Light-matter interaction for photonic QIP and quantum communications

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National Research Council of Canada

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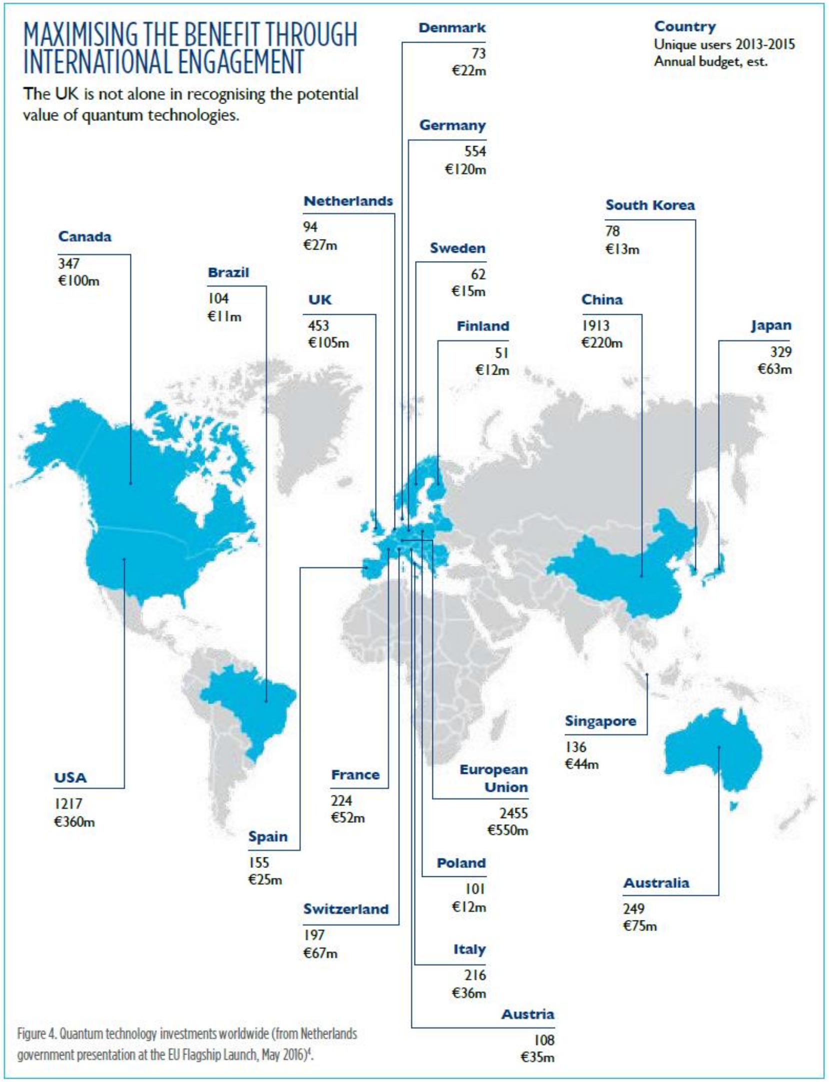
Quantum efforts around the globe



UK's Government office for science
The quantum age: technological opportunities

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Quantum light-matter interfaces

- **Mapping quantum states of photons to stationary qubits/matter** (atoms, artificial atoms, vibrational states of solids, …)
- **Manipulating photons while maintaining their quantum properties/states**, such as wavelength conversion, bandwidth manipulation, qubit conversion (e.g. time-bin to polarization)
- **Inducing non-linear interaction between photons for** non-destructive detection, two-qubit quantum gates, and preparing exotic states of photons or atoms (e.g. GHz states)

Application areas for quantum– Quantum Supremacy

- Quantum computation and simulation
- Quantum communications
- Quantum sensing and metrology

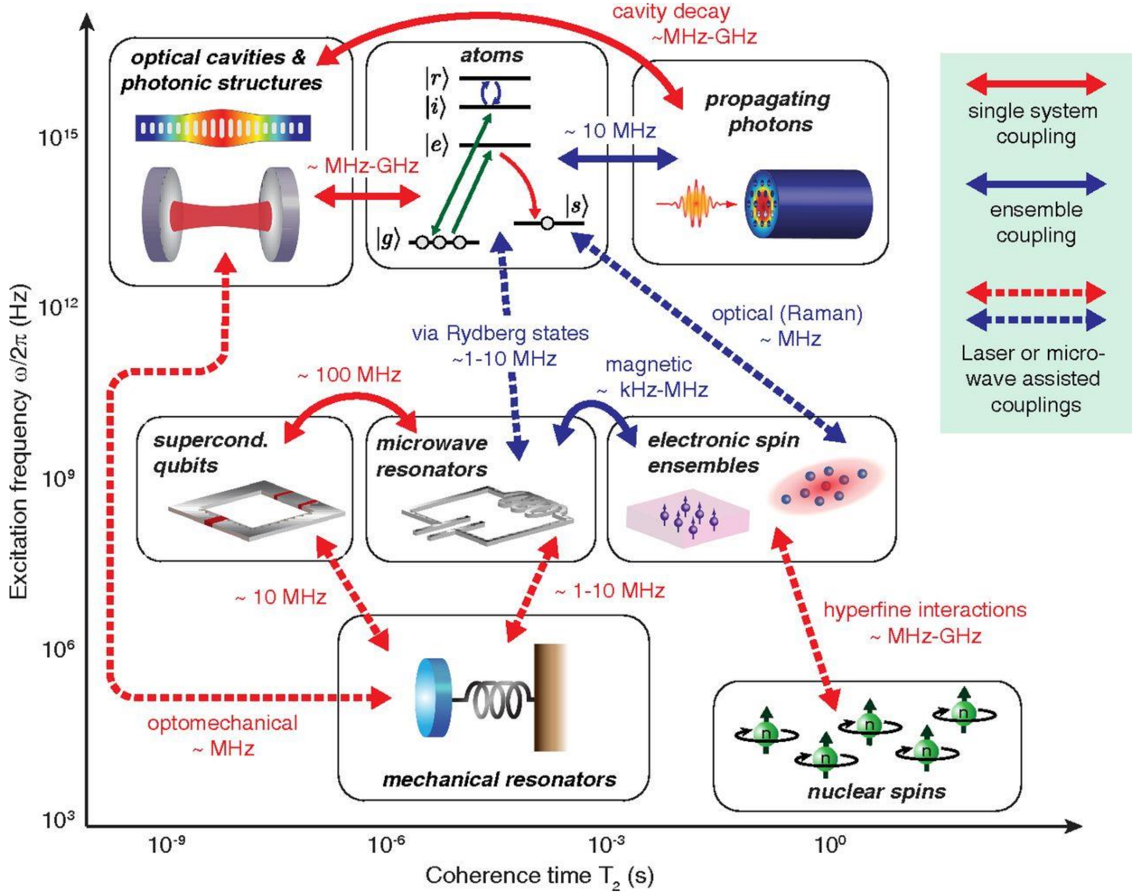
Implementations (q. computations & simulations)

- Trapped ions
- Linear optical quantum computation
- Spin-based quantum computation – donors in silicon, quantum dots
- Superconducting circuits

Scalability is a common technical limitation

Question: Distributed quantum computing and its performance?

- Photons are good candidates to interconnect different quantum systems



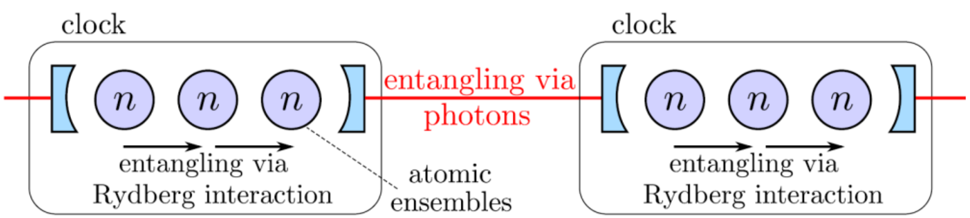
Gershon Kurizki et al. PNAS 2015;112:3866-3873

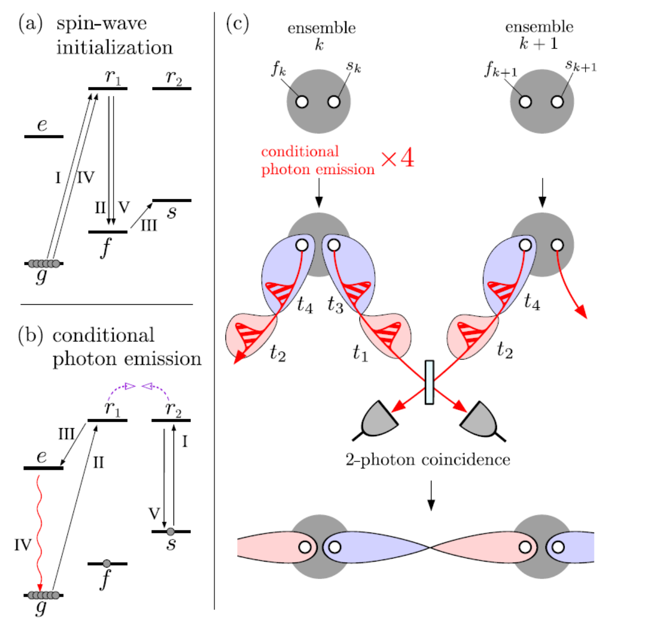
Quantum metrology

- Enhancing statistical precision using quantum resources (entanglement)

V. Giovannetti, S. Lloyd, L. Maccone, Nature Photonics 5, 222–229 (2011).

- Quantum Network of Atom Clocks, Komar et. al Phys. Rev. Lett. 117, 060506 (2016)





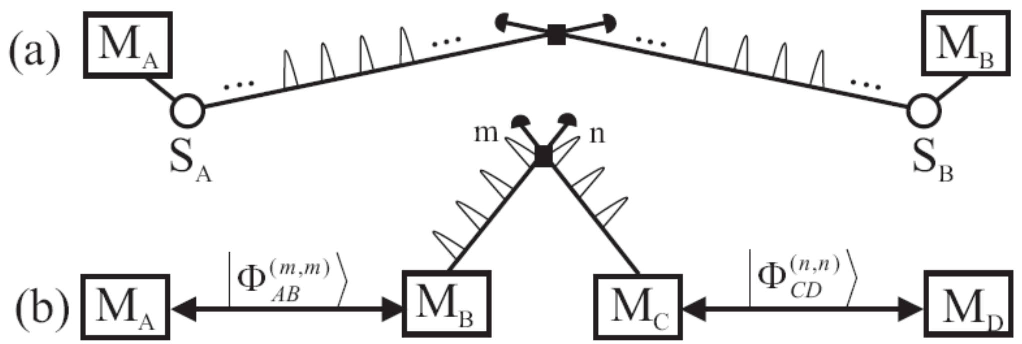
Quantum communications

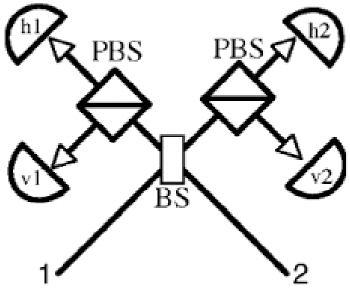
- Superposition states of photons can be used to encode and transmit secure information (Bennet-Brassard 84, Ekert 91)
- Distances for direct transmission via fibers is limited due to loss (e.g. distributing an entangled pair over 2000km through fibers with 0.15dB/km loss and with a source operating at 1GHz rate takes more than the age of universe!)
- Free-space communications through satellites or fiber-based quantum repeater networks are the alternatives

Quantum communication over long distances

Direct transmission is only useful for local networks up to about 300-400 kms!

Quantum repeaters using quantum memories, pair sources and linear optics:





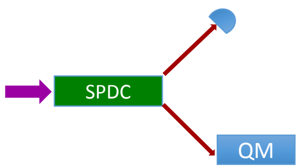
Simon et al., PRL 98, 190503 (2007)

Quantum repeaters based on fibers can distribute entanglement up 1000-2000 km.

N. Sinclair et al., Phys. Rev. Lett. 113, 053603 (2014).

Other applications of quantum memories

- Deterministic single photon sources



S. Chen *et al*, PRL **97**, 173004 (2006)

- Processing quantum optical pulses

Saglamyurek et al., New Journal of Physics 16 (6), 065019 (2014)

Hosseini *et al.,* Nature **461**, 241 (2009)

K. Fisher *et al.*, Nature Communications **7**, Article number: 11200 (2016)

- Quantum gates based on storage
- Quantum non-demolition measurement based on storage

Quantum memories (definition)

- An ideal quantum memory takes an input state, preserves it's quantum state, and allows one to recall and generate an output state.

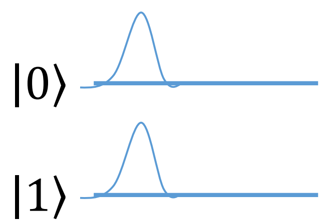
- Fidelity (this has to surpass fidelity of a measure-and-prepare box or an optimal cloning device):

$$F=\text{avg}\left\{|\langle\varphi_{in}|\varphi_{out}\rangle|^2, \forall|\varphi_{in}\rangle\right\}$$

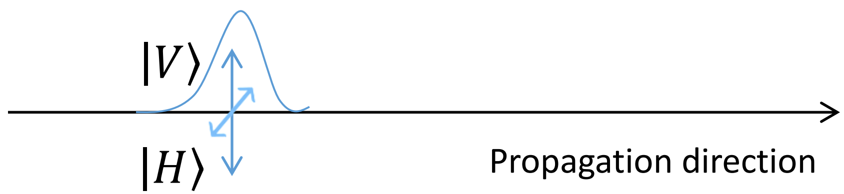
Quantum memories for photons

- Information can be encoded in different degrees of freedom of photons

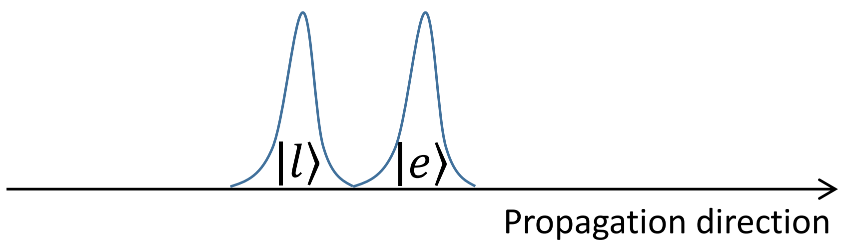
- Path



- Polarization



- Time



$$|\varphi_{in}\rangle = \frac{|e\rangle + e^{i\theta}\,|l\rangle}{\sqrt{2}}$$

Quantum memory schemes

- Optically controlled quantum memories: Raman & Electromagnetically Induced Transparency (EIT)
- Controlled inhomogeneous broadening: Gradient Echo Memory (GEM) & Atomic Frequency Comb (AFC)

Review papers:

1) Heshami et al., Quantum memories: emerging applications and recent advances, arXiv: 1511.04018, Journal of Modern Optics (2016).
2) Bussieres et al., Journal of Modern Optics 60, 1519-1537 (2013).
3) Simon et al., Eur. Phys. J. D - At. Mol. Opt. Plasma Phys. 58, 1–22 (2010).
4) Tittel et al., Laser Photonics Rev. B, 244–267 (2010).
5) Lvovsky, Sanders, Tittel, Nat. Photonics B, 706–714 (2009).

This is not a complete list, and it only to describe some of the well-known quantum memory schemes that are related to the remainder of this talk.

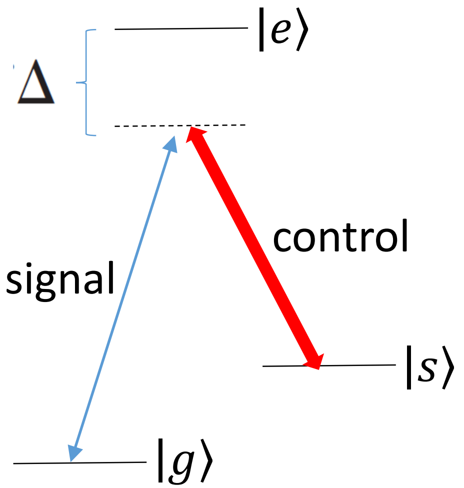
Raman quantum memories

- Raman quantum memory relies on optical coupling
- Allows on-demand recall

$$(\partial_t + c\partial_z)\hat{\mathcal{E}} = ig\sqrt{N}\hat{P}n(z)L/N,$$

$$\partial_t\hat{P} = -(\gamma + i\Delta)\hat{P} + ig\sqrt{N}\hat{\mathcal{E}} + i\Omega\hat{S} + \sqrt{2\gamma}\hat{F}_P,$$

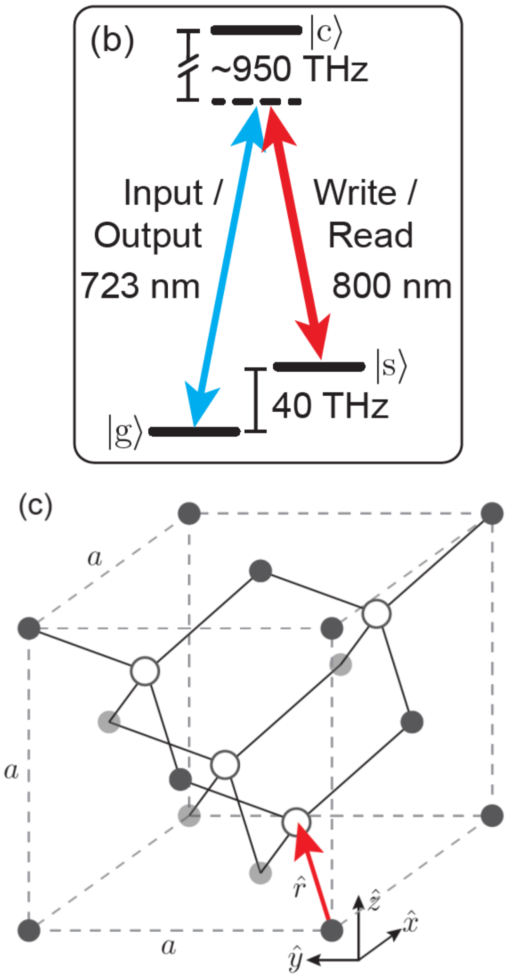
$$\partial_t\hat{S} = -\gamma_s\hat{S} + i\Omega^*\hat{P} + \sqrt{2\gamma_s}\hat{F}_S,$$



AV Gorshkov, A André, MD Lukin, AS Sørensen, Physical Review A 76 (3), 033805 (2007)
J. Nunn, I. A. Walmsley, M. G. Raymer, K. Surmacz, F. C. Waldermann, Z. Wang, and D. Jaksch, Phys. Rev. A 75, 011401(R) (2007)
DG England, KG Fisher, J-P W MacLean, PJ Bustard, K Heshami, KJ Resch, and BJ Sussman
Phys. Rev. Lett. **117**, 073603 (2016)

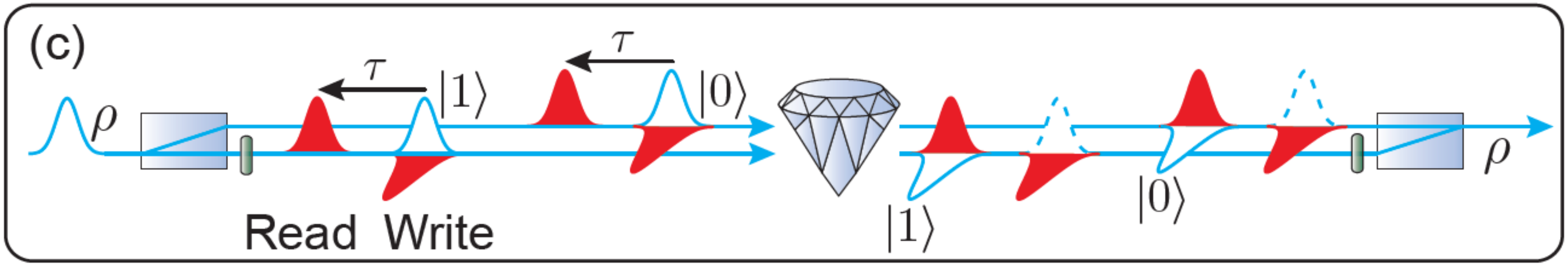
Raman storage in diamond

- Input photons can be mapped to optical phonons (vibrational modes) of the diamond
- Lifetime is as short as 3.5 ps
- With time-bandwidth product of over 10, this platform can be used as testbed for many quantum experiments
- This system has been used for wavelength conversion and other quantum signal processing tasks, see Fisher et al, Nature Communications **7**, 11200 (2016)

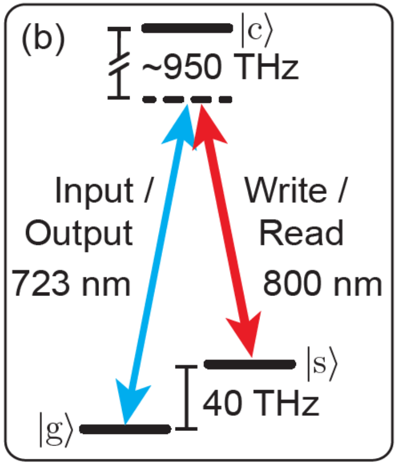


Kent Fisher, PhD thesis, IQC, Waterloo

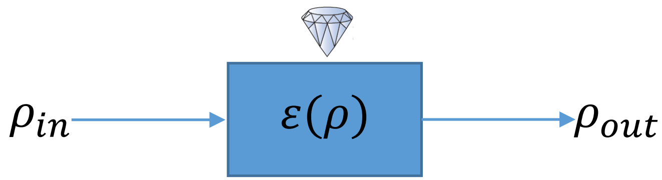
Raman storage of polarization qubits in diamond



- Polarization encoding is converted to path
- Each mode (path) is independently stored inside the diamond
- Each mode is recalled and recombined for state tomography



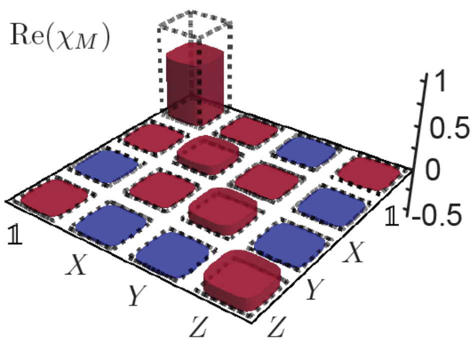
Process fidelity

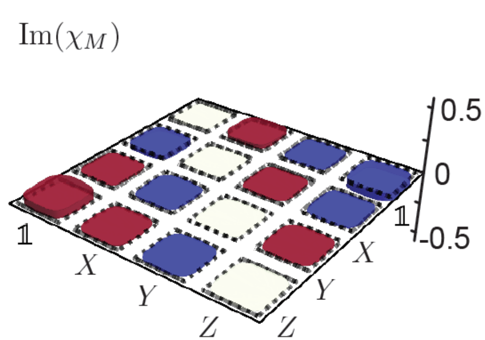


$$\mathcal{E}(\rho) = \sum_i A_i \rho A_i^\dagger$$

$$\begin{aligned}\mathcal{E}(\rho) &= \sum_i \left(\sum_m c_{i,m}\sigma_m\right)\rho\left(\sum_n c_{i,n}^*\sigma_n\right)\\ &= \sum_{m,n}\left(\sum_i c_{i,m}c_{i,n}^*\right)\sigma_m\rho\sigma_n\\ &= \sum_{m,n}\chi_{m,n}\sigma_m\rho\sigma_n\end{aligned}$$

$$\begin{aligned}f(\vec{t}) &= \sum_{a,b}\frac{\left[N_{ab}/\mathcal{N} - \langle\phi_b|\left(\sum_{m,n}\chi(\vec{t})_{mn}\sigma_m|\psi_a\rangle\langle\psi_a|\sigma_n\right)|\phi_b\rangle\right]^2}{2\langle\phi_b|\left(\sum_{m,n}\chi(\vec{t})_{mn}\sigma_m|\psi_a\rangle\langle\psi_a|\sigma_n\right)|\phi_b\rangle}\\ &\quad+\lambda\sum_k\left[\sum_{mn}\chi_{mn}(\vec{t})\mathrm{Tr}(\sigma_n\sigma_m\sigma_k) - \mathrm{Tr}(\sigma_k)\right]^2\end{aligned}$$





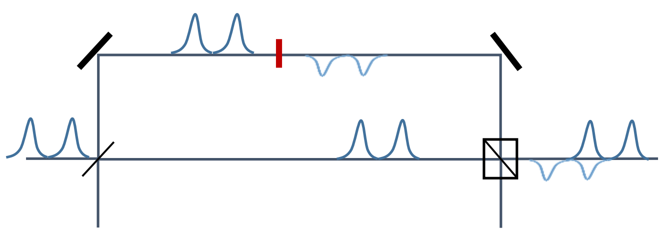
$$\rho_{\mathrm{out}} = p(\tau)\rho_{\mathrm{in}} + [1 - p(\tau)]\,\mathbb{1}_2/2$$

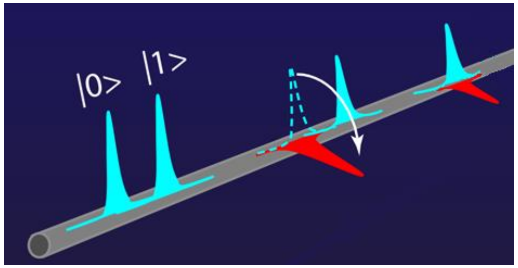
$$p(\tau) = S_0 e^{-\tau/\tau_{\mathrm{m}}}/[N_c + (S_0 + N_0)e^{-\tau/\tau_{\mathrm{m}}}]$$

$$\mathcal{F}_p(\chi_1,\chi_2) = \left(\mathrm{Tr}\sqrt{\sqrt{\chi_2}\cdot\chi_1\cdot\sqrt{\chi_2}}\right)^2$$

Efficient and ultrafast conversion of qubits between time-Bin and polarization Encodings

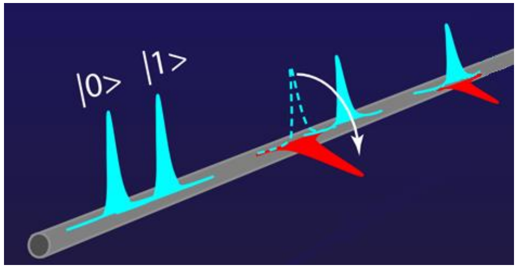
- Time-bin encoding of information in photons are useful for long-distance propagation in fibers
- Polarization encoding is desirable for detection/processing
- An efficient time-bin to polarization conversion requires active optical elements

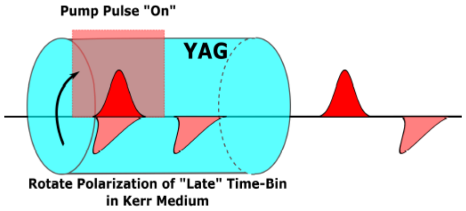


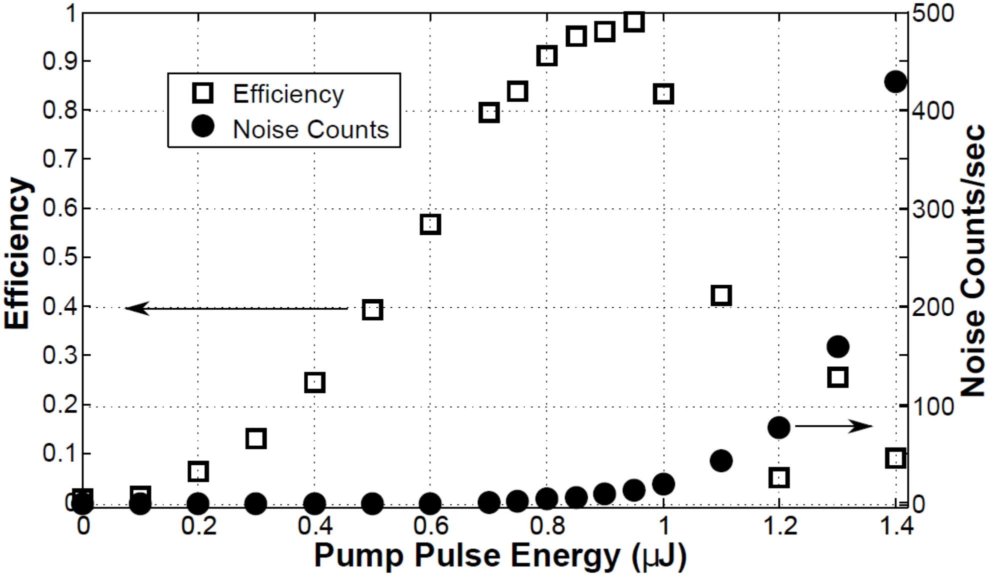


Optical Kerr Shutter

- A strong optical field can induce an asymmetry in the optical response of the medium (generate birefringence)







Time-bin to polarization conversion

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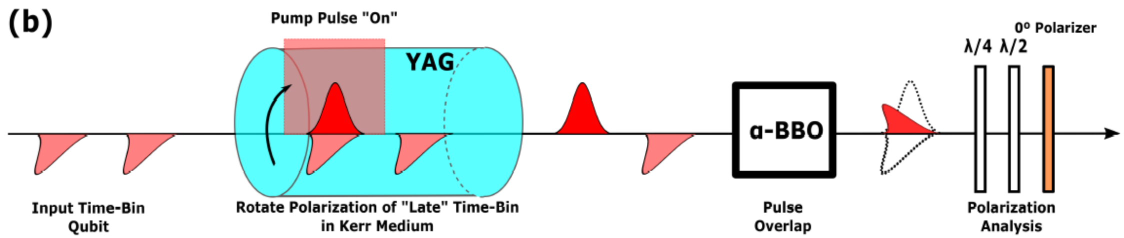

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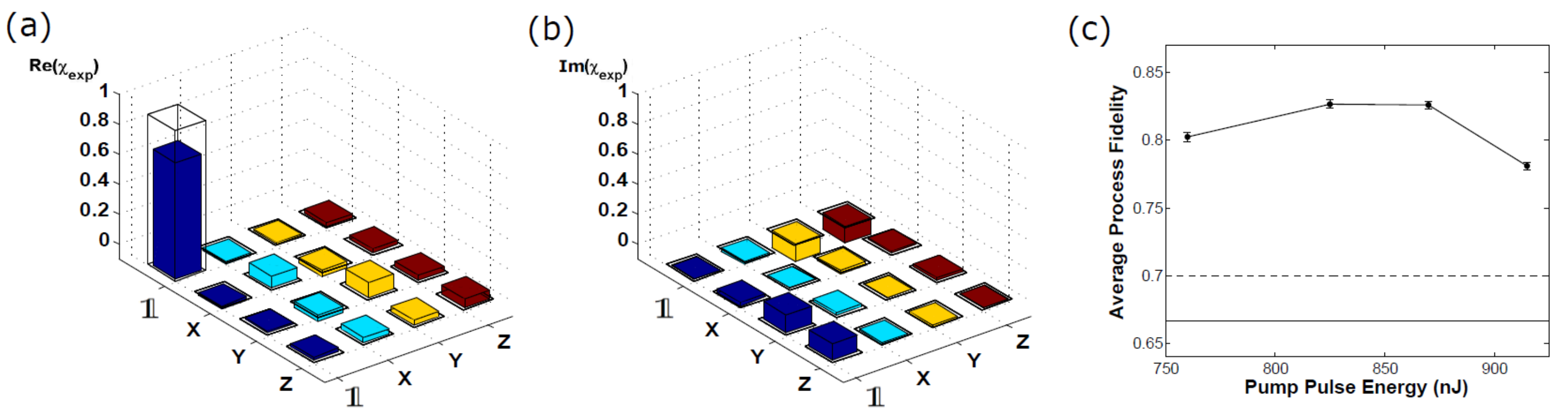

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Thanks!

- Theory:

Christoph Simon (PI), QND & Ent.

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Sandeep Goyal, Ent.

- Experiment:

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