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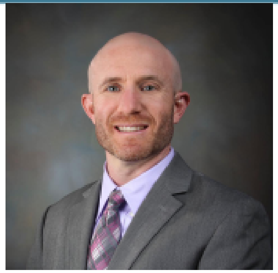
High-Fidelity Qubit Transfer Between Leaky Memory Blocks



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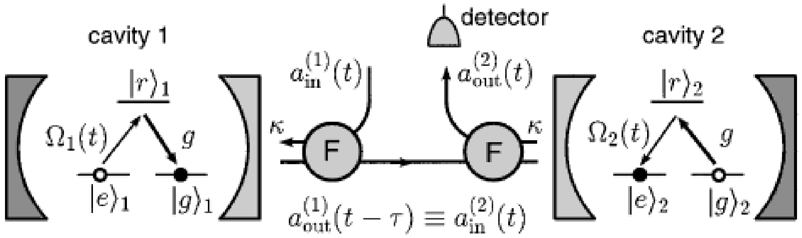
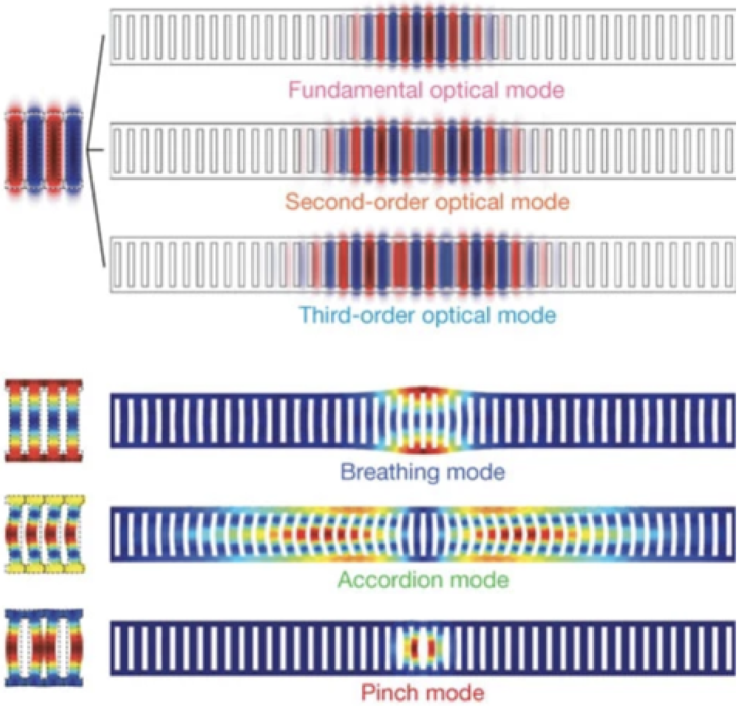
Motivation

- **Goal:** Transfer a qubit from one long-term memory to another
- **Problem:** Memory mode typically not well-suited for qubit transduction
  - Example: Phonons are excellent for storing qubits but are poorly suited for transporting qubits, while opposite is true for photon modes
- **Solution:** Convert qubit in source block's memory mode to intermediate mode, transport it to destination block, and then convert to memory mode there
  - Optimal pulse profiles were previously solved (Cirac *et al.*, *Phys. Rev. Lett.* **78**, 3221 (1997)) for idealized 2-atom system (lossless and physically equivalent)
  - General systems (e.g., optomechanical, spins) feature intrinsic loss and asymmetry
  - **Key question:** What fidelity can we achieve given these nonidealities?

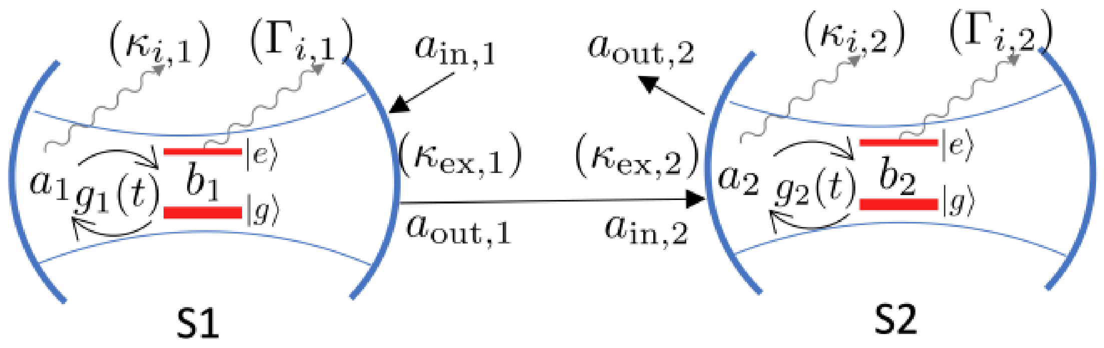


Cirac *et al.*, *PRL* **78**, 3221 (1997)



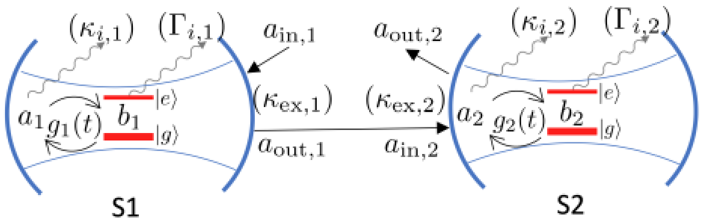
Eichenfield *et al.*, *Nature* **462**, 78 (2009)

Physical Setup



- Coupling rate between memory and intermediate modes in each memory block is **dynamically tunable** (e.g., photon-phonon coupling in optomechanical oscillator)
- **Question:** How do we tune the inter-mode coupling rates for the two blocks in order to optimize the qubit transfer from the source memory mode to the destination memory mode?
- **Requirement:** Reflection of the wave traveling from the source intermediate mode to the destination intermediate mode must be cancelled out by the output from the destination intermediate mode (destructive interference)
  - ➢ Qubit carried by traveling wave is then fully transferred to the destination block

Quantitative Methods



- Use master equation for open quantum systems:
  - Interaction within Hilbert space: Model with **Hamiltonian** (*H*)
  - Loss to environment: Model with **Lindbladian** (*L*)

Inter-mode interactions

$$H_T = -\hbar g_1(t)(a_1^\dagger b_1 + a_1 b_1^\dagger) - \hbar g_2(t)(a_2^\dagger b_2 + a_2 b_2^\dagger) + \frac{i\hbar}{2}\sqrt{\kappa_{\mathrm{ex},1}\kappa_{\mathrm{ex},2}}(a_1^\dagger a_2 - a_1 a_2^\dagger),$$

Inter-block transfer

$$L_T = \begin{pmatrix} \sqrt{\kappa_{i,1}}a_1 \\ \sqrt{\Gamma_{i,1}}b_1 \\ \sqrt{\kappa_{\mathrm{ex},1}}a_1 + \sqrt{\kappa_{\mathrm{ex},2}}a_2 \\ \sqrt{\kappa_{i,2}}a_2 \\ \sqrt{\Gamma_{i,2}}b_2 \end{pmatrix}.$$

Source block intrinsic loss

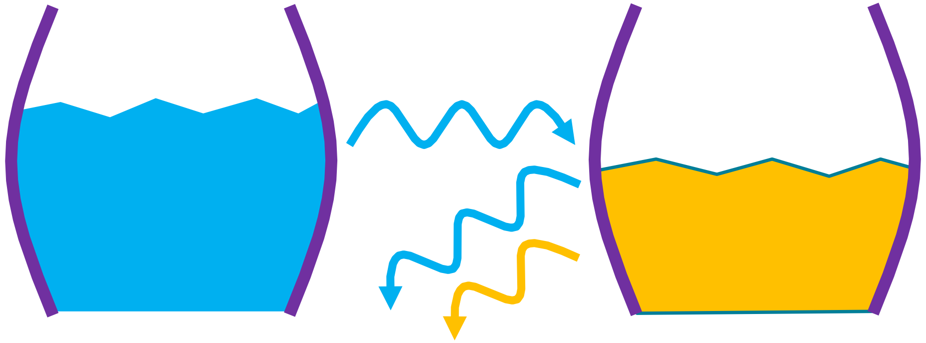
Destination block intrinsic loss

- n = 1 (source block) or 2 (destination block)
  - $g_n(t)$: Time-adjustable inter-mode coupling rate
  - $b_n^{(\dagger)}$: annihilation (creation) operator for memory mode
  - $a_n^{(\dagger)}$: annihilation (creation) operator for intermediate mode
  - $\boldsymbol{\kappa}_{\mathrm{ex},n}$: output coupling rate of intermediate mode
  - $\boldsymbol{\kappa}_{i,n}$: intrinsic loss rate of intermediate mode
  - $\boldsymbol{\Gamma}_{i,n}$: intrinsic loss rate of memory mode

Quantitative Methods (Cont.)

- Zero loss from input-output port of destination block by maintaining constant source -destination intermediate "dark mode" superposition
  - Constant population ratio between source and destination modes ensures that reflected traveling wave and raw output from destination mode cancel (destructive interference)

$$|\text{dark}\rangle = \frac{1}{\sqrt{1+\epsilon}}(|01\rangle - \sqrt{\epsilon}|10\rangle).$$



- Hilbert space is reduced from 4 to 3 dimensions
  - Incorporate Lindbladian into Hamiltonian as imaginary terms and solve Schrodinger's Eq.

$$H_T^{\text{eff}} = H' - i\hbar\frac{\kappa_i}{2}(a_b^\dagger a_b + a_d^\dagger a_d) - i\hbar\frac{\Gamma_i}{2}(b_1^\dagger b_1 + b_2^\dagger b_2).$$

$\boldsymbol{\alpha}_1$(t): source memory state coefficient
$\boldsymbol{\beta}_\alpha$(t): dark-mode intermediate state coefficient
$\boldsymbol{\alpha}_2$(t): destination memory state coefficient

$$|\Psi(t)\rangle = c_g|gg\rangle|00\rangle + c_e[\alpha_1(t)|eg\rangle|00\rangle + \alpha_2(t)|ge\rangle|00\rangle + i\beta_\alpha(t)|gg\rangle|\text{dark}\rangle].$$

$$\dot{\alpha}_1(t) = \frac{\sqrt{\epsilon}}{\sqrt{1+\epsilon}}g_1(t)\beta_\alpha(t) - \frac{\Gamma_i}{2}\alpha_1(t),$$

$$\dot{\alpha}_2(t) = -\frac{1}{\sqrt{1+\epsilon}}g_2(t)\beta_\alpha(t) - \frac{\Gamma_i}{2}\alpha_2(t),$$

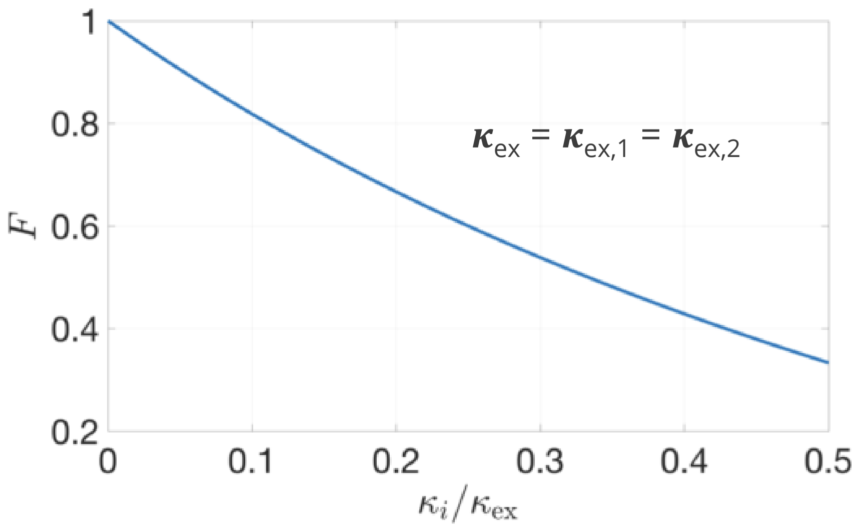
$$\dot{\beta}_\alpha(t) = \frac{1}{\sqrt{1+\epsilon}}g_2(t)\alpha_2(t) - \frac{\sqrt{\epsilon}}{\sqrt{1+\epsilon}}g_1(t)\alpha_1(t) - \frac{\kappa_i}{2}\beta_\alpha(t).$$

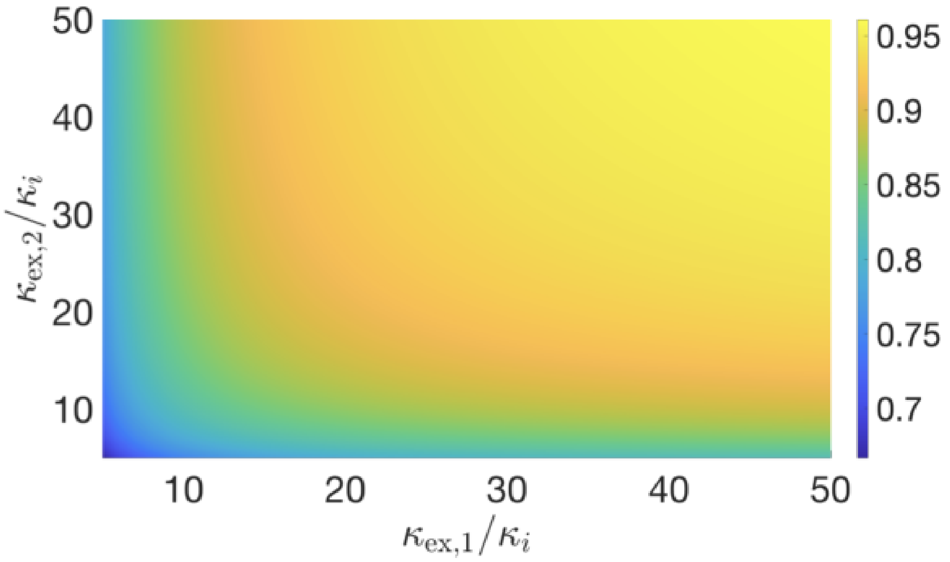
Maintains system in dark mode

$$0 = \frac{\sqrt{\epsilon}}{\sqrt{1+\epsilon}}g_2(t)\alpha_2(t) + \frac{1}{\sqrt{1+\epsilon}}g_1(t)\alpha_1(t) + \frac{\kappa_{\text{ex},1}\sqrt{\epsilon}}{2}\beta_\alpha(t).$$

Results

- For low memory mode loss rate, transfer fidelity decreases with ratio between intermediate mode intrinsic loss and output coupling rates
  - Output coupling rate sets transfer speed
  - Higher output coupling rate thus means less time in lossy intermediate state

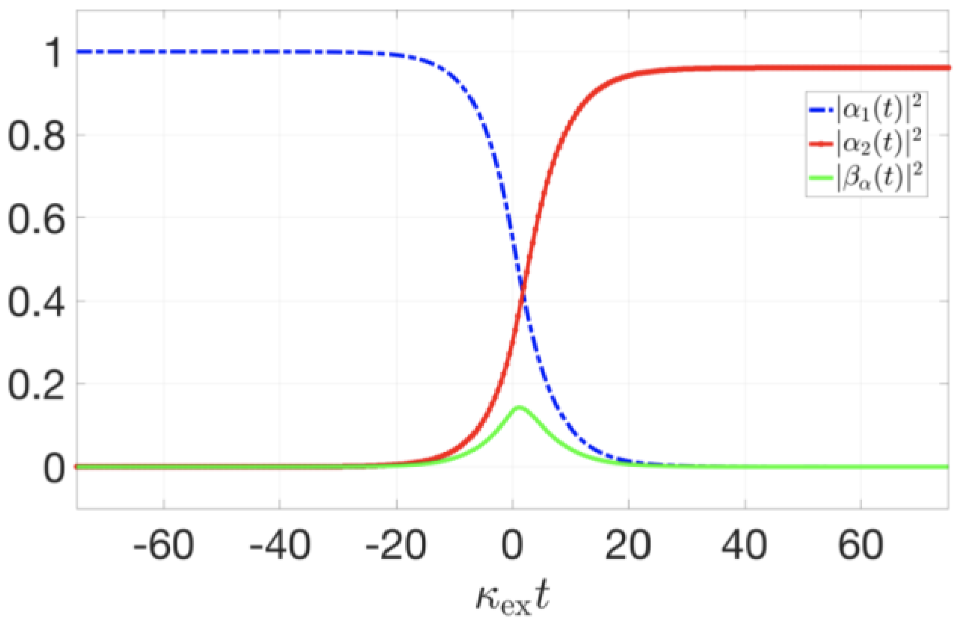




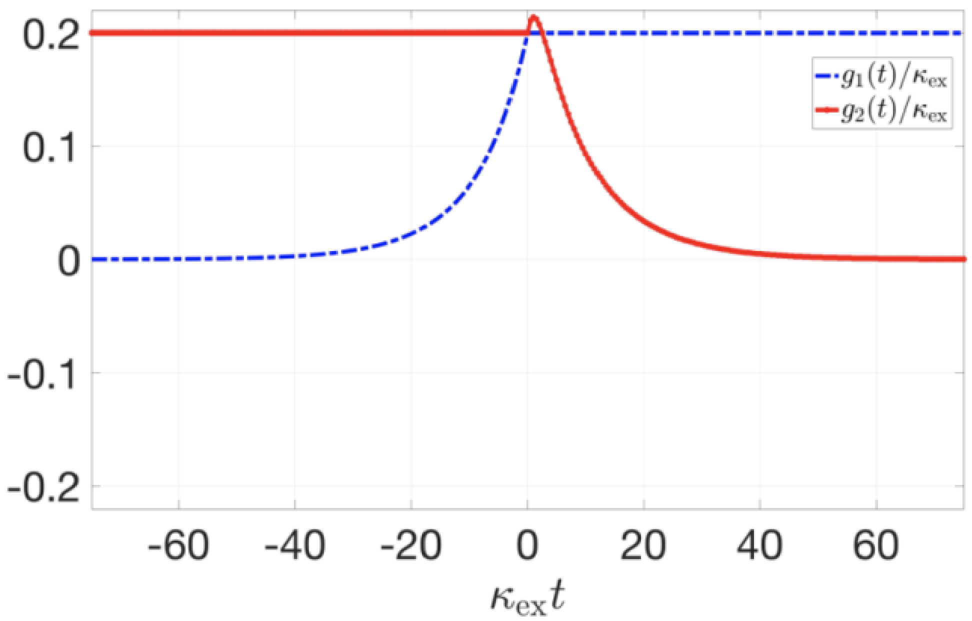
Results (Cont.)

- For phonon memory modes and optical photon intermediate mode, **96% fidelity** is reached given practical parameters
  - $\kappa_{ex} = 2\pi \times 5$ GHz, $\kappa_i = 2\pi \times 100$ MHz (i.e., $\kappa_{ex} = 50\kappa_i$)
  - Optimal solution: Maintain inter-mode coupling for destination (source) block constant during first (second) half of transfer

State populations



Optimal inter-mode coupling rates



Conclusion

- We have derived the recipe for optimally transferring quantum information between two spatially separated memory modes through a realistic lossy intermediate channel featuring asymmetric output coupling rates
- Quantum state transfer will be essential in constructing a quantum network
- Result published in Physical Review Research

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High-fidelity state transfer between leaky quantum memories

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