Feasible coupling of two superconducting resonators by a single trapped atom

Sergey Filippov

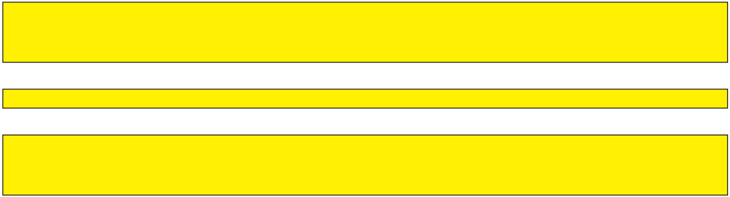
Department of Experimental Physics
Comenius University
Bratislava

Research Center for
Quantum Information
Institute of Physics SAS

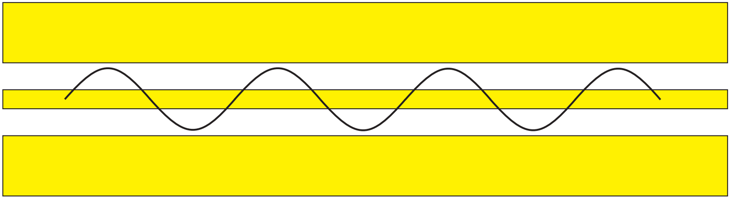
Integrated Quantum Information Technology

Corfu
September 23–27, 2013

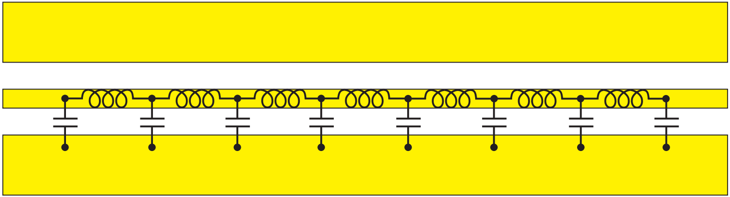
Coplanar waveguide



Coplanar waveguide

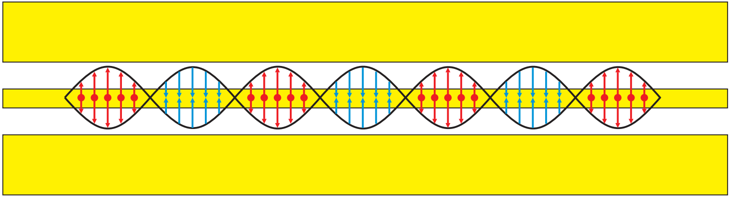


Coplanar waveguide



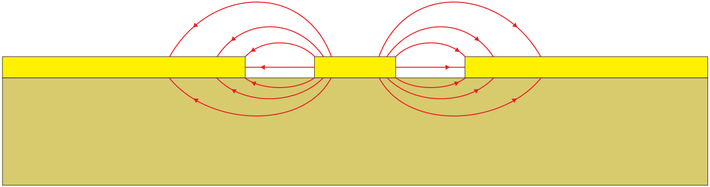
- $Z_0 = \sqrt{\frac{L_l}{C_l}}$

Coplanar waveguide

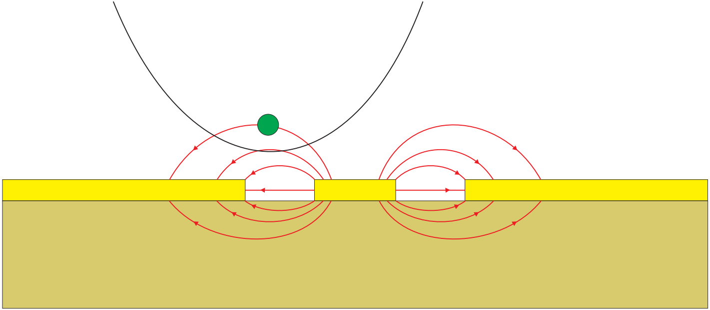


- $v = \frac{c}{\sqrt{\epsilon_{\text{eff}}}}$
- $f \sim 1$ GHz

Cross section of coplanar waveguide

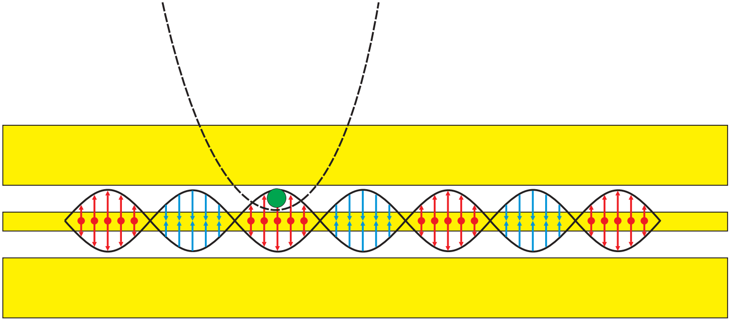


Coupling EM field with ion vibrations



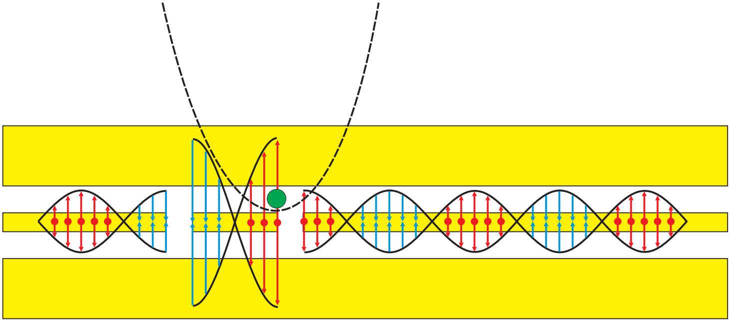
- $f_{\text{vib}} \sim 1$ MHz
- $\sqrt{\frac{\hbar}{m\omega_{\text{vib}}}} \sim 10$ nm
- $h \gtrsim 25 \quad \mu$m

Coupling itinerant EM field with ion vibrations



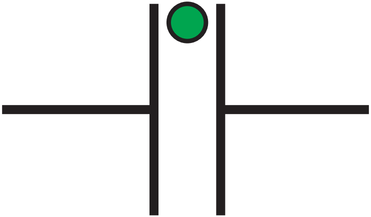
- $g \sim 10$ Hz

Coupling standing EM wave with ion vibrations



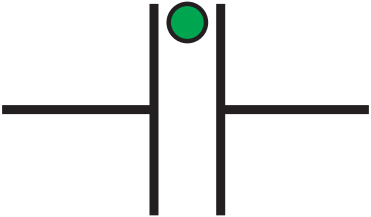
- $Q \sim 10^5 - 10^6$
- $\langle H_{\text{int}} \rangle \ \to \ \sqrt{Q} \langle H_{\text{int}} \rangle$

Beyond naive dipole interaction

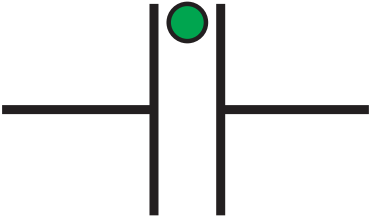


Beyond naive dipole interaction

Beyond naive dipole interaction

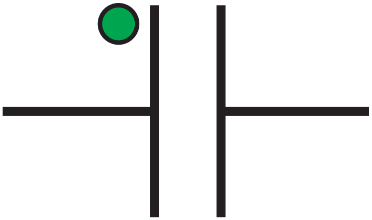


Beyond naive dipole interaction

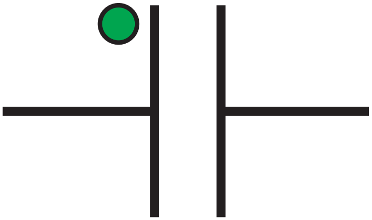


- $f_{\text{atomic}} \gg f_{\text{microwave}} \gg f_{\text{vibrational}}$

Beyond naive dipole interaction

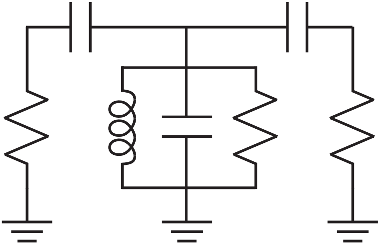


Beyond naive dipole interaction

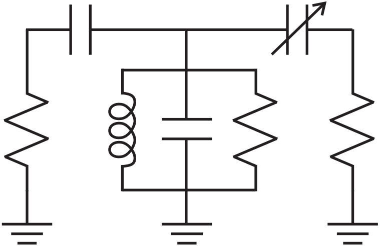


- $C = C_0(1 + \eta \cos \nu t)$
- $C_0 \sim 1$ fF, $\eta \sim 10^{-3}$, $\nu = 2\pi f_{\text{vib}} \sim 2\pi \times 1$ MHz

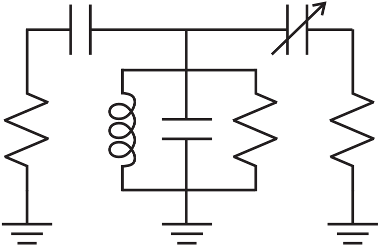
Equivalent scheme



Equivalent scheme

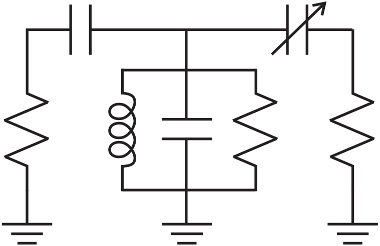


Equivalent scheme



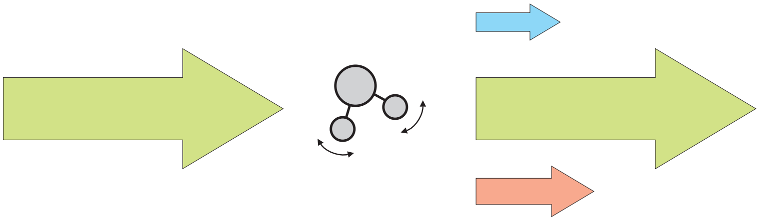
- $H_{\text{int}} = \frac{1}{2}C(V_1 - V_2)^2 = \cdots - C_0\eta V_{10}V_{20}(a_1 - a_1^\dagger)(a_2 - a_2^\dagger)\cos\nu t$
- $V_0 = \omega\sqrt{\frac{\hbar Z_0}{2}} \sim 10^{-8}\sqrt{Z_0[\Omega]}$ V

Equivalent scheme

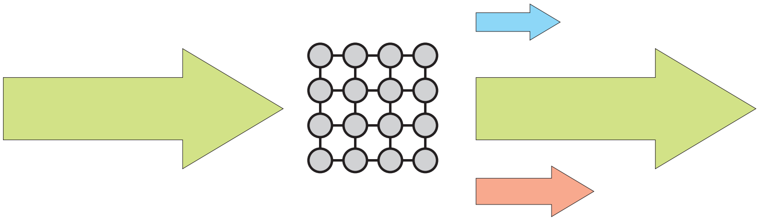


- $H_{\text{int}} = \frac{1}{2}C(V_1 - V_2)^2 = \cdots - C_0\eta V_{10}V_{20}(a_1 - a_1^\dagger)(a_2 - a_2^\dagger)\cos\nu t$
- $V_0 = \omega\sqrt{\frac{\hbar Z_0}{2}} \sim 10^{-8}\sqrt{Z_0[\Omega]}$ V
- RWA: $H_{\text{int}} = \hbar\kappa_s(a_1 b^\dagger a^\dagger_{2,\omega-\nu} + \text{h.c.}) + \hbar\kappa_{as}(a_1 b a^\dagger_{2,\omega+\nu} + \text{h.c.})$
- $\hbar\kappa_{s,as} \sim C_0\eta V_{10}V_{20} \sim \hbar \times 10^3\eta\sqrt{Z_{01}[\Omega]Z_{02}[\Omega]}$ Hz

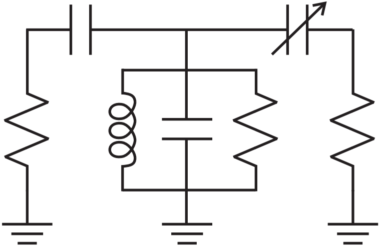
Raman effect

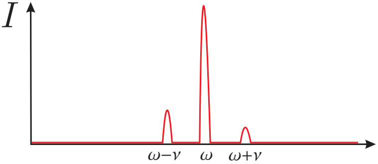


Raman (Brillouin) effect



Equivalent scheme

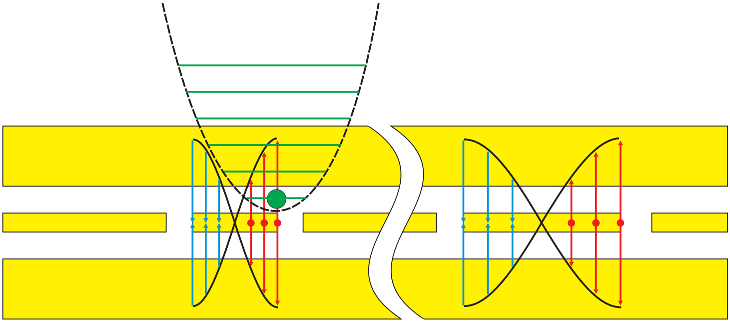




$$P_s = \frac{n_1(n_{2,s}+1)(n_{\text{vib}}+1)\kappa_s^2}{n_1(n_{2,s}+1)(n_{\text{vib}}+1)\kappa_s^2 + n_1(n_{2,as}+1)n_{\text{vib}}\kappa_{as}^2 + (\Delta\omega)^2} \times \sin^2 \sqrt{n_1(n_{2,s}+1)(n_{\text{vib}}+1)\kappa_s^2 + n_1(n_{2,as}+1)n_{\text{vib}}\kappa_{as}^2 + (\Delta\omega)^2}\, t$$

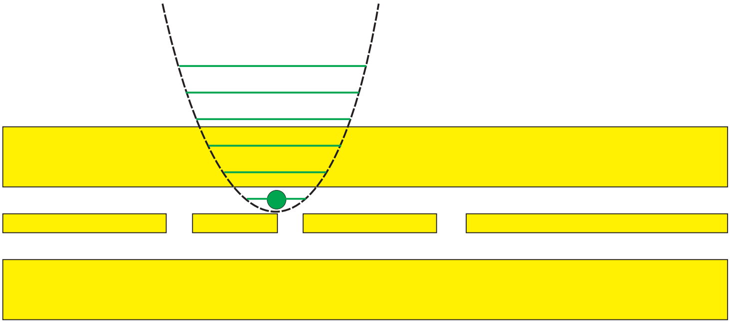
- $4\Delta\omega = 2\omega - \omega_s - \omega_{as}$

Filtering

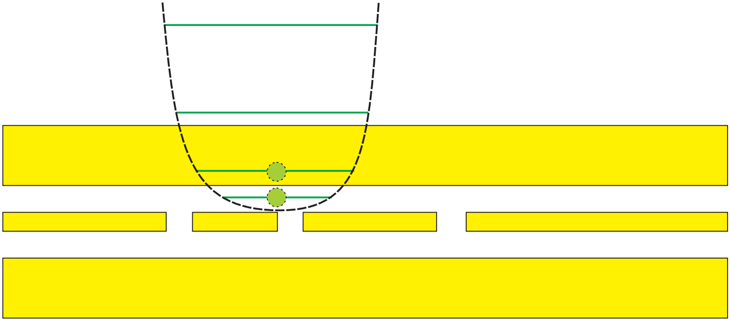


- $\Delta l = \frac{\Delta f}{f} l \sim 10\ \mu$m
- $Q \sim \frac{\omega}{\Delta\omega} > \frac{\omega}{\nu} \sim 10^3$
- $Q \lesssim \frac{10^6}{\eta\sqrt{n_1 Z_{01}[\Omega] Z_{02}[\Omega]}}$

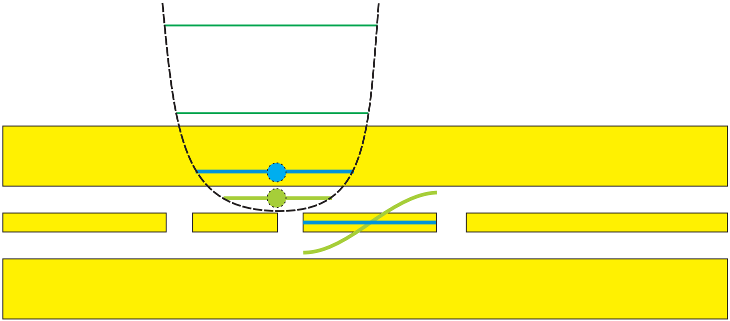
Coupling of resonators (via harmonic potential)



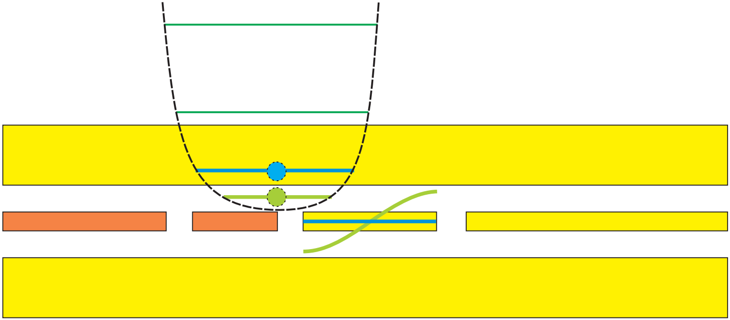
Coupling of resonators (via nonharmonic ion trap)



Single-photon operations

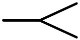


Single-photon operations



- $n_1 \sim 10^6$, $\kappa \sim 10^2$ Hz
- Operation rate $\sim 10^5$ Hz

. . . and much more

- Conversion of degree of freedom:
  electronic $\longleftrightarrow$ vibrational $\longleftrightarrow$ standing (itinerant) EM waves $\longleftrightarrow$ superconducting qubit
- Zeno effect 
- Switch 

Summary

- Ion trap as MHz modulator (semiclassical)
- Raman effect for microwaves (quantum spectroscopy)
- 1st resonator as “amplifier” of interaction
- 2nd resonator as filter

Thank you for listening!