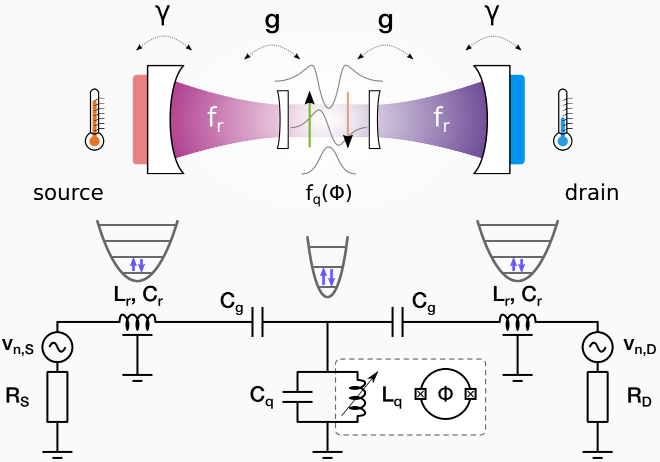
Quantum Heat Valve

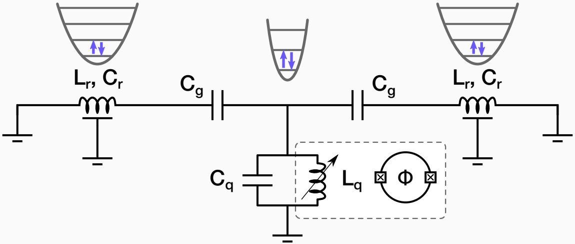
LTL Quantum Physics Seminar

Alberto Ronzani

February 1, 2018


γ
g
g
γ
fr
fr
source
fq(Φ)
drain
Lr, Cr
Cg
Cg
Lr, Cr
vn,S
vn,D
RS
RD
Cq
Lq
Φ

Hamiltonian limit: coupled oscillators (undamped)

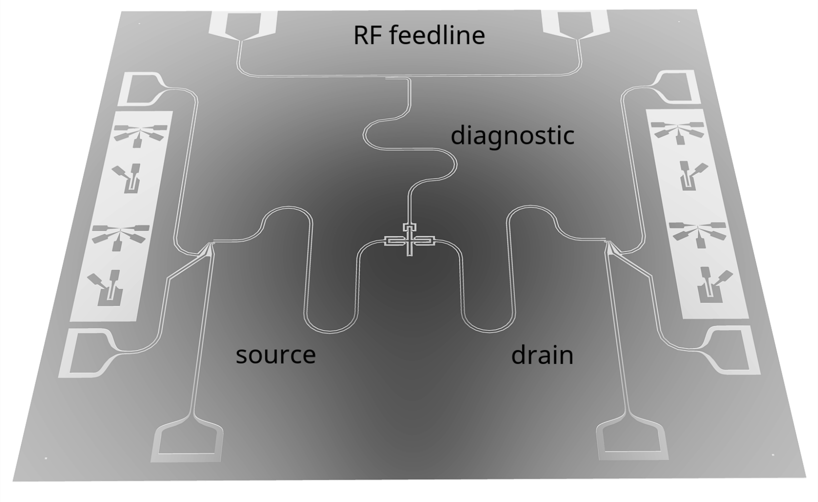


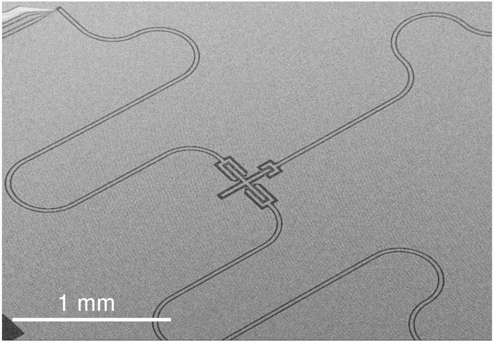
$$\hat{H}/hf_{\mathrm{r}} = (\hat{a}_{\mathrm{D}}^{\dagger}\hat{a}_{\mathrm{D}} + \hat{a}_{\mathrm{S}}^{\dagger}\hat{a}_{\mathrm{S}}) + f_{\mathrm{q}}/f_{\mathrm{r}}\,\hat{b}^{\dagger}\hat{b}$$

$$+ g\,(\hat{b}\hat{a}_{\mathrm{D}}^{\dagger} + \hat{b}^{\dagger}\hat{a}_{\mathrm{D}} + \hat{b}\hat{a}_{\mathrm{S}}^{\dagger} + \hat{b}^{\dagger}\hat{a}_{\mathrm{S}})$$

$$+ \tilde{g}\,(\hat{a}_{\mathrm{D}}\hat{a}_{\mathrm{S}}^{\dagger} + \hat{a}_{\mathrm{D}}^{\dagger}\hat{a}_{\mathrm{S}})$$

Hamiltonian limit: chip design





$$f_{\mathrm{r}} = 6.4\,\mathrm{GHz}$$

$$f_{\mathrm{d}} = 7.4\,\mathrm{GHz}$$

fabrication

- Nb (200 nm) on sapphire
- EBL mask patterning
- RIE etching

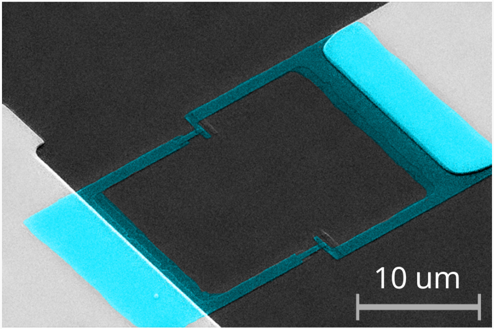
design

- coplanar waveguides

$$Z_\infty \approx 50\,\Omega$$

- interdigitated capacitors

$$C_{\mathrm{g}} \approx 10\,\mathrm{fF}$$
$$C_{\mathrm{d}} \approx 3\,\mathrm{fF}$$



$$h\,f_{\mathrm{q}}(\Phi) = \sqrt{8E_J(\Phi)E_C} - E_C$$

$$E_J(\Phi) \approx E_{J0}|\cos(\pi\Phi/\Phi_0)|$$

fabrication (SQUID)

- EBL shadow mask
- Ar milling
- Al/Ox/Al deposition

design

- Josephson junctions

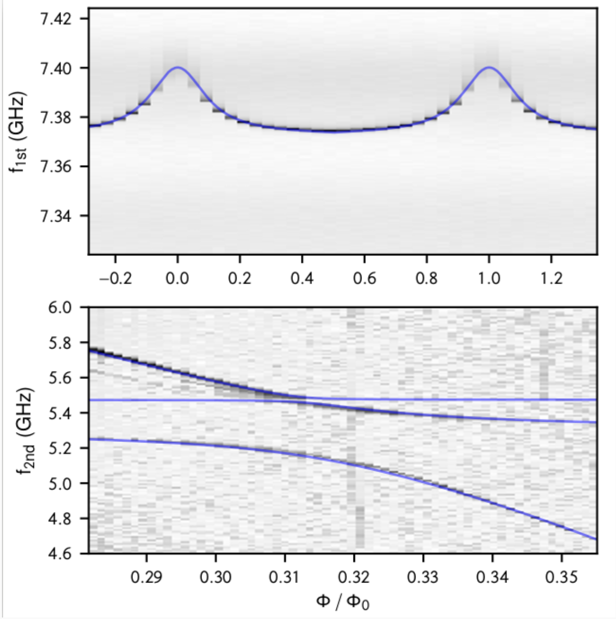
$$R_T \approx 7\,\mathrm{k\Omega}$$

- Max. Josephson energy

$$E_{J0}/h \approx 45\,\mathrm{GHz}$$

- Charging energy

$$E_C/h \approx 0.15\,\mathrm{GHz}$$



parameters

$$f_{\mathrm{r}} = 5.39\,\mathrm{GHz}$$

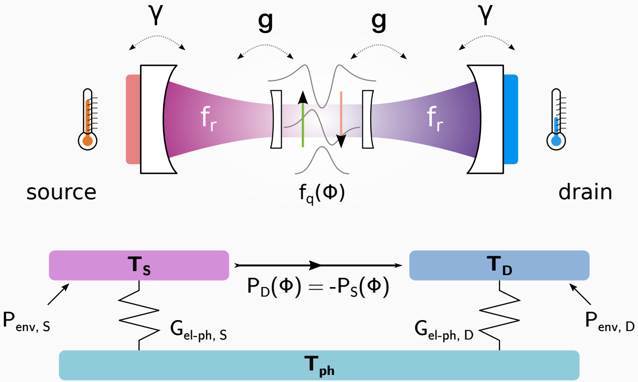
$$g = 2.0 \times 10^{-2}$$

$$\tilde{g} = -1.5 \times 10^{-2}$$

$$E_{J0}/h = 45.0\,\mathrm{GHz}$$

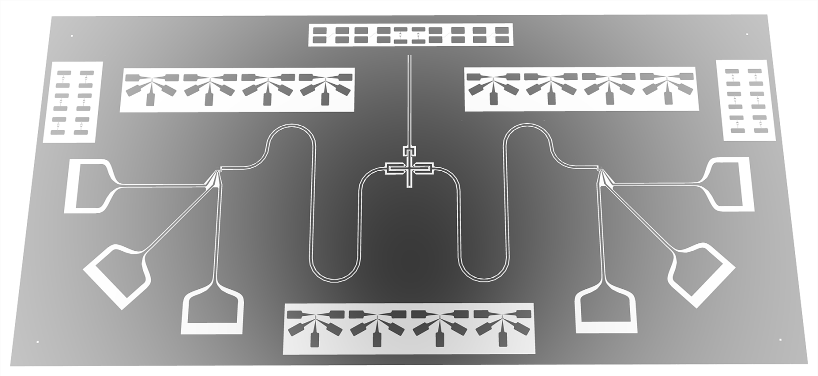
$$E_C/h = 0.15\,\mathrm{GHz}$$

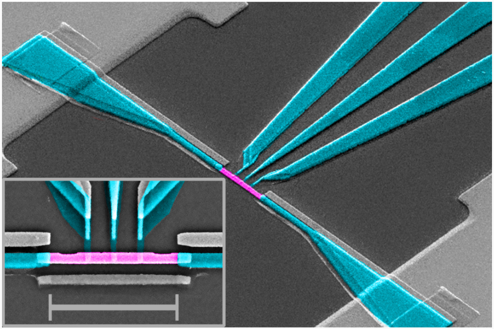
now with reservoirs: thermal model



$$P_{\mathrm{el-ph}} = \Sigma \mathcal{V}(T_{\mathrm{el}}^5 - T_{\mathrm{ph}}^5)$$

now with reservoirs: chip design





$$Q_{\mathrm{r}} = \frac{\pi}{4}\frac{Z_\infty}{R_N} \approx 20$$

fabrication (SQUID)

- EBL shadow mask
- Ar milling
- Al/Ox/Cu/Al deposition

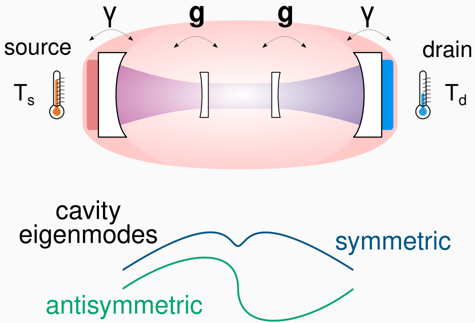
design

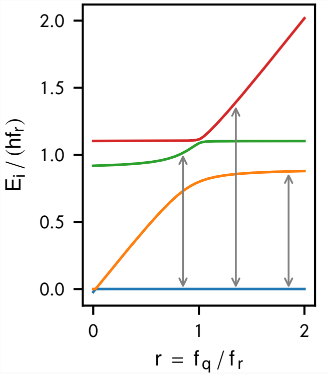
- Tunnel probe electrodes

$$R_T \approx 25\,\mathrm{k}\Omega$$

- Al / Cu / Al shunt

$$R_N \approx 2\,\Omega$$

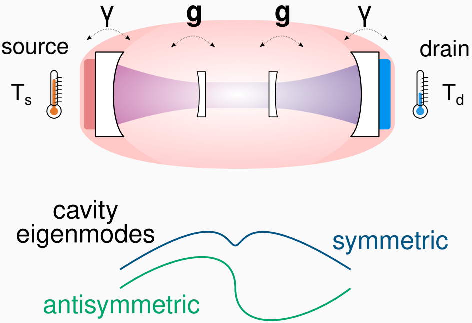




$$P_{\mathrm{D}} = \sum_{i,\,j} \rho_{ii}\, E_{ij}\, \Gamma_{i \to l,\,\mathrm{D}} \qquad \text{(steady-state)}$$

density matrix: ρ transition energy: E_{ij} transition rate: $\Gamma_{i \to l,\,\mathrm{D}}$

quasi Hamiltonian picture



summary

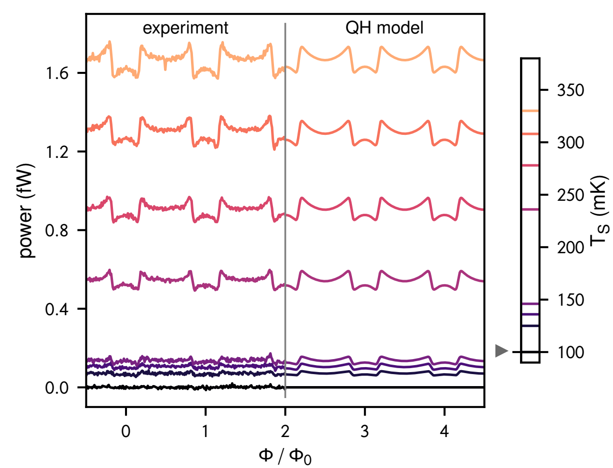
- moderate dissipation

$$Q_{\mathrm{r}}^{-1} \equiv \gamma \simeq g$$

- delocalized modes
- transport bottleneck: γ
- heat transport present

  when qubit is detuned

$$P_{\mathrm{D}} = 2\pi h \gamma f_{\mathrm{r}}^2 \sum_{i,\,j} \rho_{ii} \frac{|< i\,|\hat{a}_{\mathrm{D}} - \hat{a}_{\mathrm{D}}^{\dagger}|\,j >|^2}{1 + Q_{\mathrm{r}}^2 (f_{ij}/f_{\mathrm{r}} - f_{\mathrm{r}}/f_{ij})^2} \frac{(f_{ij}/f_{\mathrm{r}})^2}{1 - \exp[-(h f_{ij}/k T_{\mathrm{D}})]}$$



parameters

$$f_r = 5.30\,\mathrm{GHz}$$

$$Q_r = 20$$

$$g = 1.93 \times 10^{-2}$$

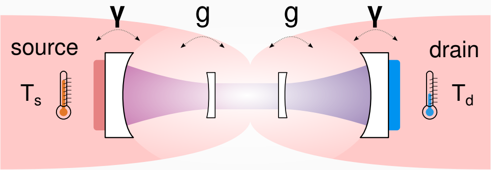
$$\tilde{g} = -2.01 \times 10^{-2}$$

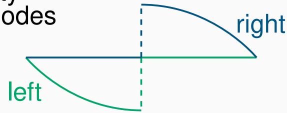
$$E_{J0}/h = 28.8\,\mathrm{GHz}$$

$$E_C/h = 0.15\,\mathrm{GHz}$$

$$g\,/\,\gamma \equiv g\,Q_r \approx 0.4$$

non Hamiltonian picture





summary

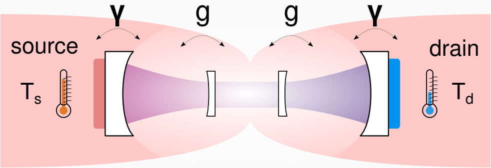
- strong dissipation

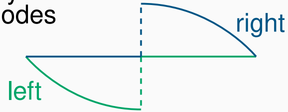
$$Q_{\mathrm{r}}^{-1} \equiv \gamma \gg g$$

- localized modes
- transport bottleneck: g
- heat transport absent when qubit is detuned

$$P_{\mathrm{D}} = \frac{\pi h g f_{\mathrm{r}}^2}{1 + Q_{\mathrm{r}}^2 (f_{\mathrm{q}}/f_{\mathrm{r}} - f_{\mathrm{r}}/f_{\mathrm{q}})^2} \frac{n(\theta_{\mathrm{S}}) - n(\theta_{\mathrm{D}})}{\coth(\theta_{\mathrm{S}}/2) + \coth(\theta_{\mathrm{D}}/2)}$$

$$\theta_{\mathrm{S,D}} = \frac{h f_{\mathrm{q}}}{k T_{\mathrm{S,D}}} \quad ; \quad n(x) = \frac{1}{\exp(x) - 1}$$





summary

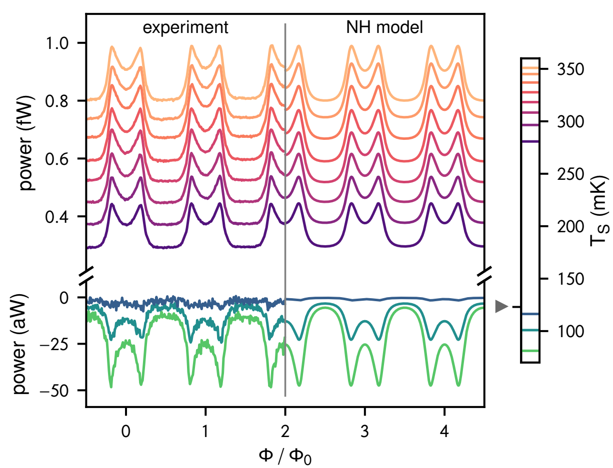
- strong dissipation

$$Q_{\mathrm{r}}^{-1} \equiv \gamma \gg g$$

- localized modes
- transport bottleneck: g
- heat transport absent when qubit is detuned

$$P_{\mathrm{D}} = \frac{\pi h g f_{\mathrm{r}}^2}{1 + Q_{\mathrm{r}}^2 (f_{\mathrm{q}}/f_{\mathrm{r}} - f_{\mathrm{r}}/f_{\mathrm{q}})^2} \frac{n(\theta_{\mathrm{S}}) - n(\theta_{\mathrm{D}})}{\coth(\theta_{\mathrm{S}}/2) + \coth(\theta_{\mathrm{D}}/2)}$$

$$+\pi h \tilde{g} f_{\mathrm{r}}^2 \int_0^{+\infty} \frac{n(x\, h f_{\mathrm{r}}/kT_{\mathrm{S}}) - n(x\, h f_{\mathrm{r}}/kT_{\mathrm{D}})}{[1 + Q_{\mathrm{r}}^2 (x - 1/x)^2]^2} x^3 \mathrm{d}x$$



parameters

$$f_{\mathrm{r}} = 5.61\,\mathrm{GHz}$$

$$Q_{\mathrm{r}} = 3.15$$

$$g = 1.56 \times 10^{-2}$$

$$\tilde{g} = 0.21 \times 10^{-2}$$

$$E_{J0}/h = 35.7\,\mathrm{GHz}$$

$$E_C/h = 0.15\,\mathrm{GHz}$$

$$g\,/\,\gamma \equiv g\,Q_{\mathrm{r}} \approx 0.05$$

conclusions

performance

- N.E.T. $\approx\ 0.1\,\mathrm{mK}/\sqrt{\mathrm{Hz}}$
- incertitude in power estimates $< 5\,\mathrm{aW}$
- typical power modulation: $\approx\ 200\,\mathrm{aW}$

two limiting regimes

- **quasi Hamiltonian**: $g \sim \gamma$, nonlocal mixed eigenmodes
- **non Hamiltonian**: $g \ll \gamma$, transmon acts as spectral filter

for more details

preprint:

Realisation of a quantum heat valve

Ronzani, Karimi, Senior, Chang, Peltonen, Chen, Pekola

arXiv:1801.09312