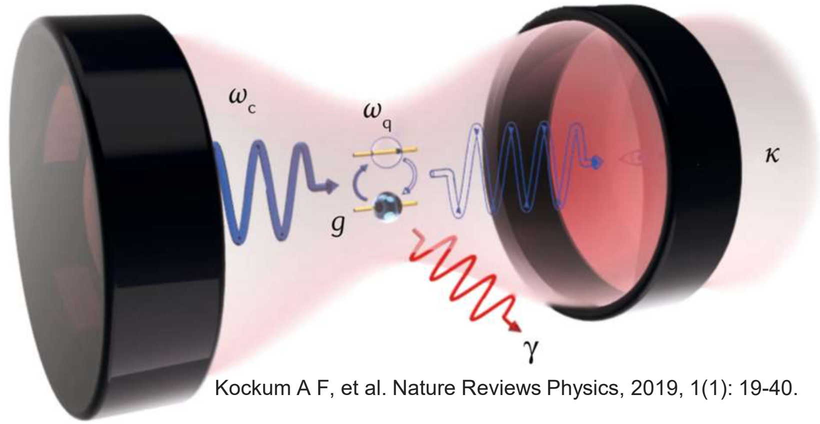
Exploring the applications of dissipative coupling in microwave frequencies



Kockum A F, et al. Nature Reviews Physics, 2019, 1(1): 19-40.

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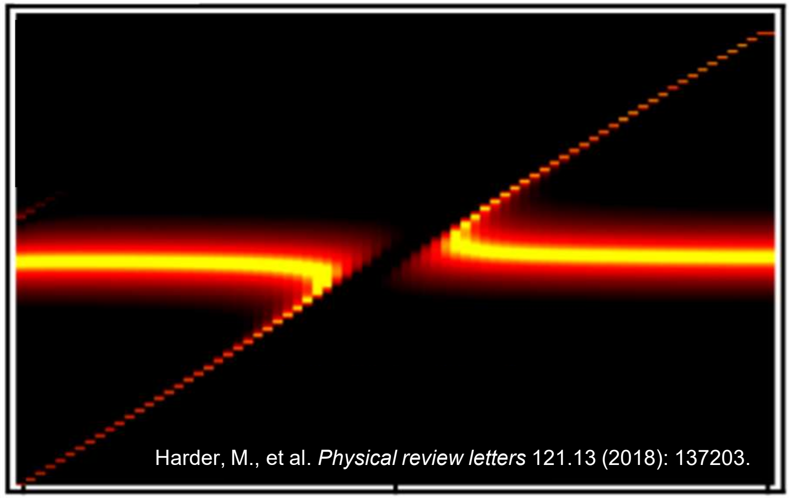
Supervisor: Dr. Can-Ming Hu

Committee: Dr. Gregory Bridges

Dr. Jacob Burgess



Harder, M., et al. *Physical review letters* 121.13 (2018): 137203.

Table of Content

Research and academic progress

Course Work:

PHYS 7720
Quantum Mechanics 1 (A+)

2018

2018.09 Start of the program

Course Work:

PHYS 7510
Condensed Matter Physics 2 (A)
PHYS 7590
Electromagnetic Theory (A+)

2019

2019.04 1st Progress meeting
+ Thesis proposal

Course Work:

ECE 7440
Microwave Materials
Measurement Techniques (A+)

2020

2020.06 2nd Progress meeting + Thesis submission
2020.07 Published 1st paper
2020.08 Thesis defense + Finial submission

Publications

First authored

[1]. Zhao, Y. T., et al. "Broadband nonreciprocity realized by locally controlling the magnon’s radiation." Physical Review Applied, 2020, 14(1): 014035.

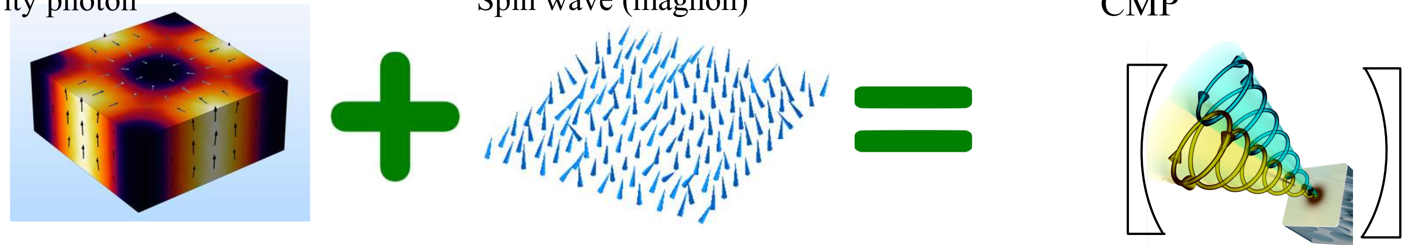
Co-authored

[2]. Rao, J. W., et al. "Analogue of dynamic Hall effect in cavity magnon polariton system and coherently controlled logic device." Nature communications 10.1 (2019): 1-7.

[3]. Yao, B.M., et al. "Coherent control of magnon radiative damping with local photon states", Communications Physics (2019):0482

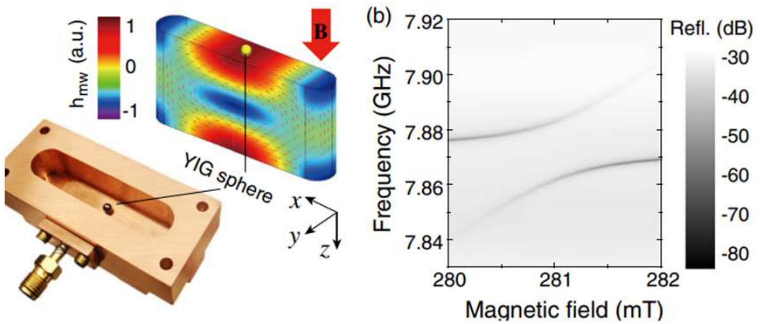
[4]. Rao, J. W., et al. "Level attraction and level repulsion of magnon coupled with a cavity anti-resonance." New Journal of Physics 21.6 (2019): 065001.

Introduction to cavity-magnon-polariton (CMP)



Coupling Mechanics of CMP

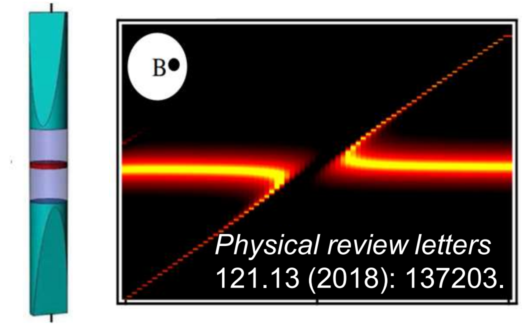
Coherent coupling



Physical review letters 113.15 (2014): 156401.

Level repulsion has been widely studied in CMP

Dissipative coupling

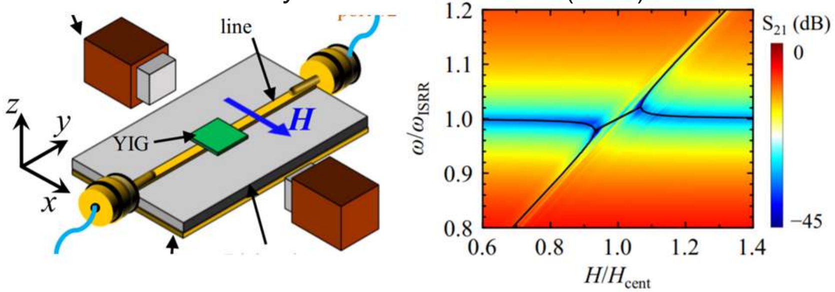


Discovery of **level attraction** in CMP

My research is focused on dissipative coupling.

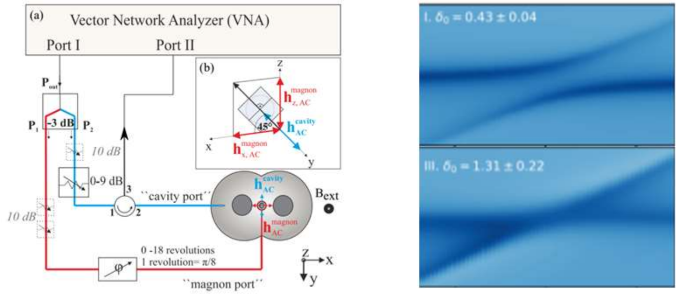
What we can make use of dissipative coupling?

Physical Review B 99.13 (2019): 134426.



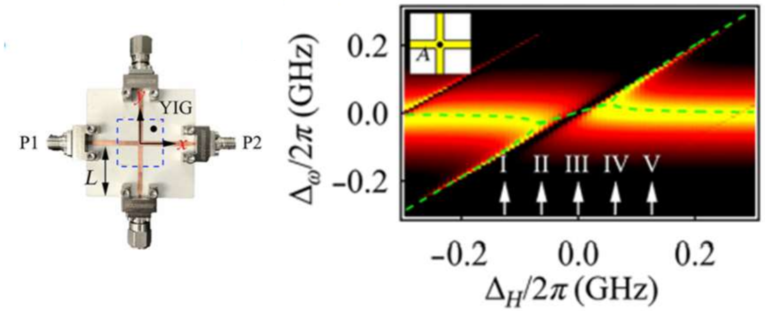
On-chip level attraction with planar YIG

Physical Review Research 2.1 (2020): 013154.



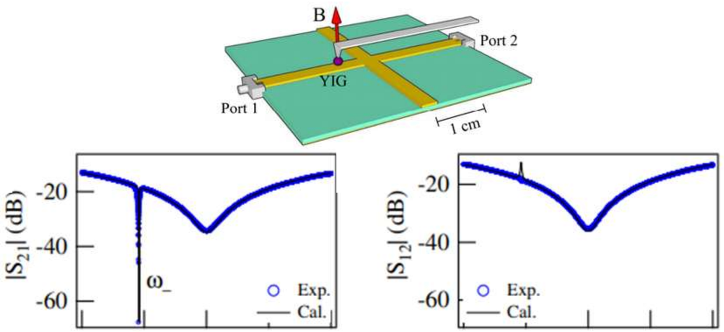
Linewidth control use level merging

On-chip device utilizing level attraction



Physical Review Applied 11.5 (2019): 054023.

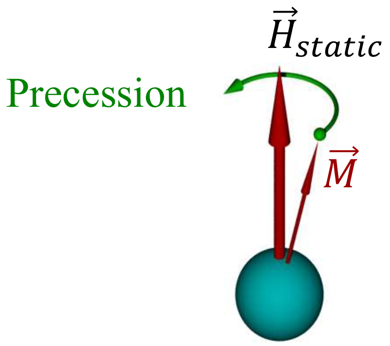
Nonreciprocal microwave transmission



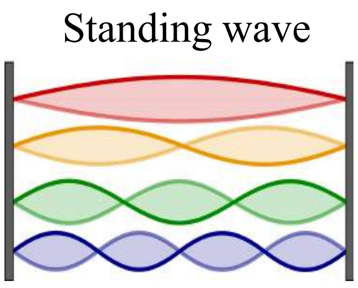
Physical review letters 123.12 (2019): 127202.

How do we understand CMP?

- Coupled photon and magnon

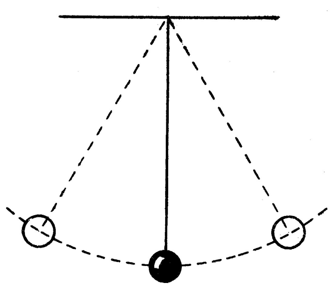


Ferromagnetic resonance



Photon cavity resonance

→ Periodic motion



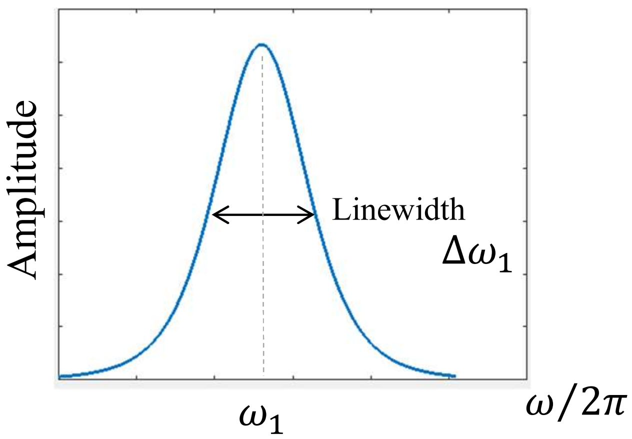
Simplified to Pendulum

Complex frequency

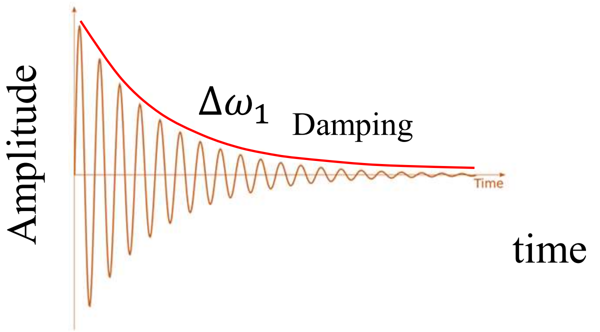
$$\tilde{\omega}_1 = \omega_1 - i\Delta\omega_1$$

Resonance (real) + damping (imaginary)

Frequency response

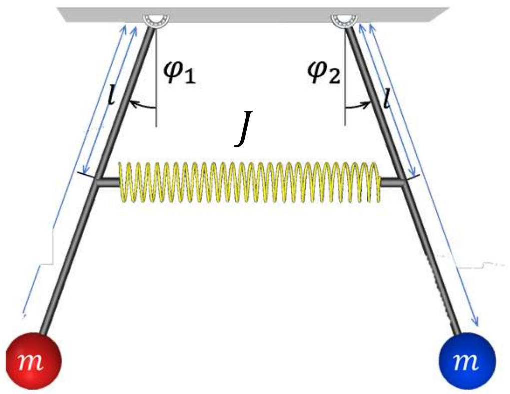


Time-domain response



Coherent coupled pendulums

Schematic – Spring



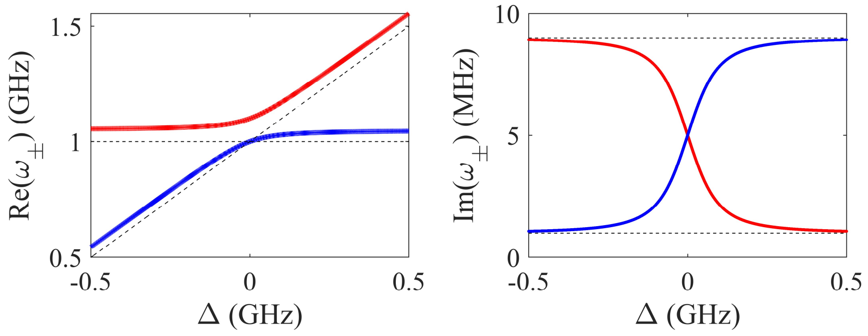
Equation of motion:

$$\ddot{\varphi}_1 + 2\lambda_1\dot{\varphi}_1 + \omega_1^2\,\varphi_1 \; - 2\omega_1 J(\varphi_2 - \varphi_1) = 0$$

$$\ddot{\varphi}_2 + 2\lambda_2\dot{\varphi}_2 + \omega_2^2\,\varphi_2 \; - 2\omega_2 J(\varphi_1 - \varphi_2) = 0$$

Matrix form

$$\begin{bmatrix} \omega - \widetilde{\omega}_1 - J & J \\ J & \omega - \widetilde{\omega}_2 - J \end{bmatrix} \begin{bmatrix} |\varphi_1| \\ |\varphi_2| \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$



coupling = Real

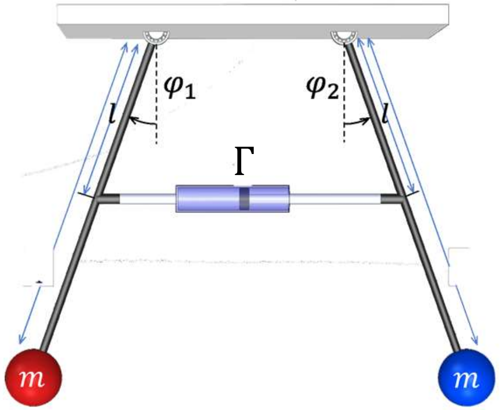
→ Conservative force

→ Level repulsion

→ Linewidth exchange

Dissipative coupled pendulums

Schematic – Dashpot



Matrix form

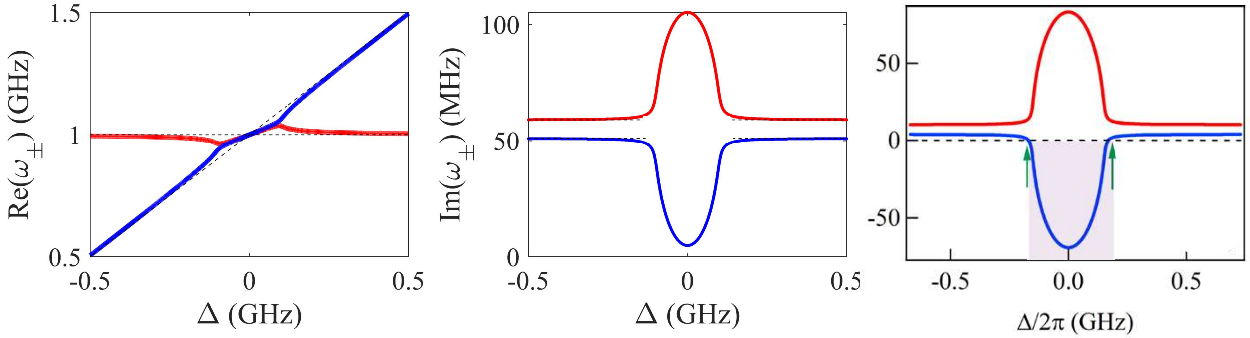
$$\begin{bmatrix} \omega - \tilde{\omega}_1 - i\Gamma & i\Gamma \\ i\Gamma & \omega - \tilde{\omega}_2 - i\Gamma \end{bmatrix} \begin{bmatrix} |\varphi_1| \\ |\varphi_2| \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

coupling $=$ imaginary

→ Nonconservative force

Mechanical systems

Polariton systems



Green arrow → zero damping

Shade area → negative damping

→ Level attraction

→ Linewidth “repulsion”

Numerical methods for time domain analysis

Equation of motion:

$$\dot{\varphi}(t) = f(\varphi(t), t)$$

→ Ordinary Differential Equations (ODEs)

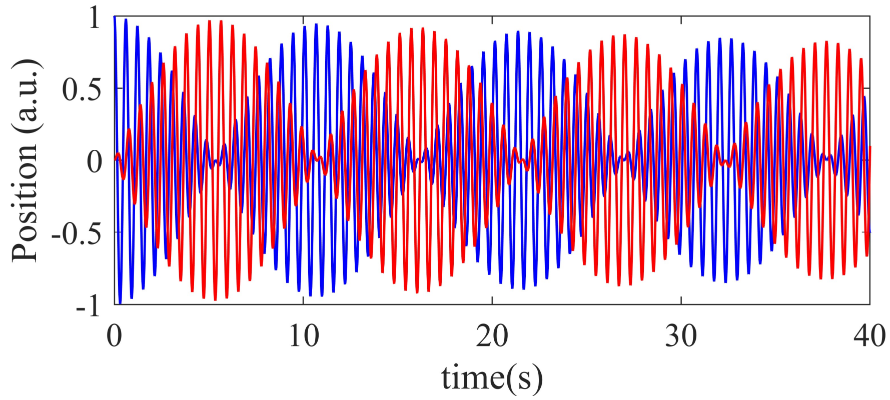
Next moment | This moment (initial conditions)

$$\varphi(t_{n+1}) \ = \varphi(t_n) + \int_{t_n}^{t_{n+1}} f(\varphi(t), t)\, dt$$

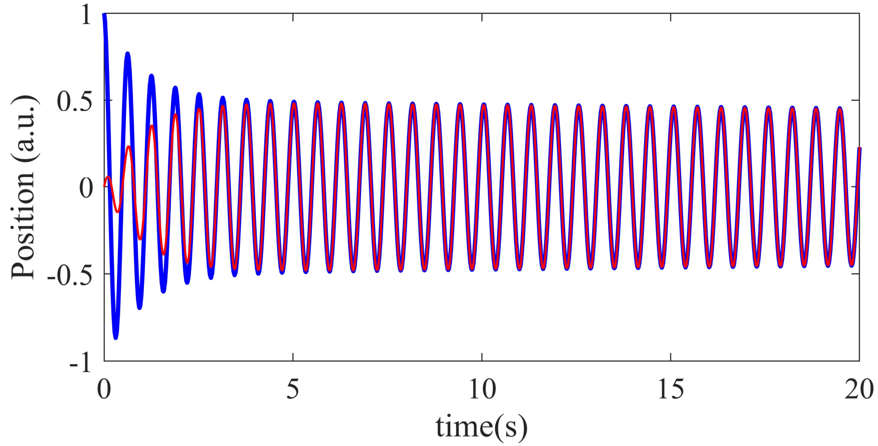
Numerical approximation $\quad f(\varphi(t), t) \sim \text{constant}$

$$\varphi(t_{n+1}) \ = \varphi(t_n) + f(\varphi(t), t)(t_{n+1} - t_n)$$

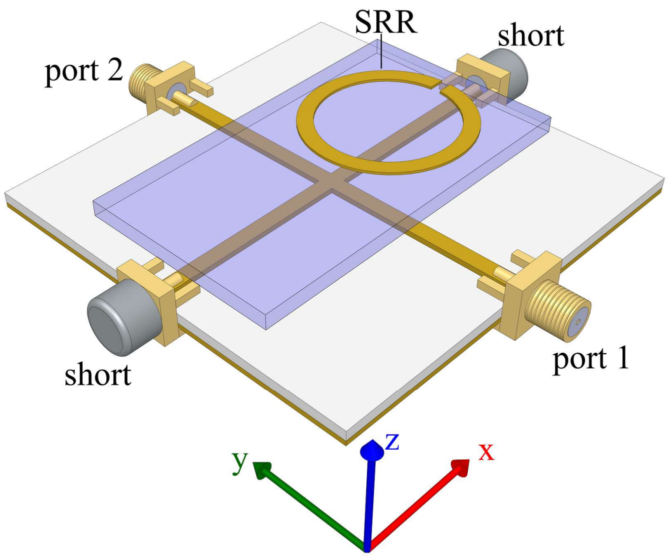
Coherent coupling - Rabi Oscillation like



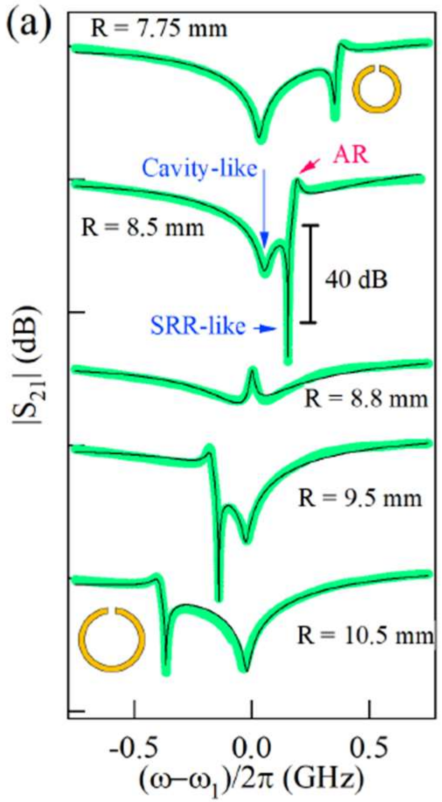
Dissipative coupling - Synchronization like



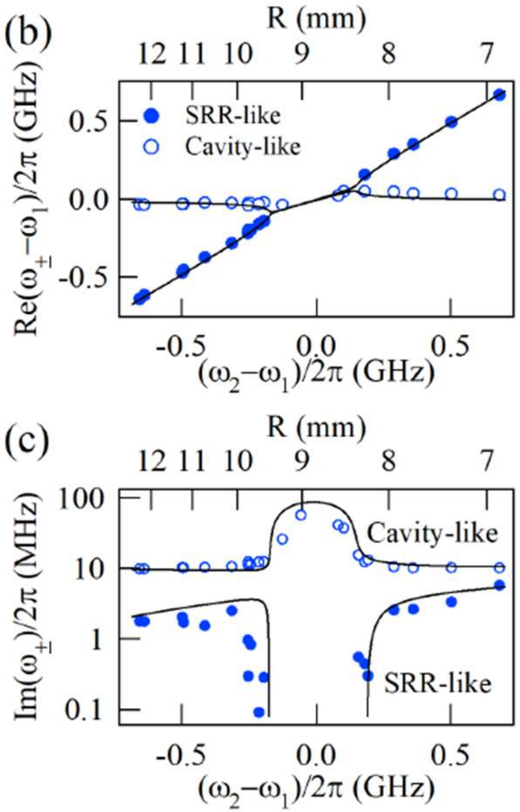
Dissipative coupling in metamaterials



Experiment design



Measured Spectra

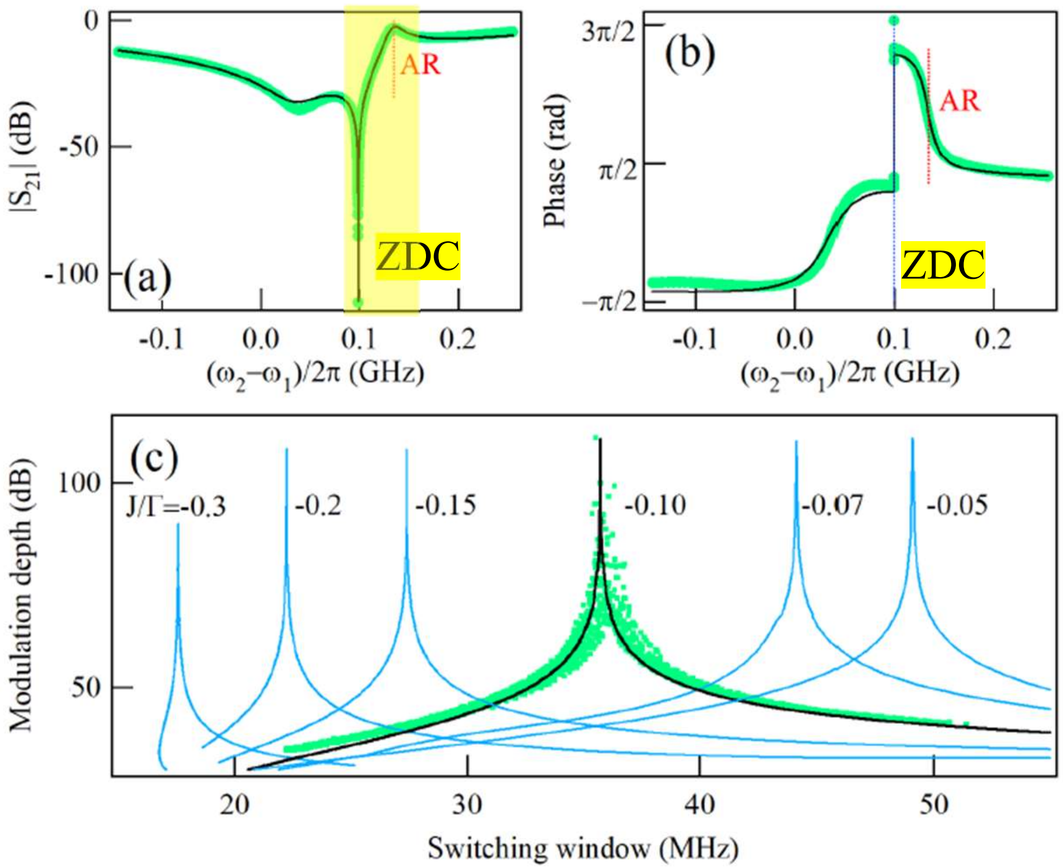


Level attraction

Linewidth Narrowing

Dispersion

Transmission transition from 0 to 1



Asymmetry resonance is a typical Fano resonance

We have observed a transition from 0 to 1 in transmission.

1 → on

0 → off

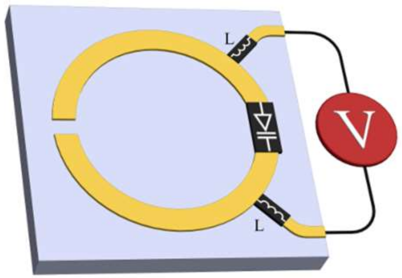
Potential to design switching device.

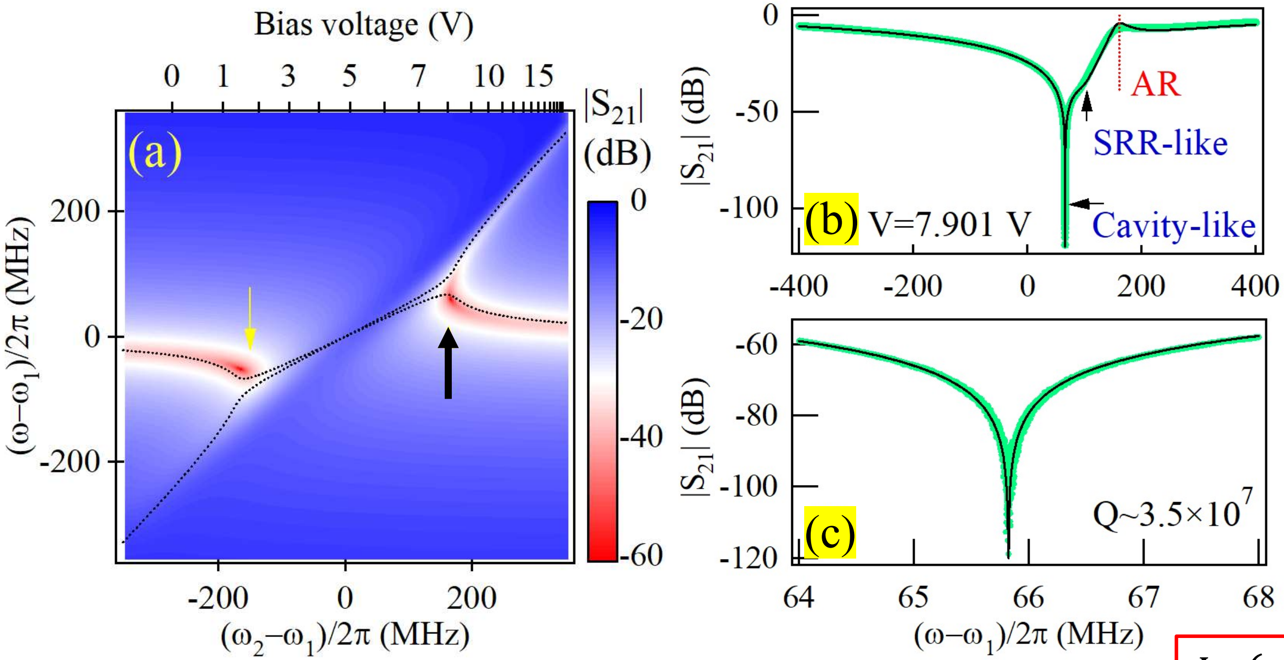
Smaller window → high performance

Voltage-controlled level attraction

Varactor loaded split-ring resonator

$$\omega_{srr} = \frac{1}{\sqrt{LC}}$$



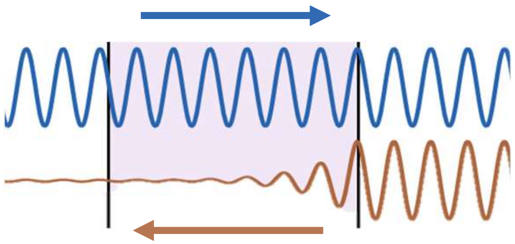


$\boxed{Im(\omega_c) = 30\ Hz!}$

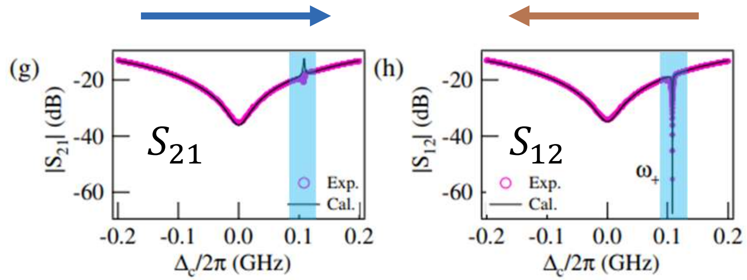
Ultra-high Quality factor → sensitive detection / sensor design

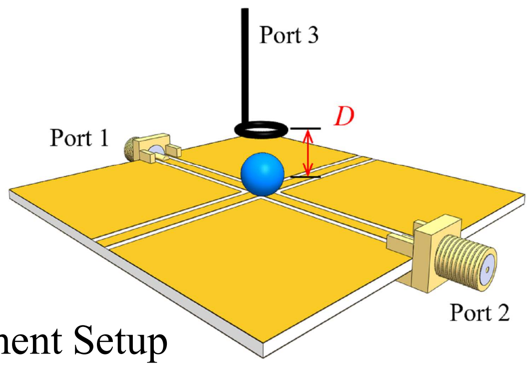
Nonreciprocity in cavity magnon polariton

Wang, Yi-Pu, et al. "Nonreciprocity and unidirectional invisibility in cavity magnonics." *Physical review letters* 123.12 (2019): 127202.

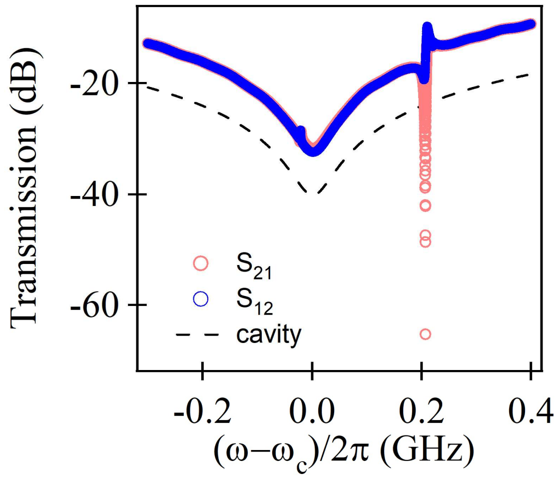


Unidirectional transmission





Experiment Setup



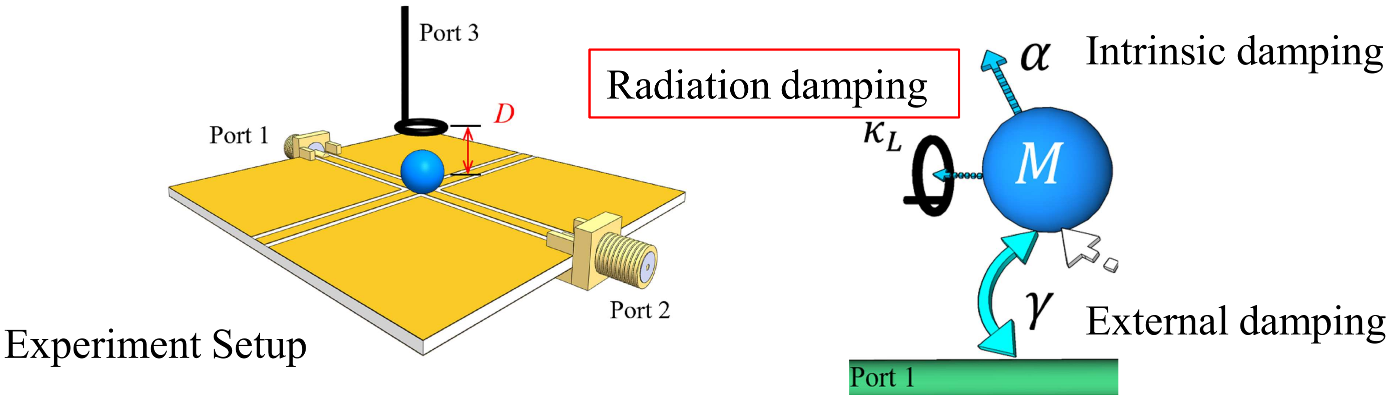
Iso. (dB)= $|S_{21}-S_{12}|$

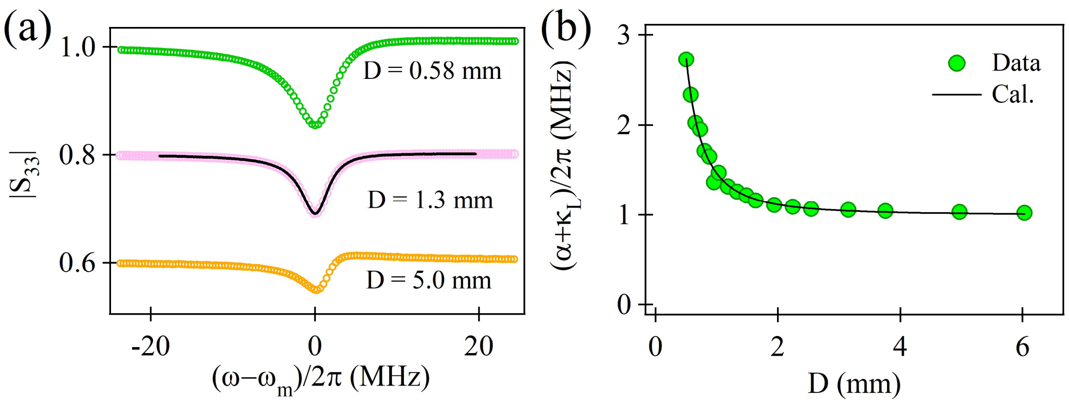
For Iso. >20db

Bandwidth ~ 0.5 MHz

~ magnon linewidth

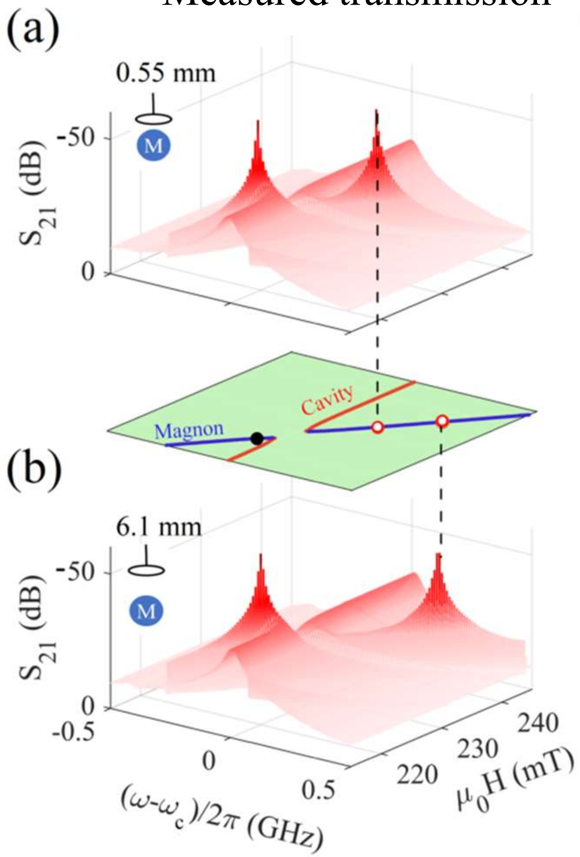
Local control of magnon damping



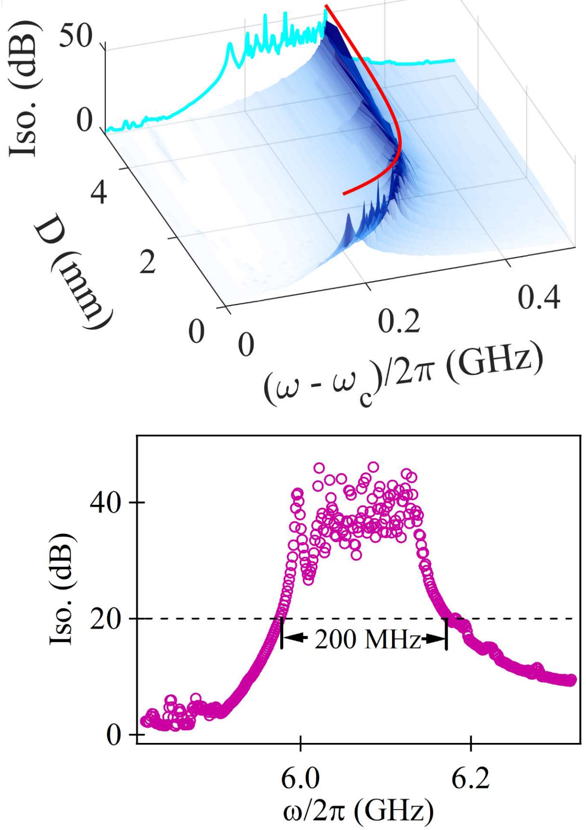


Broadband nonreciprocal device

Measured transmission



Measured nonreciprocity



Hundreds time of improvement!

Summary of Contribution

1. We proposal a numerical method to analysis time-domain signal and have potential to study non-linear and chaotic effects in dissipative coupling.

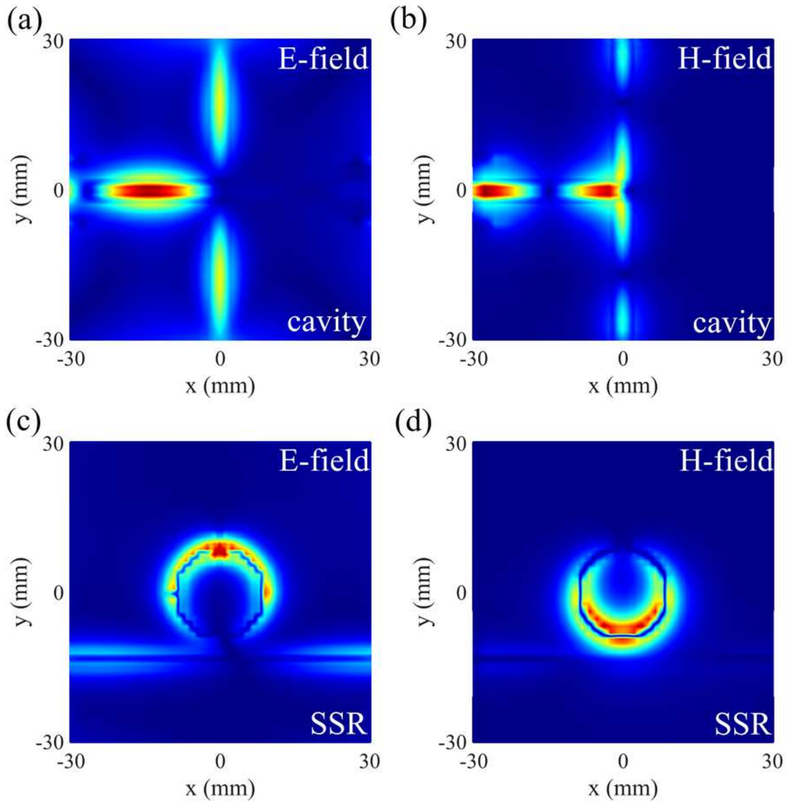
2. Dissipatively coupled metamaterials for sensitive detectors, switching device.

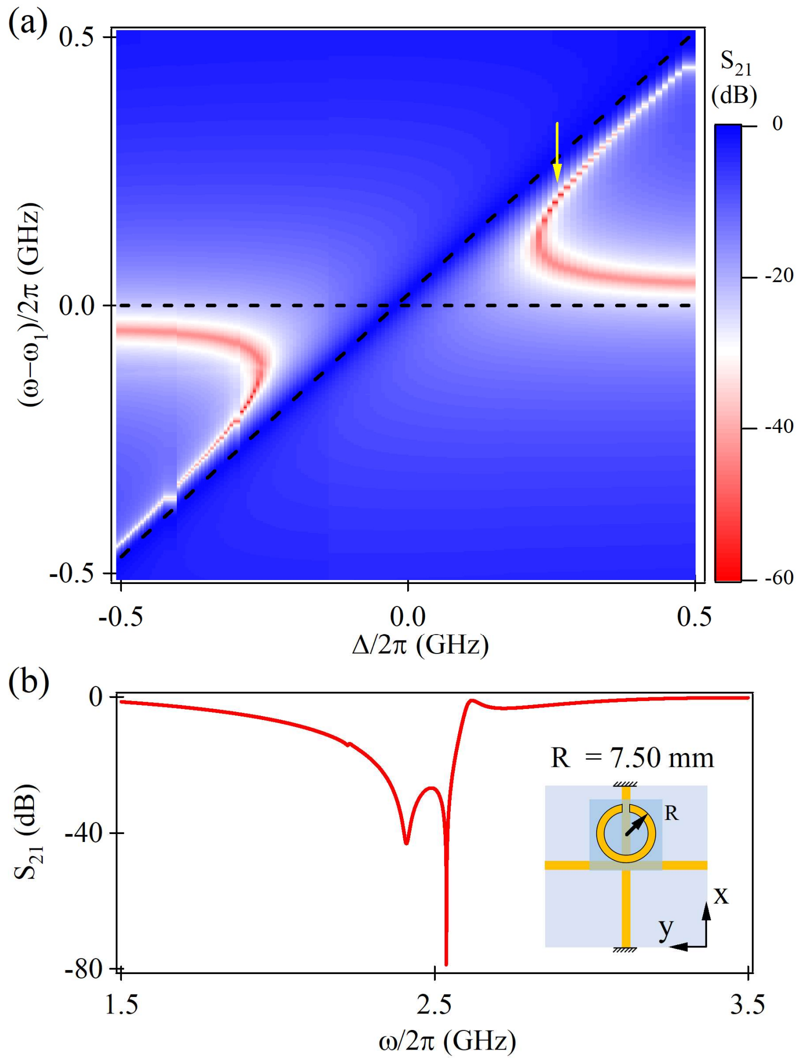
3. Broadband nonreciprocal device by locally control magnon damping in CMP.

Additional Information for Clarification

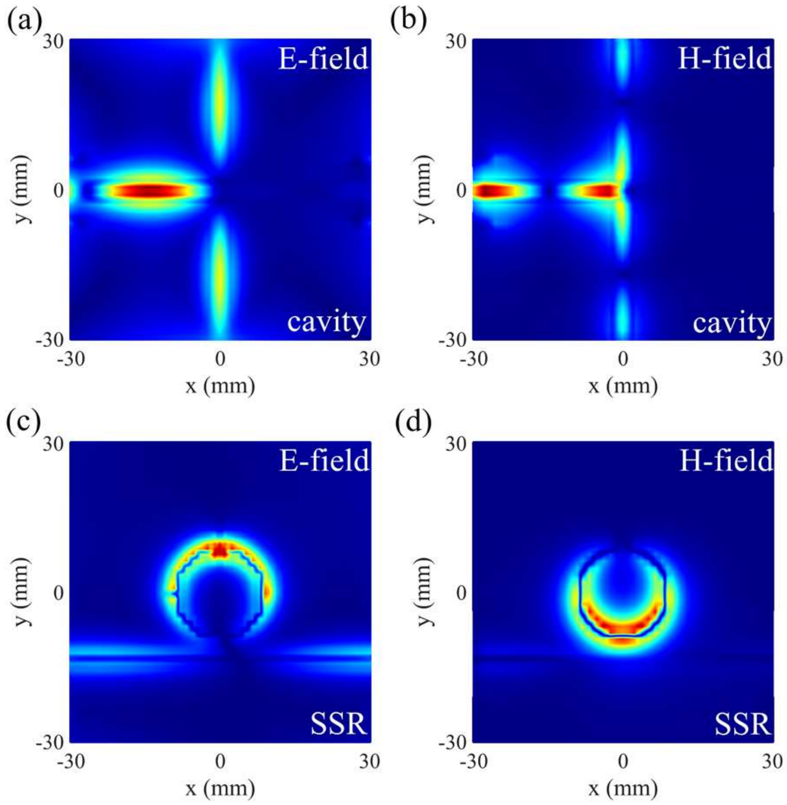
1. Level attraction in Simulation
2. Magnetic Resonance of Split-ring Resonator
3. Classical circuit model for level attraction
4. Negative damping/resistance
5. Negative damping - coherent coupling calculation result
6. Negative damping - dissipative coupling calculation result
7. Relation between damping rates and quality factors
8. Linewidth evolution for dissipative coupling (negative damping)
9. Fano Resonance
10. Fano Resonance (2)
11. Fano Resonance for designing switching devices
12. Fano Resonance for designing sensors
13. Rabi Oscillation
14. Rabi oscillation for coherent coupling – time domain
15. Faraday Rotation
16. Why do people need nonreciprocal devices?
17. Between oscillators and polaritons
18. Damping control by Inverse-square law
19. Antiresonance
20. ODEs solvers for nonlinear / chaotic analysis (1-3)

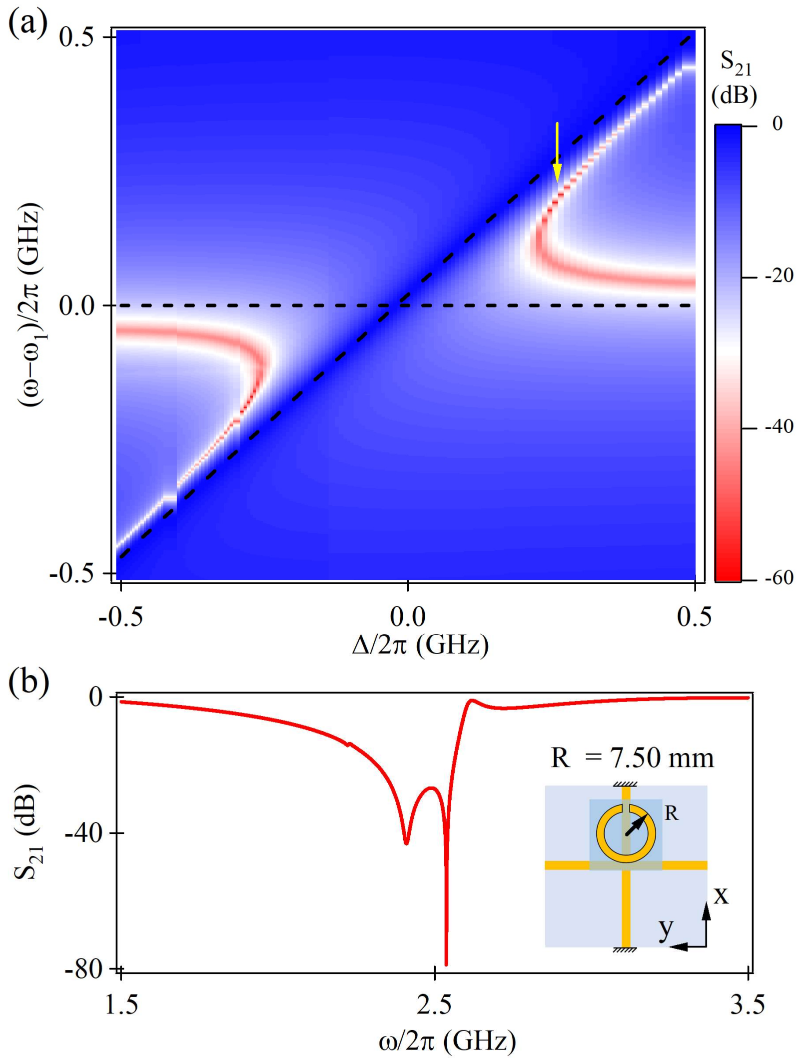
Level attraction in Simulation





Level attraction in Simulation (2)





Magnetic Resonance of Split-ring Resonator

Three ways to excite resonance of an SRR.

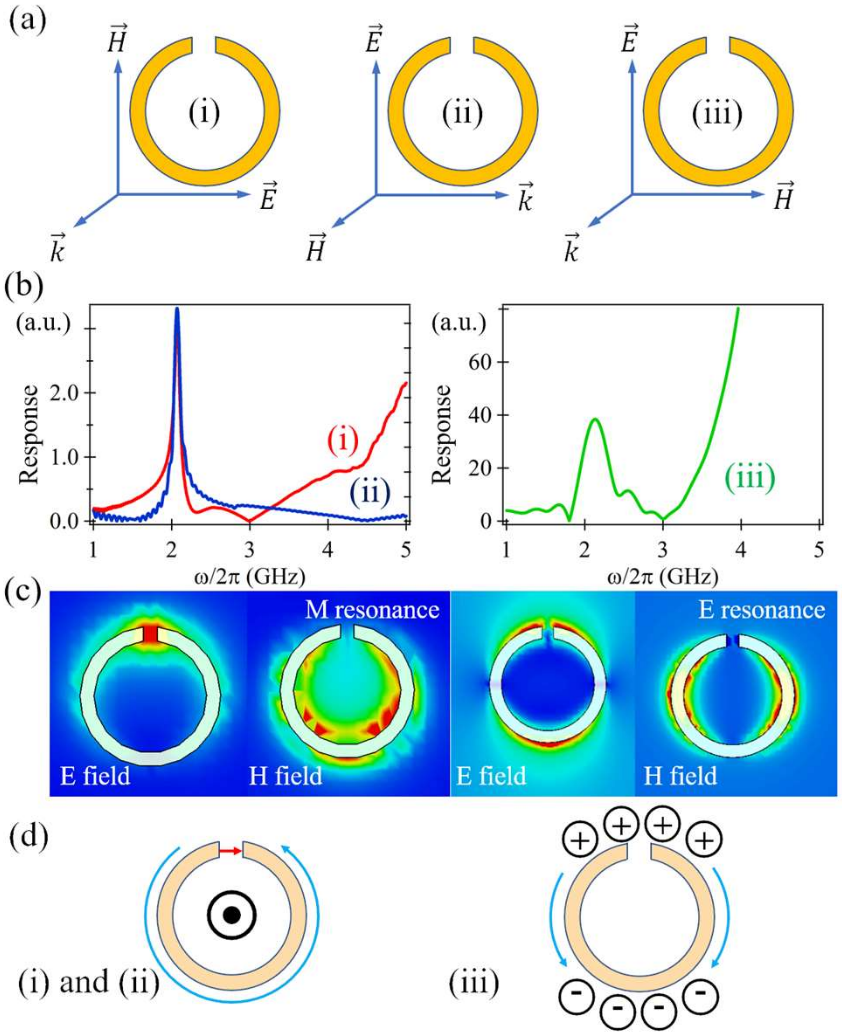
(i) Electric coupling to magnetic resonance

(ii) Magnetic coupling to magnetic resonance

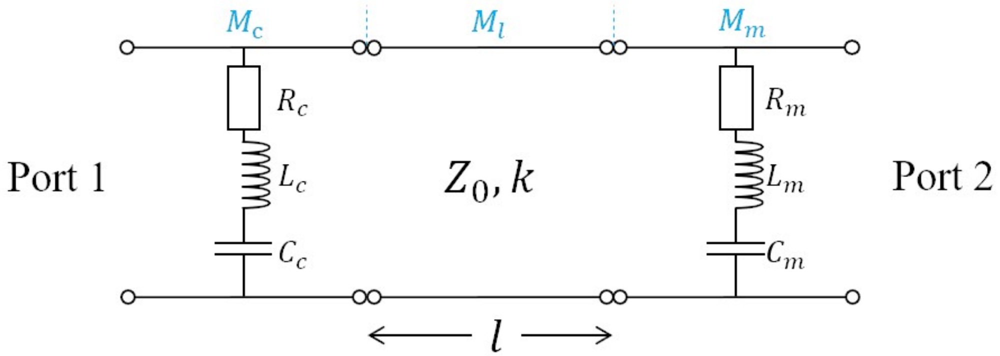
(iii) Electric coupling to electric resonance

(i) + (ii) → magnetic dipole in z-direction

(iii) → electric dipole in y-direction



Classical circuit model for level attraction



Impedance Z → transmission matrix (ABCD) → Scattering matrix (S_{21} & S_{11})

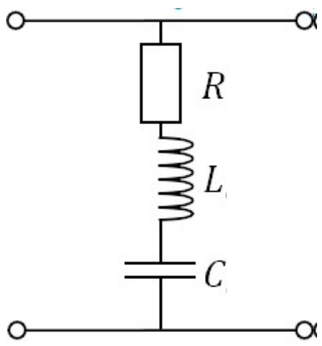
$$S_{21} \approx 1 + \frac{\kappa}{i(\omega - \omega_1) - (\beta + \kappa) + \dfrac{\kappa\gamma e^{i(2kl+\pi)}}{i(\omega - \omega_m) + \alpha + \gamma}}$$

Equivalent to Hamiltonian model

Two classical RLC oscillator coupled with a transmission line.

This model confirms the importance of travelling wave in this system.

Negative damping/resistance



Single RLC resonator in a Two-port Network

$$S_{21} = 1 - \frac{\kappa}{i(\omega - \omega_1) + \kappa + \gamma},$$

$\omega_1 = 1/\sqrt{LC}$ – resonance frequency

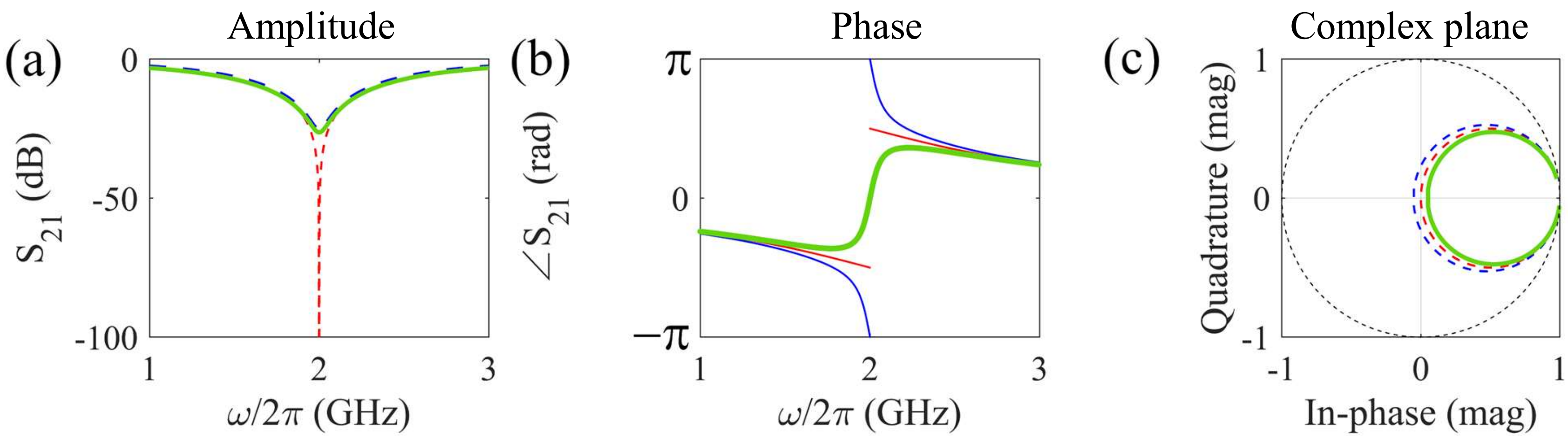
$\kappa = Z_0/4L$ – external damping

$\gamma = R/2L$ – intrinsic damping

Zero damping

Positive damping

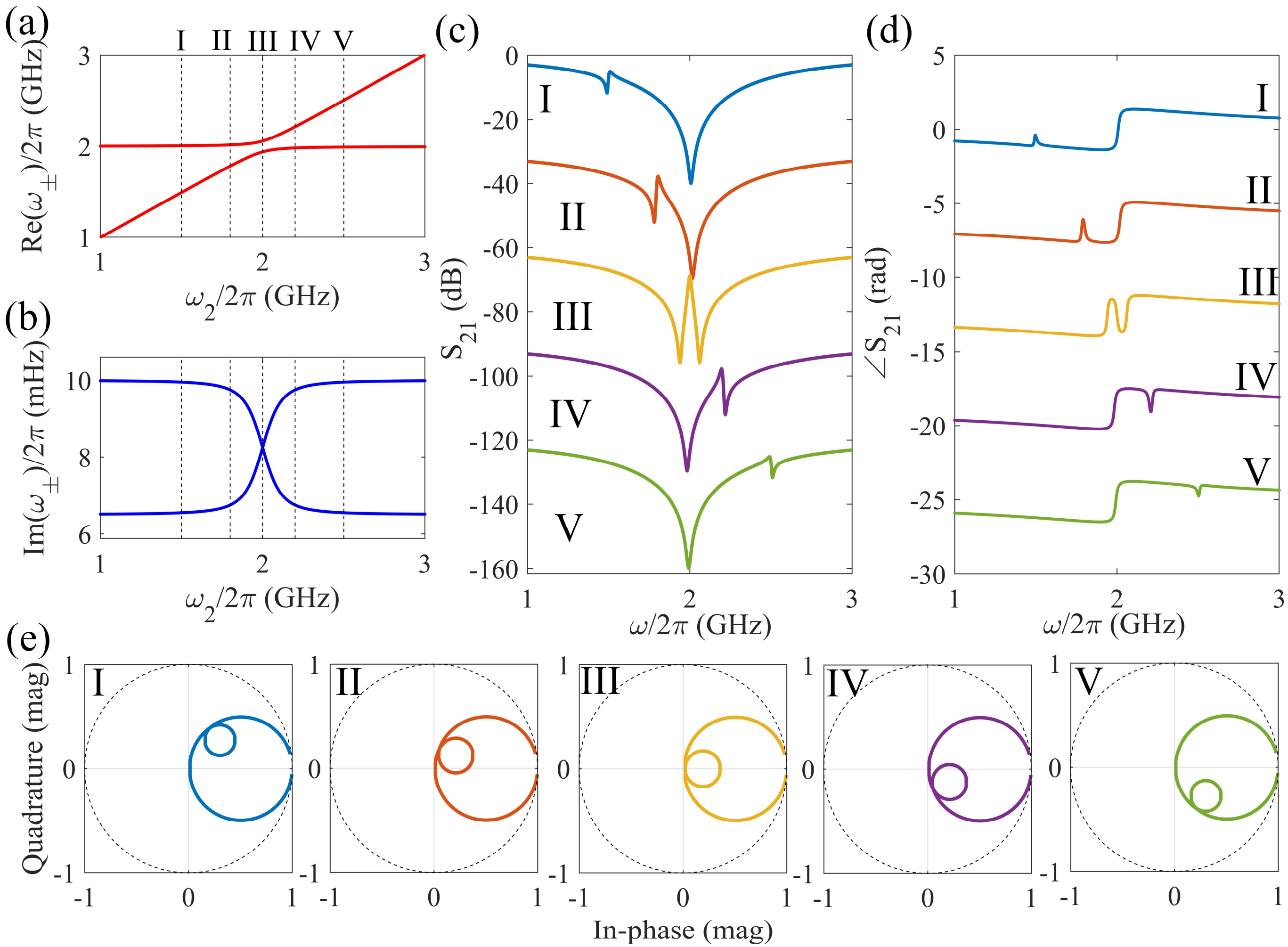
Negative damping



Negative damping/resistance (2)

Coherent coupling case

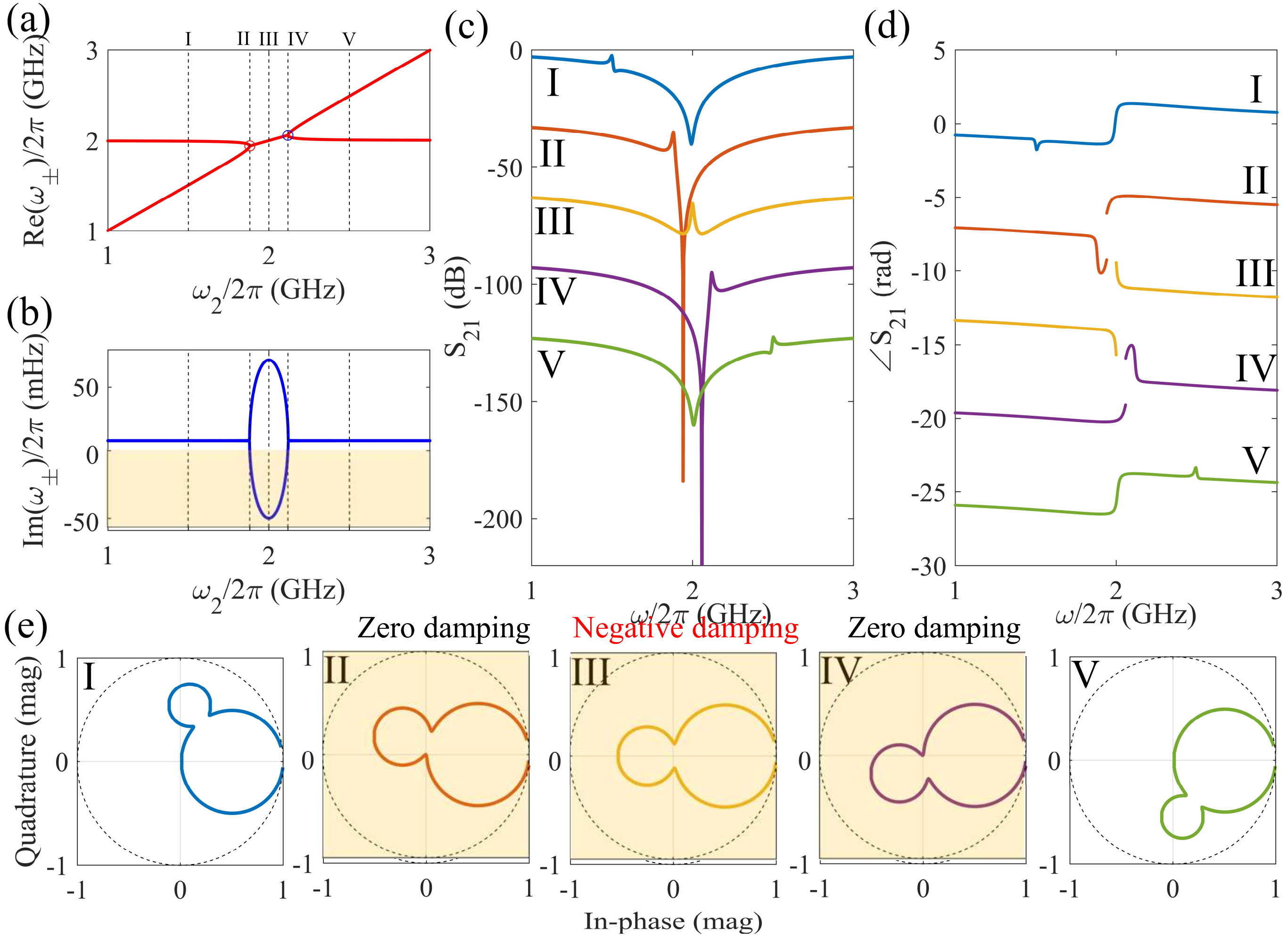
The S21 trajectory always exclude origin, showing the damping is always positive



Negative damping/resistance (3)

Dissipative coupling case

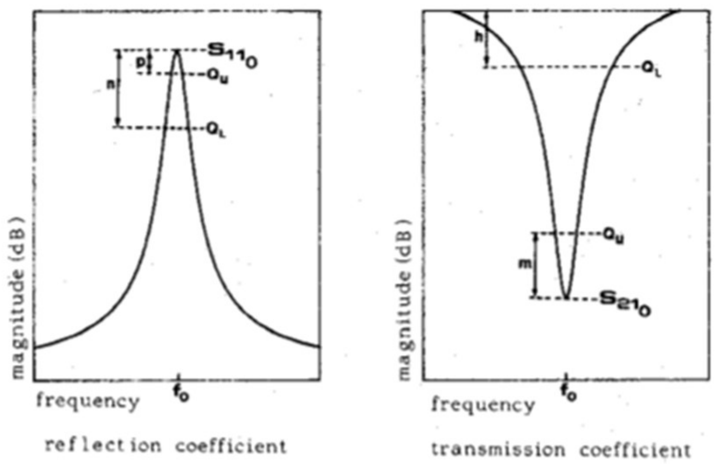
The S21 trajectory sometimes include origin, showing the damping could be zero/negative!



Relation between damping rates and quality factors

Determination of Loaded, Unloaded, and External Quality Factors of a Dielectric Resonator Coupled to a Microstrip Line

APS KHANNA AND Y. GARAULT



External Q factor → intrinsic + external damping

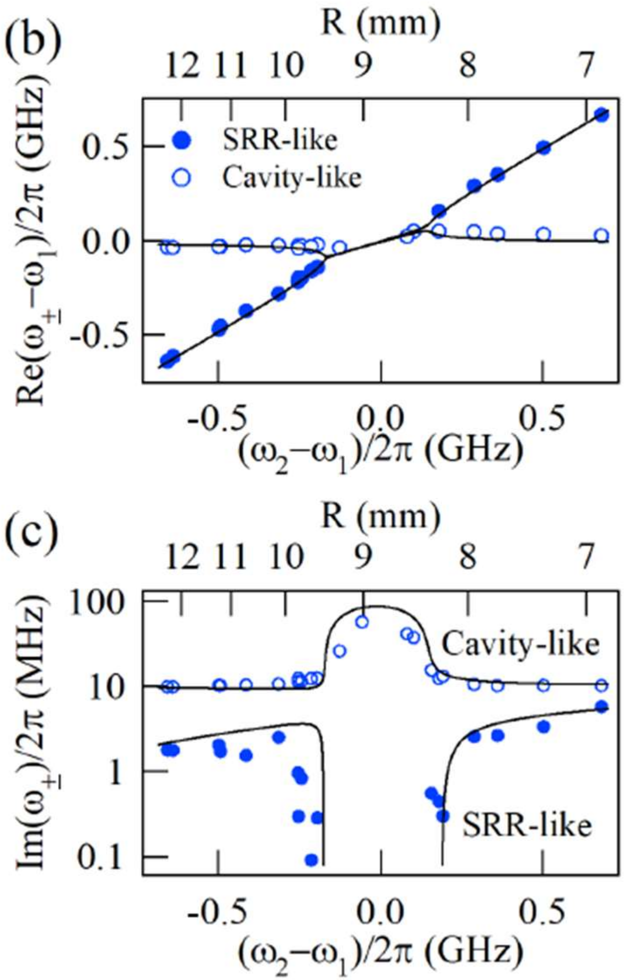
Unloaded Q factor → intrinsic damping ∝ R

Loaded Q factor → external damping

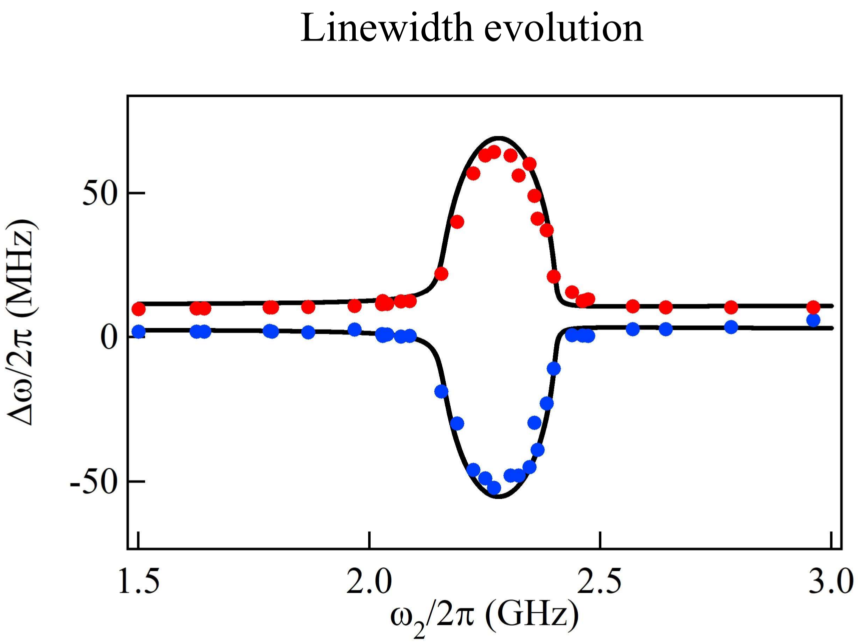
$$Q = \frac{\omega_1}{\Delta\omega}$$

Khanna, A. P. S., and Y. Garault. *IEEE Transactions on Microwave Theory and Techniques* 31.3 (1983): 261-264.

Linewidth evolution for dissipative coupling



Taking phase
into consideration

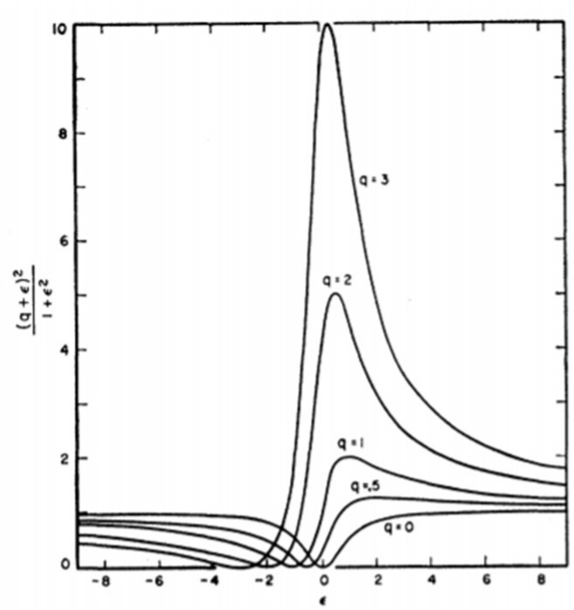


Fano Resonance

In 1961, Ugo Fano discovered a distinctly asymmetric shape while studying the autoionizing states of atoms.

Characteristic : One discrete state and one continuum

$$I \propto \frac{(F\gamma + \omega - \omega_0)^2}{(\omega - \omega_0)^2 + \gamma^2}$$



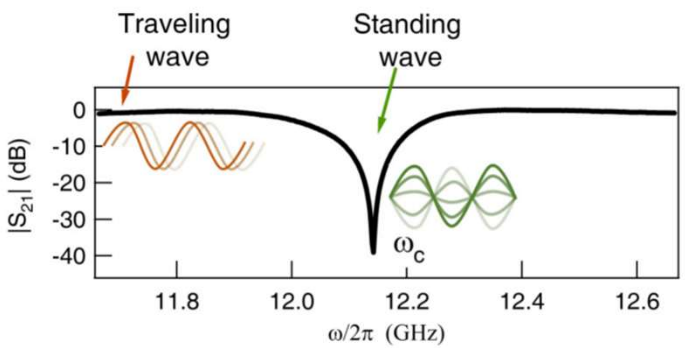
Fano, Ugo. "Effects of configuration interaction on intensities and phase shifts." *Physical Review* 124.6 (1961): 1866.

In our case:

travelling wave → continuum states

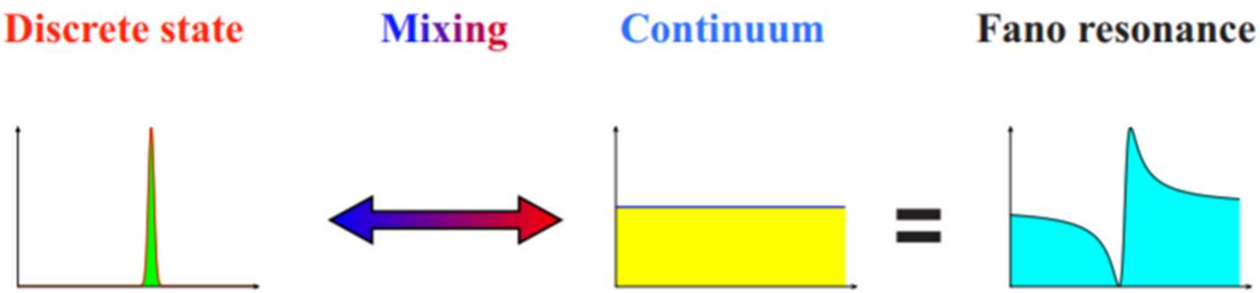
SRR → discrete state

Yao, Bimu, et al. "The microscopic origin of magnon-photon level attraction by traveling waves: Theory and experiment." *Physical Review B* 100.21 (2019): 214426.



Fano Resonance (2)

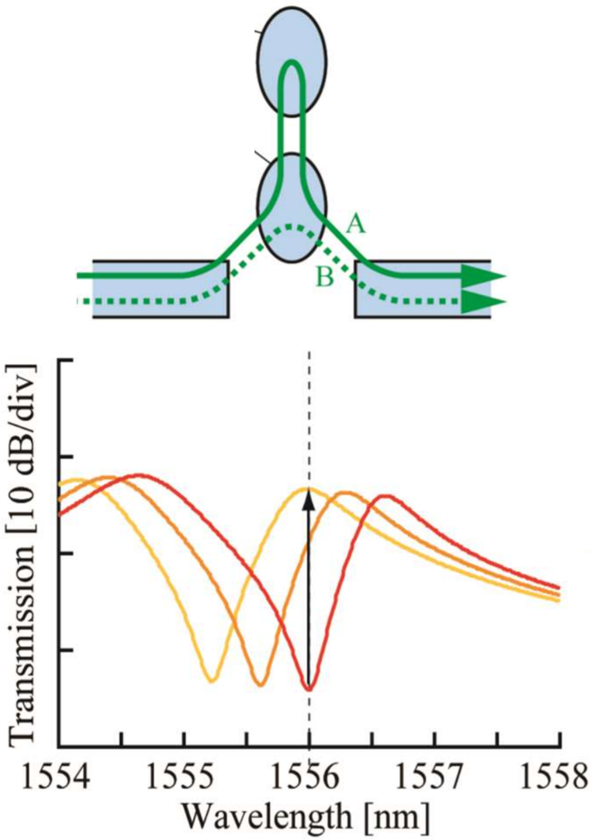
Miroshnichenko, Andrey E., Sergej Flach, and Yuri S. Kivshar.
"Fano resonances in nanoscale structures." *Reviews of Modern Physics* 82.3 (2010): 2257.



“ Such waveguide-cavity systems can naturally exhibit Fano resonances with high quality factors, and they can be used for optical modulations and switching. ”

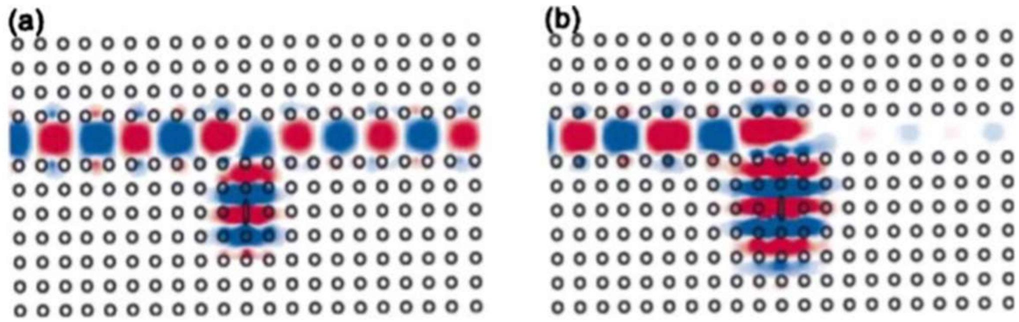
“ Therefore, the Fano resonance can be considered as a precursor of BICs, with unique properties that may lead to applications including optical sensors, filters and waveguides, as well as low-loss fibres and large-area lasers. ”

Fano Resonance for designing switching devices



Nozaki, Kengo, et al. "Ultralow-energy and high-contrast all-optical switch involving Fano resonance based on coupled photonic crystal nanocavities." *Optics express* 21.10 (2013): 11877-11888.

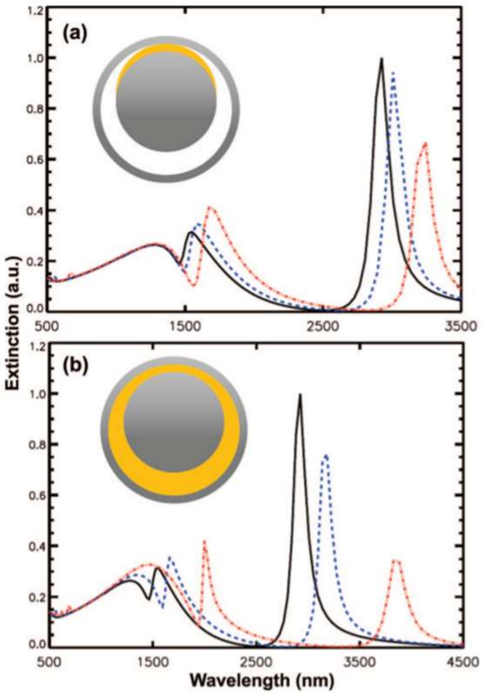
ON OFF



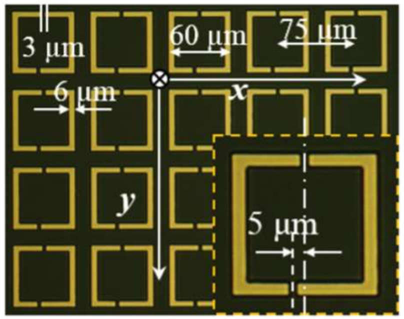
Yanik, Mehmet Fatih, Shanhui Fan, and Marin Soljačić. "High-contrast all-optical bistable switching in photonic crystal microcavities." *Applied Physics Letters* 83.14 (2003): 2739-2741.

Fano Resonance for designing sensors

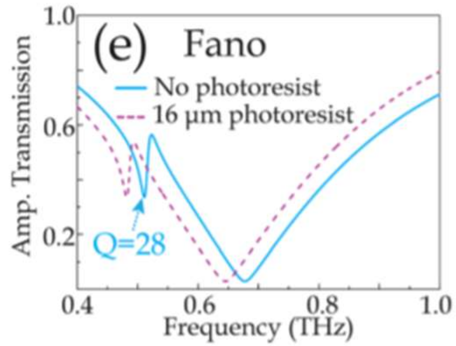
Yellow material:
Dielectric material under test

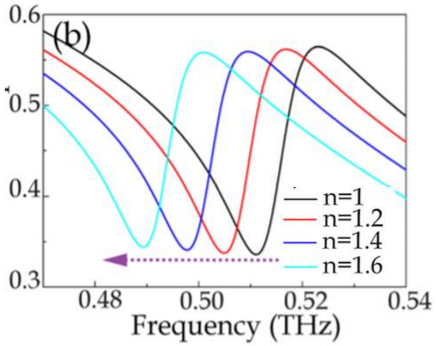


Sensor design

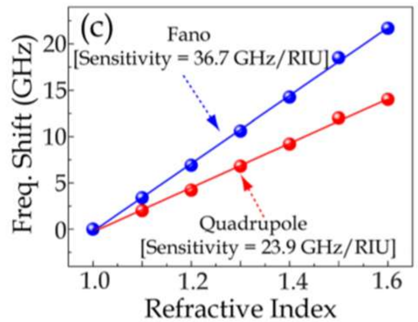


Fano resonance spectrum





Frequency shift



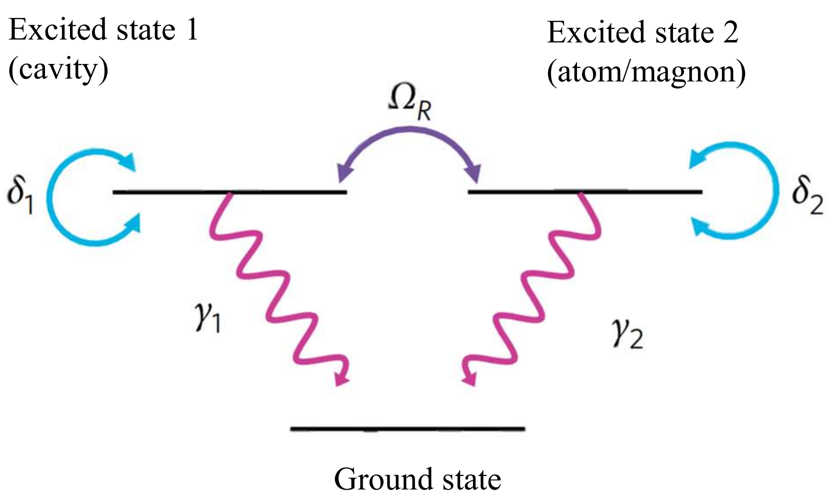
Sensitivity

Hao, Feng, et al. "Symmetry breaking in plasmonic nanocavities: subradiant LSPR sensing and a tunable Fano resonance." *Nano letters* 8.11 (2008): 3983-3988.

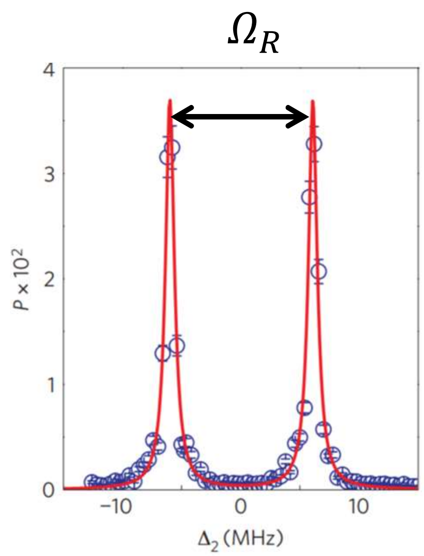
Singh, Ranjan, et al. "Ultrasensitive terahertz sensing with high-Q Fano resonances in metasurfaces." *Applied Physics Letters* 105.17 (2014): 171101.

Rabi Oscillation

A Rabi oscillation is a damped oscillation of an initially excited atom coupled to an electromagnetic resonator or cavity. In this process, atom alternately emits photons into a single-mode electromagnetic cavity and reabsorbs them.

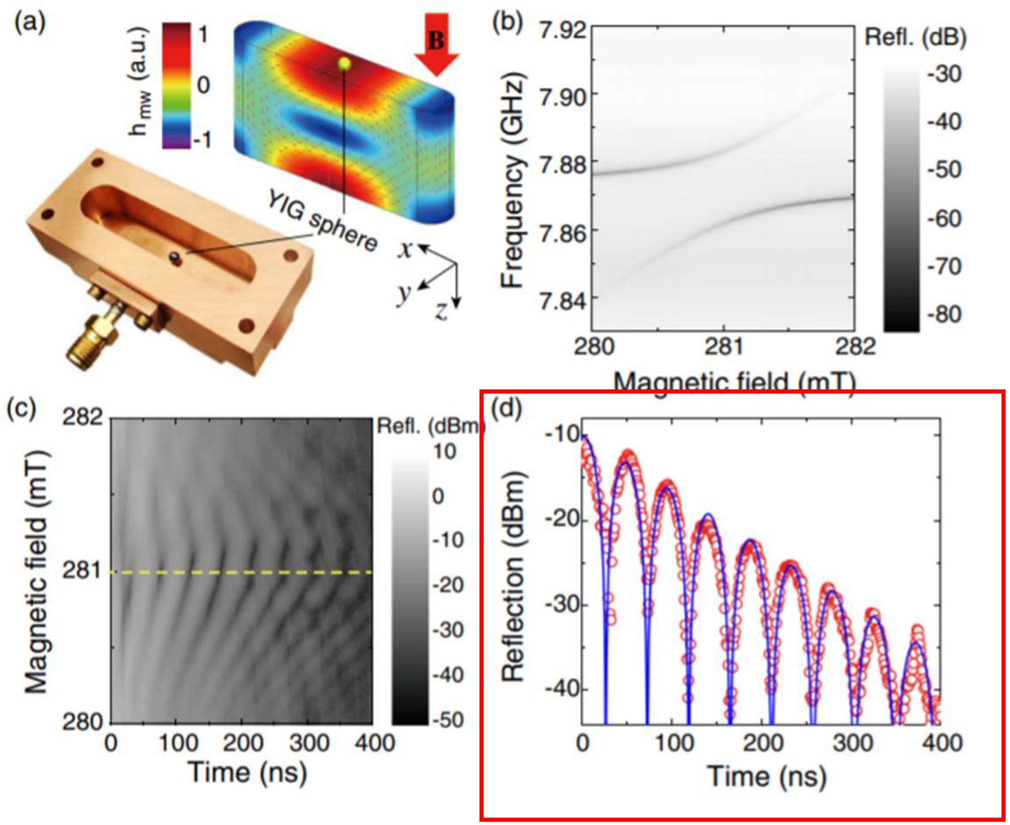


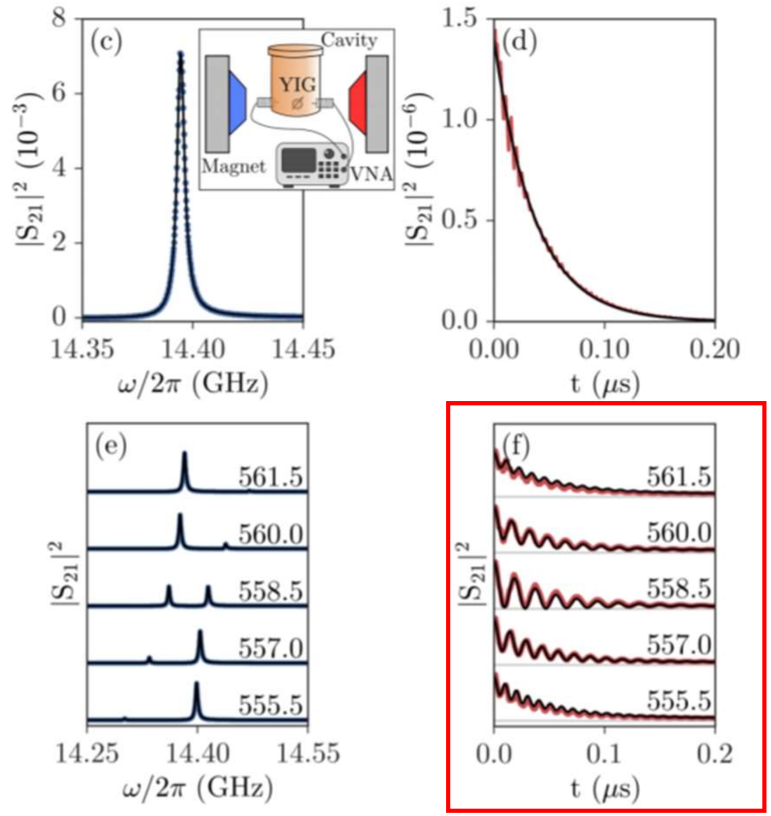
Schematic for a two-level system



Typical frequency-domain observation

Rabi oscillation for coherent coupling – time domain





Zhang, Xufeng, et al. "Strongly coupled magnons and cavity microwave photons." *Physical review letters* 113.15 (2014): 156401.

Match, Christophe, et al. "Transient response of the cavity magnon-polariton." *Physical Review B* 99.13 (2019): 134445.

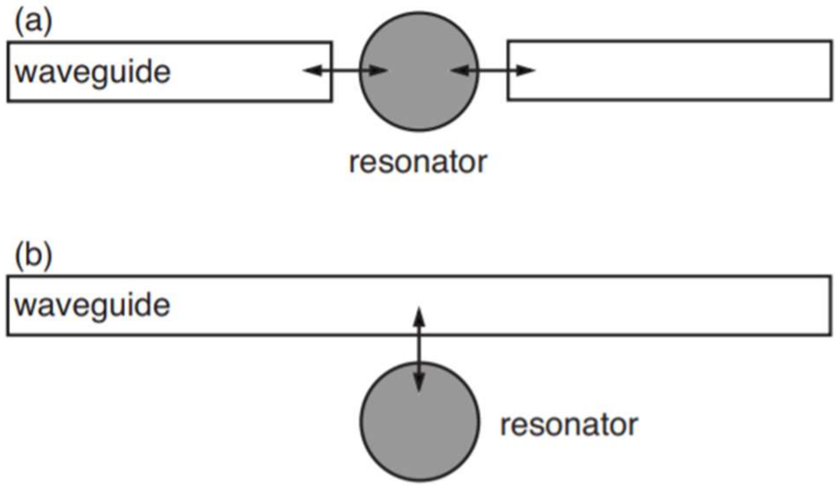
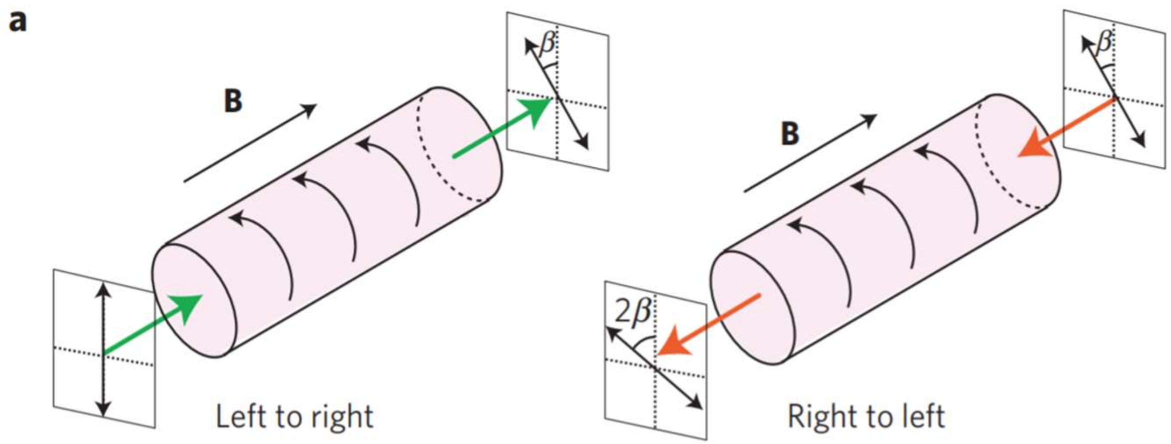


FIG. 17. Typical resonant structures. Schematic setup for (a) a waveguide directly coupled to a cavity and (b) a waveguide side-coupled to a cavity.

Faraday Rotation

The Faraday effect causes a rotation of the plane of polarization which is linearly proportional to the component of the magnetic field in the direction of propagation.

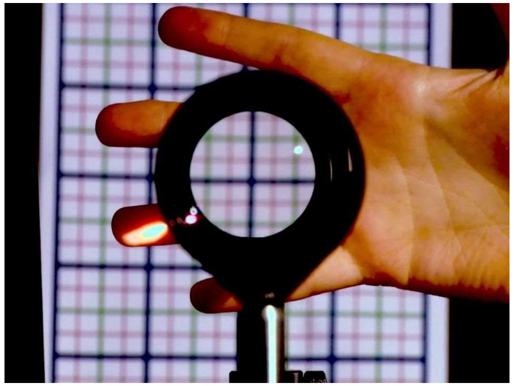


Non-reciprocity can be generated by inserting a polarizer.

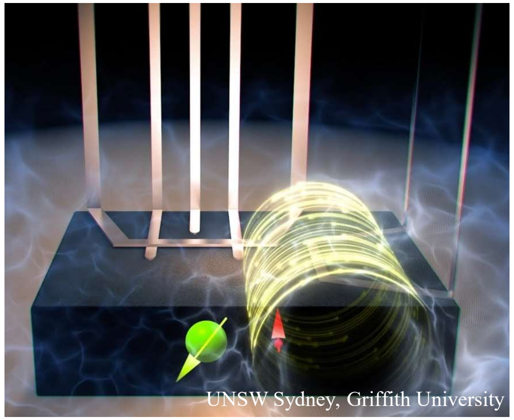
Kamal, Archana, John Clarke, and M. H. Devoret. "Noiseless non-reciprocity in a parametric active device." *Nature Physics* 7.4 (2011): 311-315.

Why do people need nonreciprocal devices?

1. invisible sensing or cloaking
2. noise-free information processing
3. qubit shield / protection
4. Other circuit design



Optical invisibility of a human hand



Shielding qubits from environmental noise

He, Cheng, et al. "One-way cloak based on nonreciprocal photonic crystal." *Applied Physics Letters* 99.15 (2011): 151112.

Sounas, Dimitrios L., and Andrea Alù. "Non-reciprocal photonics based on time modulation." *Nature Photonics* 11.12 (2017): 774-783.

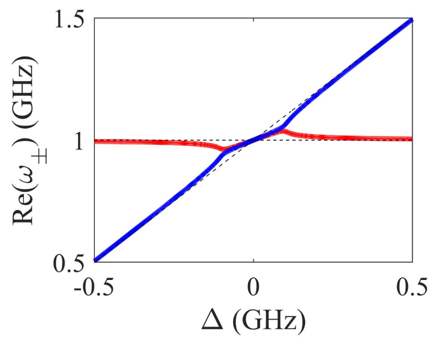
Between oscillators and polaritons

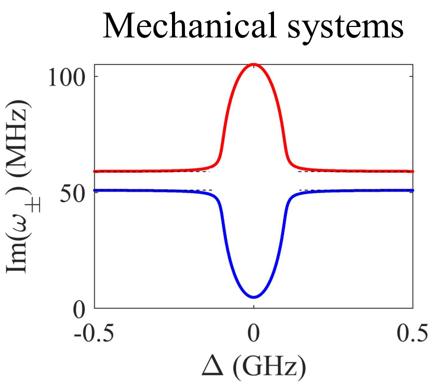
Simplified model to explain the behavior of polariton and pendulums

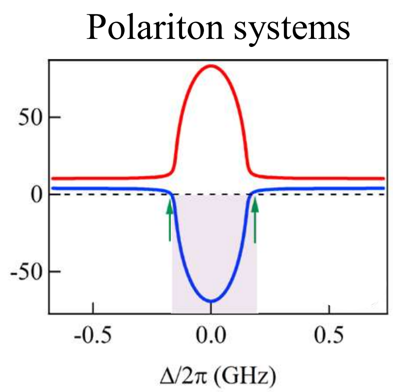
$$\begin{bmatrix} \omega - \widetilde{\omega}_1 - i\Gamma & i\Gamma \\ i\Gamma & \omega - \widetilde{\omega}_2 - i\Gamma \end{bmatrix} \begin{bmatrix} |\varphi_1| \\ |\varphi_2| \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} \omega - \widetilde{\omega}_1 & i\Gamma \\ i\Gamma & \omega - \widetilde{\omega}_2 \end{bmatrix} \begin{bmatrix} |\varphi_1| \\ |\varphi_2| \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Mechanical oscillators

Polaritons

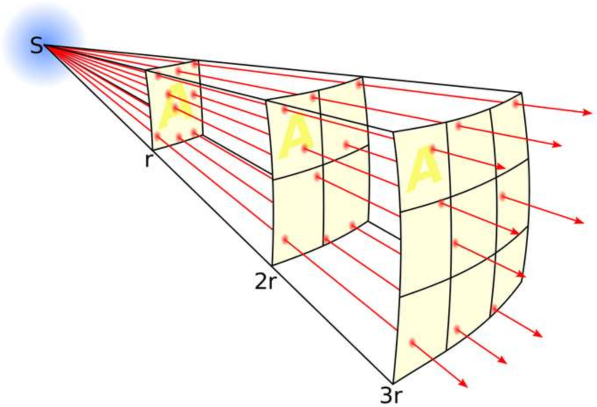






Damping control by Inverse-square law

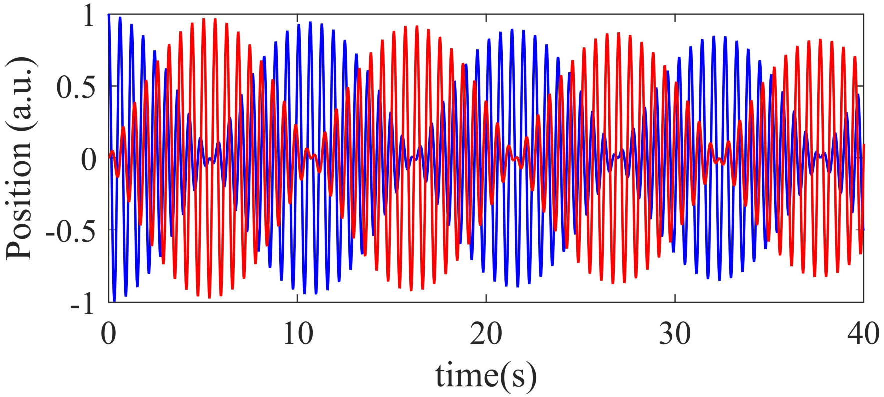
Suppose the magnetic loop antenna introduce an anisotropic environment with certain area around magnon.



This area influence the environment would decay with the inverse-square law

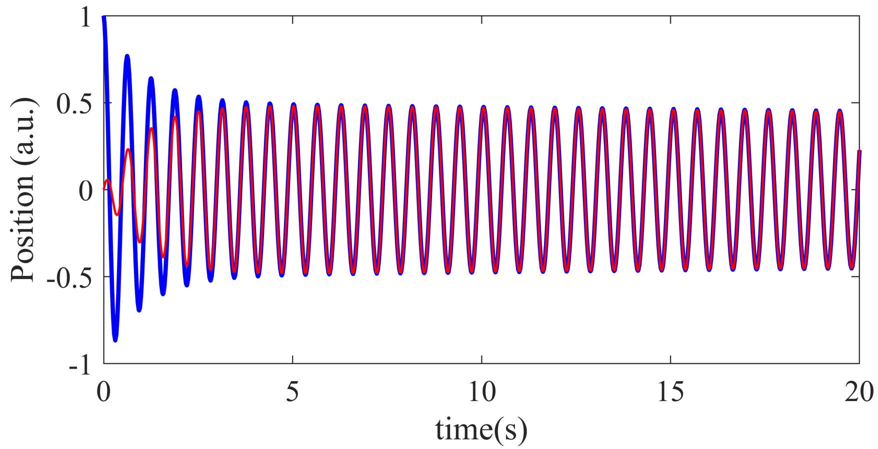
Calculation parameter for ODEs solvers

Coherent coupling - Rabi Oscillation like



$$J = 0.5\ Hz$$

Dissipative coupling - Synchronization like

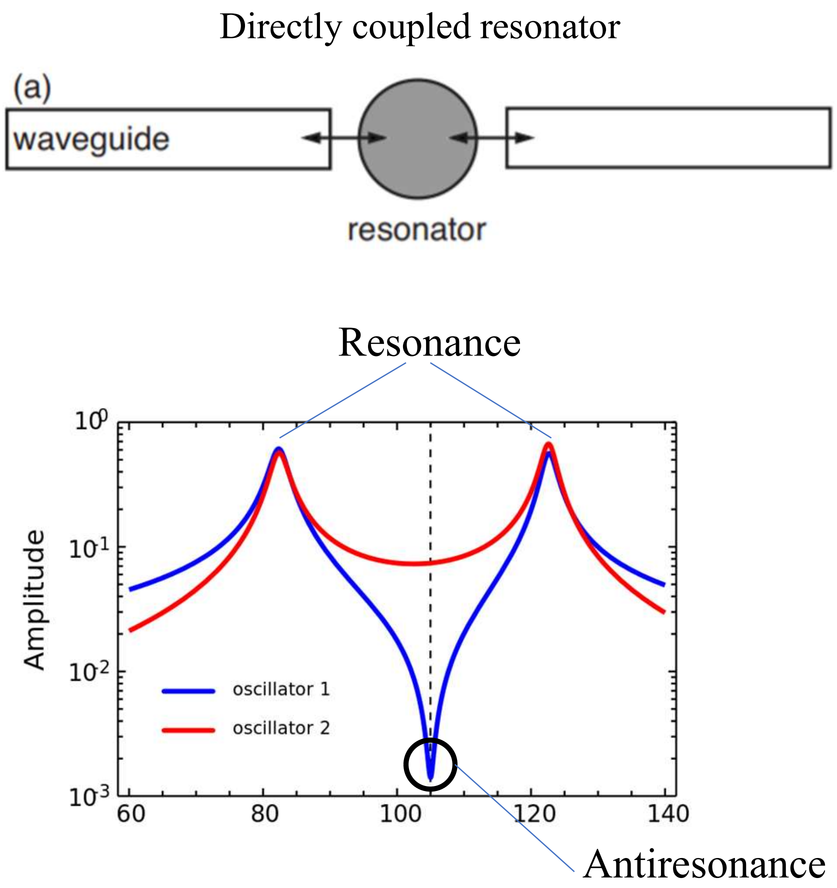


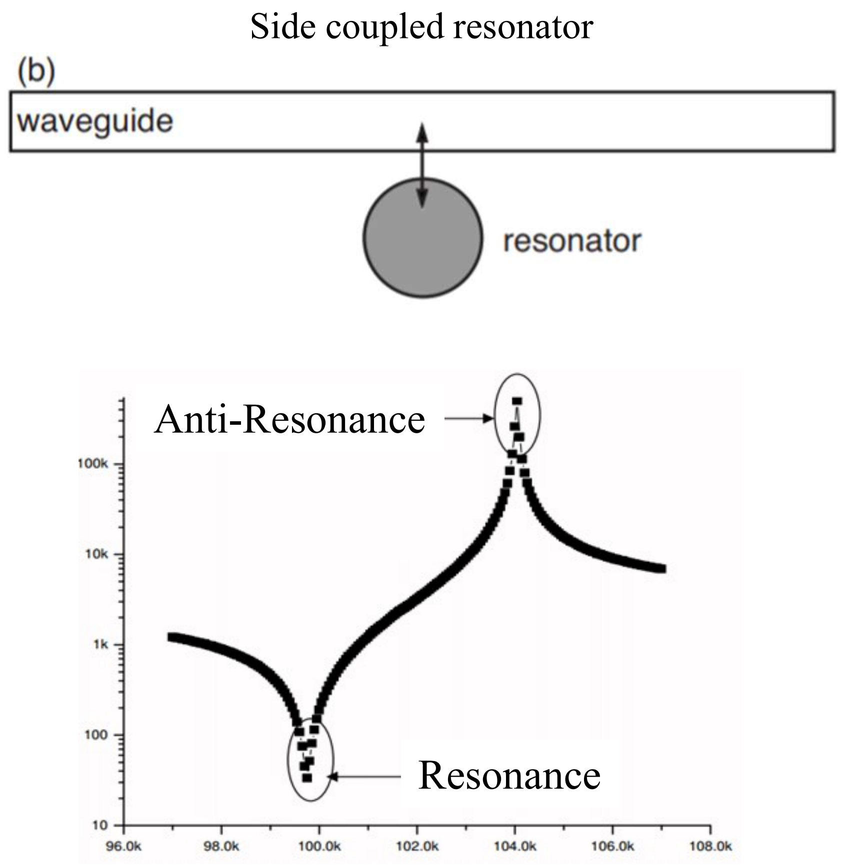
$$\Gamma = 0.5\ Hz$$

$$\omega_1 = \omega_2 = 10\ Hz$$

$$\Delta\omega_1 = \Delta\omega_2 = 0.01\ Hz$$

Antiresonance



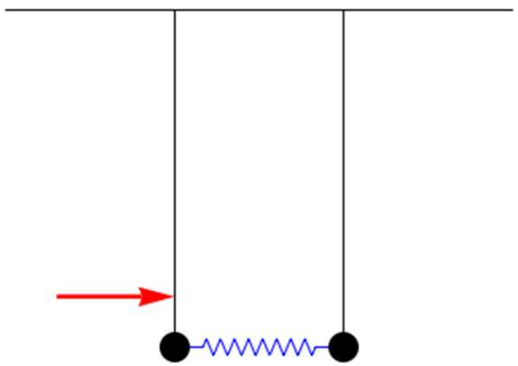


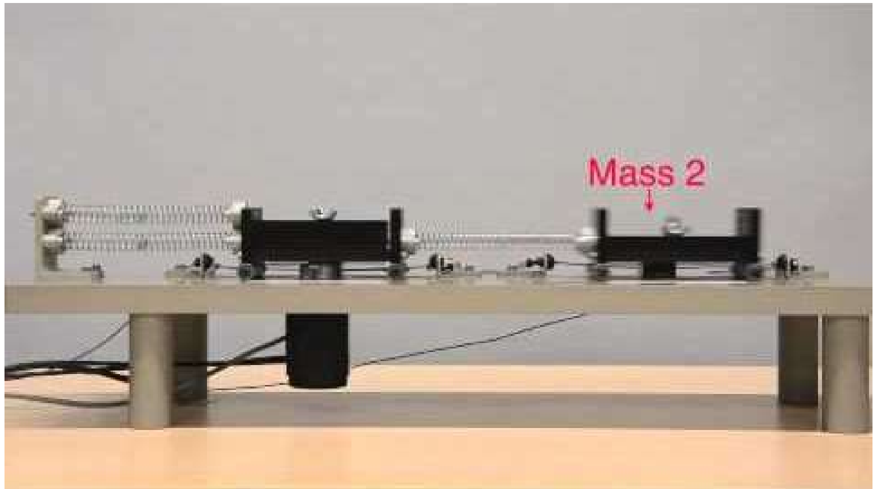
Journal of Electrical Engineering & Technology 12.2 (2017): 846-851.

→ Minimum response to external driving

Antiresonance (2) video demonstration

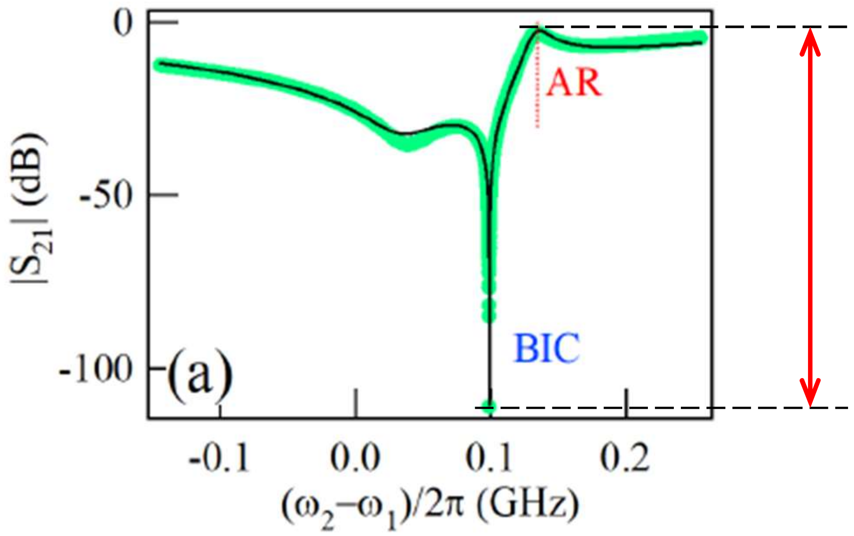
Minimum response to external driving

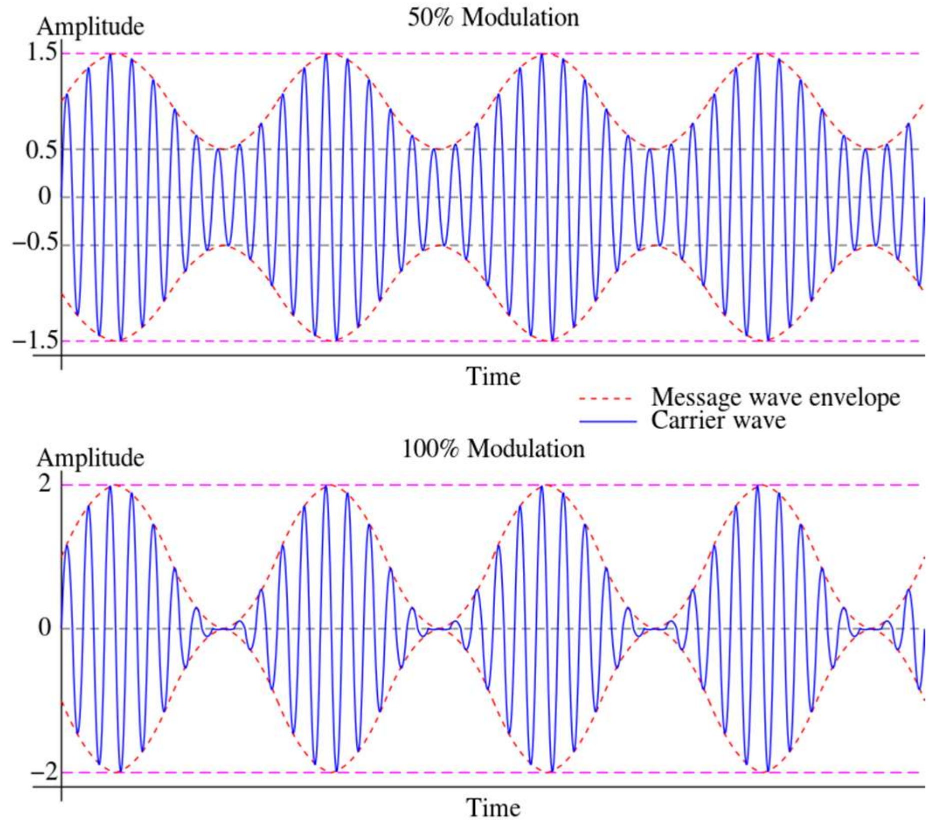




Modulation depth

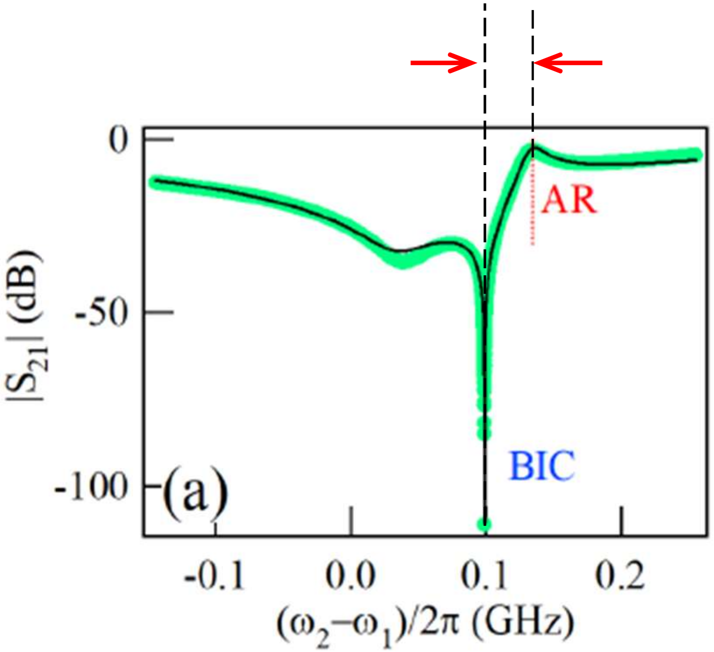
A relative modulation amplitude, or the maximum change in transmission.



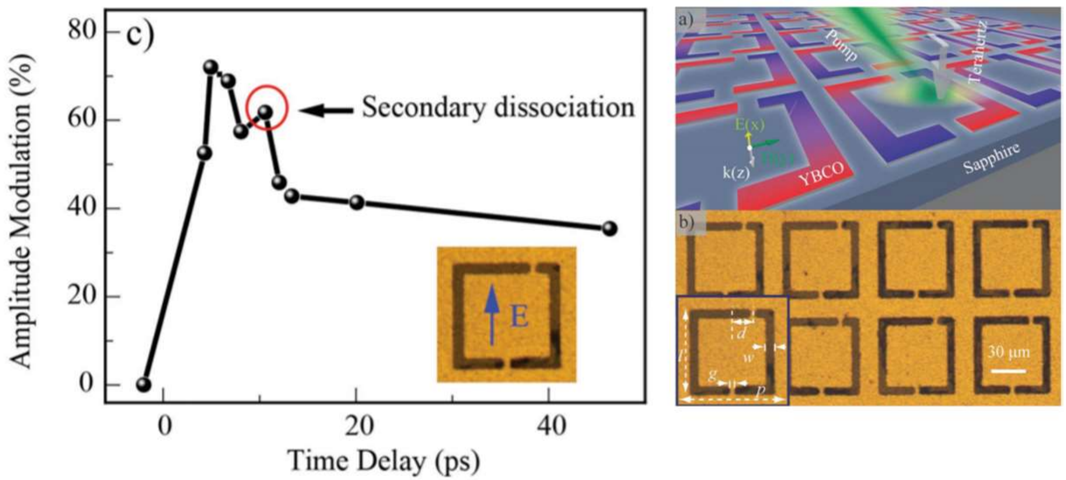


Switching window

The frequency window between the transmission 1 to zero



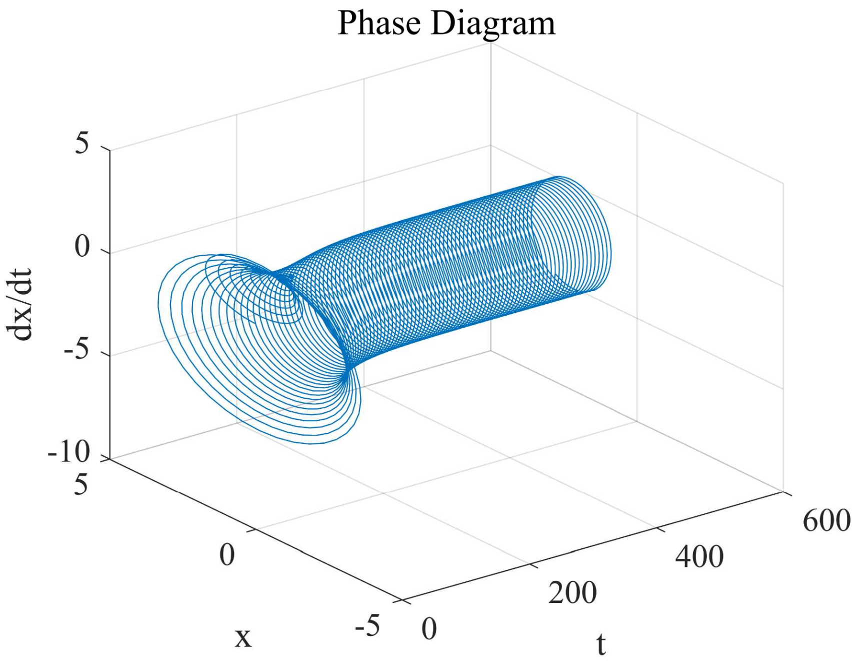
Application: Ultrafast switch

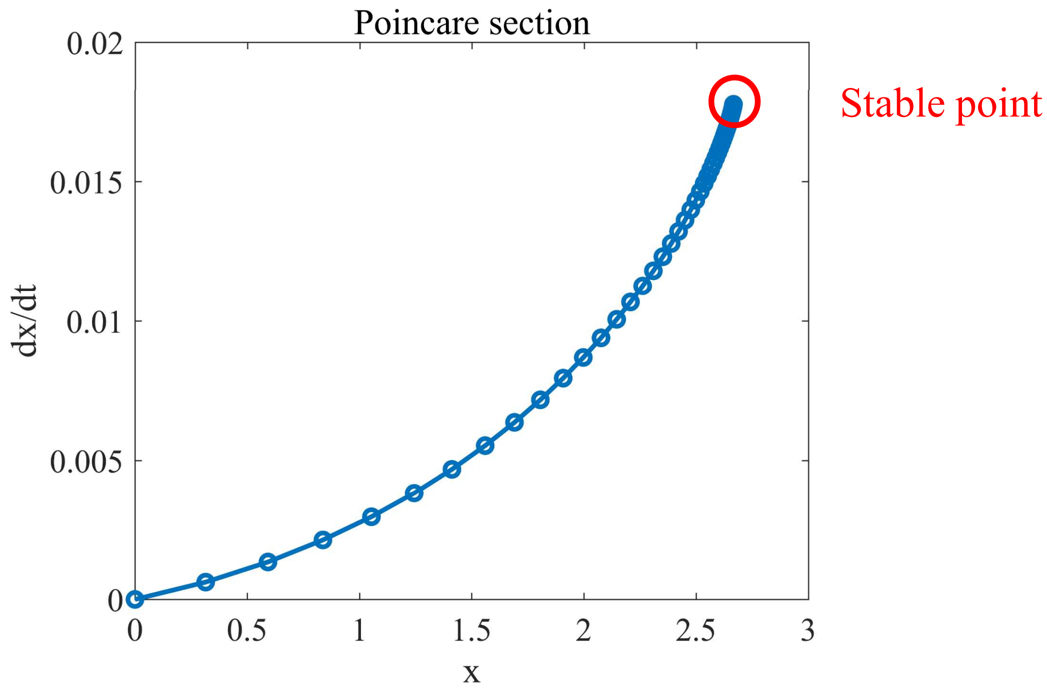


Srivastava, Yogesh Kumar, et al. "A Superconducting Dual-Channel Photonic Switch." *Advanced materials* 30.29 (2018): 1801257.

ODEs solvers for nonlinear / chaotic analysis (1)

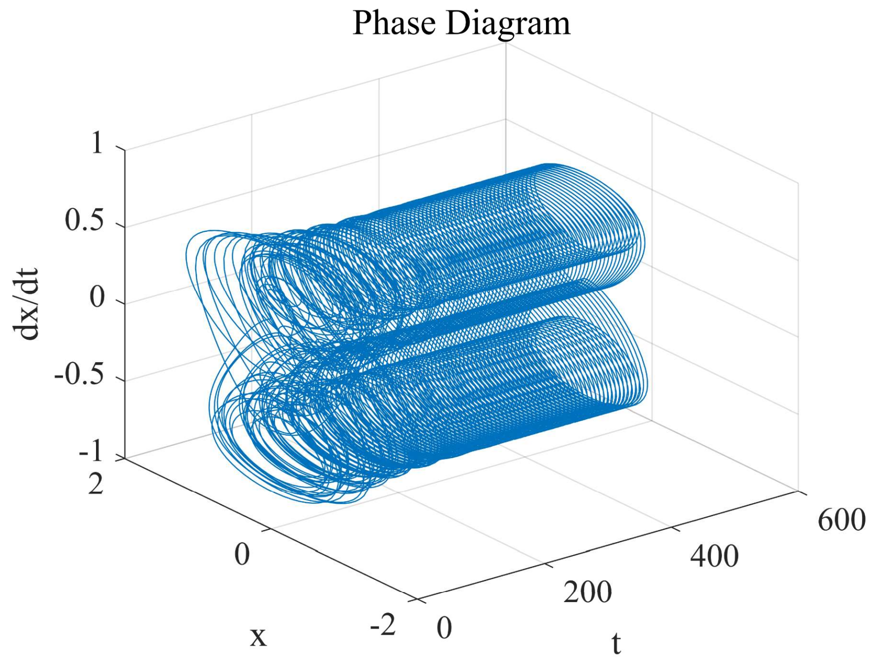
For a **linear** oscillator with driving force, we can calculate the trajectory.

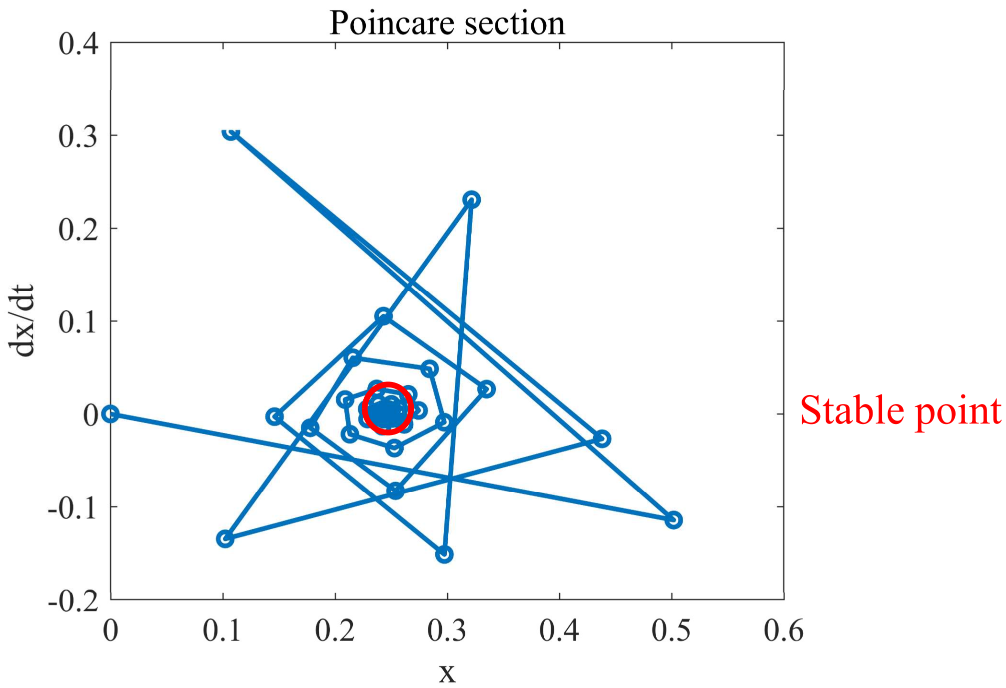




ODEs solvers for nonlinear / chaotic analysis (2)

For a **nonlinear** oscillator with driving force, we can calculate the trajectory.





ODEs solvers for nonlinear / chaotic analysis (1)

For a **chaotic** oscillator with driving force, we can calculate the trajectory that depends on initial conditions.