Optical cavities and trapped ions: building blocks for quantum networks

Tracy Northup
Institute for Experimental Physics, University of Innsbruck

Zeiss Symposium 2018: Optics in the Quantum World
What roles does optics play in quantum technology?

- Quantum light fields for computing, communication & simulation
- Classical light fields for manipulation & measurement of matter-based qubits

Here, optical cavities as an interface between quantum light and quantum matter.
Ingredients for a quantum network

Photons travelling along quantum channels... linking quantum nodes:
• generation & measurement of quantum states
• quantum memories
• quantum computers

Network applications:
• quantum communication
• quantum sensing
• distributed quantum computing

Key concept:
Coherent interface between nodes and channels.

» Trapped-ion qubits for quantum information science

» Optical cavities as building blocks for quantum networks
  Entangling ions and photons
  Transferring quantum states between ions and photons

» Outlook: applications for ion-based networks
Trapped ions as quantum bits

Ions: a highly controllable two-level system.

» Coherence can be preserved for long times in hyperfine and optical qubits
» Deterministic, high-fidelity, coherent manipulation of both individual qubits and gate operations between qubits
» High-fidelity state readout via electron shelving

Linear Paul trap: RF field creates a rotating pseudopotential for charged particles.
Two examples of the state of the art:

1. Multi-partite entanglement in a register of 20 qubits
   • Entanglement characterized for neighboring groups of qubits
   • Each qubit individually controlled & qubit-qubit interactions turned on and off

2. Spectroscopy of molecular ions via quantum logic
   • Quantum state of molecular ion measured via its coupling to an atomic ion

ions as sensors: talk today by J. Hecker Denschlag
» Trapped-ion qubits for quantum information science

» Optical cavities as building blocks for quantum networks
   Entangling ions and photons
   Transferring quantum states between ions and photons

» Outlook: applications for ion-based networks
An ion trap integrated with an optical cavity
A Raman process generates single cavity photons
Entangled ions and photons: a network resource

A bichromatic Raman field generates entanglement.

\[ S \rightarrow DH \]
\[ S \rightarrow D'V \]
\[ S \rightarrow DH + D'V \]

...the ion and photon are maximally entangled.
Entangled ions and photons: a network resource

The photon is measured in three orthogonal bases...

...and the ion in three orthogonal bases.

A. Stute et al., Nature 485, 482 (2012)
Entangled ions and photons: a network resource

\[
4^2P_{3/2} \rightarrow \text{...and the ion in three orthogonal bases.}
\]

Fidelity \( \equiv \langle \psi | \rho | \psi \rangle = 97.4(2)\% \)

classical bound: 50%

A. Stute et al., Nature 485, 482 (2012)
Ion-photon entanglement enables remote entanglement

Cavities aren’t required...
  • ions in separate traps
  • atomic ensembles, neutral atoms, NV centers, quantum dots, ...

...but they are a **means to achieve efficient collection.**
A similar protocol entangles ions in the same cavity


We prepare ion–ion entanglement with fidelity $\geq (91.9 \pm 2.5)\%$ with respect to a maximally entangled state.

**Outlook**: cavity-based methods as a route to efficient remote entanglement & teleportation-based networks.

An alternative to teleportation: quantum state transfer


neutral atoms:
S. Ritter et al., Nature 484, 195 (2012)

A bichromatic Raman process maps the quantum state

\[ S \rightarrow \text{horizontally polarized photon} \]
\[ S' \rightarrow \text{vertically polarized photon} \]
\[ aS + bS' \rightarrow aH + bV \]

Process fidelity: 92%
Classical threshold: 50%

A. Stute et al., Nat. Photon. 7, 219 (2013)
Addressing decoherence in state-transfer networks

Can we build networks based on direct state transfer along photonic channels?

A significant loss mechanism for current experiments: scattering and absorption losses in the cavity.

We compare two methods for state transfer; one method allows us to suppress these losses.

Addressing decoherence in state-transfer networks

Can we build networks based on direct state transfer along photonic channels?


 classical drive for wave packet shaping


classical drive for adiabatic passage
Addressing decoherence in state-transfer networks

Can we build networks based on direct state transfer along photonic channels?

**The key idea:**
Cavity losses are analogous to spontaneous emission in STIRAP and can be suppressed.

(Channel losses, on the other hand, can’t be suppressed.)

» Trapped-ion qubits for quantum information science

» Optical cavities as building blocks for quantum networks
   Entangling ions and photons
   Transferring quantum states between ions and photons

» Outlook: applications for ion-based networks
Scaling up cavity-based interfaces

» Smaller cavities → faster interface with higher fidelities

- high-finesse mirrors on optical fiber tips, ablated with a CO₂ laser

- see also: ions + fiber cavities in Bonn (Köhl), Sussex (Keller), Mainz (Schmidt-Kaler)...

» Scaling up ion traps: ongoing research efforts worldwide

- ... integrating optics is an important & challenging task.
  - see: work in Chiaverini group at Lincoln Labs on integrated waveguides for ion addressing

- HOA2 trap, Sandia National Laboratories
Towards a quantum internet

This talk: **ion-photon interactions at one node**

State of the art: two-node experiments

We need:
- multi-node networks over long distances
- quantum repeaters that surpass direct transmission

How to benchmark different experimental platforms?

Network applications beyond quantum key distribution:

What resources are required?

Which applications are suited to few-node networks?

Quantum Internet Alliance
http://quantum-internet.team
Optical cavities provide an interface between ions and photons, enabling building blocks for quantum networks: entanglement and quantum state transfer.

Trapped ions are a promising platform for quantum simulation, computation & sensing. Network connectivity enables distributed applications & quantum communication.

Scaling up from experiments with one and two nodes will require us to address decoherence in quantum nodes and channels.
Collaborations

**Adiabatic passage:** B. Vogell, B. Vermersch, B. Lanyon, C. Muschik @ Innsbruck

**Fiber cavities:** K. Ott, S. Garcia, J. Reichel @ ENS, Paris