Antiresonance Phase shift in strongly coupled cavity QED

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Myounggyu Hwang
Quantum field laser laboratory
Group summary

Experiments with single photons and individual atoms
Quantum Dynamics Division, Prof. Gerhard Rempe

1 director
4 scientists
1 postdoc
5 technicians
3 assistants
16 doctoral candidates
4 master student

- Bose Einstein Condensation (BEC)
- Cavity Quantum Electrodynamics
- Quantum Information Processing
- Cold Polar Molecules
Anti-resonance of coupled oscillators

- At anti-resonance frequency, one oscillator has a minimum in the amplitude and a large shift in oscillation phase.

- Anti-resonances are caused by destructive interference between an external driving force and an interaction with another oscillator.
Anti-resonance of coupled oscillators

\[
\begin{align*}
\dot{x}_1 + 2\gamma_1 x_1 + \omega_1^2 x_1 - 2g\omega_1 x_2 &= 2F \cos \omega t \\
\dot{x}_2 + 2\gamma_2 x_2 + \omega_2^2 x_2 - 2g\omega_2 x_1 &= 0
\end{align*}
\]

\[
\begin{align*}
\alpha_1 &= \omega_1 x_1 + ip_1/m_1 \\
\alpha_2 &= \omega_2 x_2 + ip_2/m_1 \\
\Delta_i &= \omega - \omega_i
\end{align*}
\]

In rotating frame of \(\omega\), with r.w.a.,

\[
\begin{align*}
\dot{\alpha}_1 &= i(\Delta_1 + i\gamma_1)\alpha_1 - ig\left(\frac{\omega_1}{\omega_2}\right)\alpha_2 + iF \\
\dot{\alpha}_2 &= i(\Delta_2 + i\gamma_2)\alpha_2 - ig\left(\frac{\omega_2}{\omega_1}\right)\alpha_1
\end{align*}
\]

Steady state solution is

\[
\begin{align*}
\alpha_{1,ss} &= \frac{-F(\Delta_2+i\gamma_2)}{(\Delta_1+i\gamma_1)(\Delta_2+i\gamma_2)-g^2} \\
\alpha_{2,ss} &= \frac{\omega_2}{\omega_1} \frac{-Fg}{(\Delta_1+i\gamma_1)(\Delta_2+i\gamma_2)-g^2}
\end{align*}
\]
Anti-resonance of atom-cavity system

\[
\langle \hat{a} \rangle = \frac{\eta (\Delta_{pa} + i \gamma)}{(\Delta_{pa} + i \gamma)(\Delta_{pc} + i \kappa) - g^2}
\]

\[
\begin{align*}
\Delta_{pa} &= \omega - \omega_{\text{atom}} \\
\Delta_{pc} &= \omega - \omega_{\text{cavity}}
\end{align*}
\]

\[
\times \quad \begin{cases} 
\alpha_{1,SS} = \frac{-F(\Delta_2 + i \gamma)}{(\Delta_1 + i \gamma_1)(\Delta_2 + i \gamma_2) - g^2} \\
\alpha_{2,SS} = \frac{\omega_2}{\omega_1} \frac{-Fg}{(\Delta_1 + i \gamma_1)(\Delta_2 + i \gamma_2) - g^2}
\end{cases}
\]
3. Experimental setup

- Single $^{85}\text{Rb}$ in intra-cavity dipole trap (785nm)
- Heterodyne measurement
- Strong coupling: $(g_0, \gamma, \kappa)/2\pi = (16, 3.0, 1.5)\text{MHz}$
- $\omega_{atom}$ is controllable by ac Stark shift
4. Result: $\Delta_{pc}$ vs. phase shift

- Anti-resonant frequency is at $\Delta_{pa} = 0$. i.e. $\Delta_{pc} = \Delta_{ac} = -3MHz$
- Negative slope occurs at anti-resonant frequency.

\[
\langle \hat{a} \rangle = \frac{\eta (\Delta_{pa} + i\gamma)}{(\Delta_{pa} + i\gamma)(\Delta_{pc} + i\kappa) - g^2}
\]
5. Result: $\Delta_{pc}$ vs. phase shift, varying $\Delta_{ac}$

- $\Delta_{ac} = (-14, -5, 12) MHz$
- Netagive slope is at anti-resonant frequency.

$$\langle \hat{a} \rangle = \frac{\eta(\Delta_{pa} + i\gamma)}{(\Delta_{pa} + i\gamma)(\Delta_{pc} + i\kappa) - \xi^2}$$
5. Result: $\Delta_{pa}$ vs. phase shift

- $\Delta_{pc} = 0 MHz$.
- $\Delta_{pa} = \Delta_{ca}$ is controlled by dipole trap power.
- 140 degree of phase shift is largest yet observed from a single emitter.

\[
\langle \hat{a} \rangle = \frac{\eta(\Delta_{pa} + i\gamma)}{(\Delta_{pa} + i\gamma)(\Delta_{pc} + i\kappa) - \xi^2}
\]