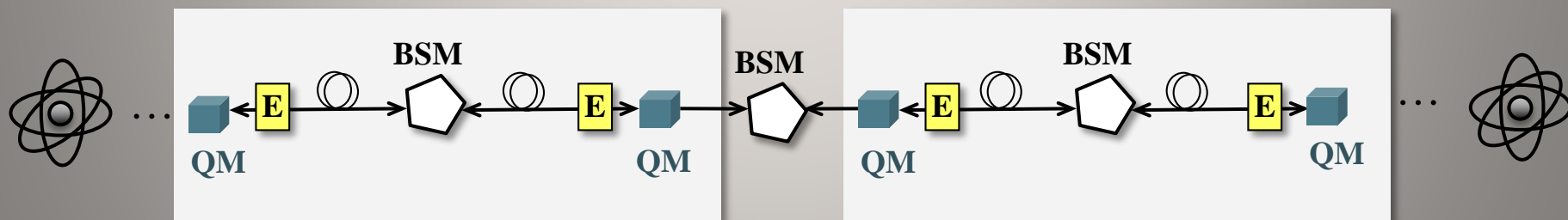
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Problem: amplification (Er-doped fibres) impossible

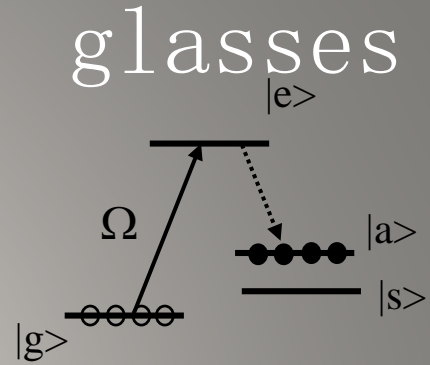
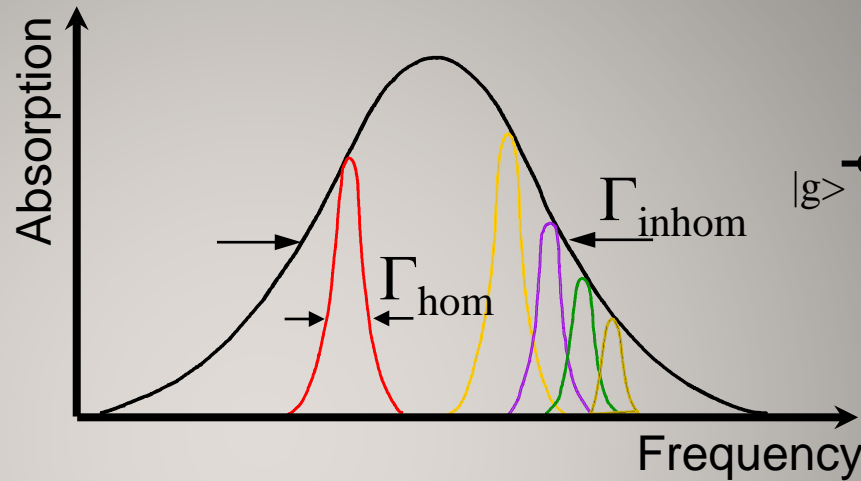
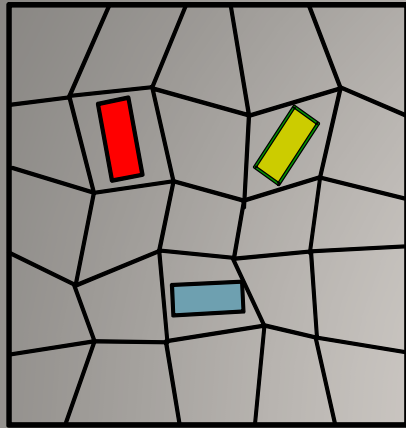
Solution: quantum repeater



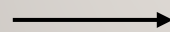
Desirable: fibre-based QM
operating at telecom wavelength

~ 100 km

Rare-earth-ion doped crystals and glasses



Stress and defects

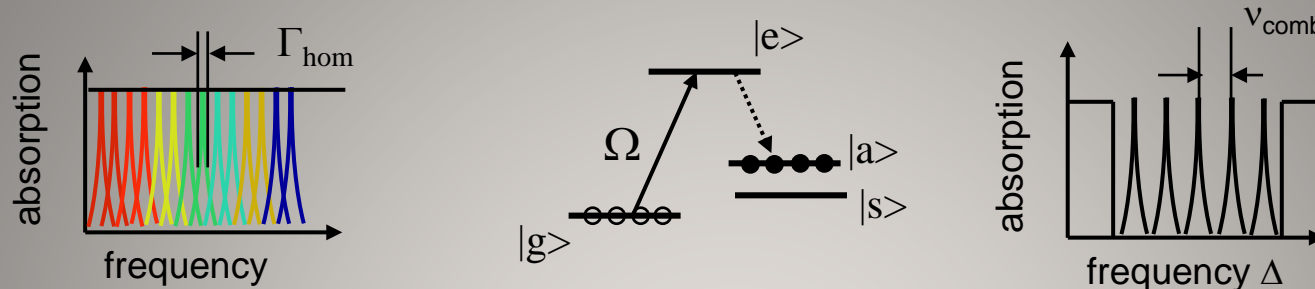


Inhomogeneous broadening

- naturally trapped emitters with free atom like spectra
- transitions at visible and telecom wavelengths
- at <1 K & (large) B: $\Gamma_{\text{hom}} \approx 50$ Hz – 100 kHz, $T_2 \sim 3$ μ s – 6 ms
- spin coherence \gg sec
- $\Gamma_{\text{inhom}} \approx 500$ MHz – THz
- possibility to burn persistent spectral holes

Photon-echo quantum memory (AFC)

1. Preparation of an atomic frequency comb



2. Absorption of a photon -> fast dephasing

$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^N c_j e^{-i2\pi\Delta_j t} e^{ikz_j} |g_1 \dots e_j \dots g_N\rangle$$

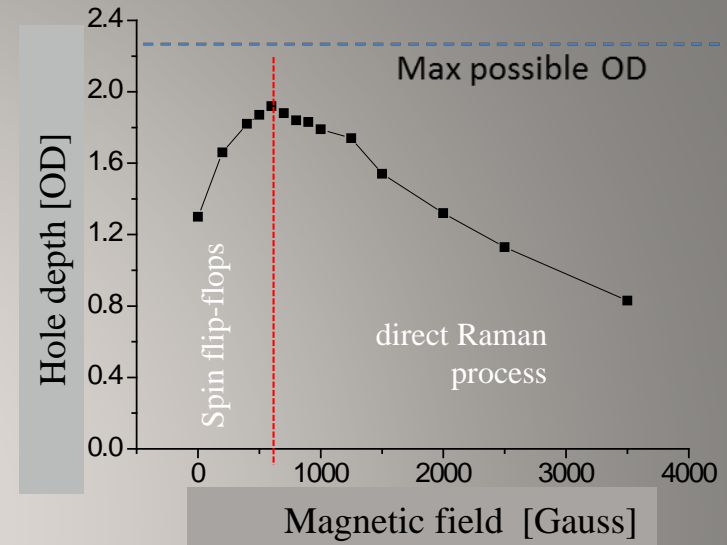
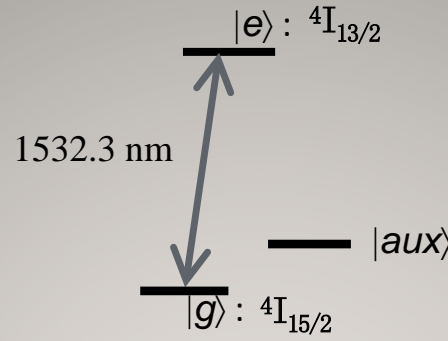
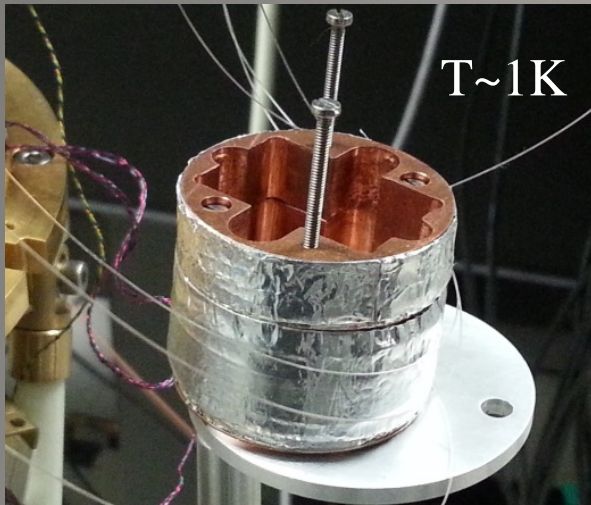
Experiments:
Geneva, Lund, Paris,
Calgary, Barcelona,
Hefei

3. Rephasing at $t_R = 1/v_{\text{comb}}$ with $2\pi\Delta_j t_R = m 2\pi$

- Storage and re-emission of light with unity efficiency and fidelity
- Multi-qubit storage
- Spin-wave mapping allows on-demand recall of temporally multiplexed qubits
- Addition of standard optical elements allows feed-forward controlled readout of frequency-multiplexed qubits

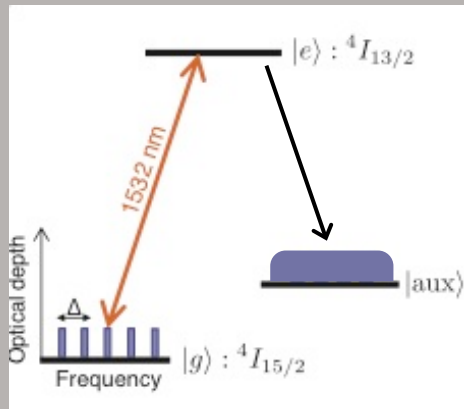
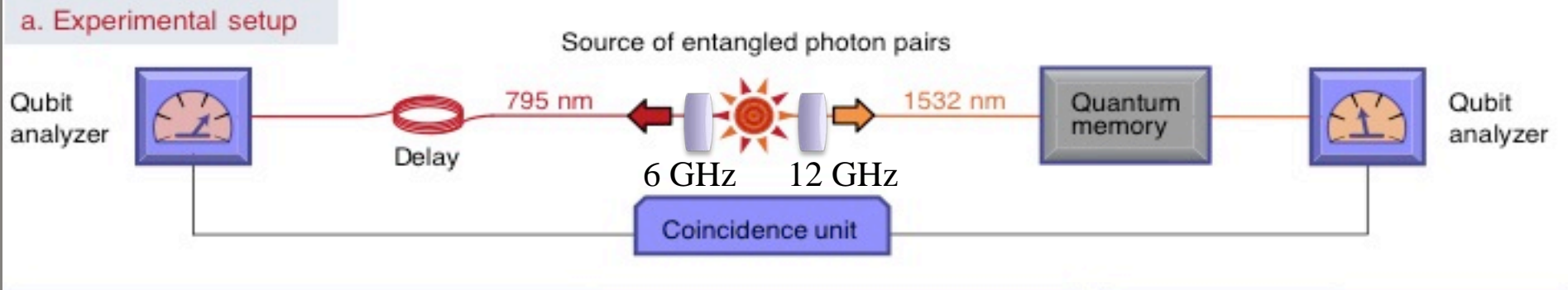
Efficient persistent spectral hole burning in Er-doped crystals or fibres not yet shown

Er: silicate fibre

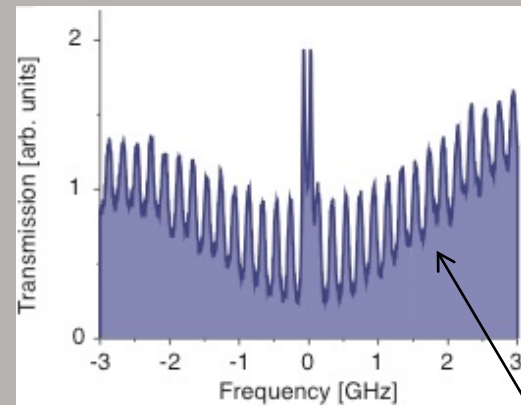


- Commercially available
- 1532 nm zero-phonon absorption line, $\Gamma_{\text{hom}} \sim 100$ kHz @ 0.1K
- Small, polarization-independent optical depth ($\alpha \sim 0.6/\text{m}$ @ 1K & 1532 nm)
- Persistent spectral hole burning ($T_1 = 1.5\text{s} - 45\text{s}$) through optical pumping into electronic Zeeman levels @ $B \sim 600\text{G}$ & $T \sim 1\text{K}$ with 85% efficiency
- Fibre length: 20m
- Simple (and low-loss) splicing to standard telecommunication fibres

$|\phi^+\rangle = \frac{1}{\sqrt{2}}(|e,e\rangle + |l,l\rangle)$ Experimental setup



8 GHz wide AFC
 →
 5 ns storage with 1% efficiency



Experimental cycle



prepare AFC

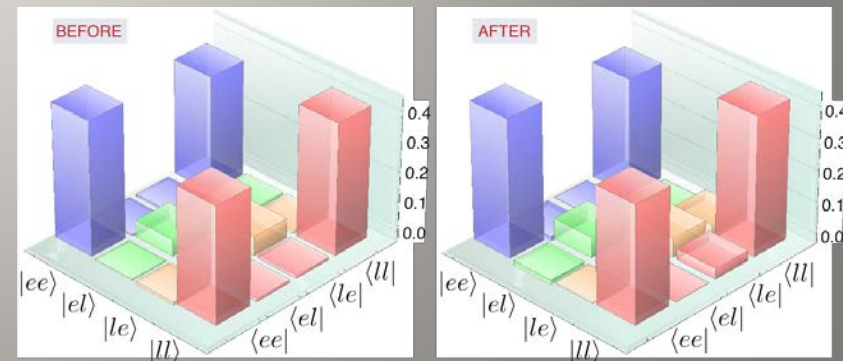
wait

store, recall & measure

Results

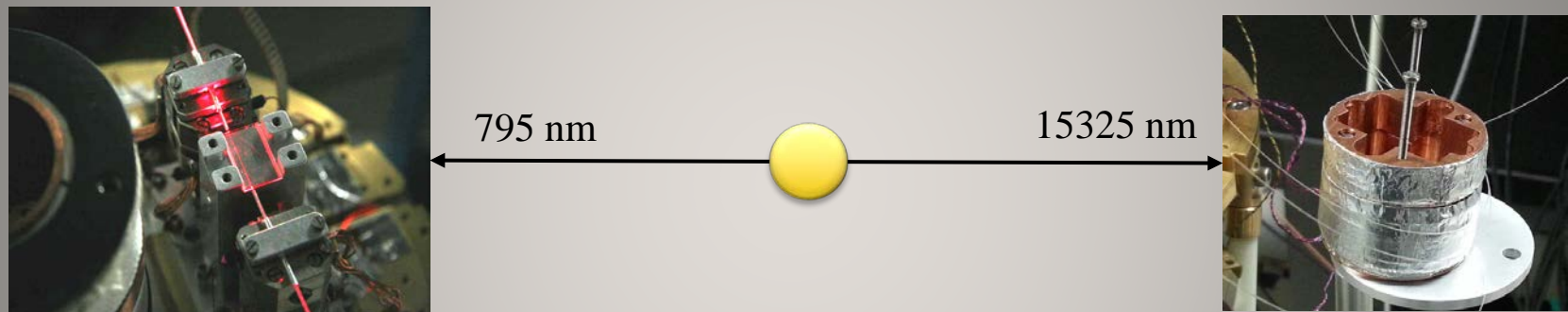
	Entanglement of formation	Input-Output Fidelity	Purity	Fidelity with $ \phi^+\rangle$	CHSH-Bell parameter S
ρ_{in}	0.531 ± 0.011	0.971 ± 0.049	0.694 ± 0.07	0.824 ± 0.04	2.38 ± 0.05
ρ_{out}	0.499 ± 0.105		0.673 ± 0.047	0.808 ± 0.048	2.33 ± 0.22

- no measurable degradation of (post-selected) entanglement during storage
- experimental violation of CHSH Bell inequality ($S_{LHV} \leq 2$)
- important step towards fibre-based memories for telecom photons, but more work required to increase efficiency and storage time



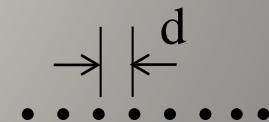
Outlook

- Possibility to entangle different QMs



- New tests of quantum/classical transition.

Does the (entangled) Dicke state break down if $d \rightarrow \lambda$?



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Collaborators:

- S.W. Nam & V.B. Verma (NIST)
- F. Marsili & M.D. Shaw (JPL)

