Long distance quantum communication using quantum memories having on-demand recall in the frequency domain

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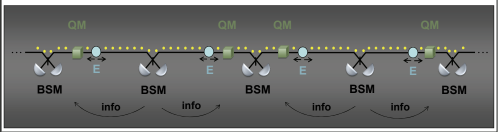
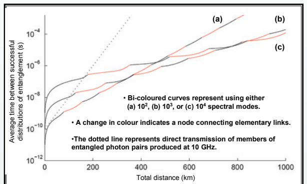
Qc2Lab quantum cryptography and communication

Motivation

- Optical quantum memories are devices that *simultaneously* store and recall many photonic quantum states *on-demand* [1].
- They are required for synchronization in quantum information applications such as quantum computation, quantum networking and *long-distance quantum communication* using quantum repeaters [2,3].
- Quantum repeaters also require sources of photonic entanglement, Bell-state measurements (BSMs), and classical communication.
- The goal of a quantum repeater is to swap entanglement to the ends of a long channel, and to do so at a high rate.
- Sources of entanglement are designed to release multiplexed (or multi-mode) entangled pairs in order increase distribution rates [3].
- Quantum memories store at least one member of an entangled photon pair until a classical signal announces that a successful BSM has succeeded with the other member. With this information the memory will synchronize its stored photon for a BSM.
- For time-bin encoding, a 50:50 beam splitter and two single photon detectors are used for the BSM [3].

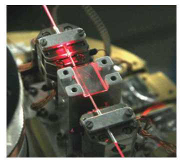


Simulation of repeater performance

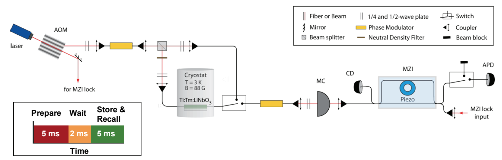


- To generate each curve, the *distribution time is minimized* while keeping *memory bandwidth* fixed to 500 GHz. Hence number of *spectral modes* sets entangled pair generation rate.
- Useful performance already achieved with 100 modes- feasible in near future.
- Fewer number of modes results in shorter elementary links. Hence more nodes per km are needed, leading to a reduction in efficiency. More modes allows longer elementary links but with lowered photon generation rates due to bandwidth limits.
- Other assumptions: fibre loss of 0.2 dB/km, max. entangled time-bin qubits, 90% efficient memories and single photon detectors (zero dark counts), storage times set by link distance (e.g. 500 μs for 100 km link), 50% BSM probability.

Setup



$Ti:Tm:LiNbO_3$ waveguide butt-coupled using single-mode fibres and piezo-driven translation stages, and held at 3 Kelvin in cryostat.



Atomic frequency comb (AFC) based on quantum memory in *$Ti:Tm:LiNbO_3$* is well suited for simultaneous frequency storage:

- Zero phonon line > 300 GHz [4].
- AFC bandwidth up to 20 GHz.
- Hole burning using long-lived Zeeman sub-levels [5].
- On-demand recall w.r.t. time domain not compatible with Tm-doped materials.
- AFC, phase modulator [7] and monolithic cavity (MC) [8] used for read out on demand.

- AOM carves, from a c.w. 795 nm laser, AFC preparation pulses of 5 ms duration, or pairs of 10 ns-duration pulses, with pulses separated by 20 ns.
- A phase modulator shifts frequency of preparation pulse to generate twenty-six 100 MHz-wide AFCs (each separated by 200 MHz gap). Each AFC is programmed to provide 60 ns storage time.
- A variable number of spectrally multiplexed time-bin qubits, encoded into pulse pairs comprising on average 0.5, 0.1 or zero photons at the entrance of the cryostat, are generated simultaneously using sinusoidal modulations of the phase modulator and an attenuator.
- Storage and retrieval of a specific qubit consists of *reversibly mapping* all qubits to the AFCs followed by *frequency shifting* with phase modulator and *filtering* with MC.
- Projection measurements are performed by an Si-APD-based single photon detector (APD), or a Mach-Zehnder interferometer (MZI) folllowed by an APD. This yields the storage (and recall) fidelity.

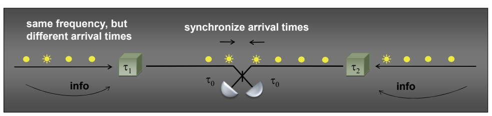
Temporal vs. spectral multiplexed quantum repeaters

Temporal multiplexing

- Entangled photons created with *same spectrum*, but generated at *different times.*

Temporally on-demand

- Retrieve photons in *certain temporal modes*, and *equalize arrival time of photons* coming from neighboring memories on beam splitter for BSM [3].



Spectral multiplexing

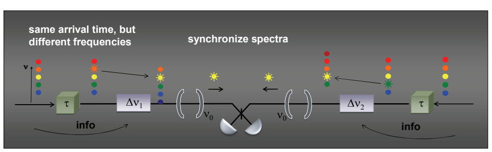
- Entangled photons generated at the same *time*, but have *different spectra*.

Spectrally on-demand

- Retrieve photons in *certain frequency modes*, and *equalize spectra of photons* coming from neighboring memories on beam splitter for BSM.

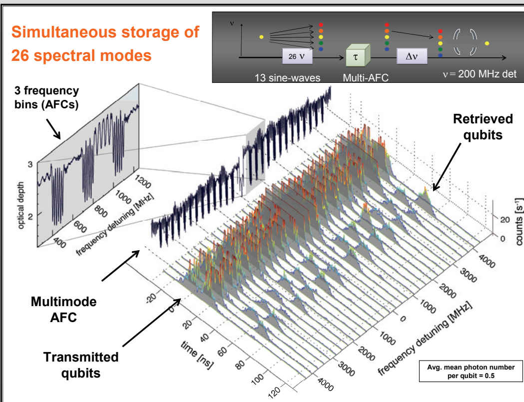
This *new approach* is based on having:

- Memory storage times pre-set depending on distance photons are sent.
- Storage followed by frequency shifting and spectral filtering.



Demonstration of multimode storage and retrieval on demand

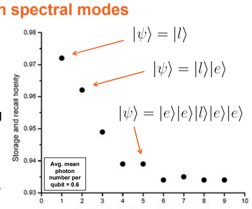
Simultaneous storage of 26 spectral modes



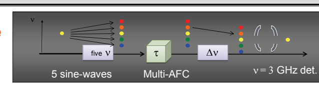
- 26 qubits are prepared simultaneously in separate spectral, and alternating temporal, modes.
- All qubits are stored for 60 ns and then individually retrieved.
- No AFCs prepared at ± 150 and ± 4350 MHz detuning; no recall observed.
- Cross-talk between qubits in adjacent spectral modes is hardly visible.

Measurement of cross-talk between spectral modes

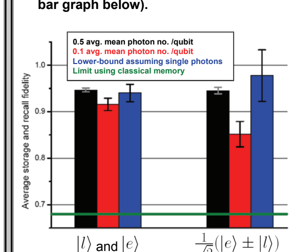
- Single 'test' qubit is created in *late* state. The storage fidelity is assessed.
- The number of simultaneously stored qubits is increased by adding orthogonal early states one-by-one into neighbouring spectral bins. The storage and retrieval fidelity of the test qubit is assessed each time an early state is added.
- Cross-talk limited to coming from *nearest and second-nearest neighbour.*



Measurement of storage and recall fidelity



- A 'test' qubit, at 1350 MHz detuning, and four orthogonal qubits occupying neighbouring spectral bins (see 26-mode figure) are stored simultaneously.
- Storage and recall fidelity is assessed and procedure repeated for test qubit prepared in *early or late (z-basis) states, or superpositions thereof (x-basis).*
- Measurements performed with qubits encoded into laser pulses of various mean values (0.5, 0.1 and zero photons per qubit).
- A decoy state method [9] allows calculation of a *lower-bound on the fidelity assuming a qubit was encoded into a single photon.*
- Average fidelity for both early/late and superposition bases is calculated (see bar graph below).



- Averaging fidelities over all (properly weighted) input states we find a lower bound of 0.97 ± 0.04 for the single photon fidelities,
- Violating the classical bound ($F_{clas.}$=2/3) (see bar graph) by 7.5 standard deviations.
- *First time storage and recall on demand of multimode (>2 mode) qubits is shown using a protocol (AFC) scalable w.r.t. multimode capacity.*

Sponsors

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