STIMULATED EMISSION
AND MICROWAVE ROUTER
WITH A SUPERCONDUCTING QUBIT

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Fluorescence (spontaneous emission)

\[ |g\rangle \rightarrow |e\rangle \quad \text{Drive} + \text{Stimulated photons} \]

Resonant excitation of an atom
RESONANT EXCITATION OF AN (artificial) ATOM in CAVITY QED

Fluorescence (spontaneous emission)

Drive + Stimulated photons

Houck, Nature 2007

Astafiev, Science 2010

Campagne, PRX 2016

Campagne, Jezouin PRL 2016
Josephson junction with large capacitive shunt

\[ \hat{H} = 4E_c (\hat{n} - n_g)^2 - E_J \cos \phi \]

Charging energy \( \frac{e^2}{2C} \)
Number of Cooper pairs
Superconducting phase

\( E_J \gg E_c \) → \[ \hat{H} \approx 4E_c \hat{n}^2 + E_J \frac{\phi^2}{2} - E_J \frac{\phi^4}{4!} \]
3D TRANSMON QUBIT

Non-linear, lossless element... strongly (dipole) coupled...

\( f_q = 7.09 \, \text{GHz} \)
\( f_c = 7.91 \, \text{GHz} \)
\( \chi = 33 \, \text{MHz} \)
\( \kappa = 0.77 \, \text{MHz} \)
\( T_1 = 1.95 \, \mu\text{s} \)
\( T_2 = 2.95 \, \mu\text{s} \)

... to a 3D cavity resonant mode
MEASURING THE STIMULATED PHOTONS?

\[ a_{out} = \sqrt{\gamma_a} \sigma_- \]

Purcell rate

\[ = |g\rangle \langle e| \]

(lowering operator)

\[ \beta_{in} > 0 \]

\[ b_{out} = \beta_{in} + \sqrt{\gamma_b} \sigma_- \]

\[ \langle a_{out}^+ a_{out} \rangle = \gamma_a \langle \sigma_+ \sigma_- \rangle \]

\[ = \gamma_a \frac{1 + z(t)}{2} \]

Spontaneous emission

\[ \langle b_{out}^+ b_{out} \rangle = \beta_{in}^2 + \gamma_b \langle \sigma_+ \sigma_- \rangle + 2 \sqrt{\gamma_b} \beta_{in} \operatorname{Re} \langle \sigma_- \rangle \]

\[ = \beta_{in}^2 + \gamma_b \frac{1 + z}{2} + \frac{\Omega}{2} x \]

Photon flux in the drive

Stimulated emission
HETERODYNE MEASUREMENT

Zero background when transmitted

Large background when reflected

\[ \langle b_{out} \rangle \propto \overline{V_{Re}} + i\overline{V_{Im}} \]

\[ \langle b_{out} \rangle = \beta_{in} + \frac{\sqrt{Y_b}}{2} x(t) \]
Zero background when transmitted

Large background when reflected
PHOTON RATE MEASUREMENT

Almost flat when transmitted

\[ \langle b_{out} \rangle \propto V_{\text{Re}} + i V_{\text{Im}} \]

\[ \langle b_{out}^+ b_{out} \rangle \propto |V|^2 = V_{\text{Re}}^2 + V_{\text{Im}}^2 \]

\[ \langle b_{out}^+ b_{out} \rangle = \beta_{in}^2 + \gamma_b \frac{1 + z(t)}{2} + \frac{\Omega}{2} x(t) \]
ENERGY TRANSFER ACROSS THE QUBIT

Energy transfer from port a to port b, although the local field is zero!

\[ \sqrt{\gamma_a} \alpha_{in} + \sqrt{\gamma_b} \beta_{in} = 0 \]

\[ \langle a^+_\text{out} a_{\text{out}} \rangle = \alpha_{in}^2 + \gamma_a \frac{1 + z}{2} - \frac{\Omega}{2} x \]

\[ \langle b^+_\text{out} b_{\text{out}} \rangle = \beta_{in}^2 + \gamma_b \frac{1 + z}{2} + \frac{\Omega}{2} x \]

Add a 2nd drive to freeze the qubit
Energy transfer across the qubit

\[ \sqrt{\gamma_a} \alpha_{in} + \sqrt{\gamma_b} \beta_{in} = 0 \]

Energy transfer from port \( a \) to port \( b \), although the local field is zero!

Add a 2\textsuperscript{nd} drive to freeze the qubit.

\[ \langle a_{out}^+ a_{out} \rangle = \alpha_{in}^2 + \gamma_a \frac{1 + z}{2} - \frac{\Omega}{2} x \]

\[ \langle b_{out}^+ b_{out} \rangle = \beta_{in}^2 + \gamma_b \frac{1 + z}{2} + \frac{\Omega}{2} x \]
Energy transfer across the qubit

Energy transfer from port a to port b, although the local field is zero! & phase dependent.

$\langle a_{out}^+ a_{out} \rangle = \alpha_{in}^2 + \gamma_a \frac{1+z}{2} - \frac{\Omega}{2} x$

$\langle b_{out}^+ b_{out} \rangle = \beta_{in}^2 + \gamma_b \frac{1+z}{2} + \frac{\Omega}{2} x$

$\sqrt{\gamma_a} \alpha_{in} + \sqrt{\gamma_b} \beta_{in} = 0$

Add a 2\textsuperscript{nd} drive to freeze the qubit
Prepare qubit in $|e\rangle + e^{i\varphi}|g\rangle \over \sqrt{2}$

$$\alpha_{in} = -\sqrt{\gamma_b / \gamma_a} \beta_{in}$$

$$\beta_{in} > 0$$

$$\langle b_{out}^+ b_{out} \rangle = \beta_{in}^2 + \gamma_b {1 + z \over 2} + \Omega {\Omega \over 2} x$$
PHASE DEPENDENCE OF STIMULATED EMISSION

\[
\alpha_{in} = -\sqrt{\frac{\gamma_b}{\gamma_a}} \beta_{in}
\]

\[
\beta_{in} > 0
\]
TRANSFERRED vs INJECTED ENERGY

Preparation in: \( \frac{|e\rangle \pm |g\rangle}{\sqrt{2}} (x = \pm 1) \)  
\( \langle b^+_\text{out}b^-\text{out}\rangle_\pm = \beta^2_{\text{in}} + \gamma_b \frac{1 + z}{2} \pm \frac{\Omega}{2} x \)
Preparation in: \[ \frac{|e\rangle \pm |g\rangle}{\sqrt{2}} (x = \pm 1) \]

\[ \langle b_{out}^+ b_{out} \rangle_\pm = \beta_{in}^2 + \gamma_b \frac{1 + z}{2} \pm \frac{\Omega}{2} x \]

Large \( \Omega : \frac{\Omega}{\beta_{in}^2} \to 0 \)

Optimum when \( \Omega \sim \gamma_b \)

Small \( \Omega : \frac{\Omega}{\gamma_b} \to 0 \)
Drive during time $\tau$ and measure $N_{\pm} = \int_{-\infty}^{+\infty} \langle b_{out}^+ b_{out} \rangle_{\pm}(t) \, dt$

$$\langle b_{out}^+ b_{out} \rangle_{\pm} = \beta_{in}^2 + \gamma_b \frac{1+z}{2} \pm \frac{\Omega}{2} x$$

Up to 57% (55% predicted) of the drive energy is transmitted
The noise is the signal!

Interplay between absorption & stimulated emission of different modes

What about correlations in between those modes?

What about non-classical states?
THANKS!