Study on Coupling Between Magnons and Active Cavity Photons

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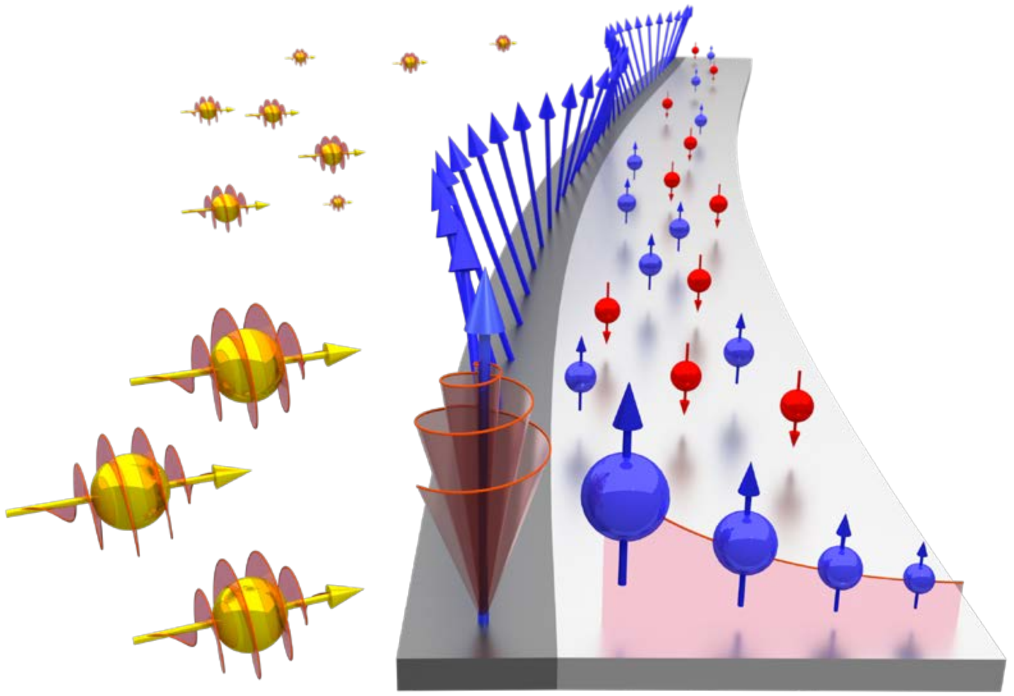

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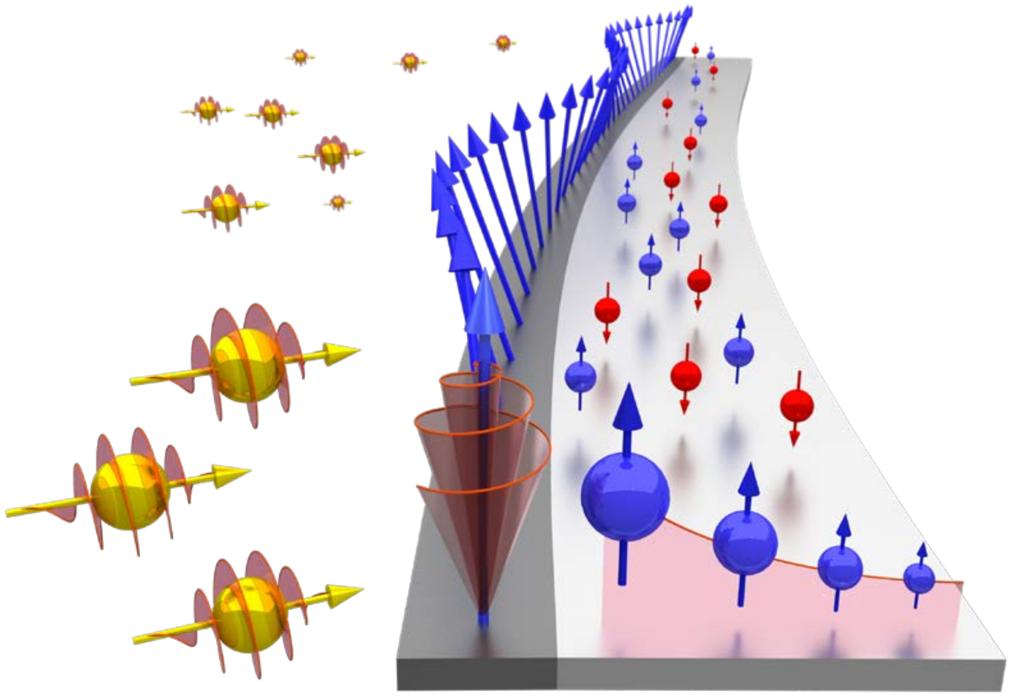
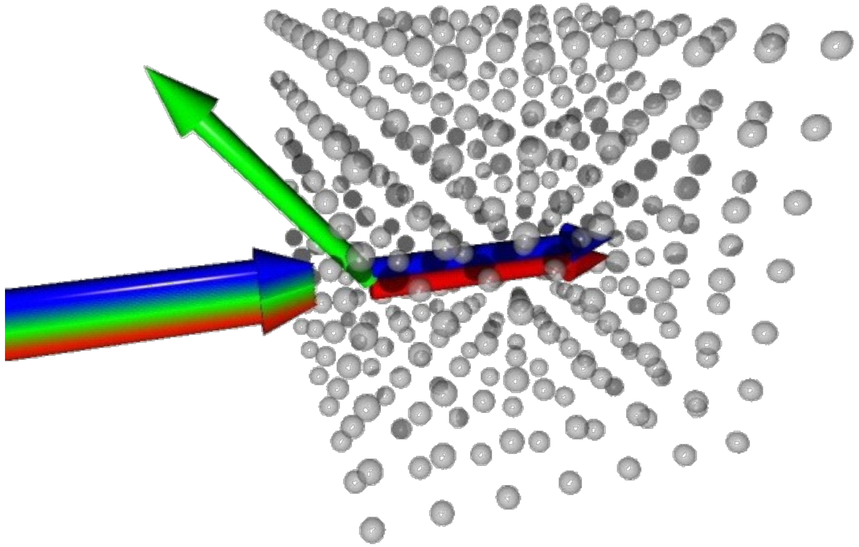


Introduction

- Light Matter interaction

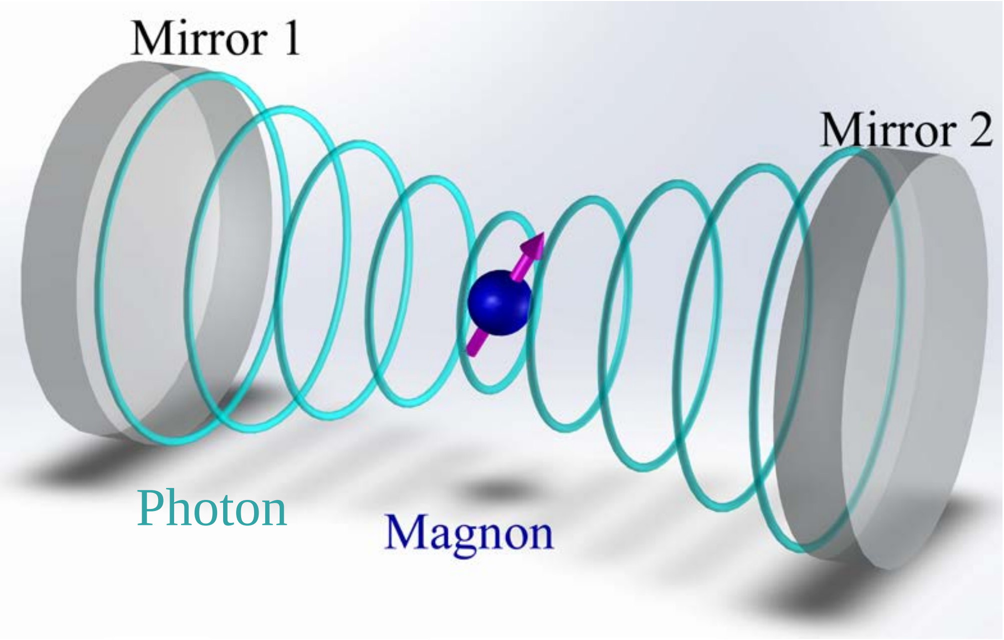


Absorption, reflection, refraction…

➔ Information of matter

All EM frequency (radio to γ-ray)

- Spin-photon interaction



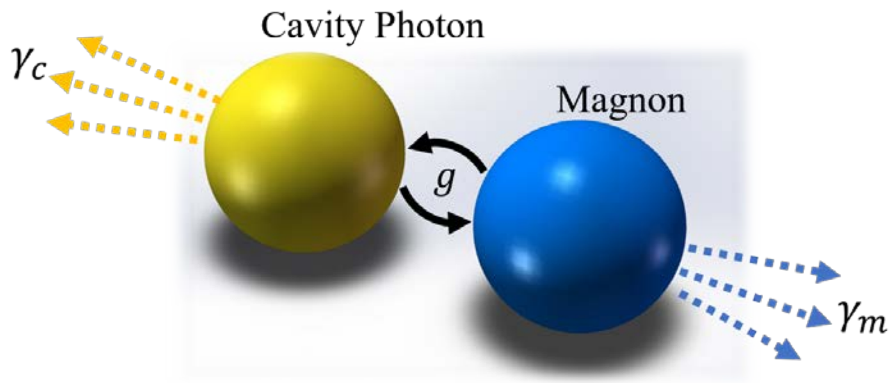
Electron spin procession: ~ GHz range

Magnetic dipole in EM field

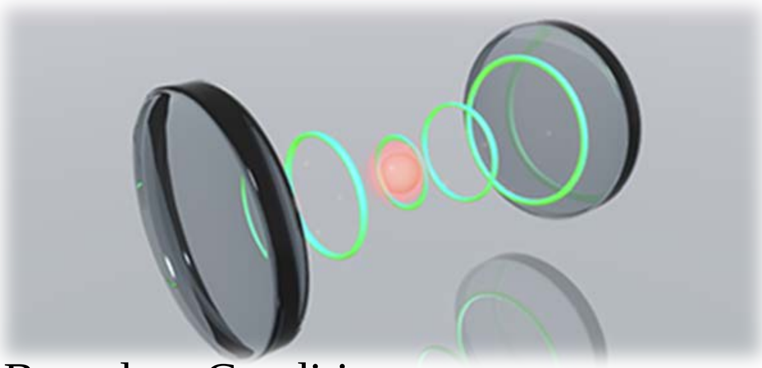
➔Ferrimagnetic material + Microwave

Introduction

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

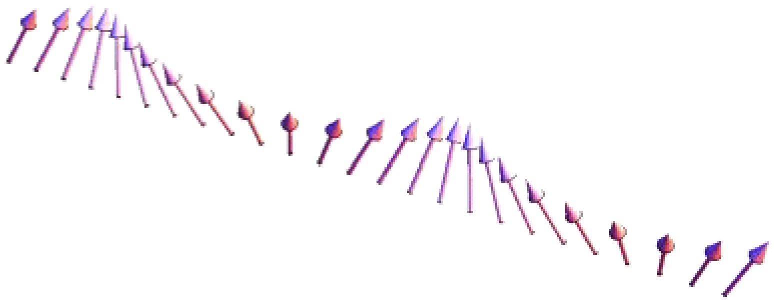


Cavity Photon: Standing wave in cavity



Boundary Condition

Magnon: Spin wave



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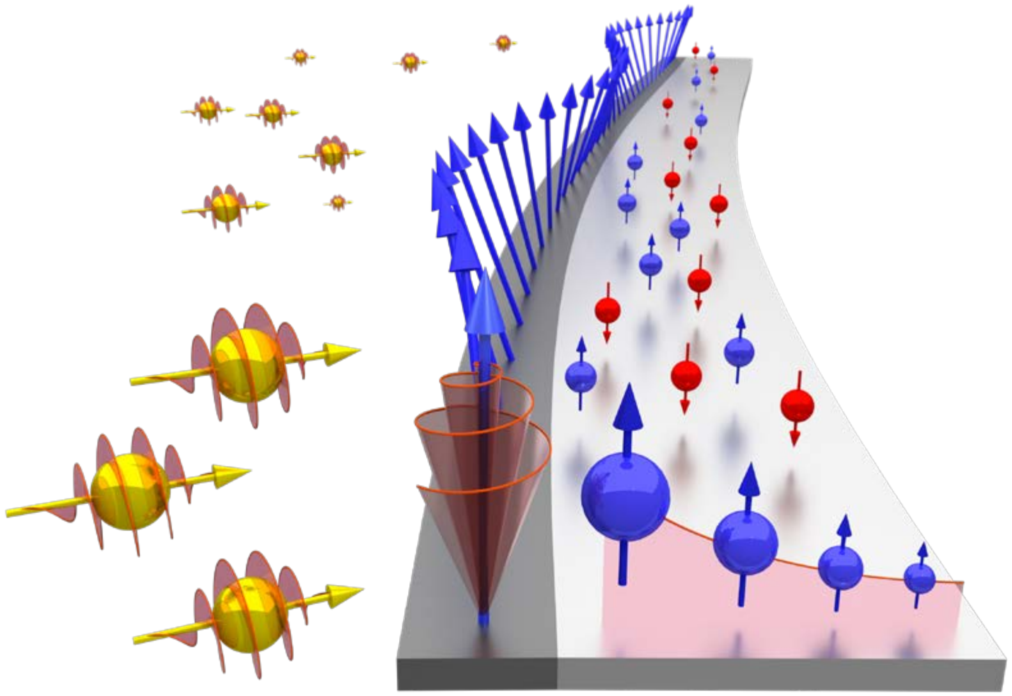
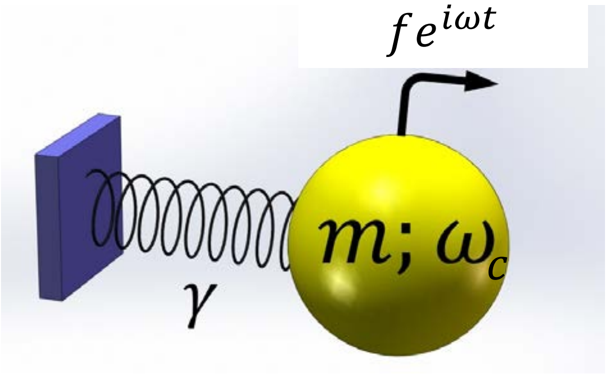
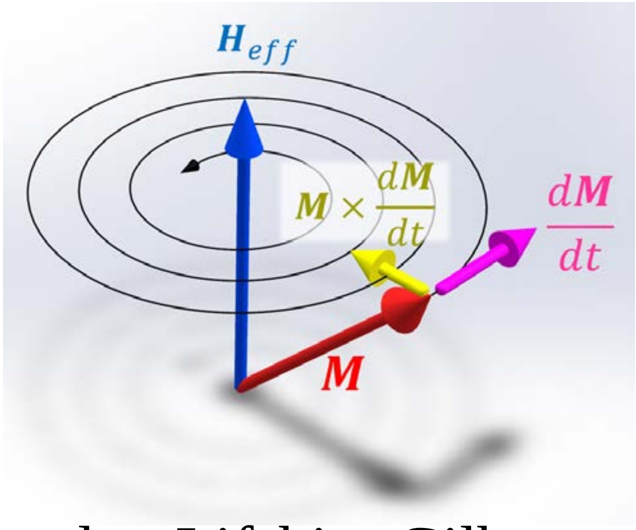


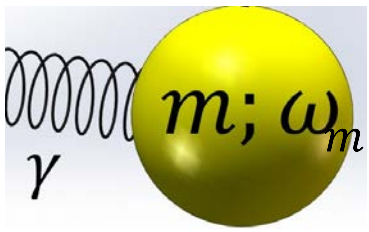
Theory: Classical



Photon Cavity



Magnon



- Damped oscillator

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

Damping

Stable solution:

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

➔ Periodic with decay

- 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

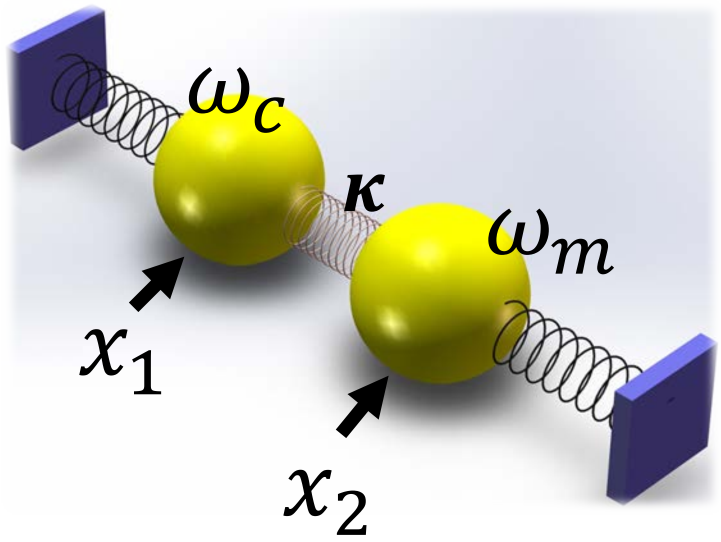
Solution using approximation:

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

➔ Also Periodic with decay

Theory: Classical

- Coupled Spring Oscillator



Equation of Motion:

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

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

Dispassion

Coupling

Assuming: $x_1 = A_c e^{i\omega t}$, and $x_2 = A_m e^{i\omega t}$

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: $\det(\omega I - M)$

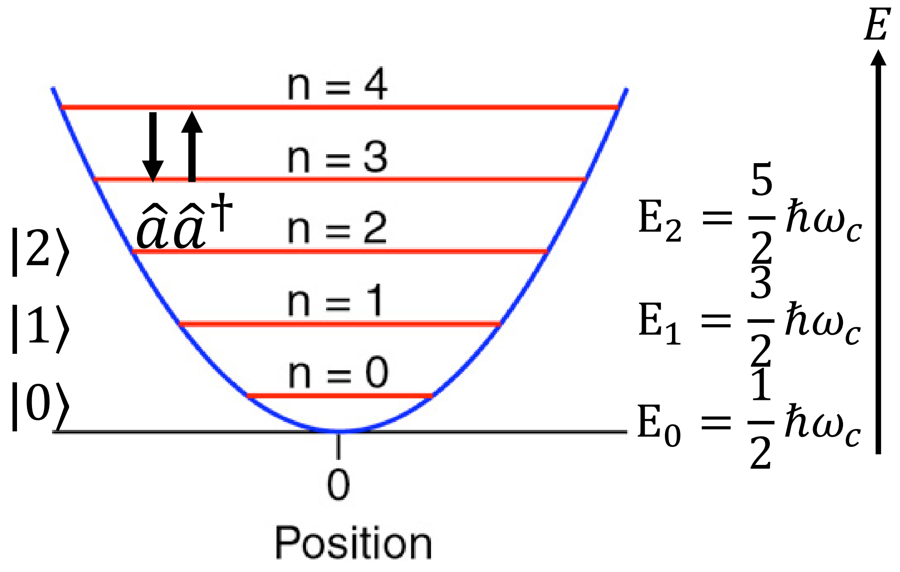
Theory: Quantum

- Quantum harmonic oscillator

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

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

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

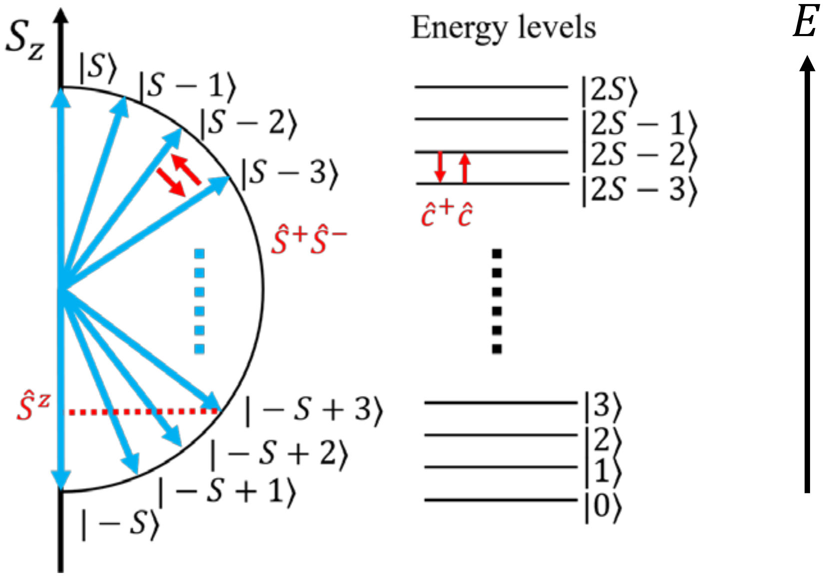


- Collective spin system

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

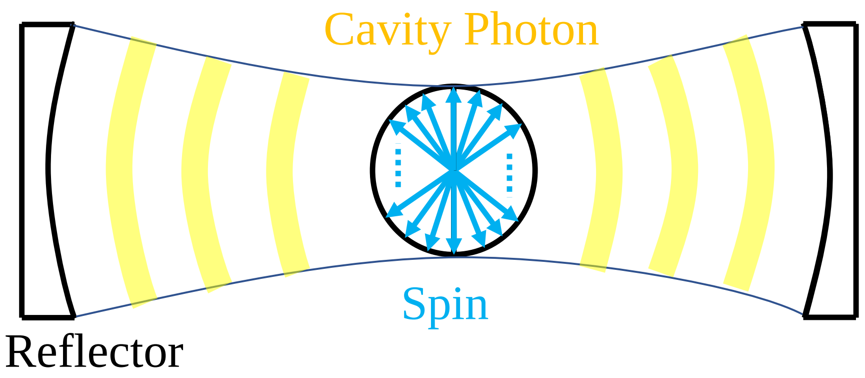
$$\hat{S}^z \left|\frac{N}{2}, -\frac{N}{2} + m\right\rangle = (-\frac{N}{2} + m)\left|\frac{N}{2}, -\frac{N}{2} + m\right\rangle$$

$$\mathrm{H}_{magnon} = \hbar\omega_m \hat{S}^z$$



Theory: Quantum

- Collective spin interact with cavity photons



Hamiltonian:

$$\frac{H}{\hbar} = \boxed{\omega_m \hat{S}^z} + \boxed{\omega_c \hat{a}^\dagger \hat{a}} + \boxed{g(\hat{a}^\dagger \hat{S}_- + a\hat{S}_+)}$$

Magnon Photon Interaction

Two degenerate states:
$|1\rangle = |\frac{N}{2}, -\frac{N}{2}, 1\rangle$ 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: $\det(\lambda I - M)$

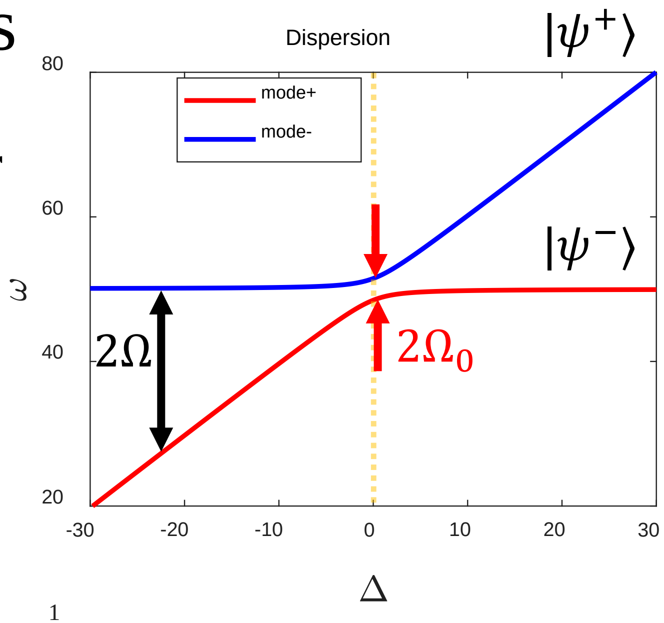
Theory: Matrix model

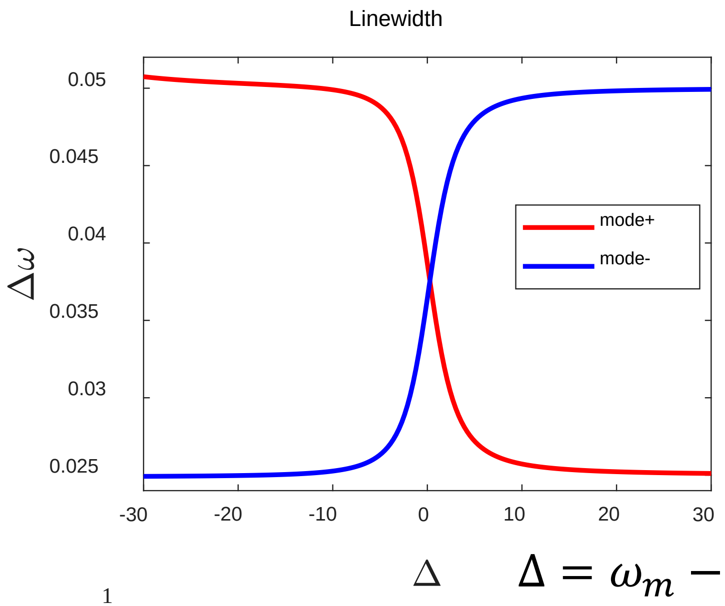
- Eigenvalues

Anti-crossing behavior

Generalized Rabi frequency

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

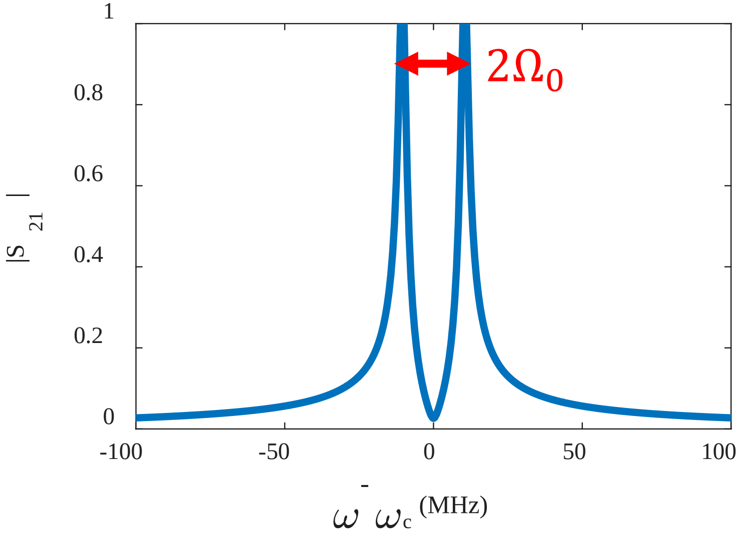


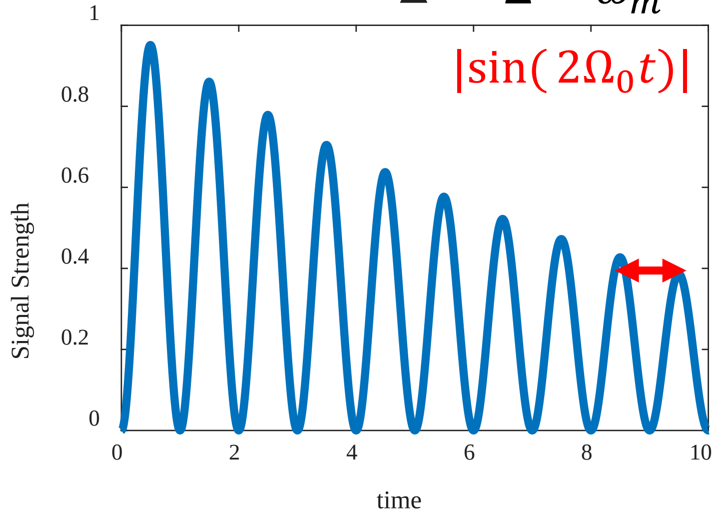


Linewidth exchange

$\Delta = \omega_m - \omega_c$

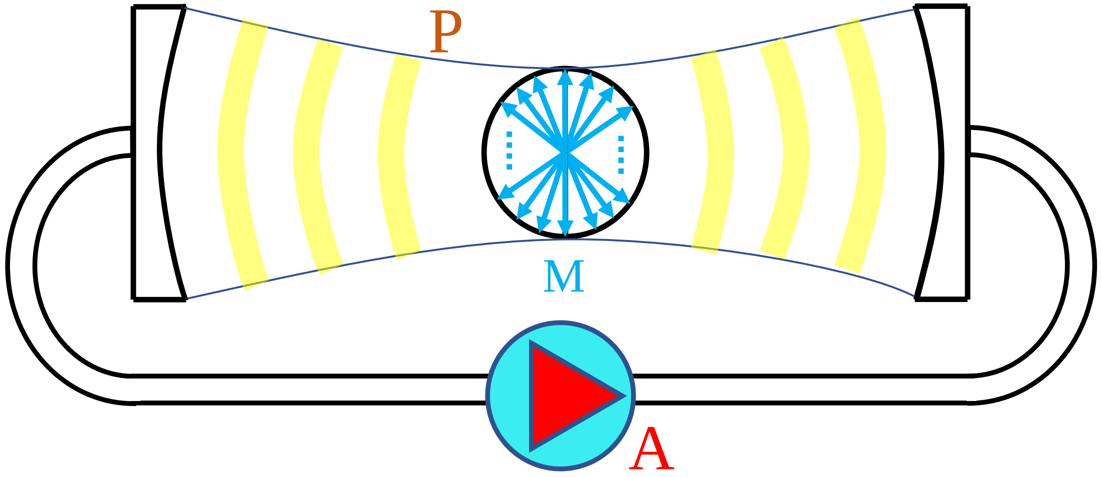
Rabi frequency Ω_0
frequency domain





Rabi oscillation Ω_0
time domain

Theory: Quintuplet H



- Hamiltonian of A-P-M system

$$\frac{H}{\hbar} = \boxed{\omega_m \hat{S}^z} + \boxed{\omega_c \hat{p}^\dagger \hat{p}} + \boxed{\omega_c \hat{a}^\dagger \hat{a}} + \Omega_{PM}\left(\hat{p}^\dagger \hat{S}_- + \hat{p}\hat{S}_+\right) + \Omega_{APM}(\hat{a}^\dagger \hat{S}_- + a\hat{S}_+)$$

M P A

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

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

Ω_{PM} --- interaction between P-M

Ω_{APM} --- interaction between A-P-M

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

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

Theory: Quintuplet

For energy levels involves in coupling:

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

$$|1e\rangle = |\psi_+\rangle|n\rangle \qquad |1g\rangle = |\psi_+\rangle|n-1\rangle$$
$$|2e\rangle = |G\rangle|n+1\rangle \qquad |2g\rangle = |G\rangle|n\rangle$$

Energy splits:

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

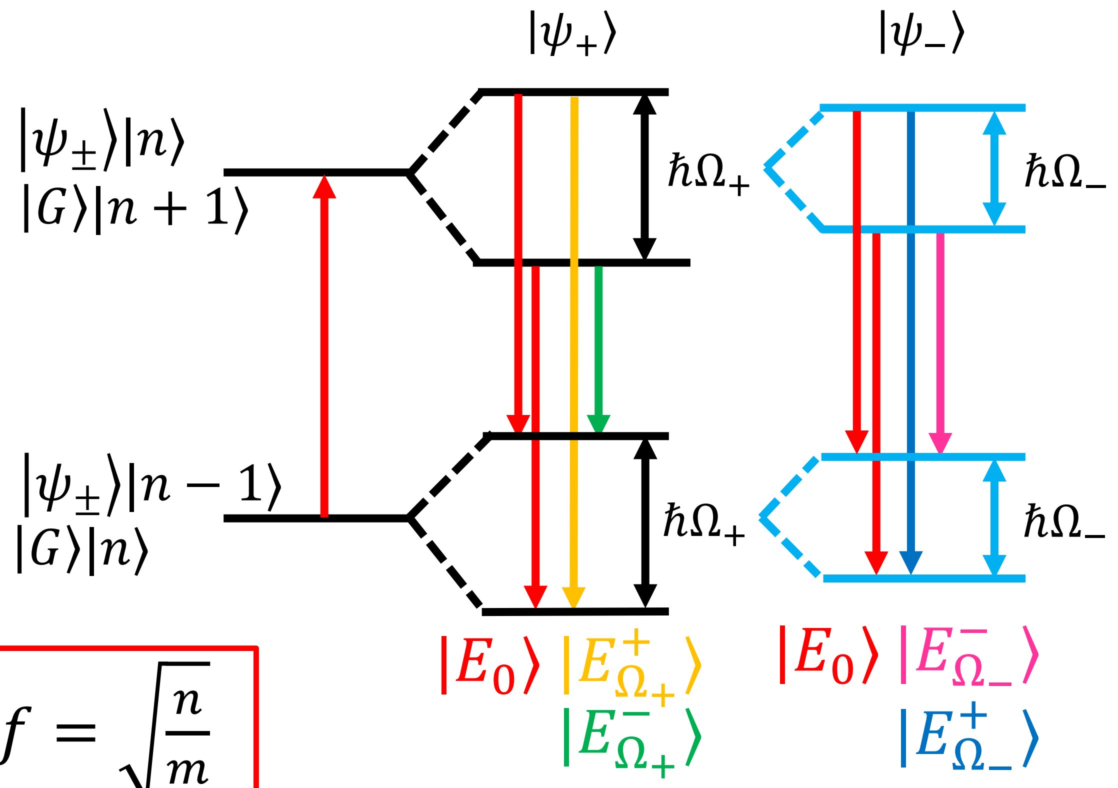
$$\Omega_+ = \sqrt{\left(\Omega + \frac{\Delta}{2}\right)^2 + (c_+\Omega_0 f)^2}$$

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

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

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

- Energy level splitting of magnon quintuplet



at $\Delta = 0$

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

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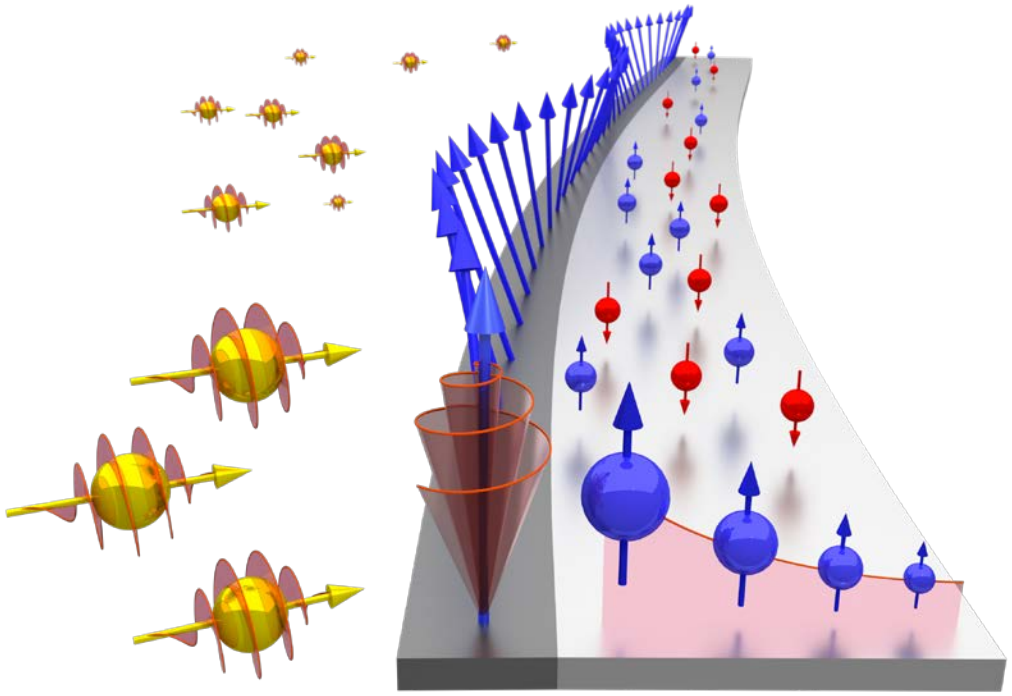
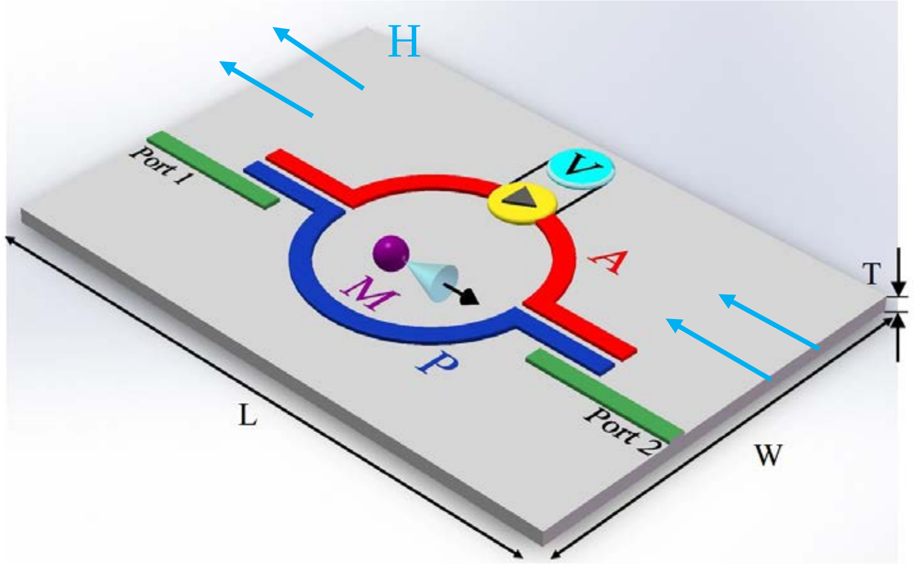


Experiment Setup

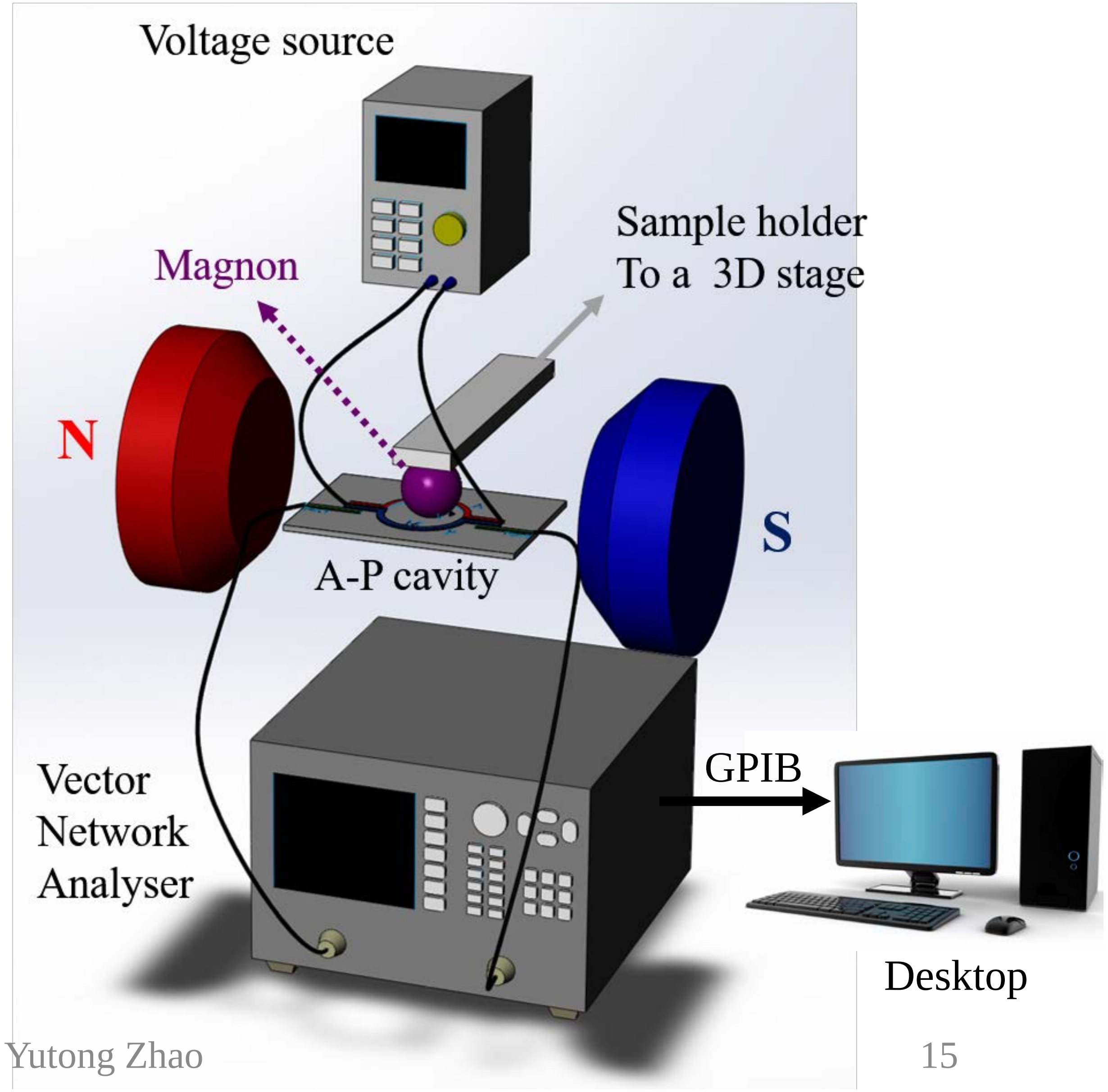
- Cavity design (A-P)



Active cavity:
L = 50 mm
W = 30 mm
T = 1.5 mm

Voltage:
0 ~ 7 V
Distance:
0 ~ 1cm

- Measurement system



Experiment Target

Study properties feedback loop effected A-P-M system

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

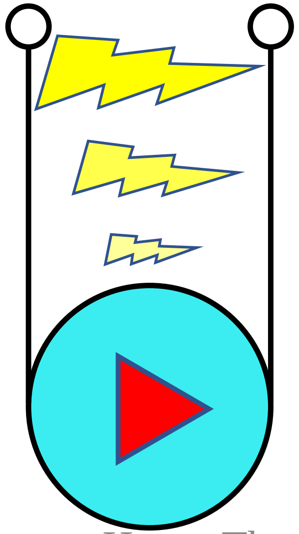
- Tune bias voltage on feedback loop

  → increase feedback photons

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

1. Experiment

   Change bias voltage



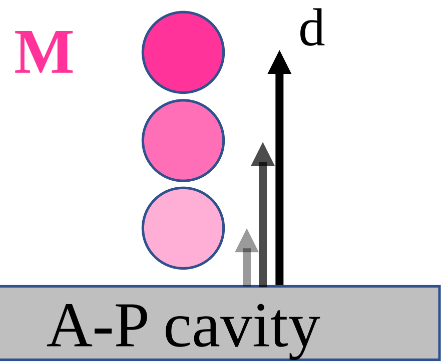
- Tune distance between YIG and cavity

  → decrease number of CMP

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

2. Experiment

   Change distance



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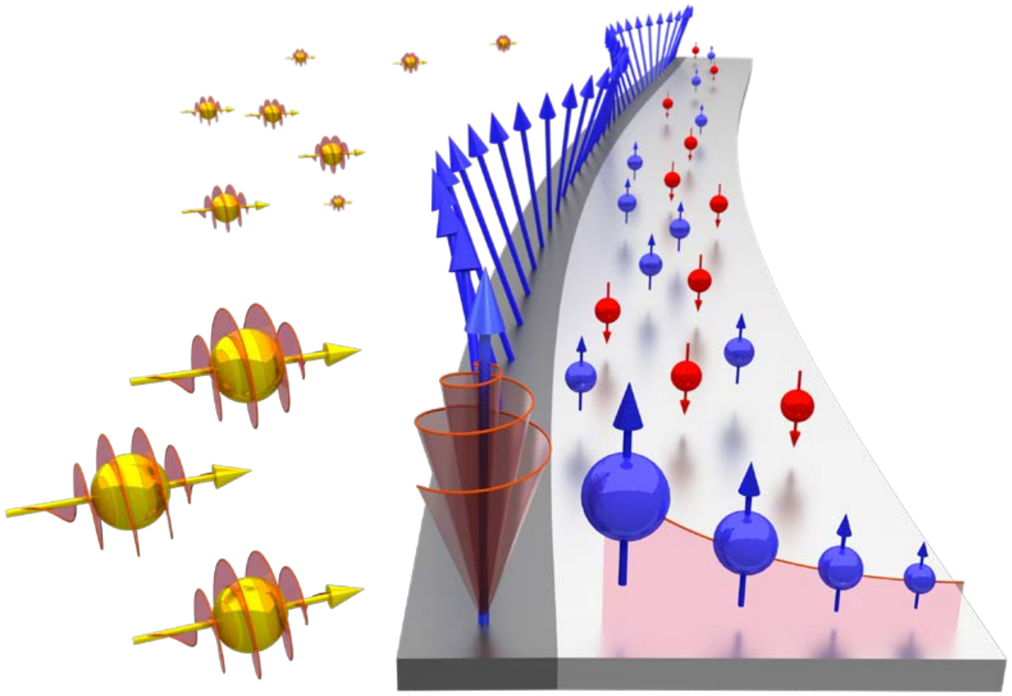


Result: Magnetically induced transparency

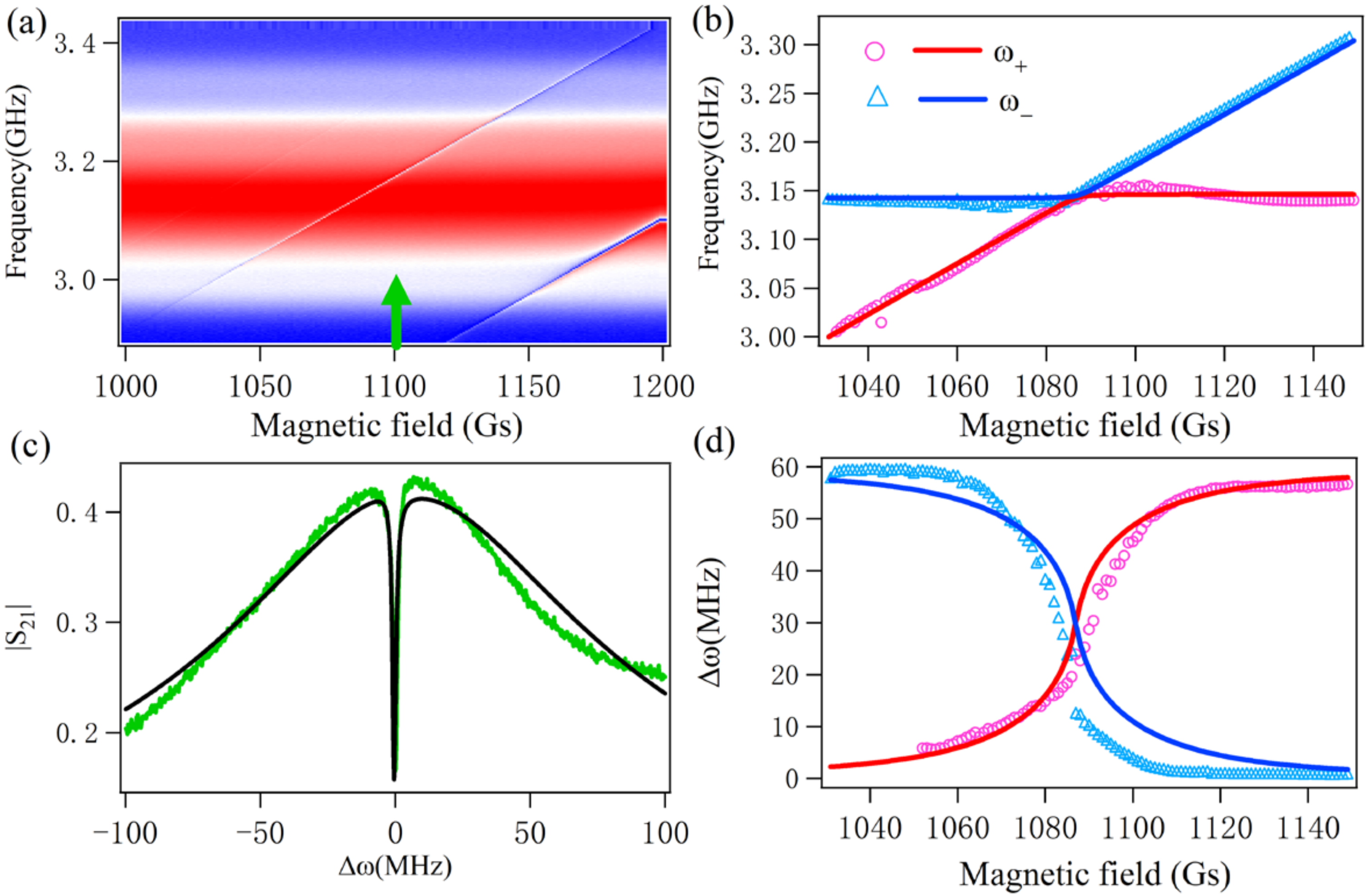
V = 0V

Spectrum mapping

Fitting and calculation

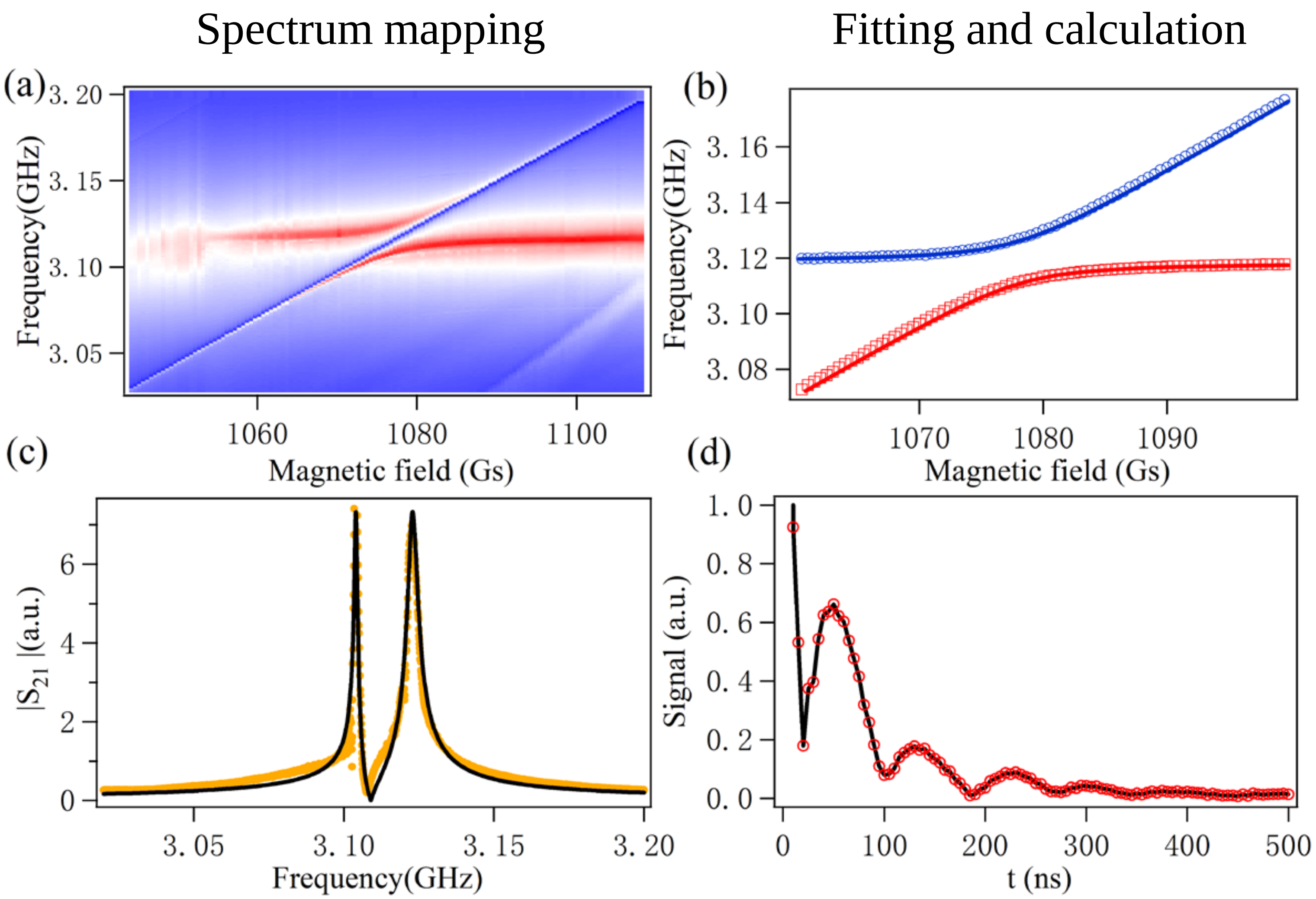
Spectrum at $\Delta = 0$

Fitted linewidth



Result: Strong coupling

V = 0.64V



Spectrum at $\Delta = 0$

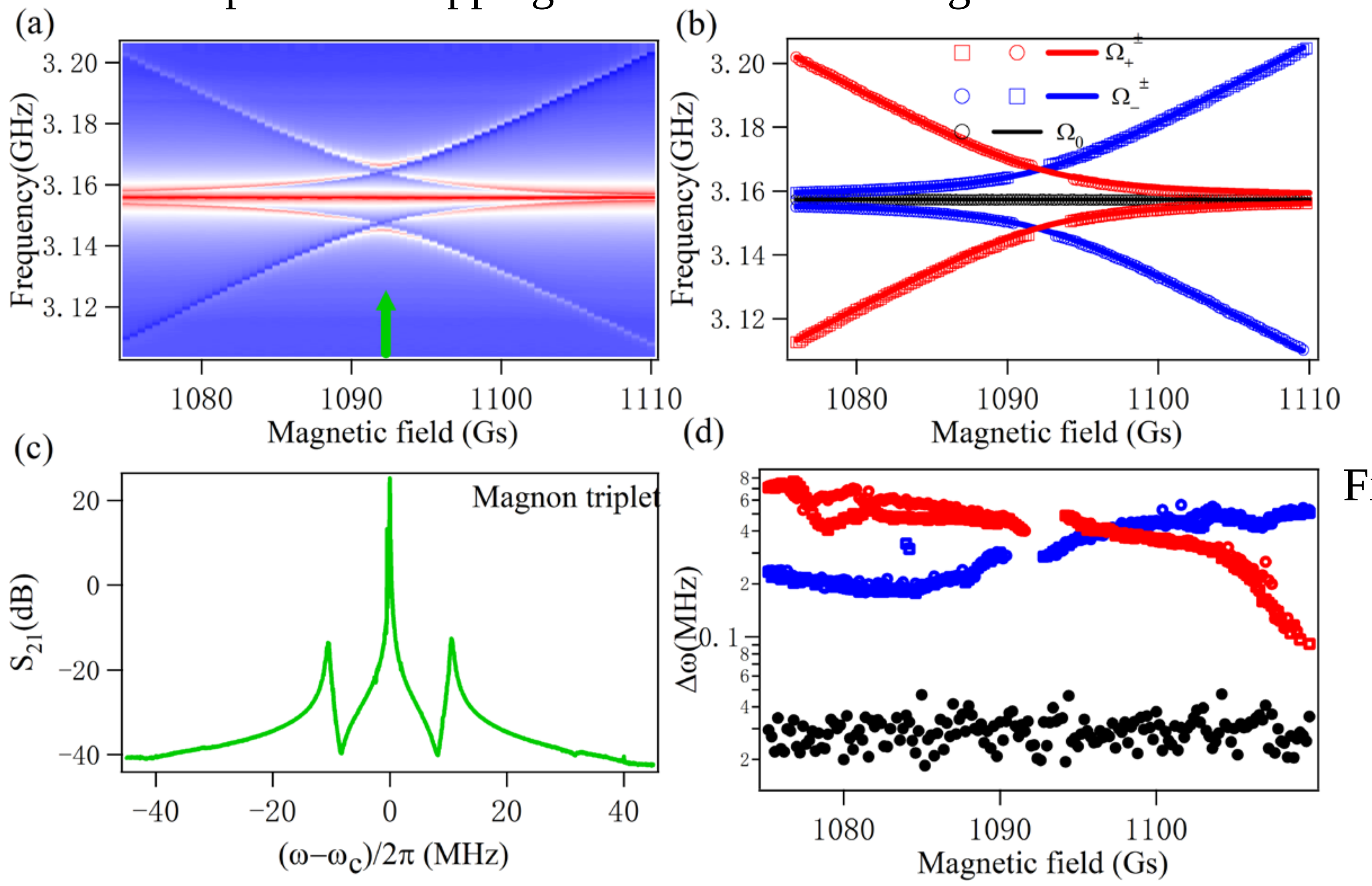
iFFt
Time domain
Rabi Oscillation

Result: Cavity magnon quintuplet

V = 7.0V

Spectrum mapping

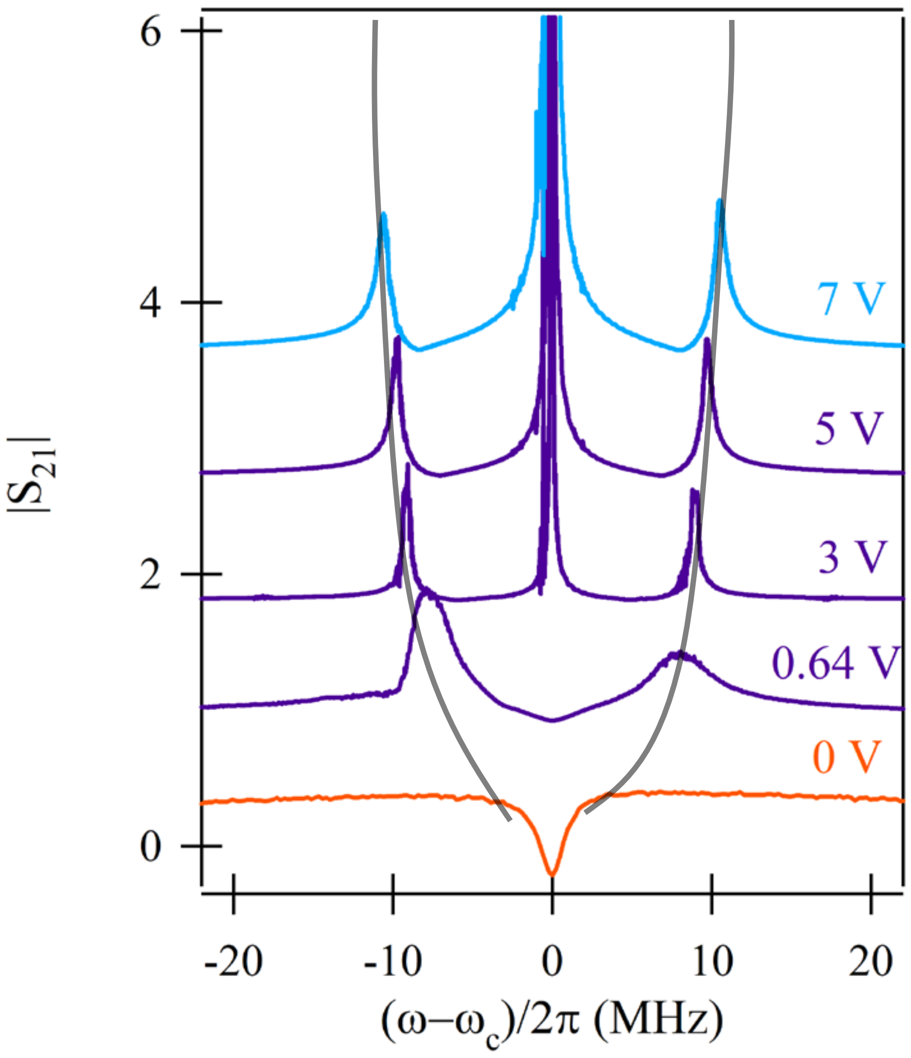
Fitting and calculation

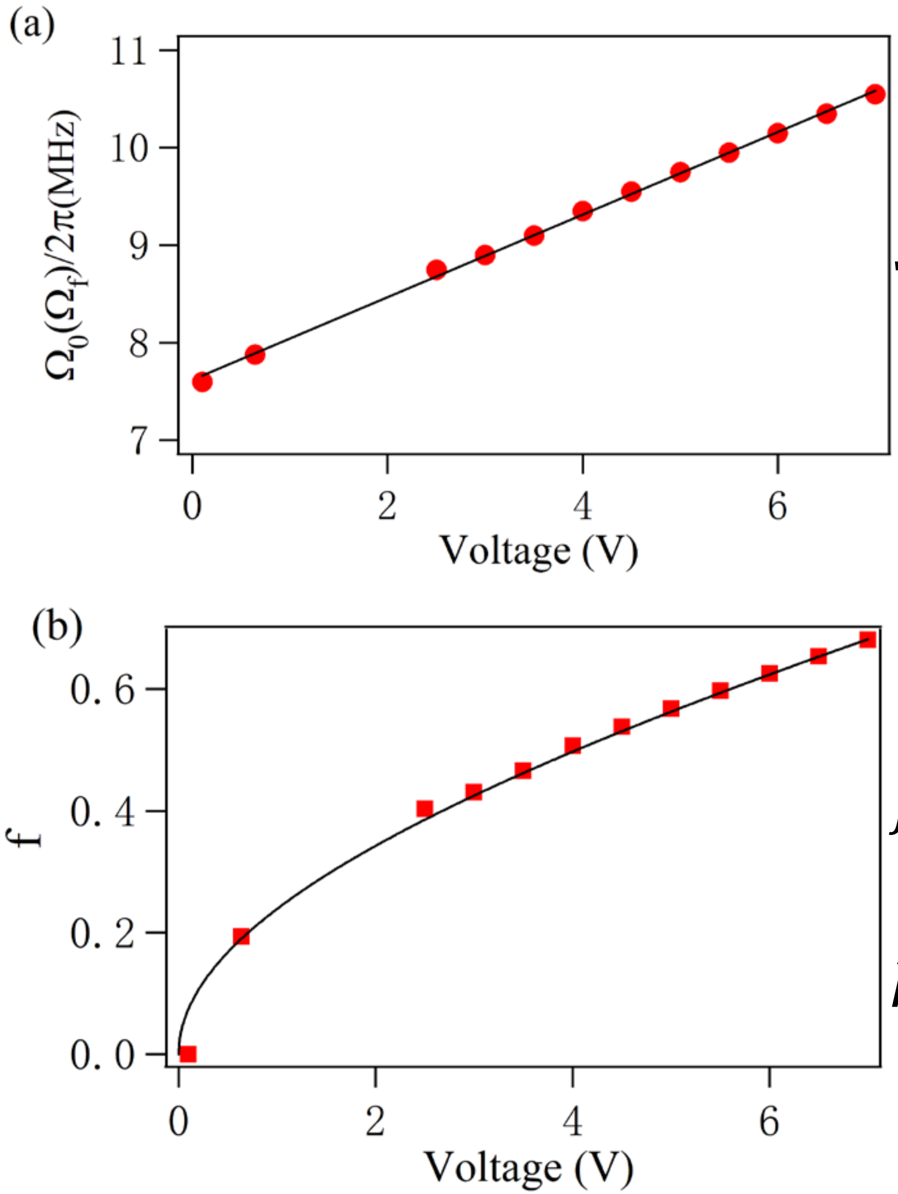


Spectrum at $\Delta = 0$

Fitted linewidth

Result: Voltage controlled feedback



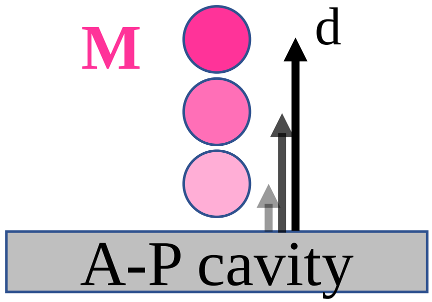


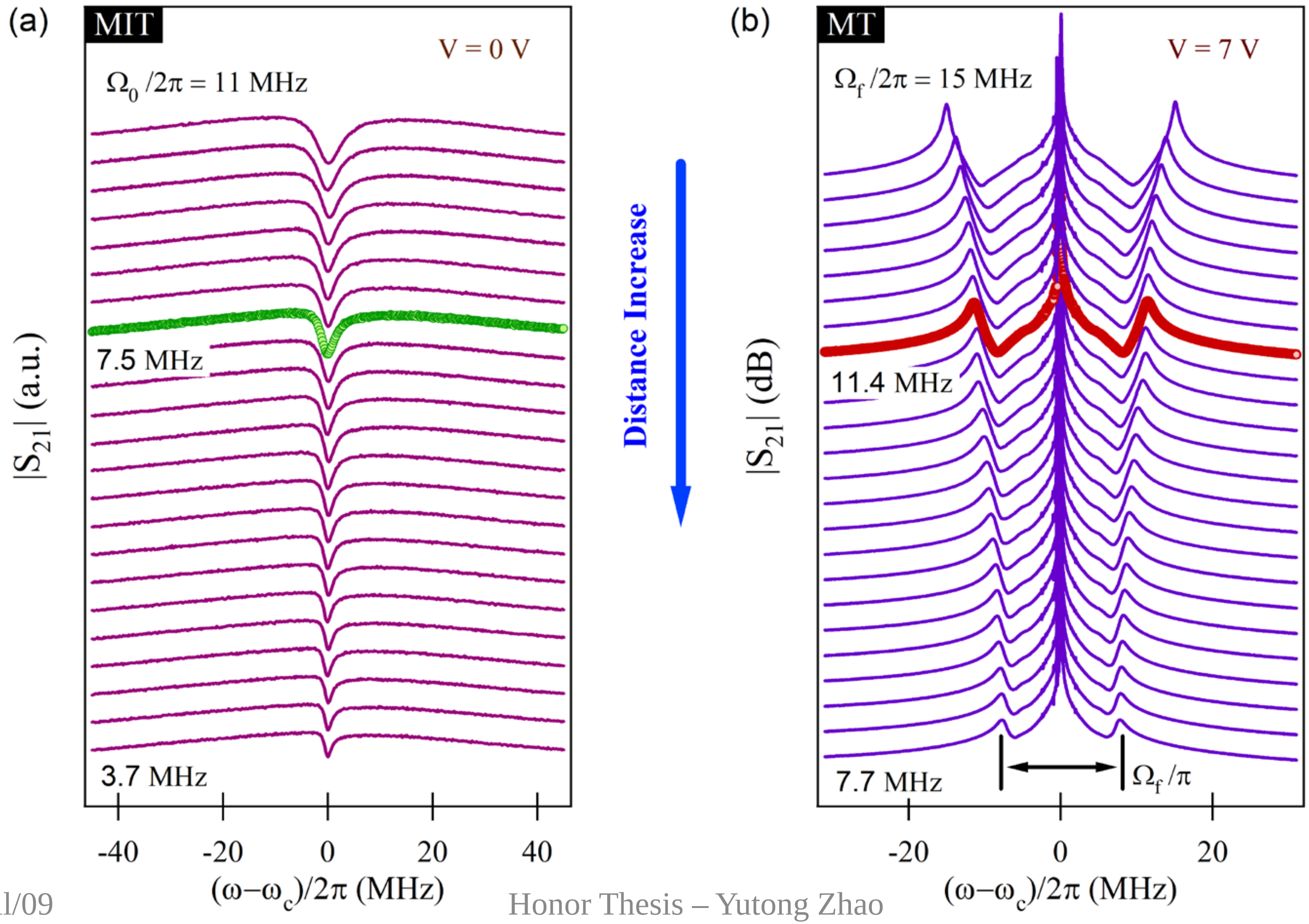
$$\Omega_{\mathrm{f}} = 0.847 \cdot V + 15.24$$

$$f = \sqrt{kV + \frac{k^2V^2}{2}}$$

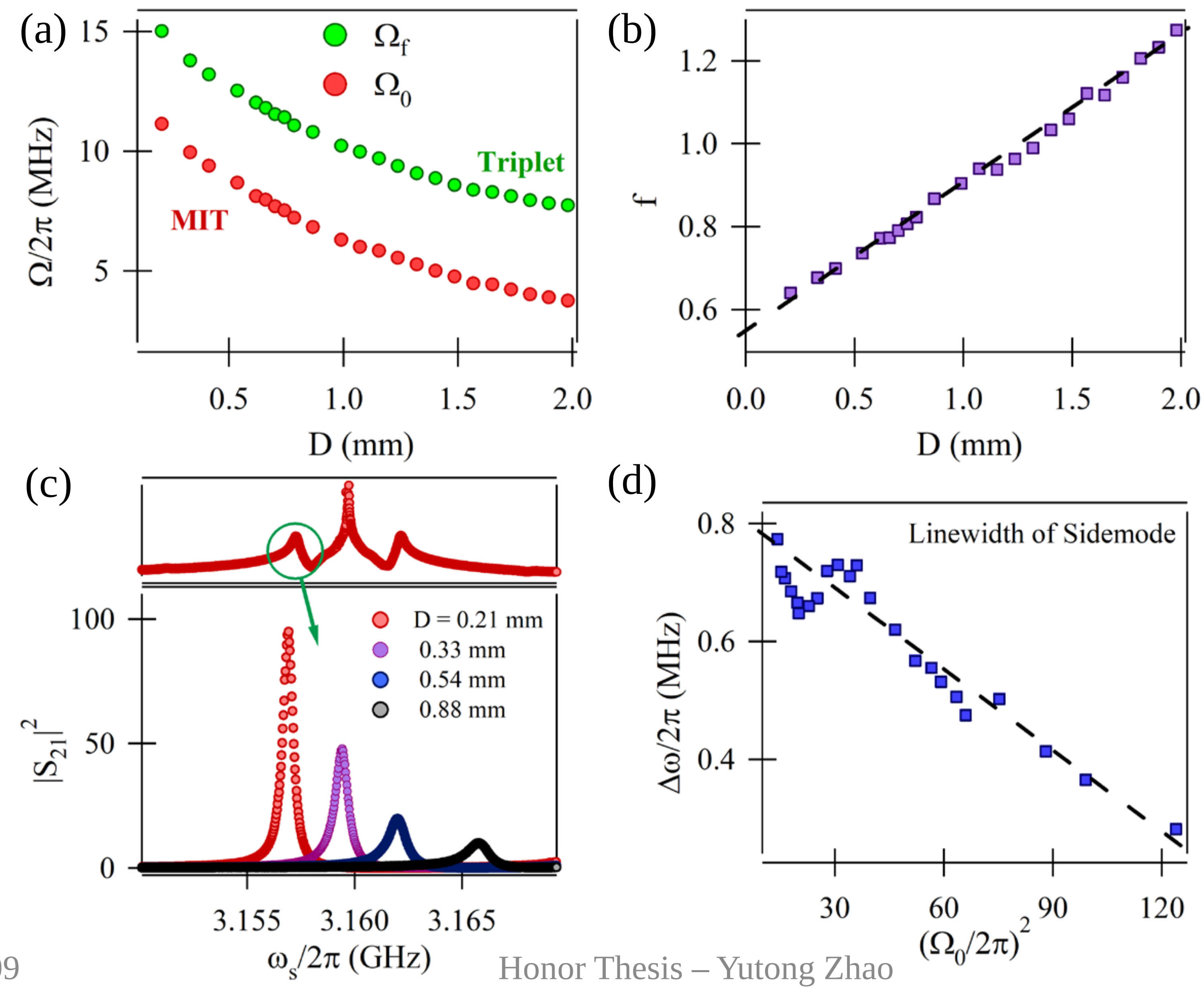
$$k = 5.56 \times 10^{-2}$$

Result: Distance Dependent Feedback





Result: Distance Dependent Feedback



$$f = 0.35 \cdot d + 0.55$$

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

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