

Study on Coupling Between Magnons and Active Cavity Photons

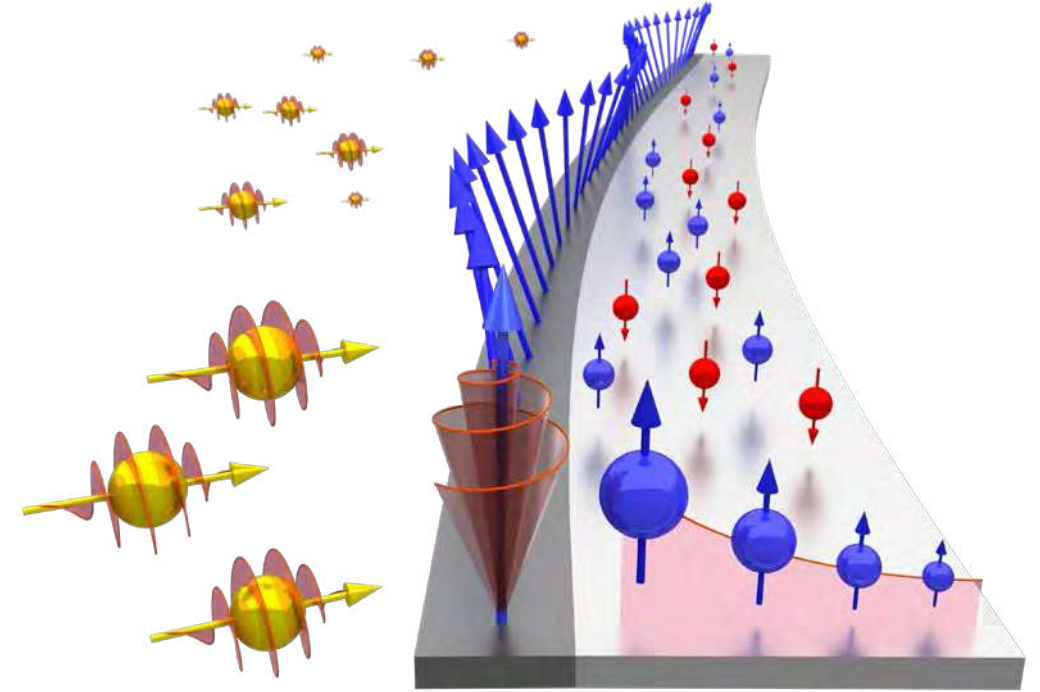
Present by: Yutong Zhao

Supervisor: Dr. Can-Ming Hu

Dec 8th 2017

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2. Theory
3. Experiment Setup
4. Experiment Results
5. Conclusion



Contents

1. Introduction

- Spin-photon interaction
- Polaritons

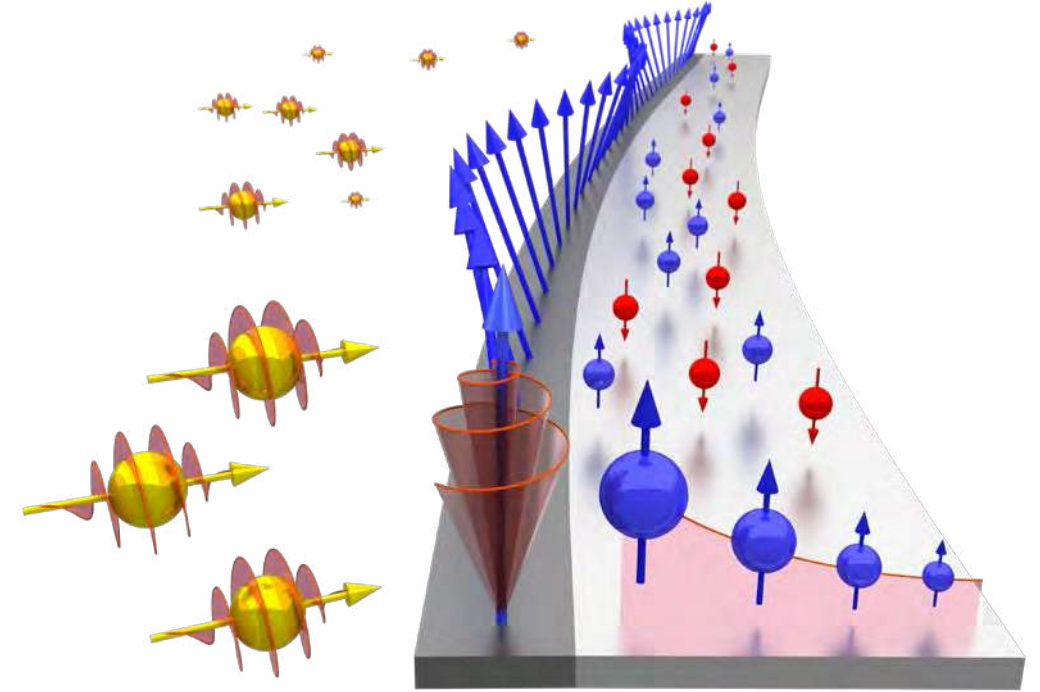
2. Theory

3. Experiment Setup

4. Experiment Results

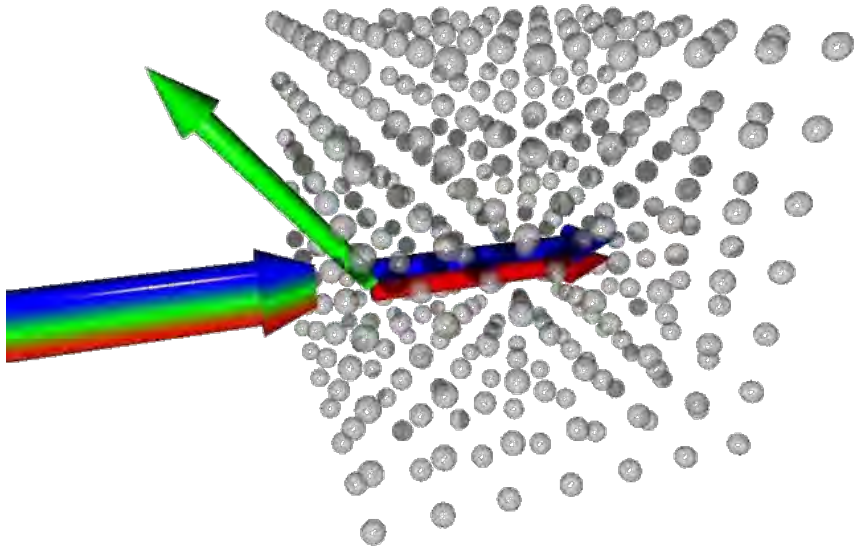
5. Conclusion

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Introduction

- Light Matter interaction

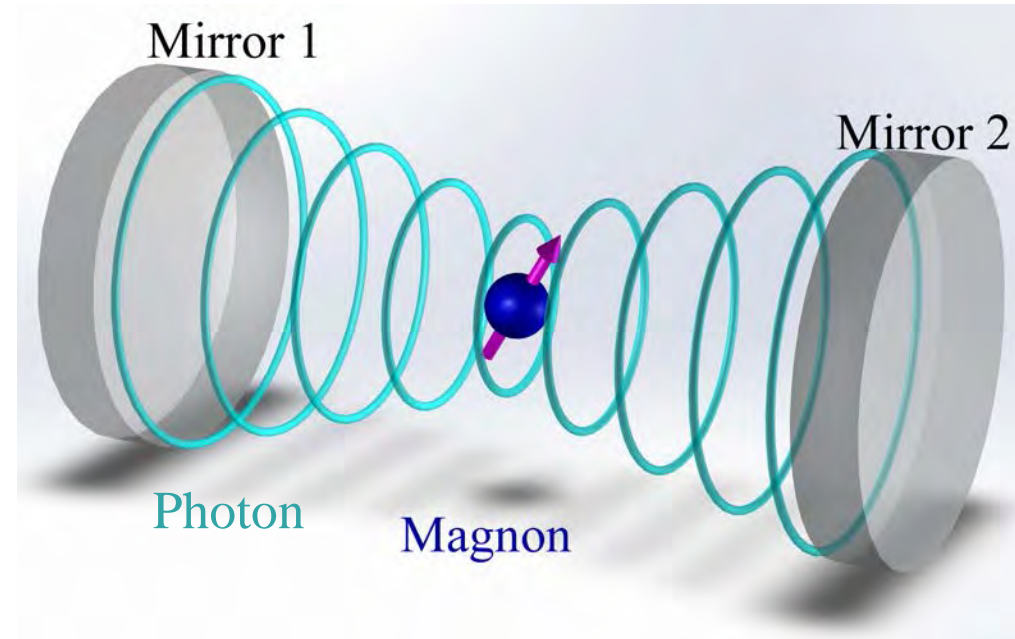


Absorption, reflection, refraction...

➔ Information of matter

All EM frequency (radio to γ -ray)

- Spin-photon interaction



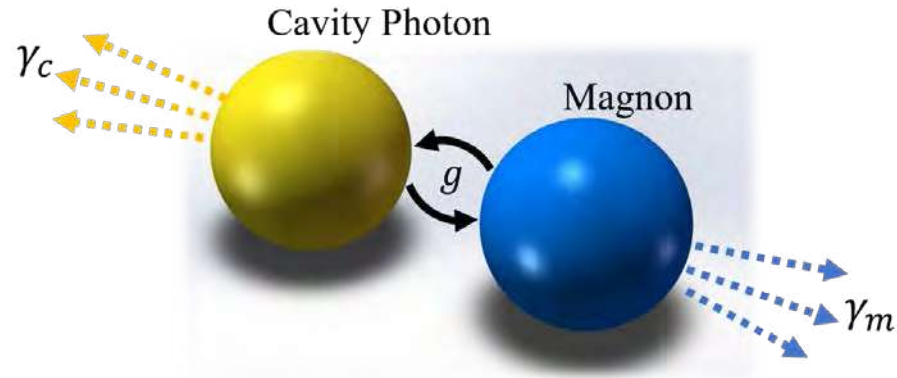
Electron spin procession: \sim GHz range

Magnetic dipole in EM field

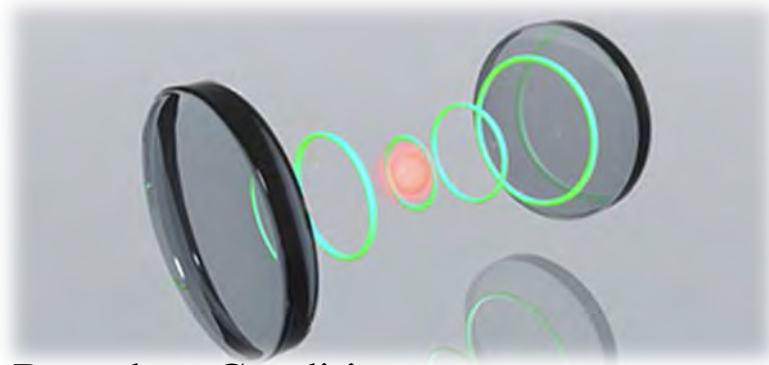
➔ Ferrimagnetic material + Microwave

Introduction

Polariton: A quasi-particle result from strong coupling of photon and matter

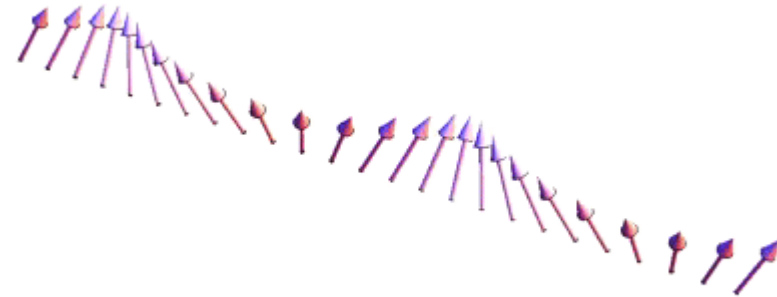


Cavity Photon: Standing wave in cavity



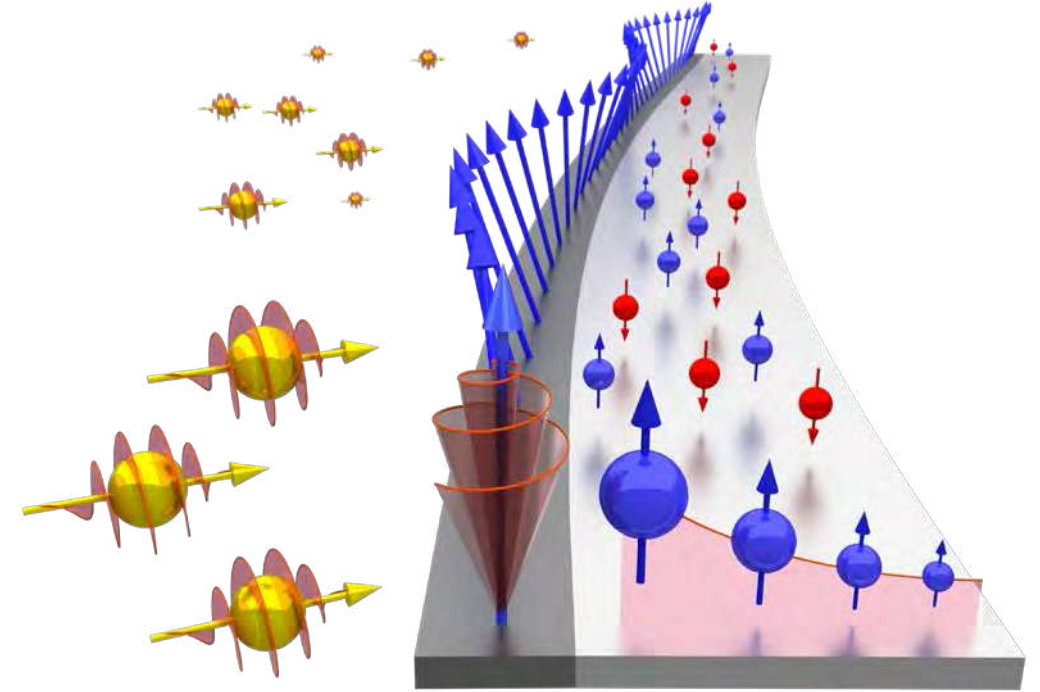
Boundary Condition

Magnon: Spin wave

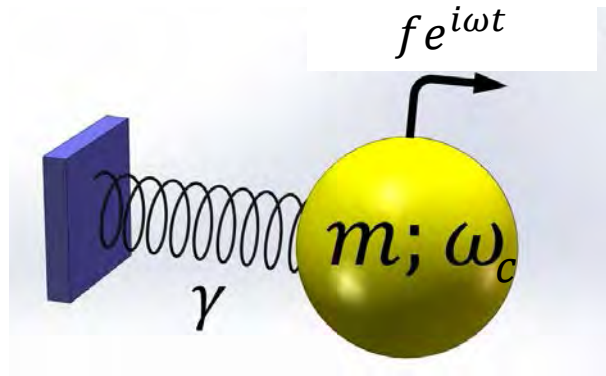


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2. Theory
 - Classical
 - Quantum
 - Matrix model
 - Magnon quintuplets
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Theory: Classical



Photon Cavity

- Damped oscillator

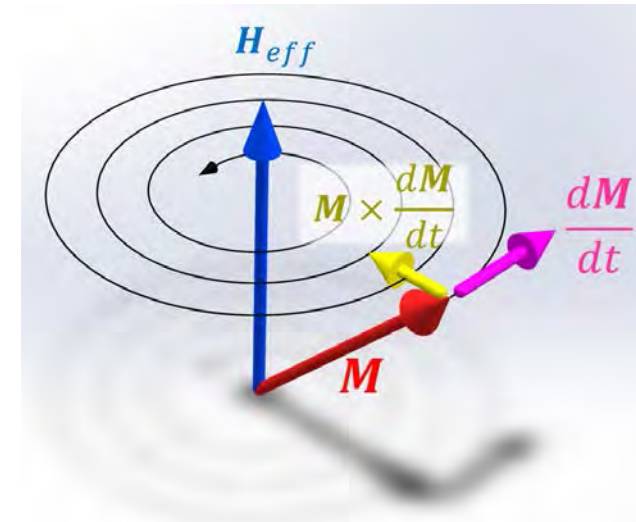
$$\ddot{x} + \boxed{\alpha\omega_c\dot{x}} + \omega_c^2 x = f e^{i\omega t}$$

Damping

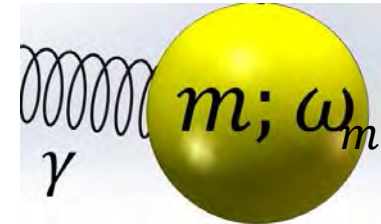
Stable solution:

$$(\omega_c^2 - \omega^2 + i\alpha\omega_c\omega)A = f$$

➔ Periodic with decay



Magnon



- Landau-Lifshitz-Gilbert equation

$$\frac{d\vec{M}}{dt} = \boxed{\gamma(\vec{M} \times \vec{H}_{eff})} + \boxed{\frac{\alpha}{M}(\vec{M} \times \frac{d\vec{M}}{dt})}$$

Torque

Gilbert Damping

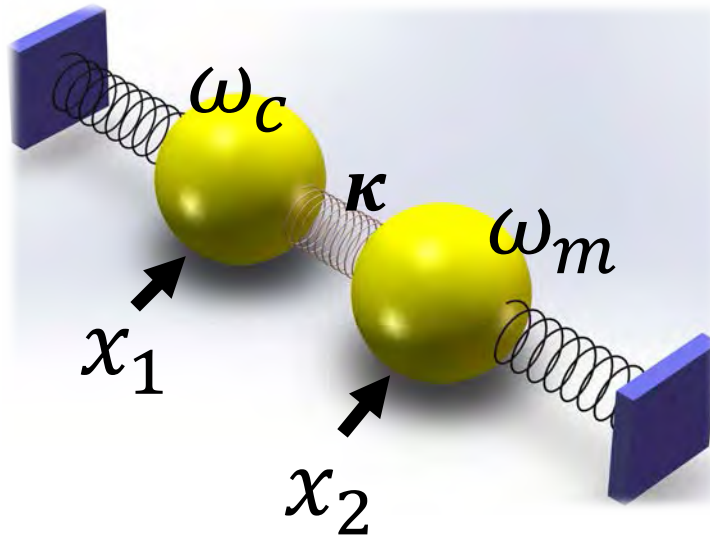
Solution using approximation:

$$(\omega_m - \omega + i\alpha\omega_m)m^+ = \omega_0 h^+$$

➔ Also Periodic with decay

Theory: Classical

- Coupled Spring Oscillator



Yield 2 by 2 matrix:

$$\begin{pmatrix} \text{Photon} & \text{Coupling} \\ \text{Coupling} & \text{Magnon} \end{pmatrix} \begin{pmatrix} A_c \\ A_m \end{pmatrix} = \begin{pmatrix} -f \\ 0 \end{pmatrix}$$

→ Eigenvalue problem: $\det(\omega I - M)$

Equation of Motion:

Photon: $\ddot{x}_1 + \alpha\omega_c\dot{x}_1 + \omega_c^2x_1 + \kappa\omega_c^2x_2 = fe^{i\omega t}$

Magnon: $\ddot{x}_2 + \beta\omega_a\dot{x}_2 + \omega_m^2x_2 + \kappa\omega_c^2x_1 = 0$

Dispassion

Coupling

Assuming: $x_1 = A_ce^{i\omega t}$, and $x_2 = A_me^{i\omega t}$

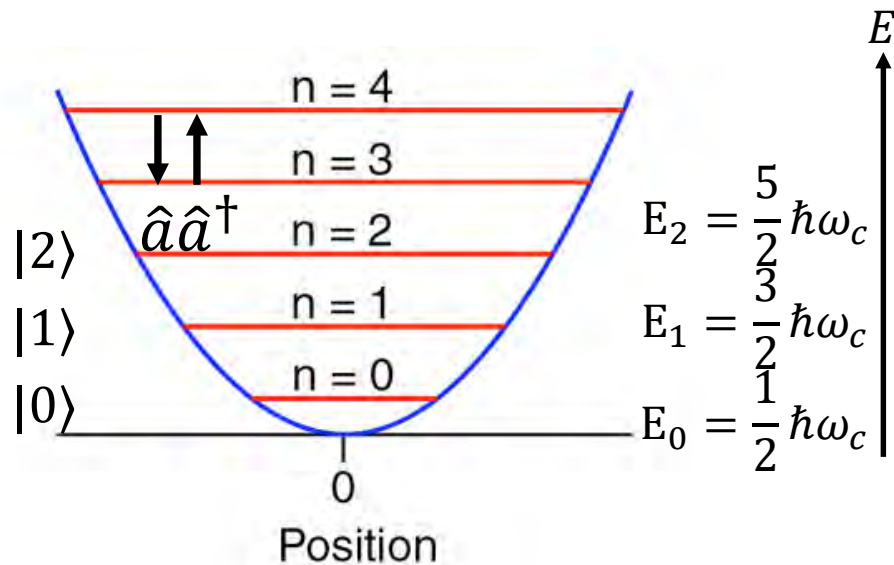
Theory: Quantum

- Quantum harmonic oscillator

$$H = \frac{\hat{p}^2}{2m} + \frac{1}{2}m\omega_c^2\hat{x}^2$$

$$E_n = \hbar\omega_c\left(n + \frac{1}{2}\right)$$

$$H_{\text{cavity}} = \Delta H = \hbar\omega_c\hat{a}^\dagger\hat{a}$$

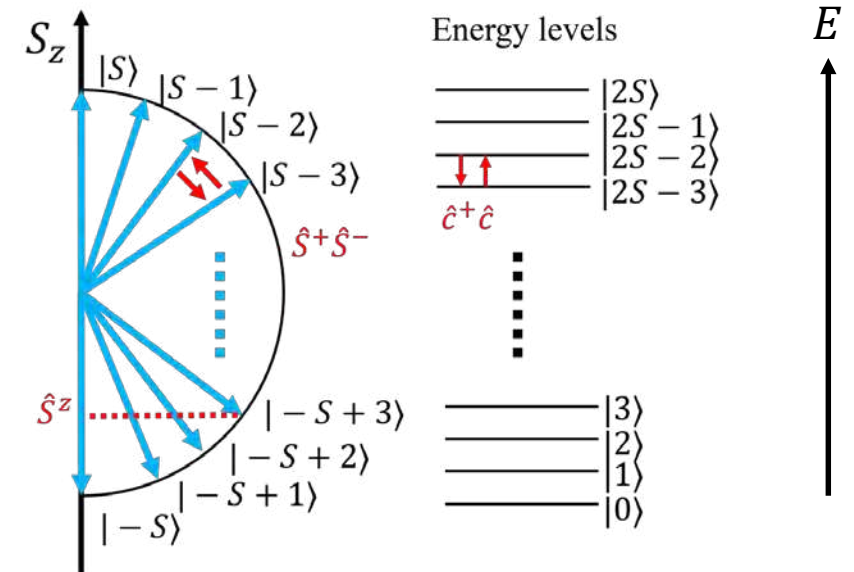


- Collective spin system

$$\text{Collective operator } \hat{S} = \frac{1}{2} \sum_{n=1}^N \hat{\sigma}_{ni} \quad i = x, y, z$$

$$\hat{S}^z \left| \frac{N}{2}, -\frac{N}{2} + m \right\rangle = \left(-\frac{N}{2} + m \right) \left| \frac{N}{2}, -\frac{N}{2} + m \right\rangle$$

$$H_{\text{magnon}} = \hbar\omega_m\hat{S}^z$$

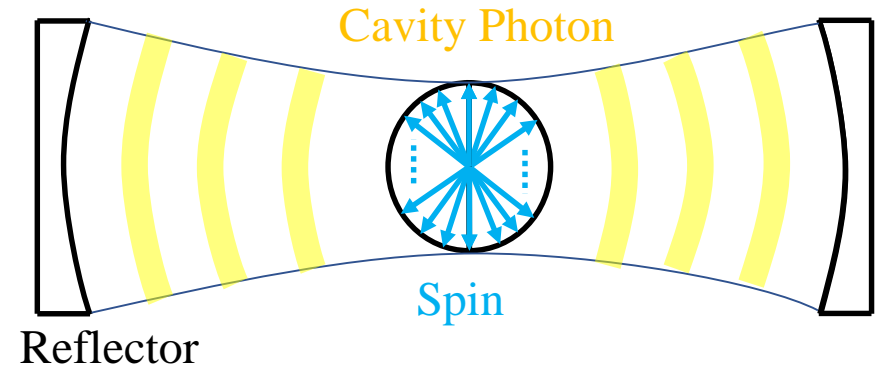


Theory: Quantum

- Collective spin interact with cavity photons

Hamiltonian:

$$\frac{H}{\hbar} = \underbrace{\omega_m \hat{S}^z}_{\text{Magnon}} + \underbrace{\omega_c \hat{a}^\dagger \hat{a}}_{\text{Photon}} + \underbrace{g(\hat{a}^\dagger \hat{S}_- + \hat{a} \hat{S}_+)}_{\text{Interaction}}$$



Two degenerate states:

$$|1\rangle = |\frac{N}{2}, -\frac{N}{2}, 1\rangle \text{ and } |2\rangle = |\frac{N}{2}, -\frac{N}{2} + 1, 0\rangle$$

Matrix component
 $H_{ij} = \langle i | H | j \rangle$

$$\left[\frac{H}{\hbar} \right] = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} \text{Photon} & \text{Coupling} \\ \text{Coupling} & \text{Magnon} \end{pmatrix}$$

→ Eigenvalue problem: $\det(\lambda I - M)$

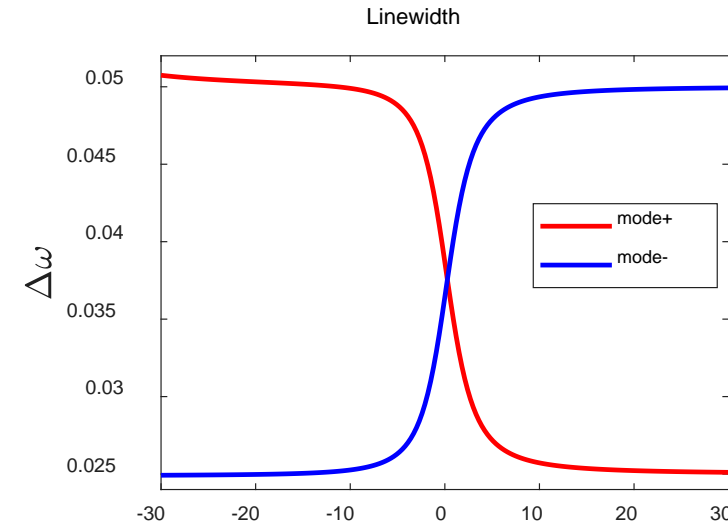
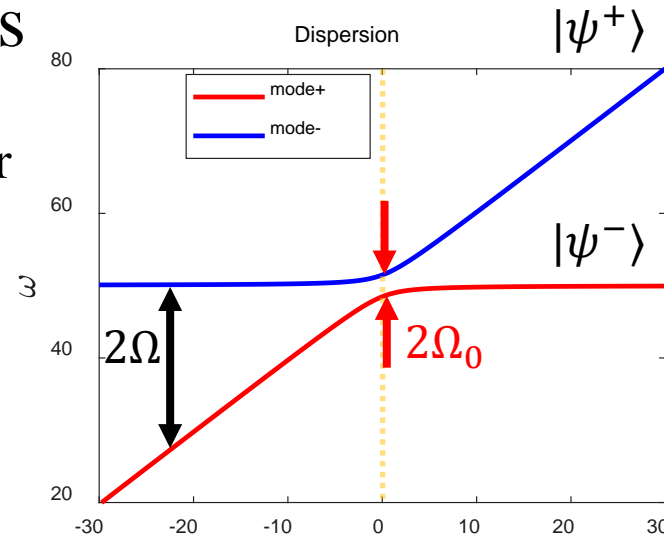
Theory: Matrix model

- Eigenvalues

Anti-crossing behavior

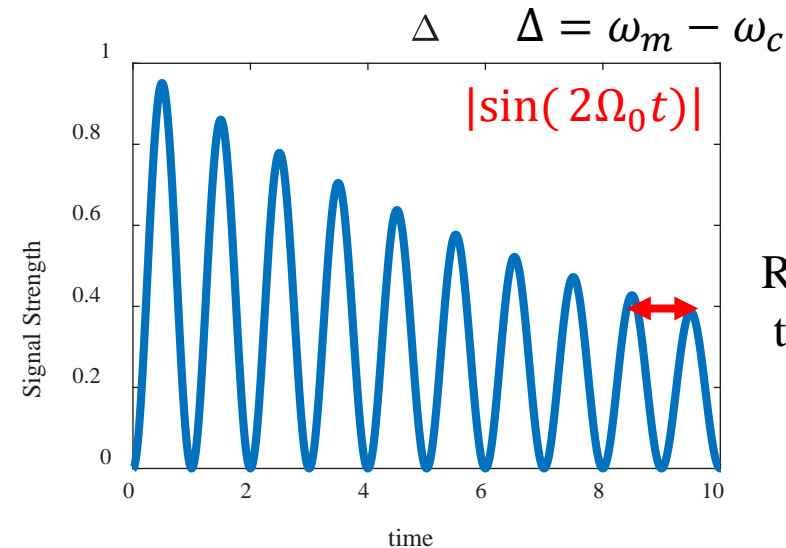
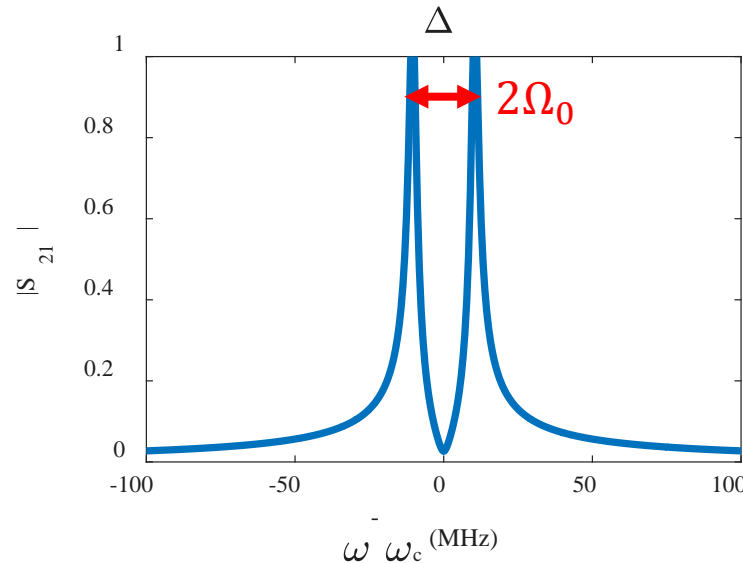
Generalized Rabi frequency

$$\Omega = \sqrt{\Omega_0^2 + \left(\frac{\Delta}{2}\right)^2}$$



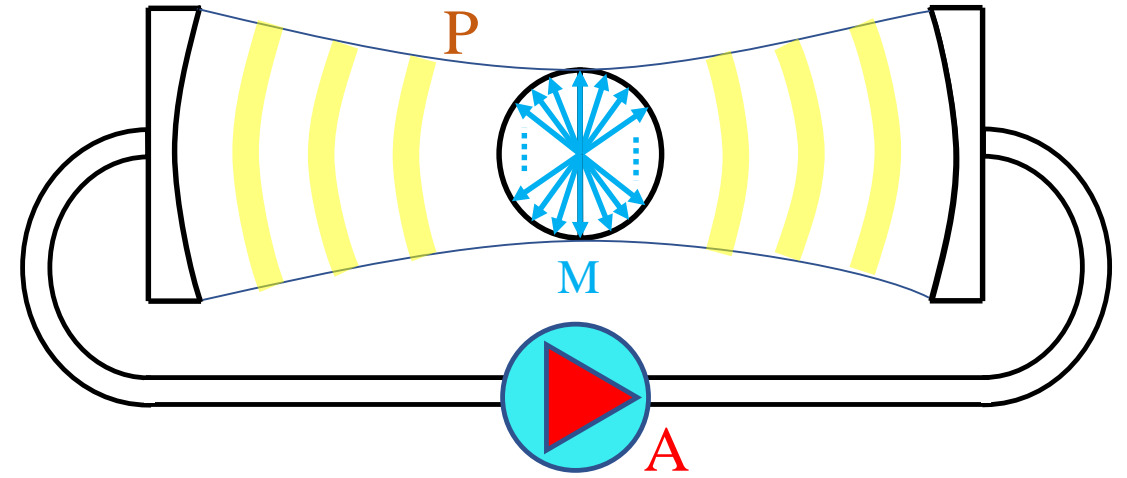
Linewidth exchange

Rabi frequency Ω_0
frequency domain



Rabi oscillation Ω_0
time domain

Theory: Quintuplet H



- Hamiltonian of A-P-M system

$$\frac{H}{\hbar} = \underbrace{\omega_m \hat{S}^z}_{\text{M}} + \underbrace{\omega_c \hat{p}^\dagger \hat{p}}_{\text{P}} + \underbrace{\omega_c \hat{a}^\dagger \hat{a}}_{\text{A}} + \Omega_{PM} (\hat{p}^\dagger \hat{S}_- + \hat{p} \hat{S}_+) + \Omega_{APM} (\hat{a}^\dagger \hat{S}_- + \hat{a} \hat{S}_+)$$

$\hat{p}^\dagger \hat{p}$ --- passive photons

$\hat{a}^\dagger \hat{a}$ --- feedback photons.

Ω_{PM} --- interaction between P-M

Ω_{APM} --- interaction between A-P-M

$$\frac{H}{\hbar} = \omega_+ \hat{m}_+^z + \omega_- \hat{m}_-^z + \omega_c \hat{a}^\dagger \hat{a} + \frac{c_+ \Omega_0}{\sqrt{m}} (\hat{m}_+^+ \hat{a} + \hat{m}_+^- \hat{a}^\dagger) + \frac{c_- \Omega_0}{\sqrt{m}} (\hat{m}_-^+ \hat{a} + \hat{m}_-^- \hat{a}^\dagger)$$

$$|\psi^+\rangle \leftrightarrow |N\rangle$$

$$|\psi^-\rangle \leftrightarrow |N\rangle$$

Theory: Quintuplet

For energy levels involves in coupling:

$$H_{int+} = \frac{c_+ \Omega_0}{\sqrt{m}} (\hat{m}_+^+ \hat{a} + \hat{m}_+^- \hat{a}^\dagger)$$

$$\begin{aligned} |1e\rangle &= |\psi_+\rangle |n\rangle & |1g\rangle &= |\psi_+\rangle |n-1\rangle \\ |2e\rangle &= |G\rangle |n+1\rangle & |2g\rangle &= |G\rangle |n\rangle \end{aligned}$$

Energy splits:

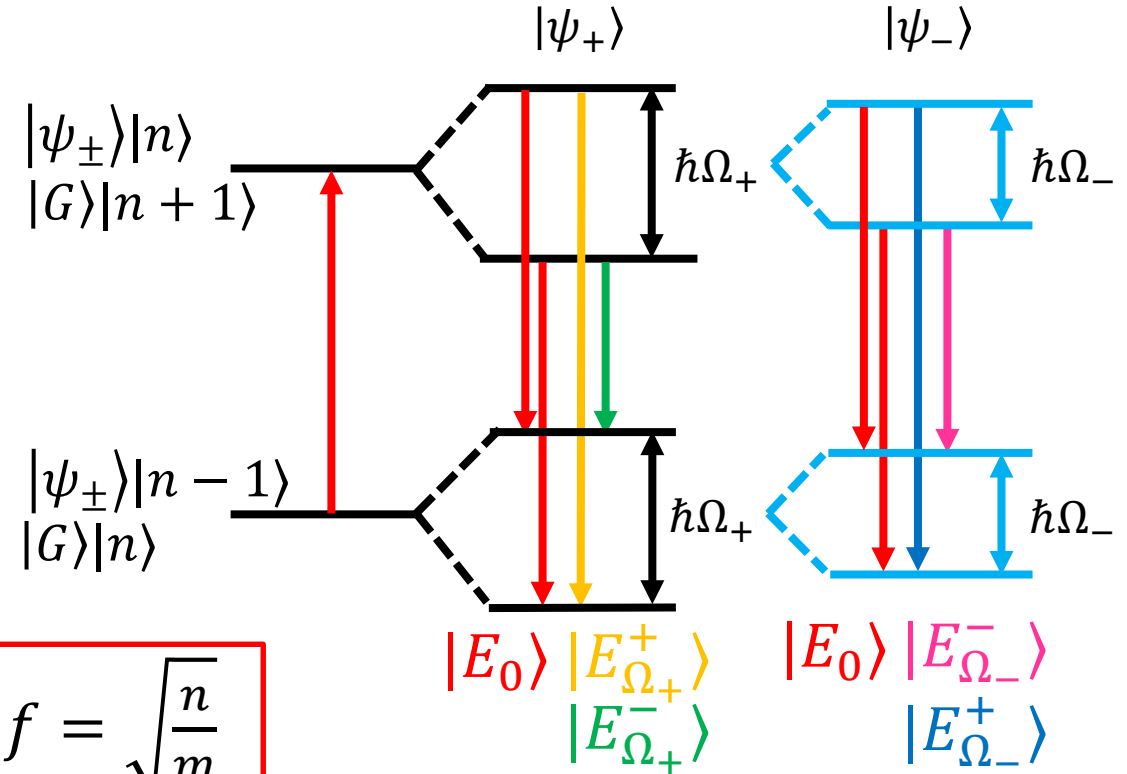
➡ $\Delta E_e \approx \Delta E_g = c_+ \Omega_0 f$

$$\Omega_+ = \sqrt{\left(\Omega + \frac{\Delta}{2}\right)^2 + (c_+ \Omega_0 f)^2}$$

➡
$$\Omega_- = \sqrt{\left(\Omega - \frac{\Delta}{2}\right)^2 + (c_- \Omega_0 f)^2}$$

→ Five different solutions if $\Delta \neq 0$

- Energy level splitting of magnon quintuplet



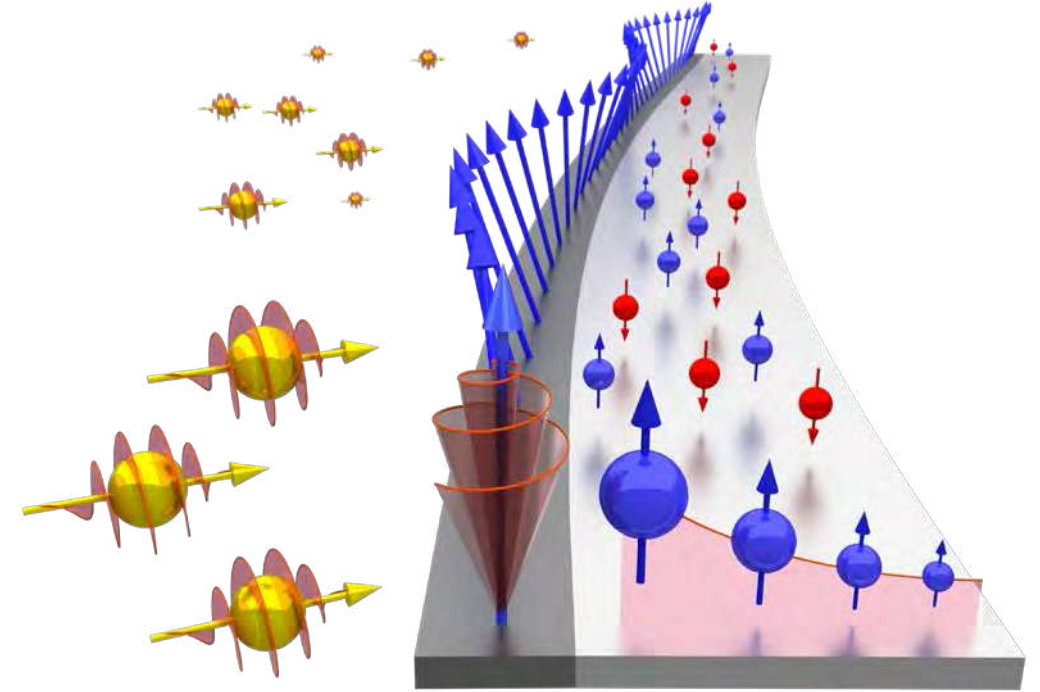
Feedback factor $f = \sqrt{\frac{n}{m}}$

at $\Delta = 0$

$$\Omega_f = \Omega_{\pm} = \Omega_0 \sqrt{1 + 2f^2}$$

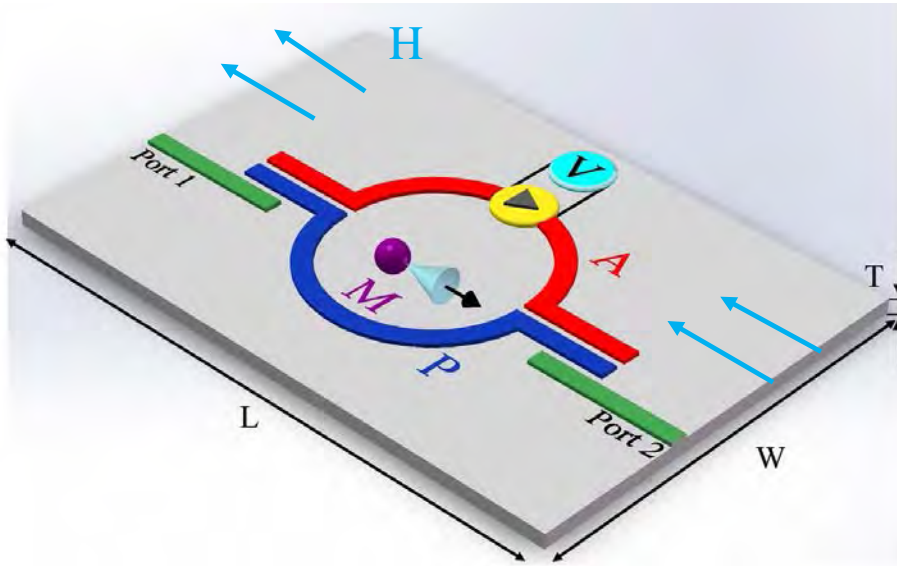
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Experiment Setup

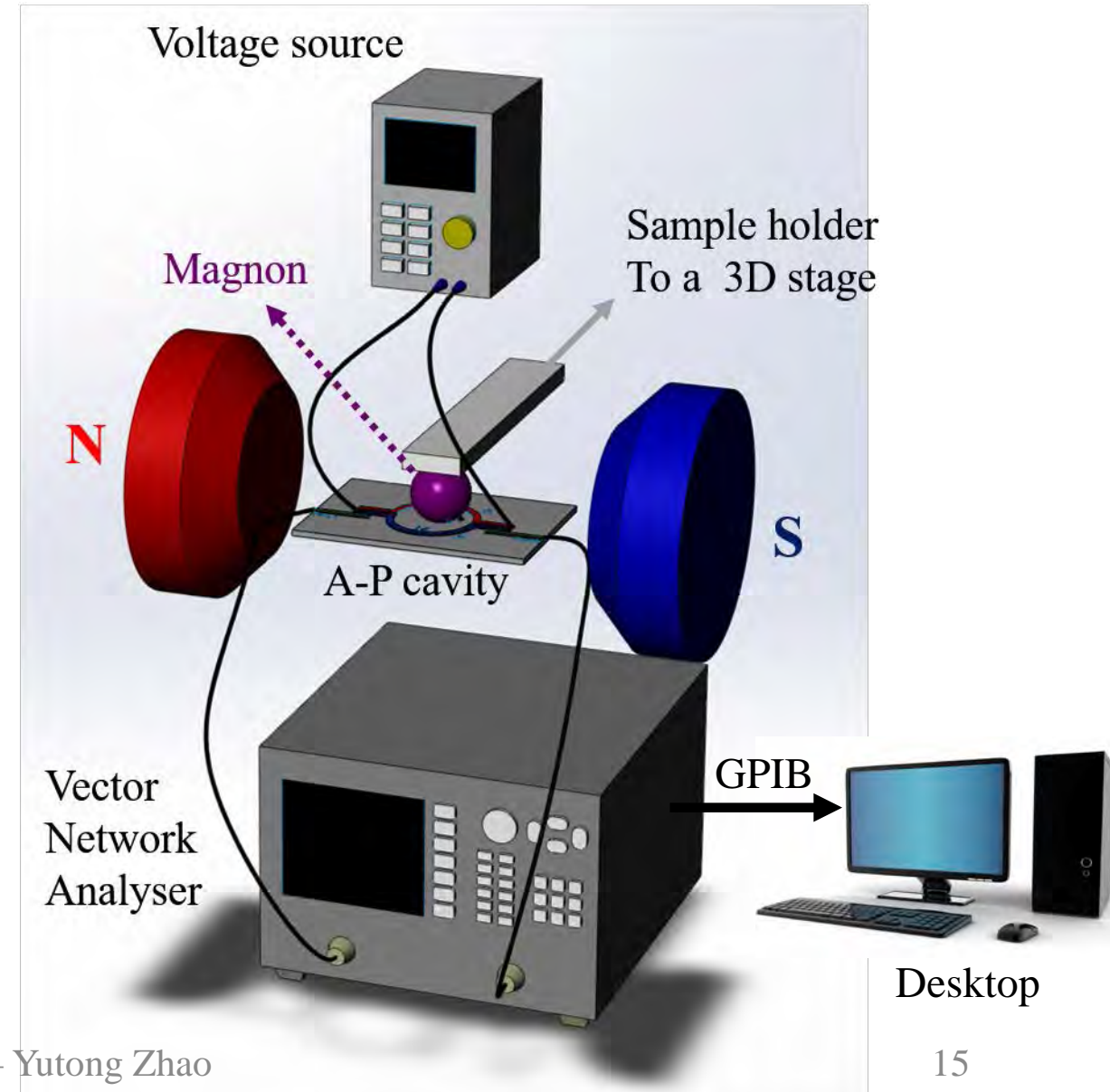
- Cavity design (A-P)



Active cavity:
 $L = 50 \text{ mm}$
 $W = 30 \text{ mm}$
 $T = 1.5 \text{ mm}$

Voltage:
 $0 \sim 7 \text{ V}$
Distance:
 $0 \sim 1 \text{ cm}$

- Measurement system



Experiment Target

Study properties feedback loop effected A-P-M system

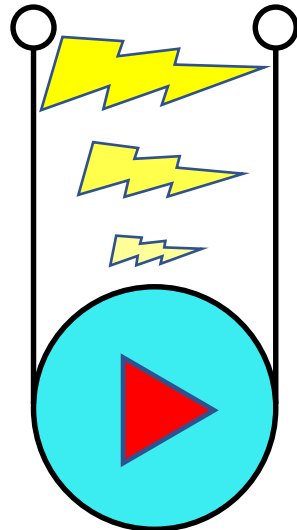
$$\text{Feedback factor } f = \sqrt{\frac{n}{m}}$$

- Tune bias voltage on feedback loop
→ increase feedback photons

$$n \uparrow \sim f \uparrow$$

1. Experiment

Change bias voltage

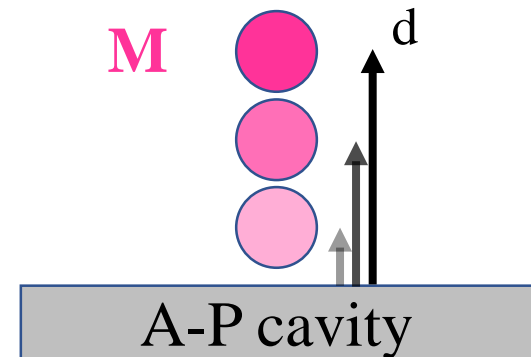


- Tune distance between YIG and cavity
→ decrease number of CMP

$$m \downarrow \sim f \uparrow$$

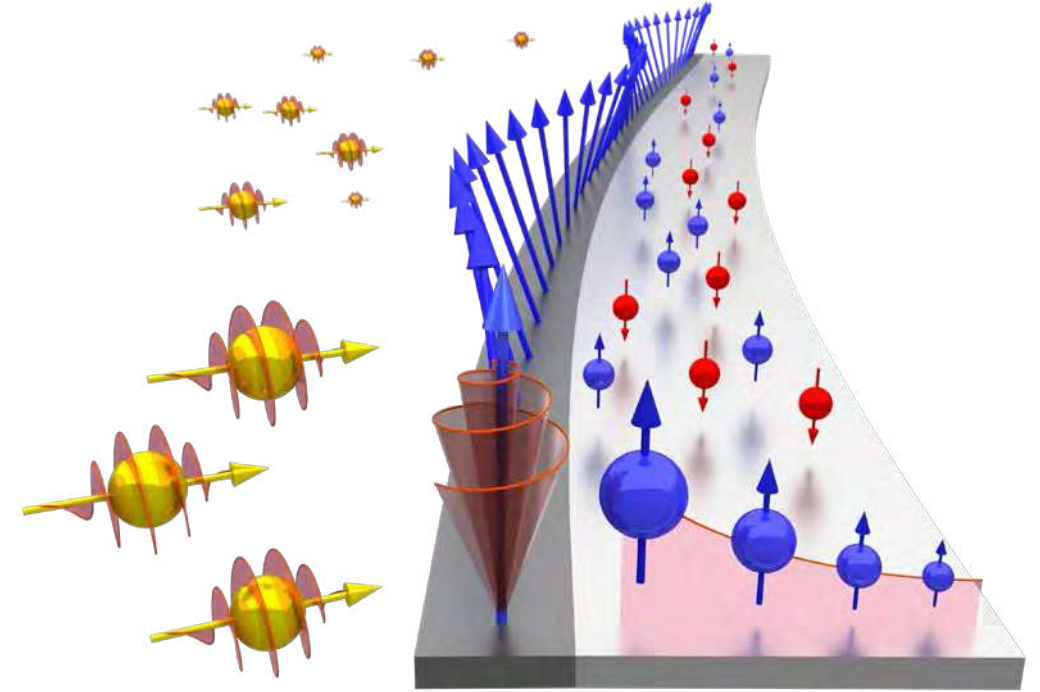
2. Experiment

Change distance



Contents

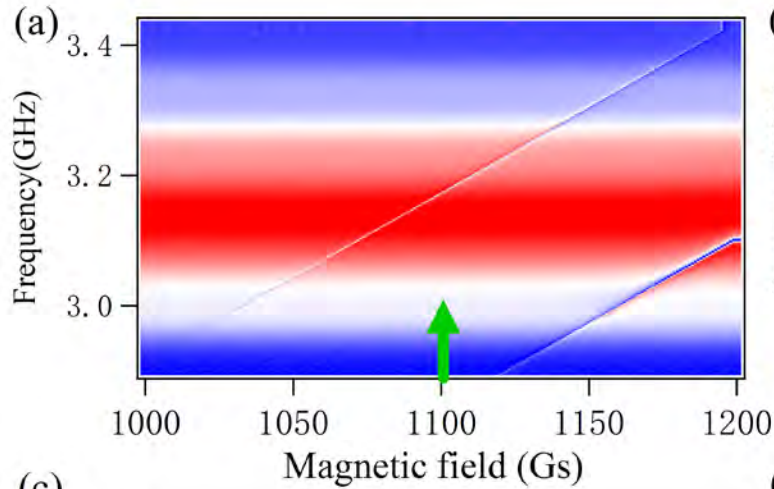
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 - Magnetically induced transparency
 - Strong coupling
 - Cavity magnon quinpuplet
 - Voltage controlled feedback
 - Distance controlled feedback
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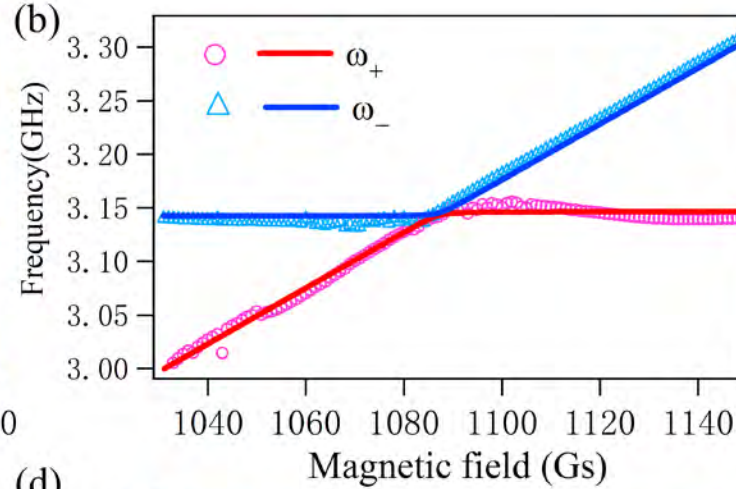
Result: Magnetically induced transparency

$V = 0V$

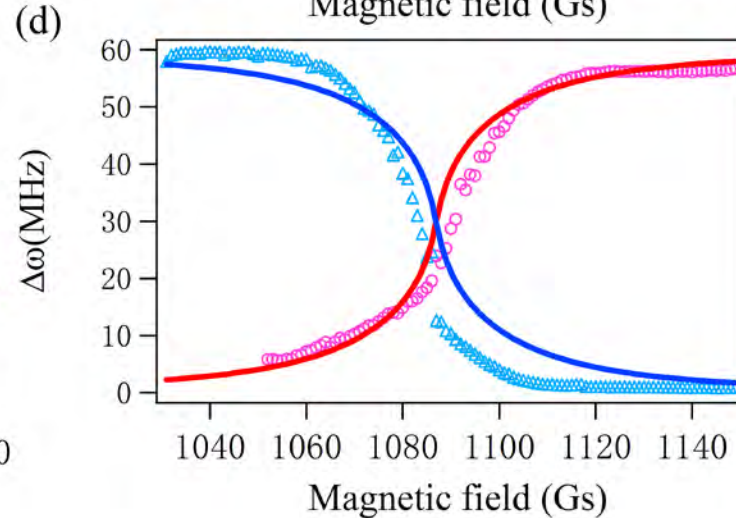
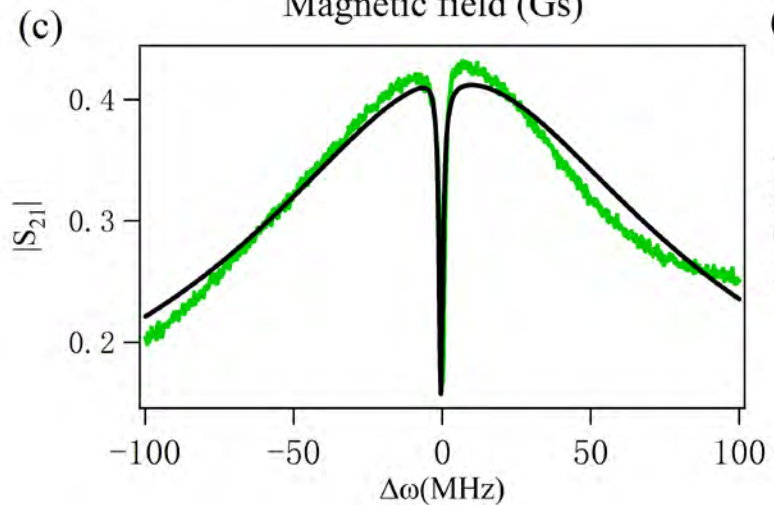
Spectrum mapping



Fitting and calculation



Spectrum
at $\Delta = 0$

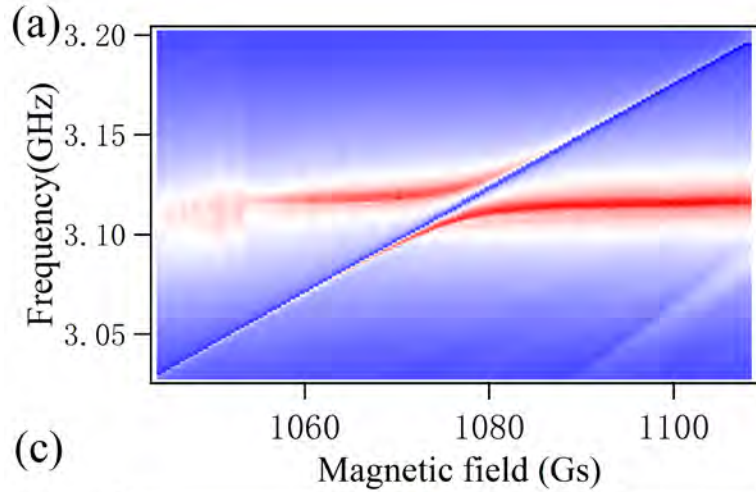


Fitted linewidth

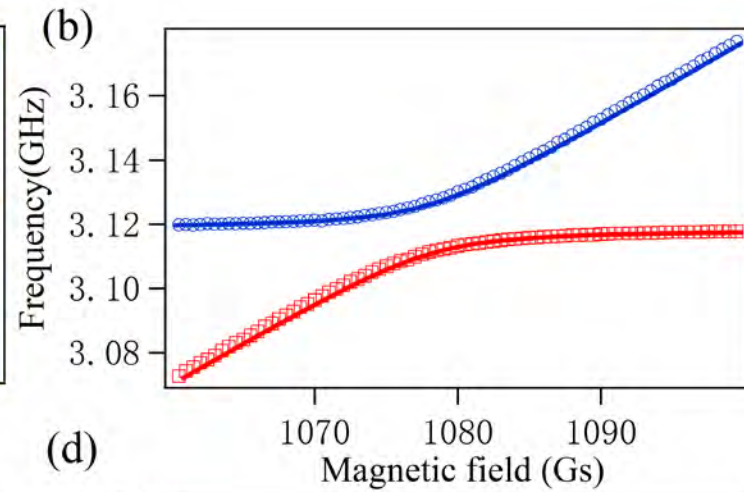
Result: Strong coupling

$V = 0.64V$

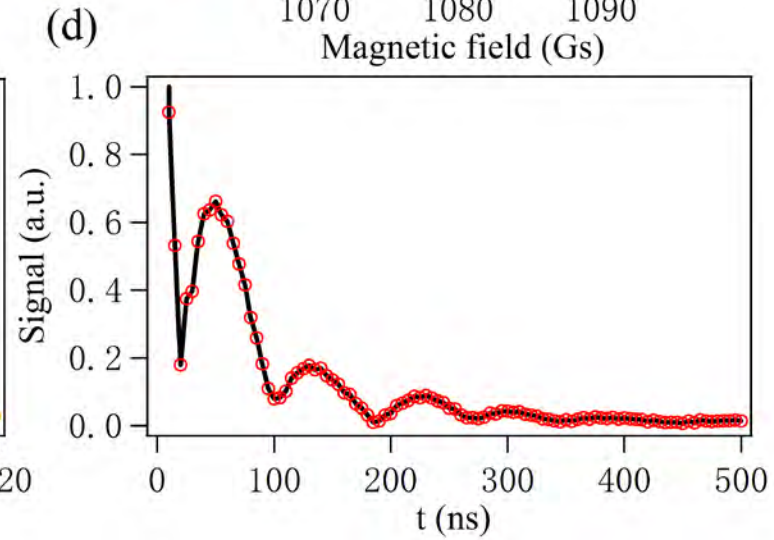
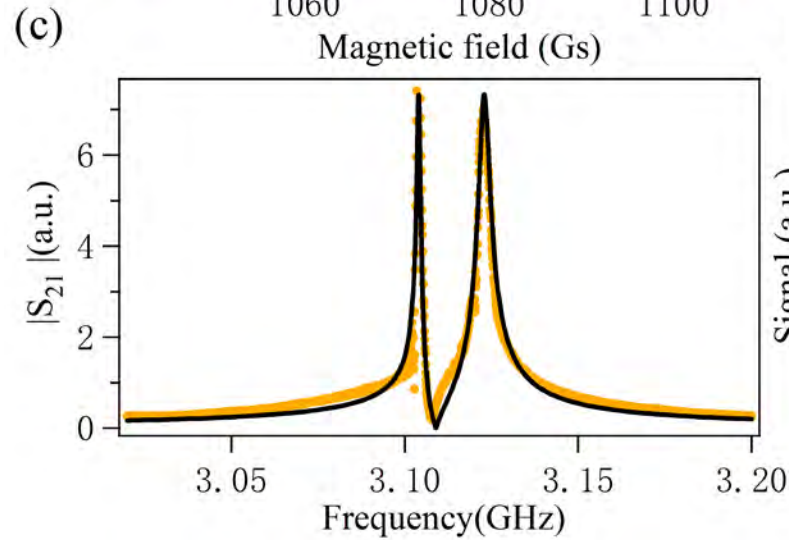
Spectrum mapping



Fitting and calculation



Spectrum
at $\Delta = 0$

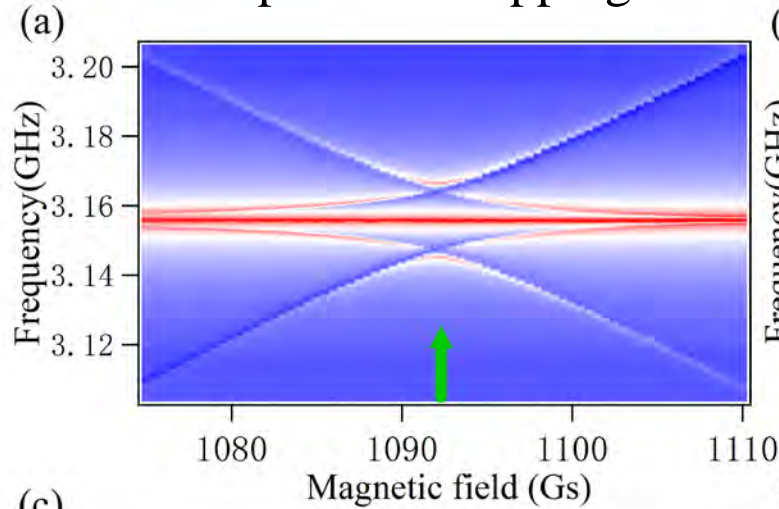


iFFt
Time domain
Rabi Oscillation

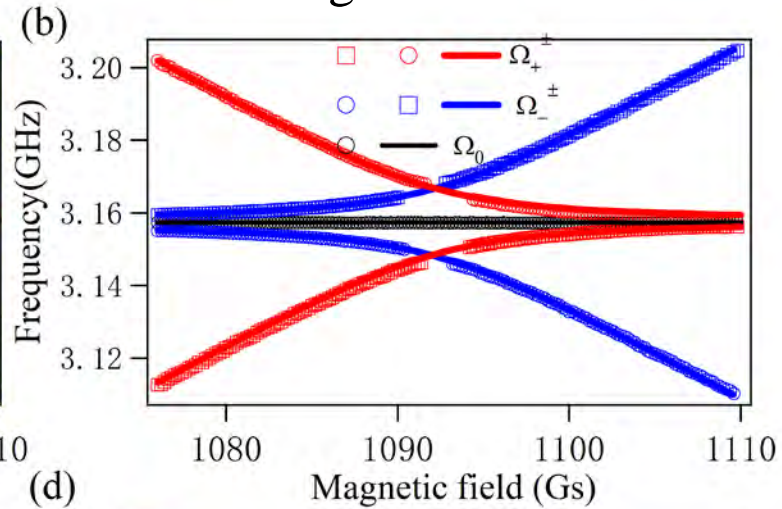
Result: Cavity magnon quintuplet

$V = 7.0\text{V}$

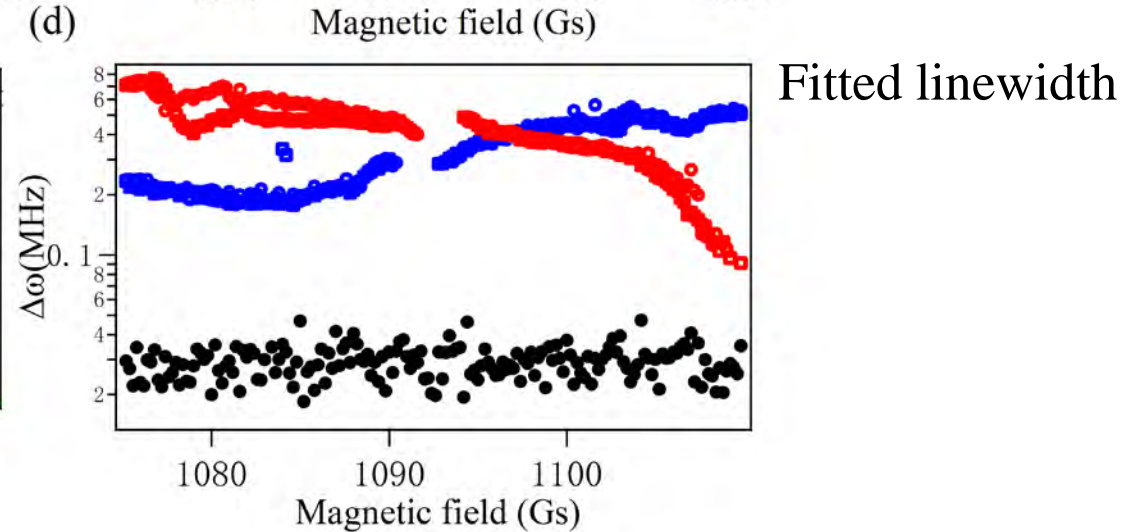
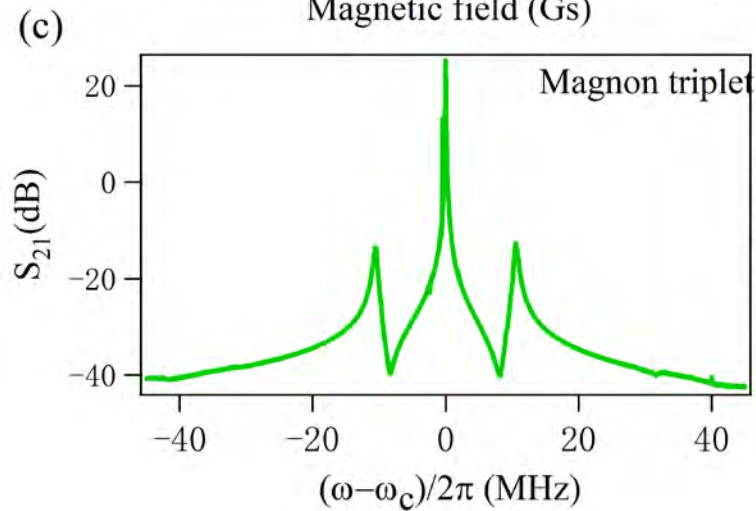
Spectrum mapping



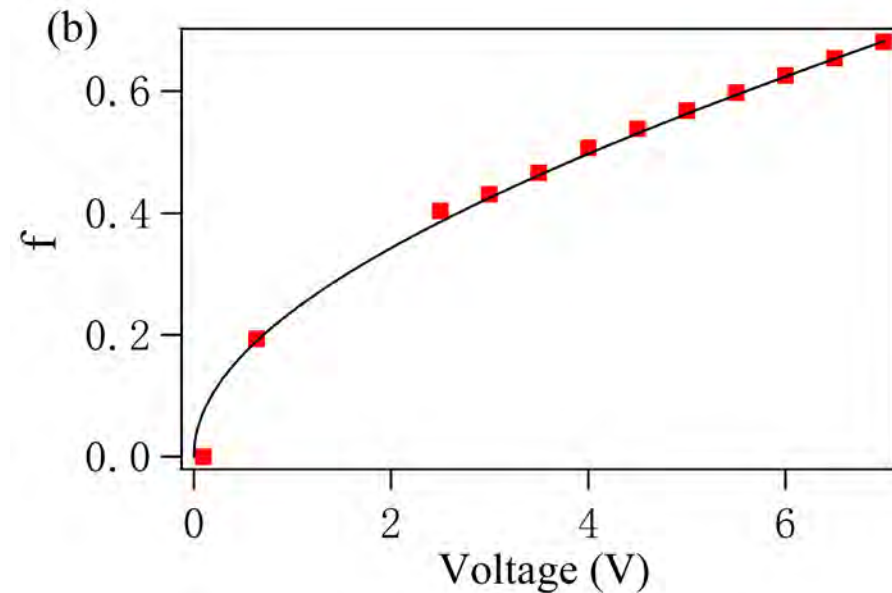
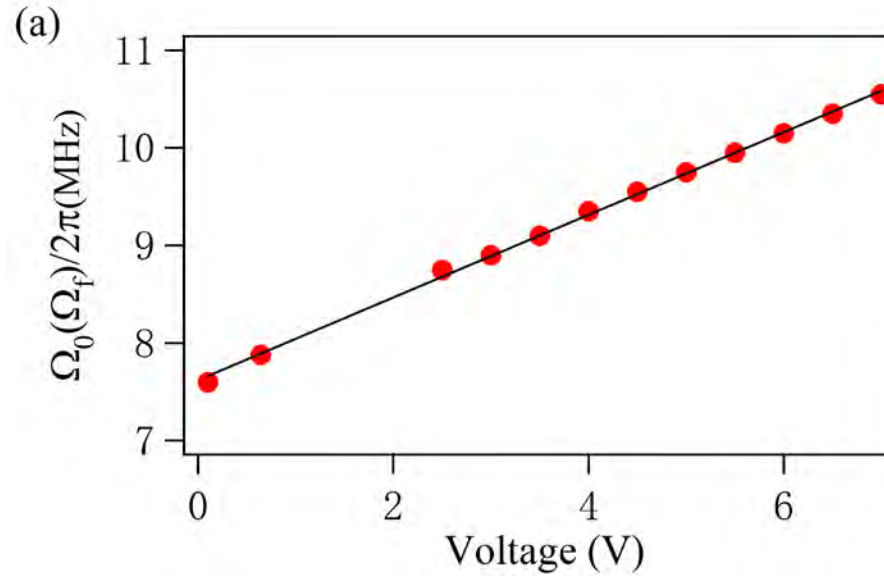
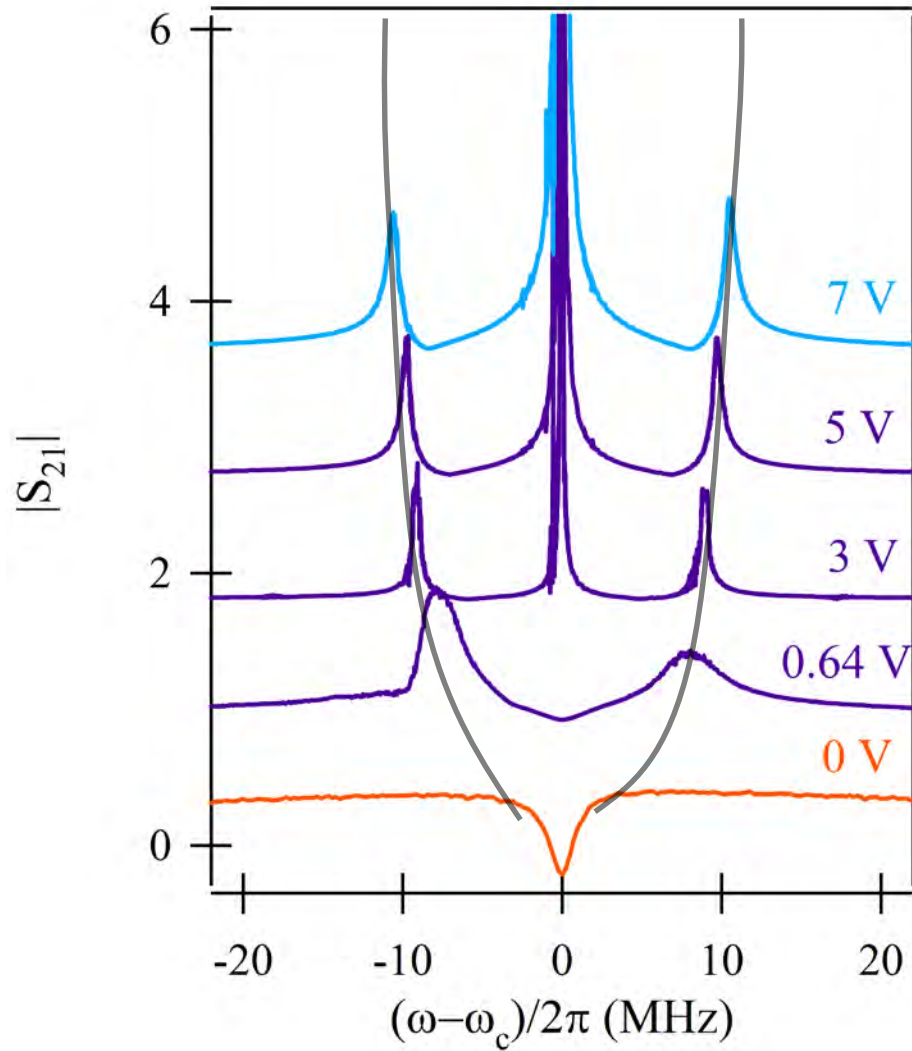
Fitting and calculation



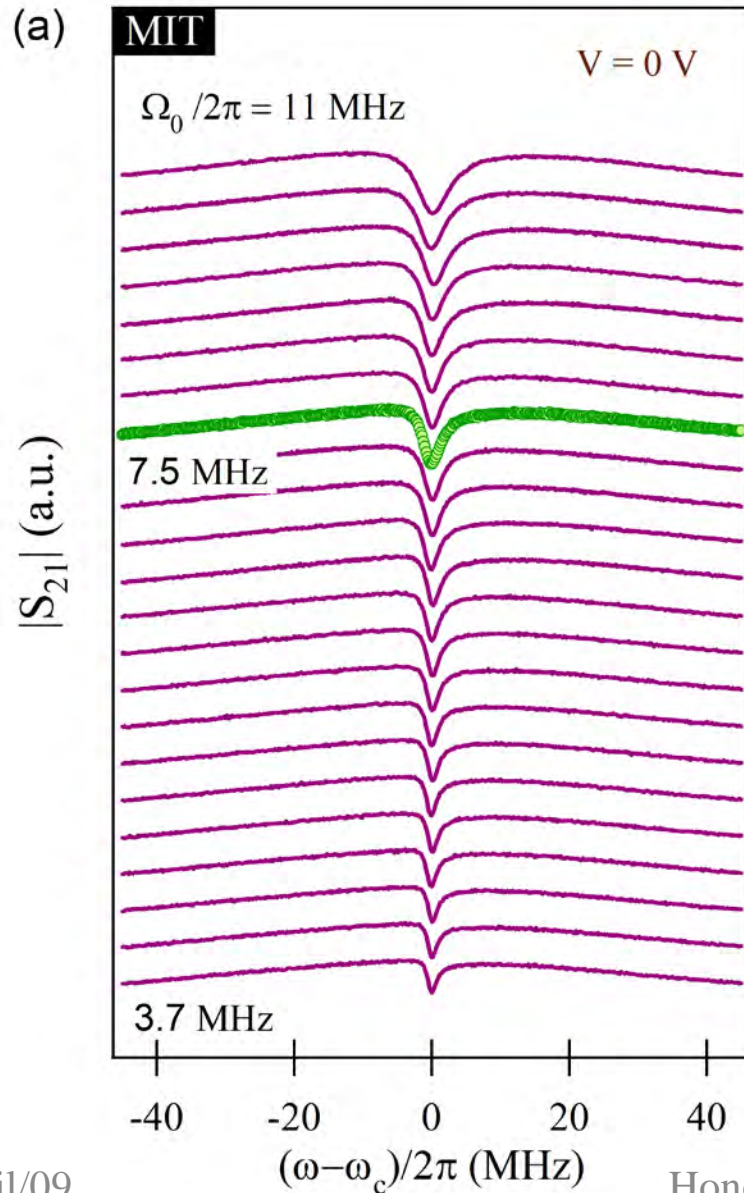
Spectrum
at $\Delta = 0$



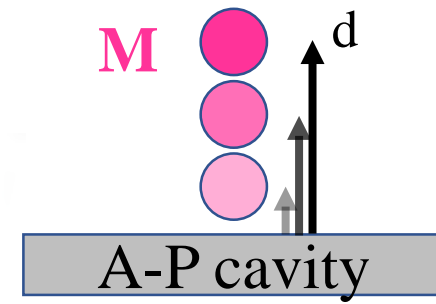
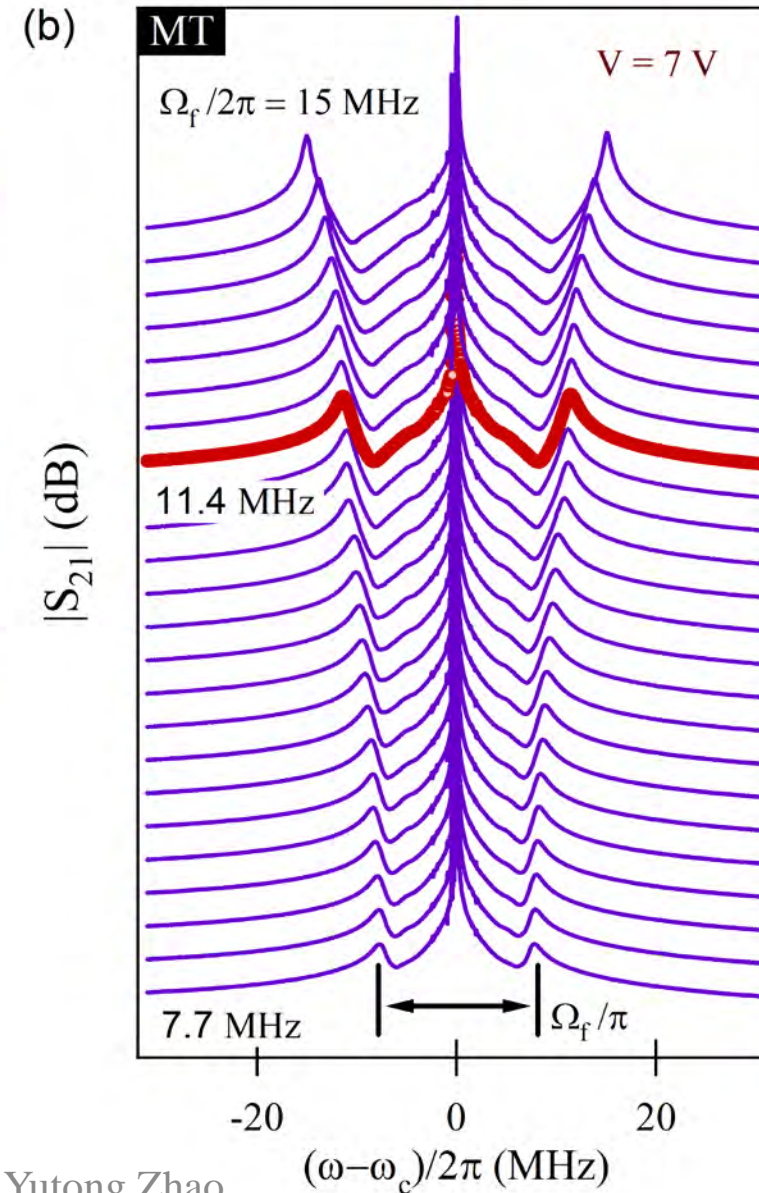
Result: Voltage controlled feedback



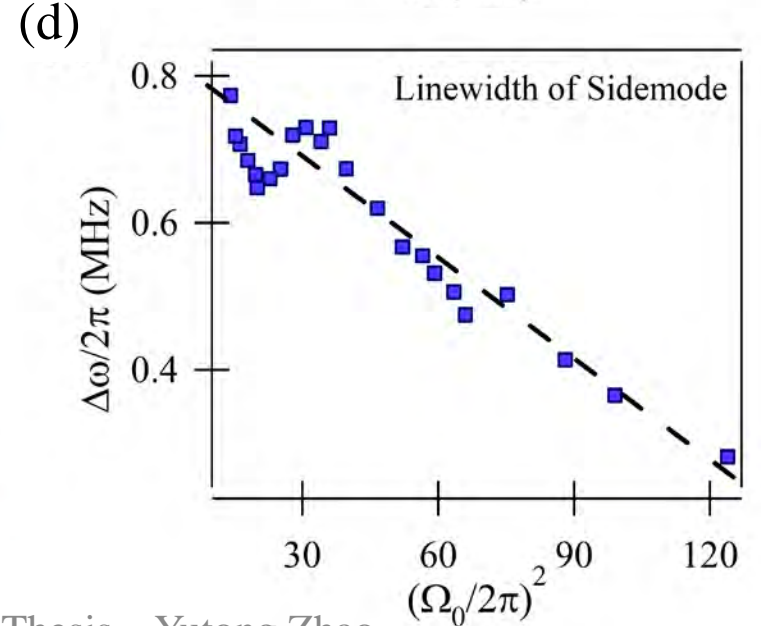
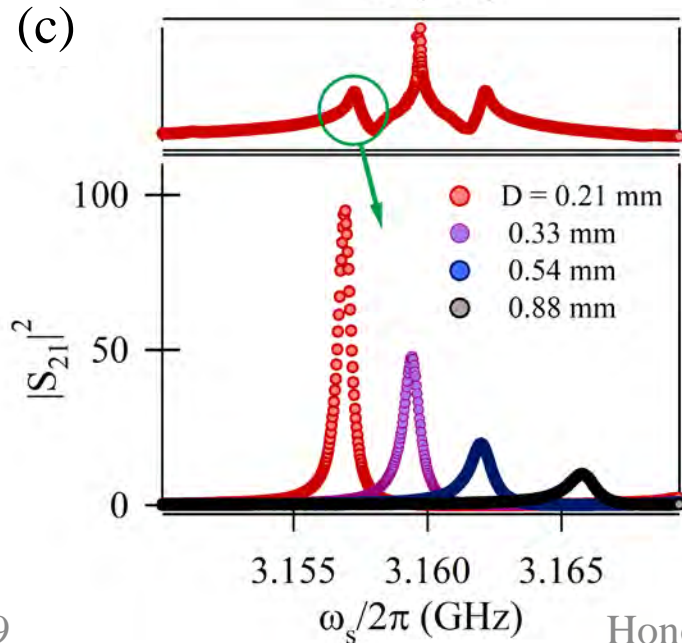
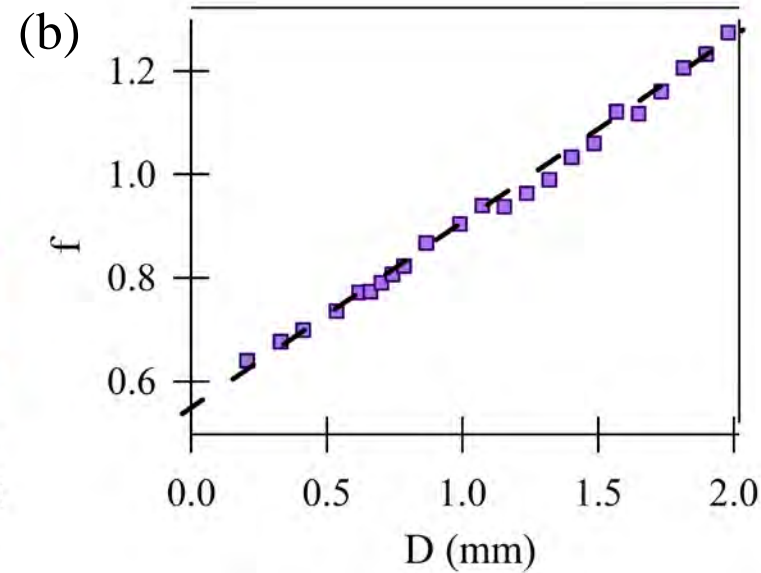
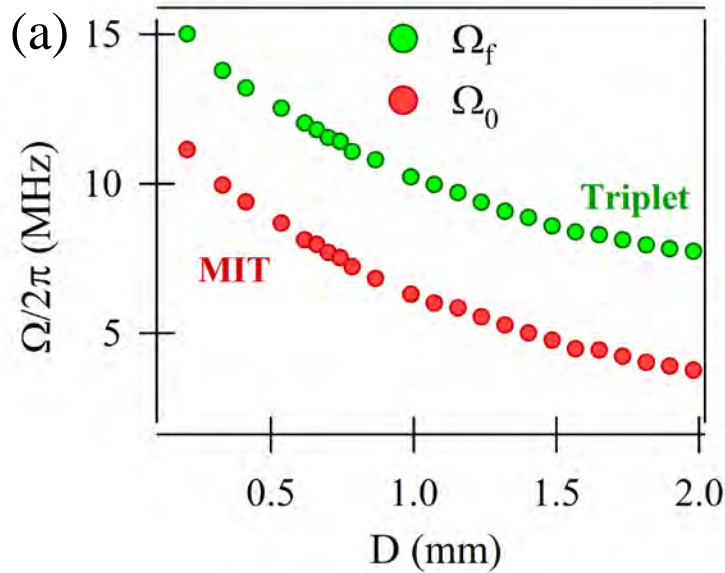
Result: Distance Dependent Feedback



Distance Increase



Result: Distance Dependent Feedback



$$\frac{\Delta\omega}{2\pi} = -4.21 \text{ (THz}^{-1}\text{)} \cdot \left(\frac{\Omega_0}{2\pi}\right)^2 + 0.797 \text{ MHz}$$

Conclusion

In this work

- We studied coupling between magnon and an active cavity
- we found
 1. Feedback voltage controlled the coupling regimes
 2. Feedback voltage controlled the feedback factor
 3. Magnon Distance controlled the feedback factor

Leads to a better understanding to spin-photon interaction