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Coherently Opening a High-Q Cavity

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We propose a general framework to effectively "open" a high-Q resonator, that is, to release the quantum state initially prepared in it in the form of a traveling electromagnetic wave. This is achieved by employing a mediating mode that scatters coherently the radiation from the resonator into a one-dimensional continuum of modes such as a waveguide. The same mechanism may be used to "feed" a desired quantum field to an initially empty cavity. Switching between an open and "closed" resonator may then be obtained by controlling either the detuning of the scatterer or the amount of time it spends in the resonator. First, we introduce the model in its general form, identifying (i) the traveling mode that optimally retains the full quantum information of the resonator field and (ii) a suitable figure of merit that we study analytically in terms of the system parameters. Then, we discuss two feasible implementations based on ensembles of two-level atoms interacting with cavity fields. In addition, we discuss how to integrate traditional cavity QED in our proposal using three-level atoms.

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Introduction

advances in cavity QED:

- high Q cavities $Q = \omega_c/\kappa$
- coherent control of individual quantum emitters

Two main issues:

light matter interaction in strong coupling regime

$$g \gtrsim \kappa$$

→ high Q

extract quantum state of cavity on short time scales

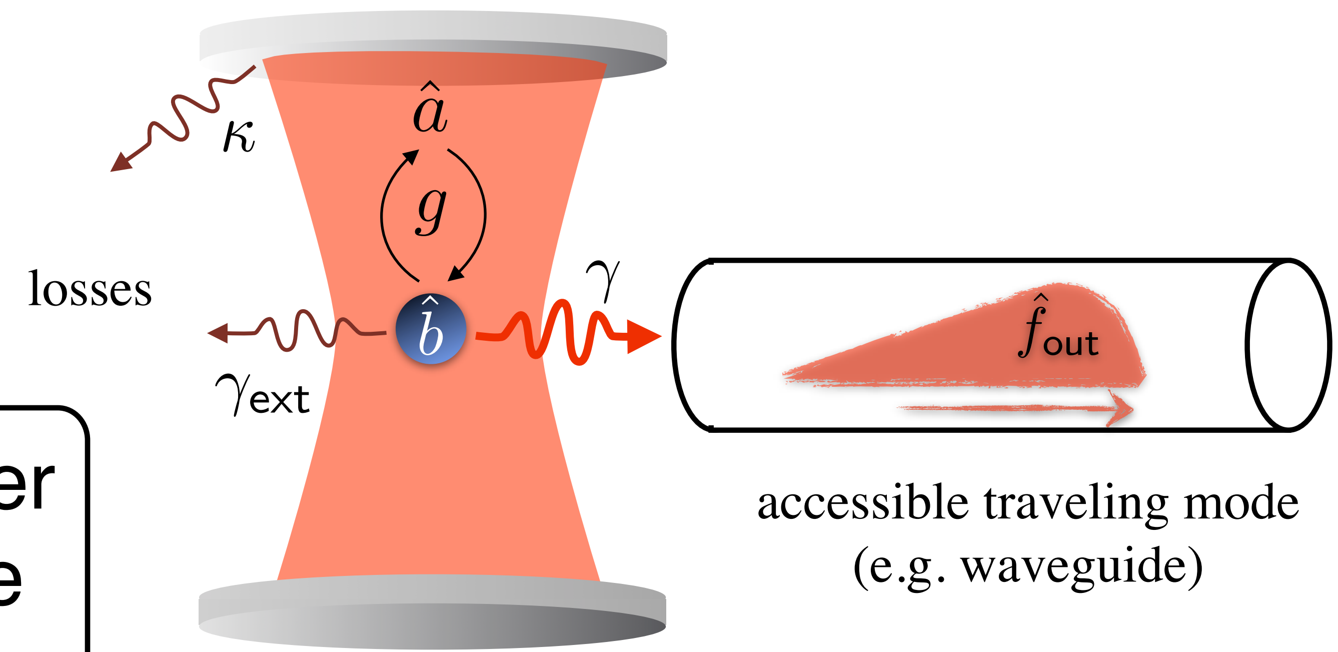
→ low Q

Control Q of cavity:

cavity in strong coupling ↔ “open” cavity

Model

- high Q cavity
- desired quantum state prepared in advance



- cavity field interacts with scatterer
- scatterer radiates into accessible waveguide

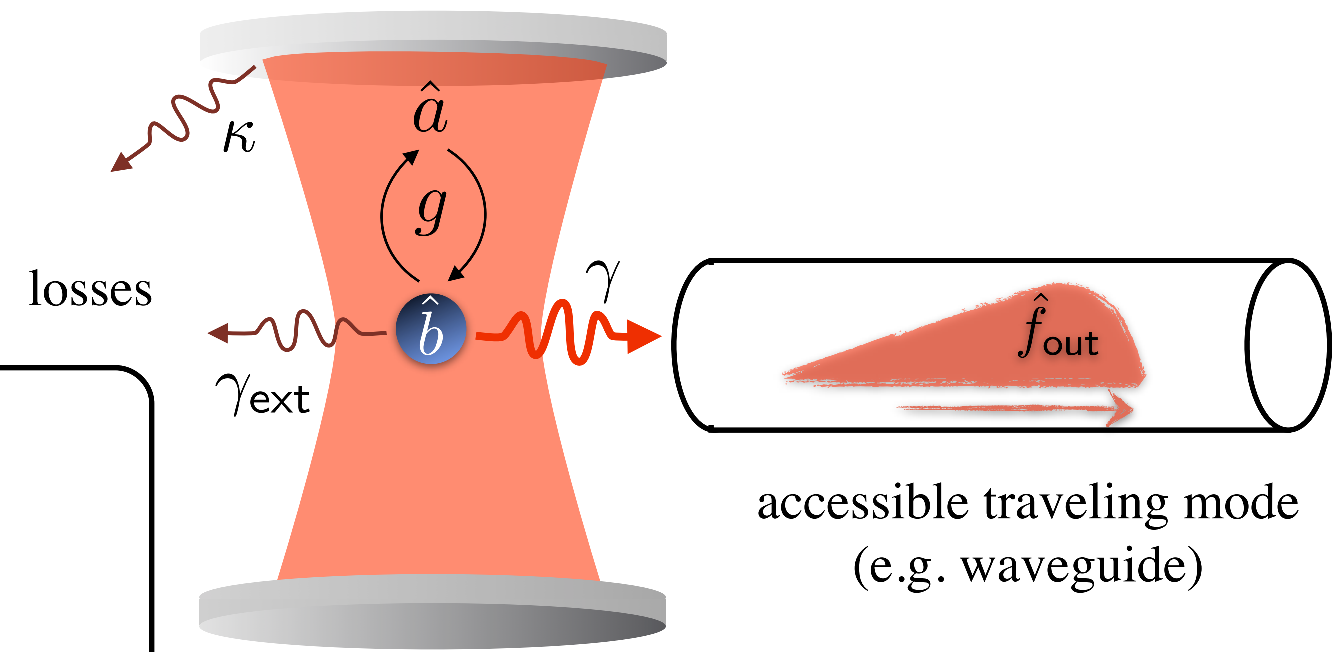
initial quantum state coherently transferred to traveling mode of light
→ "opening the cavity"

need to control coupling between cavity and scatterer

- detune the scatterer
- control time scatterer spends in cavity

Model

$$H = g(\hat{a}^\dagger \hat{b} + \hat{b}^\dagger \hat{a})$$



g	coupling
γ	interaction cavity-waveguide
κ	cavity losses
γ_{ext}	spontaneous emission of scatterer

$$\dot{\hat{a}} = -ig\hat{b} - \frac{\kappa}{2}\hat{a} + \sqrt{\kappa}\hat{a}_{\text{in}}$$

$$\dot{\hat{b}} = -ig\hat{a} - \frac{\gamma + \gamma_{\text{ext}}}{2}\hat{b} + \sqrt{\gamma}\hat{b}_{\text{in}} + \sqrt{\gamma_{\text{ext}}}\hat{b}_{\text{ext,in}}$$

$\hat{b}_{\text{in}}$	under control
$\hat{a}_{\text{in}}, \hat{b}_{\text{ext,in}}$	inaccessible environments

Focus on system's output into waveguide:

$$\hat{b}_{\text{out}} = \sqrt{\gamma}\hat{b} - \hat{b}_{\text{in}}$$

Math

$$\hat{\mathbf{v}} = (\hat{a}, \hat{b})^{\mathsf{T}}$$

$$\hat{\mathbf{v}}_{\text{out}} \equiv (\sqrt{\kappa}\hat{a}_{\text{out}}, \sqrt{\gamma}\hat{b}_{\text{out}} + \sqrt{\gamma_{\text{ext}}}\hat{b}_{\text{ext,out}})^{\mathsf{T}}$$

$$\mathbf{M} \equiv \begin{pmatrix} \frac{\kappa}{2} & -ig \\ -ig & \frac{\gamma+\gamma_{\text{ext}}}{2} \end{pmatrix}$$

$$\dot{\hat{\mathbf{v}}} = \mathbf{M}\hat{\mathbf{v}} - \hat{\mathbf{v}}_{\text{out}}$$

$$\hat{\mathbf{v}}(t_1) = \mathrm{e}^{\mathbf{M}(t_1 - t_0)}\hat{\mathbf{v}}(t_0) - \mathrm{e}^{\mathbf{M}t_1} \int_{t_0}^{t_1} \mathrm{d}t' \, \mathrm{e}^{-\mathbf{M}t'} \hat{\mathbf{v}}_{\text{out}}(t')$$

$$\hat{a}(0) = \sqrt{F}\hat{f}_{\text{out}} - \sqrt{1-F}\hat{h}_{\text{ext}}$$

$\hat{f}_{\text{out}}$ propagates away from the system along the waveguide

$\hat{h}_{\text{ext}}$ representing fields that have been dissipated into the inaccessible modes

all modes except $\hat{a}(0)$ initially $|\text{vac}\rangle$
+ total excitation number conserved

→ other output of this abstract beam-splitter one must find the vacuum

$$\sqrt{1-F}\hat{f}_{\text{out}} + \sqrt{F}\hat{h}_{\text{ext}} = \hat{a}_{\text{vac}}$$

$$\hat{f}_{\text{out}} = \sqrt{F}\hat{a}(0) + \sqrt{1-F}\,\hat{a}_{\text{vac}}$$

Results

Figure of merit:

$$F = \frac{1 - \frac{\gamma_{\text{ext}}}{\gamma_{\text{tot}}}}{1 + \frac{\kappa}{\gamma_{\text{tot}}} + \frac{\gamma_{\text{tot}}\kappa}{4g^2} + \frac{\kappa^2}{4g^2}}$$

$$\gamma_{\text{tot}} \equiv \gamma + \gamma_{\text{ext}}$$

F monotonically decreases with κ

for ideally closed cavity ($\kappa = 0$) and $\gamma_{\text{ext}} \ll \gamma_{\text{tot}}$
➡ Q-switch approaches unity

the more a cavity is closed, the better it can be opened

close to unity for:

$\gamma_{\text{ext}} \ll \gamma$

$\kappa \ll \gamma$

$\kappa \ll g$

Implementation

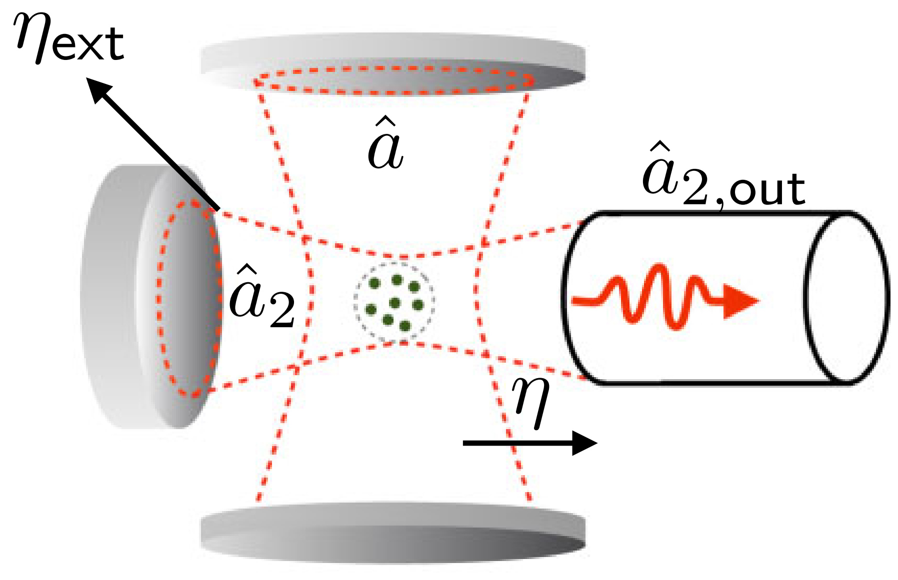
Ensemble of ***n*** two-level atoms

when extracting the high-Q mode:

- 2-level atoms in resonance with $\hat{a}, \hat{a}_2$

closed cavity:

- apply a large detuning to atoms
- remove atoms



$$H_1 = \sum_{k=1}^{n} \left[\lambda \left(\hat{\sigma}_k^+ \hat{a} + \hat{\sigma}_k^- \hat{a}^\dagger\right) + \lambda' \left(\hat{\sigma}_k^+ \hat{a}_2 + \hat{\sigma}_k^- \hat{a}_2^\dagger\right)\right] \qquad \hat{\sigma}_k^+ = (\hat{\sigma}_k^-)^\dagger \equiv |e_k\rangle\langle g_k|$$

large ***n***
majority of atoms remains in GS ($\langle \hat{a}^\dagger \hat{a} \rangle_{\text{init}} < n$) → $\hat{c} = \frac{1}{\sqrt{n}} \sum_{k=1}^{n} \hat{\sigma}_k^-$

$\eta_{\text{tot}} = \eta + \eta_{\text{ext}} \gg \lambda' \sqrt{n}$

adiabatically eliminate second mode → model as before:
one mode and scatter

Conclusion

- Scheme to coherently switch from closed to open cavity
- Advantage of high and low Q in one setup
- Complementary process also possible
- Applicable to a cavity QED setup