Strong coupling of microwaves and magnons in YIG microstructures

Nanostructured Materials

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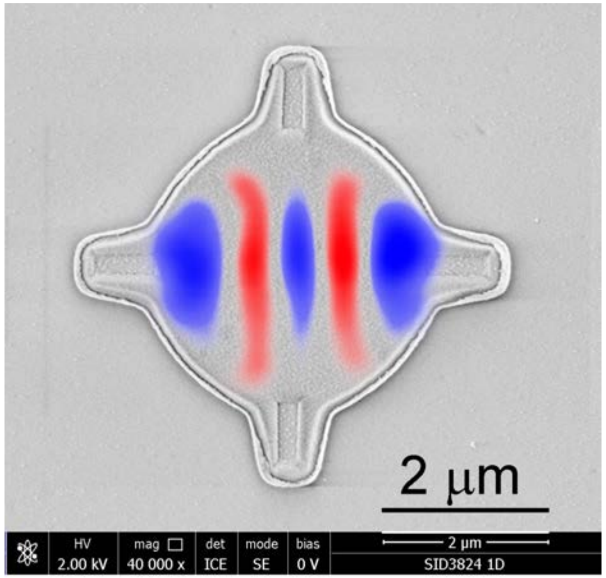

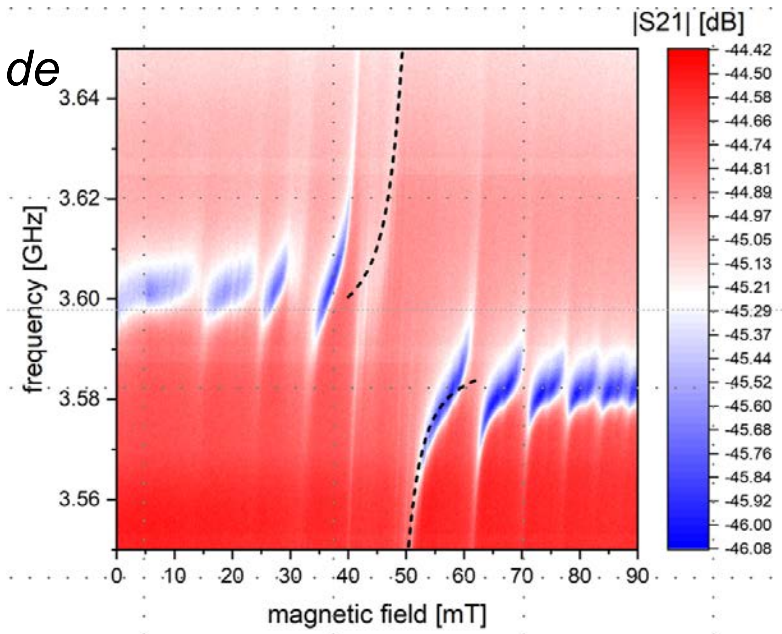

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HARMONY

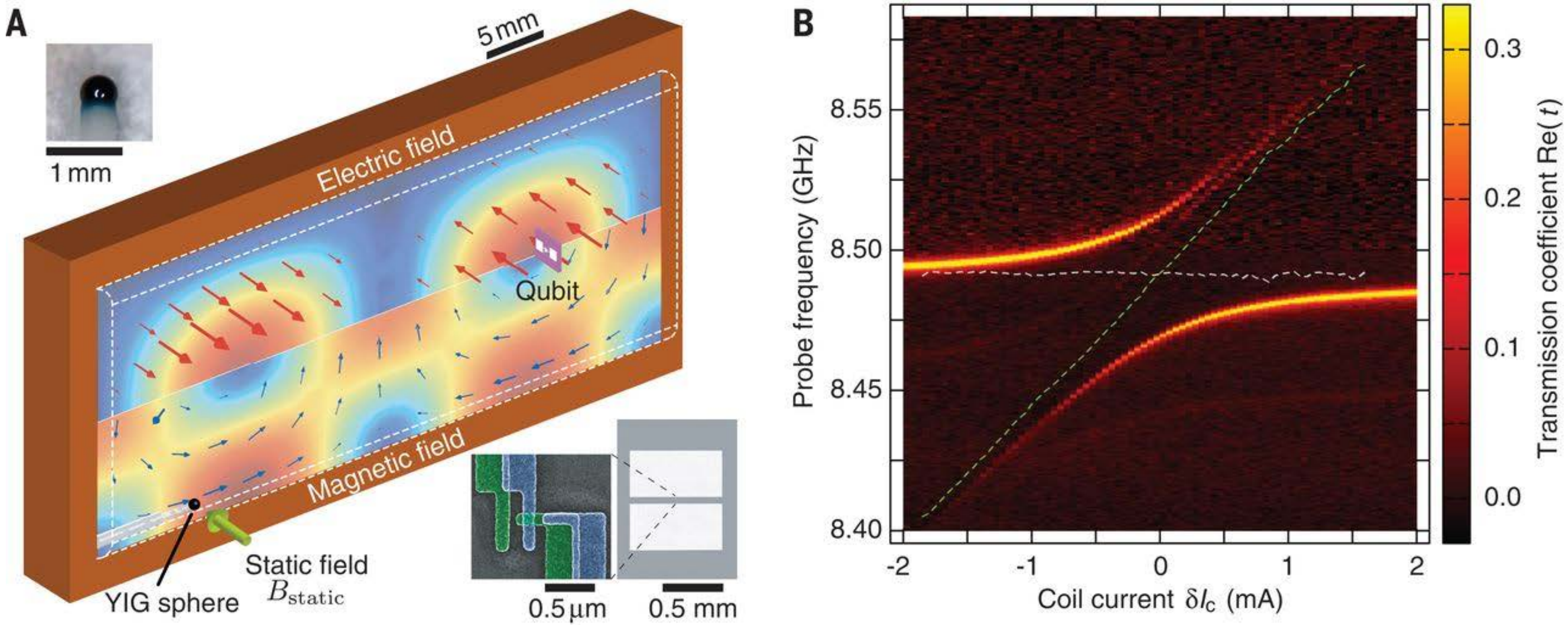
Why all this?

The use of coupling phenomena

- There is a technological need to coherently transfer elementary excitations from one type of excitation to another
  - Communication
    - Transfer between microwaves and light
  - Quantum information
    - Qbit readout
    - Transfer and storage of quantum information (single excitation quanta)
- This requires the coupling of different kinds of oscillators
  - Photons (microwave)
  - Photons (light)
  - Phonons (mechanical oscillations)
  - Magnons that can mediate between those

Quantum information processing

– Coupling of qubits to magnons successfully demonstrated
– Also promising: coupling of qubits to mechanical oscillators (by electric fields: Chu et al. Science **358**, 199 (2017))
– Why not use magnons and magnetoelastic coupling?



(Tabuchi et al. Science **349**, 405 (2015))

Magnonmechanics

Magnons and Phonons

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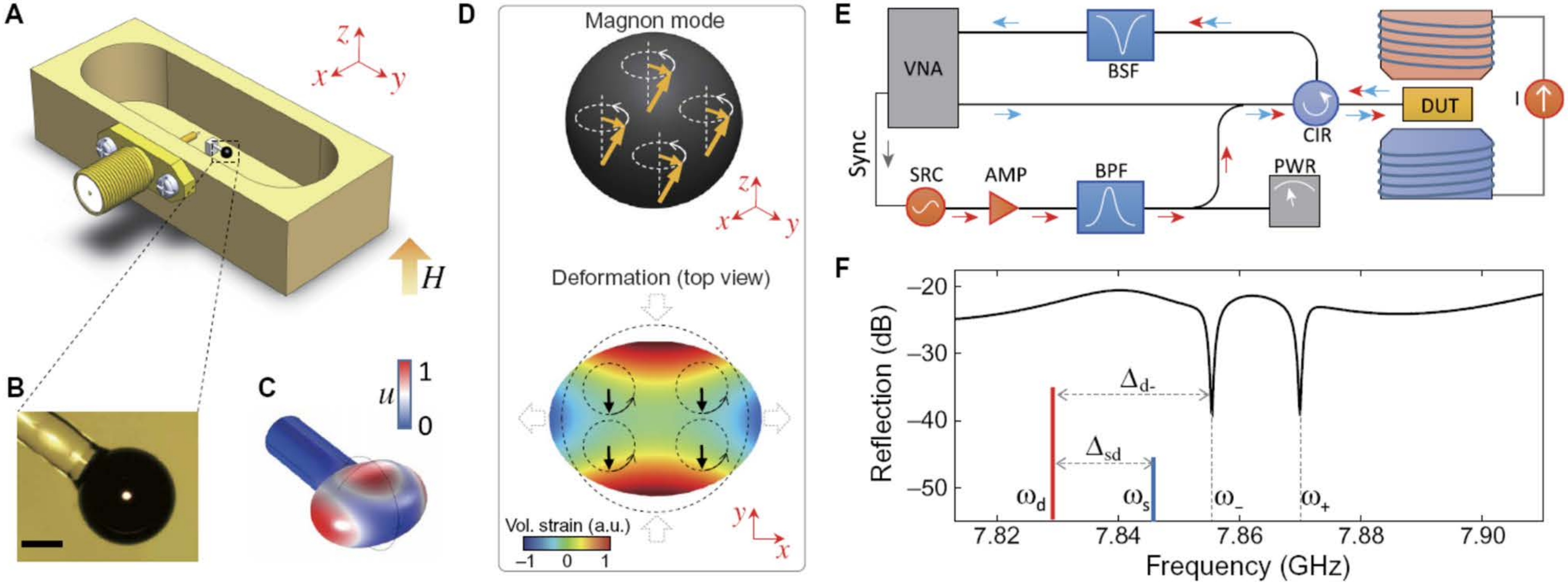
- Coupling of magnons and phonons recently demonstrated
- Drawback: YIG resonators are macroscopic spheres (250 μm) not suitable for integration



Zhang et al. Sci. Adv. 2016; 2 : e1501286

What is needed?

The effect

- We have one coherent elementary excitation
- We need fast coherent transfer to another excitation (e.g. phonon to magnon)

- Necessary prerequisites
  - Strong coupling
    - Fast coherent energy transfer between two states
  - Large mode overlap
  - Long lived excitations with long decoherence times
    - Longer than energy transfer
    - Long enough for further processing

- So we need strong coupling and narrow linewidth

YIG, linewidth, and Gilbert damping

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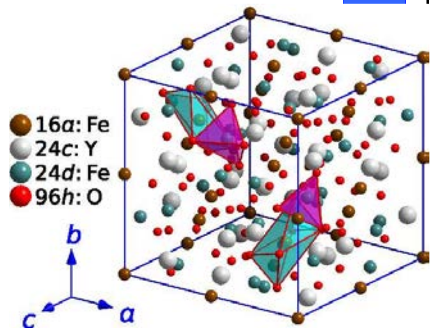
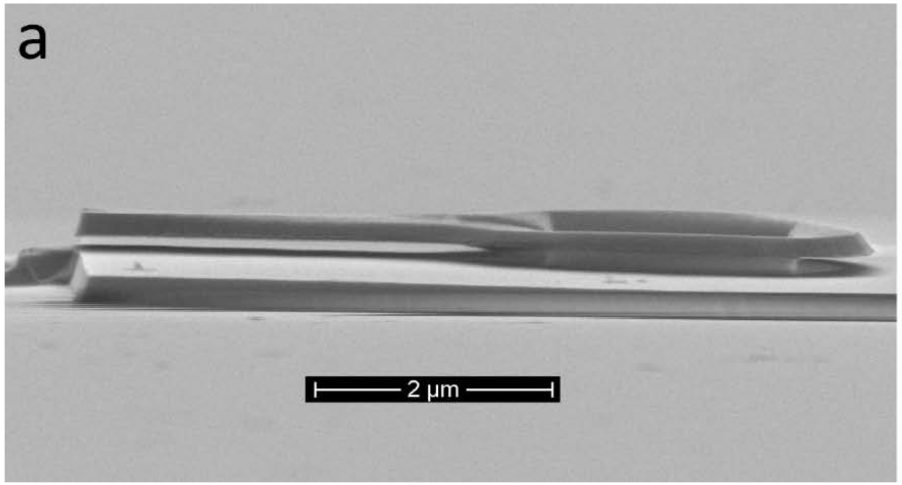
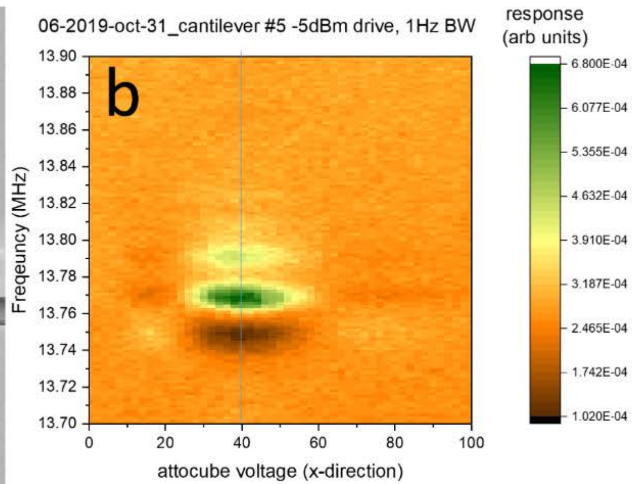
What is YIG?

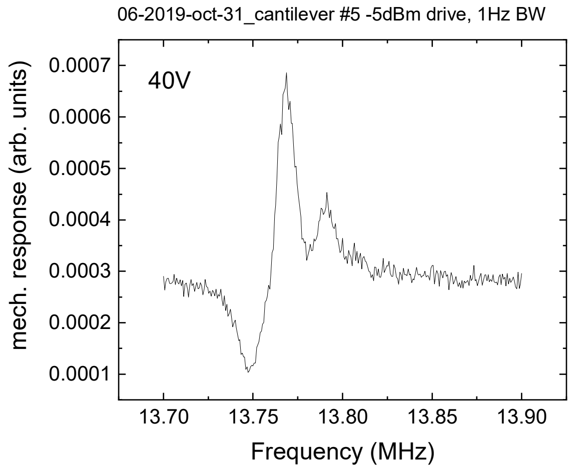
- Yttrium iron garnet is a ferrimagnetic garnet with a very complex unit cell (160 atoms)
- It can have a very low Gilbert damping (3×10^{-5})
- Also the resonance linewidth can be very small
- Furthermore it is very rigid and suitable for mechanical resonators



Andreas Kreisel PhD thesis







YIG, linewidth, and Gilbert damping

What is the damping α?

- In the LLG equation the damping appears like a friction
  - More losses at higher precession frequencies

$$\frac{d\vec{M}_{frei}}{dt} = -\gamma \vec{M}_{frei} \times [\vec{H}_{Eff}] + \alpha \vec{M}_{frei} \times \frac{d\vec{M}_{frei}}{dt}$$

- As a result the Gilbert damping α should lead to an increasing line width at higher frequencies

YIG, linewidth, and Gilbert damping

Line width or damping?

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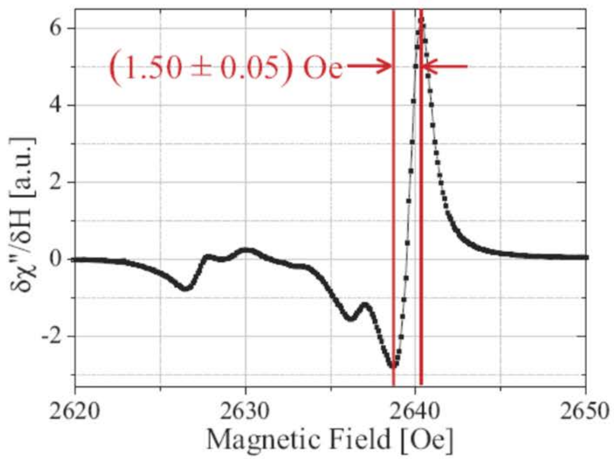
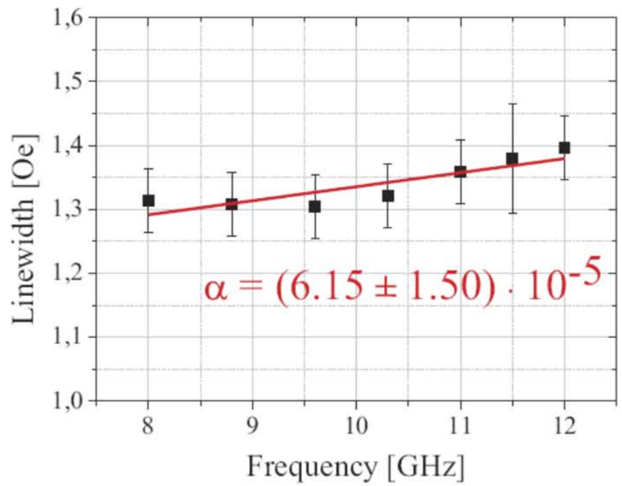
- Normally the damping is seen as the important parameter to judge the quality of YIG
- The damping α is extracted from the slope of a plot of ΔH_{FMR} versus frequency

$$\mu_0 \Delta H_{\mathrm{F}MR} = \mu_0 \Delta H_0 + \frac{\alpha f_{\mathrm{res}}}{\gamma}$$

- So in principle a low damping can be achieved even at a large linewidth
- Why?





(C. Hauser, GS et al. Scientific Reports **6**, 20827 (2016))

YIG, linewidth, and Gilbert damping

What linewidth?

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- A small detail to look at:
  - Most publications show the linewidth as ΔH_{HWHM} (Half width at half maximum)
  - Some show the linewidth as ΔH_{p-p} measured from the derivative because of lock-in measurements
  - Few show the linewidth as ΔH_{FWHM} (Full width at half maximum)

- The rule is:

$$\Delta H_{FWHM} = 2\Delta H_{HWHM}$$

$$\Delta H_{p-p} = 2/\sqrt{3}\,\Delta H_{HWHM}$$

YIG, linewidth, and Gilbert damping

The inhomogeneous broadening?

- The inhomogeneous broadening can have various reasons. One of them are inhomogeneities that lead to different regions with narrow linewidth and slightly different resonance frequencies

- Is this a problem?

YIG, linewidth, and Gilbert damping

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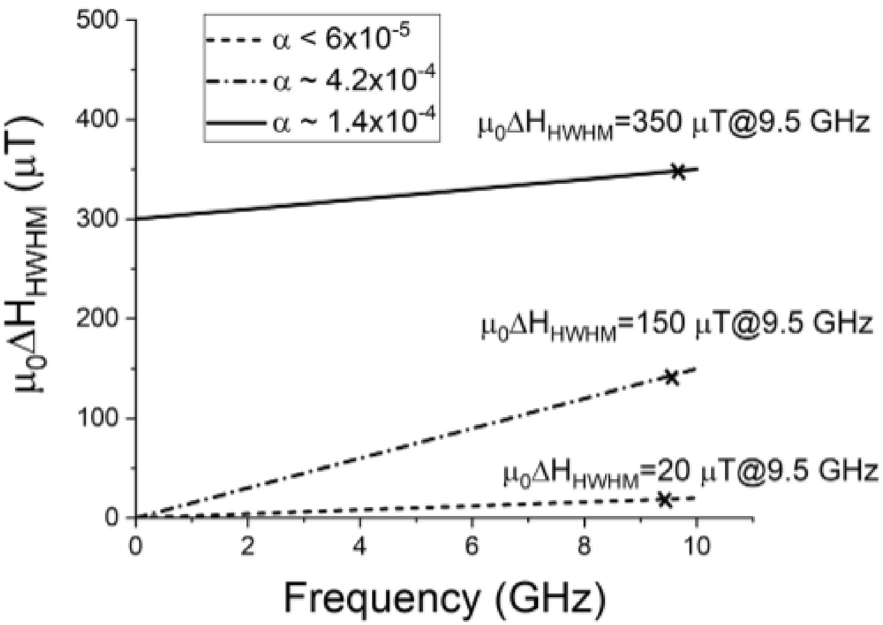
The inhomogeneous broadening?

- A large linewidth only means high damping when the linewidth at zero frequency is zero (which it is not)
- The remaining linewidth is called the inhomogeneous or intrinsic broadening: Here some examples



GS et al. Phys. Stat. Sol. B 257, 1900644 (2020)

YIG, linewidth, and Gilbert damping

Different growth methods

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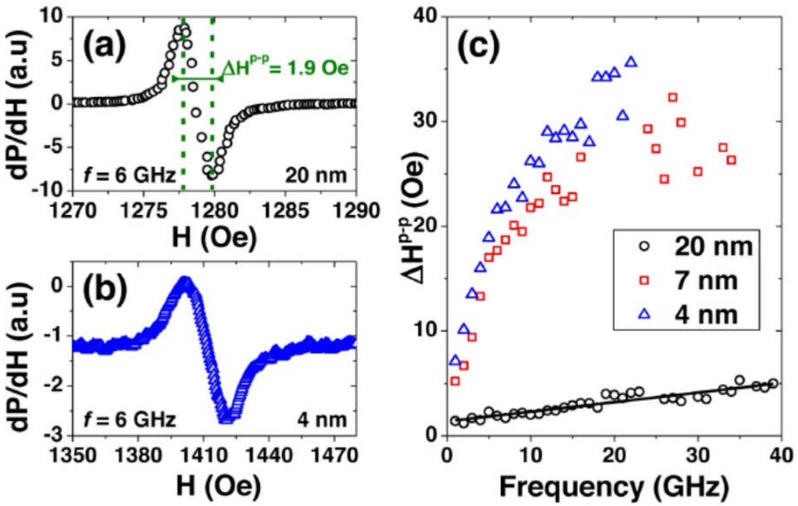
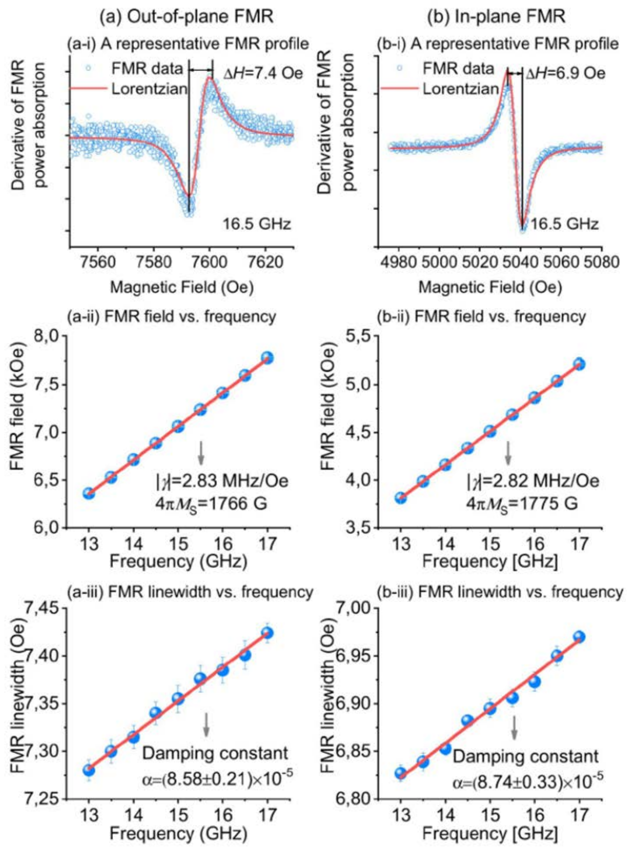
– Depending on the growth method, the ratio of linewidth and extracted damping can be quite different



High temperature PLD
d'Allivy Kelly et al., Applied Physics Letters 103(8), 082408 (2013)

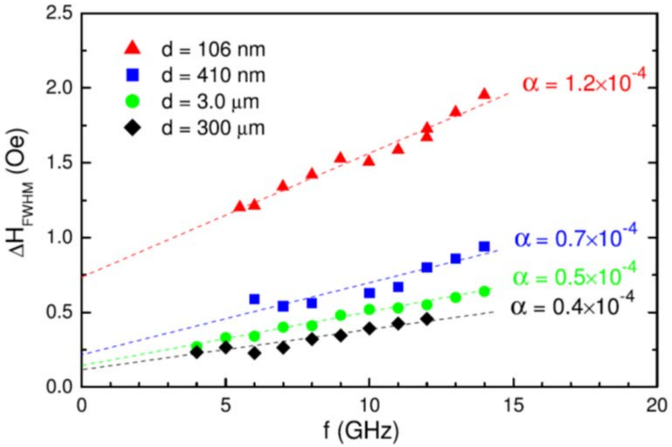


Room temperature sputtering
Chang et al., IEEE Magnetics Letters 5, 6700104 (2014)

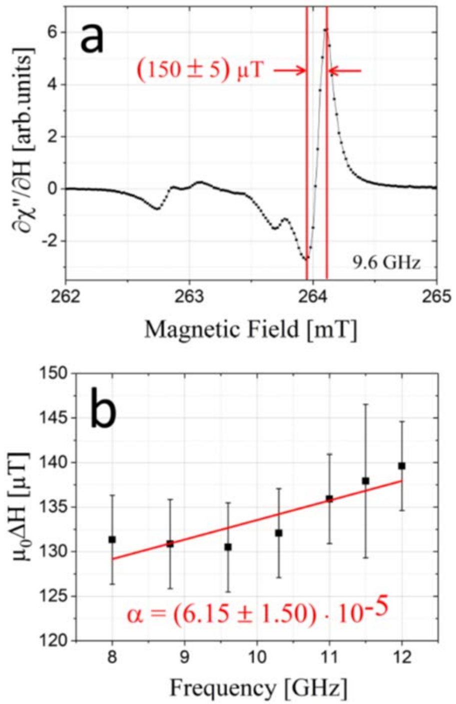
YIG, linewidth, and Gilbert damping

Different growth methods

- Depending on the growth method, the ratio of linewidth and extracted damping can be quite different



Liquid phase epitaxy
C. Dubs et al. J. Phys. D: Appl. Phys. **50** (2017) 204005



Room temperature PLD
Hauser, GS et al., Scientific Reports
6, 20827 (2016)

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YIG, linewidth, and Gilbert damping

What is important?

– For coupling experiments we need a long lifetime of the magnon states
– The lifetime in principle is given by the damping

$$\tau_0 = \frac{1}{2\pi\alpha f_{\text{res}}}$$

– Does the inhomogeneous broadening hurt?
– If the different regions are coupled, definitely yes!!!

– What if they are uncoupled?

YIG, linewidth, and Gilbert damping

What is important?

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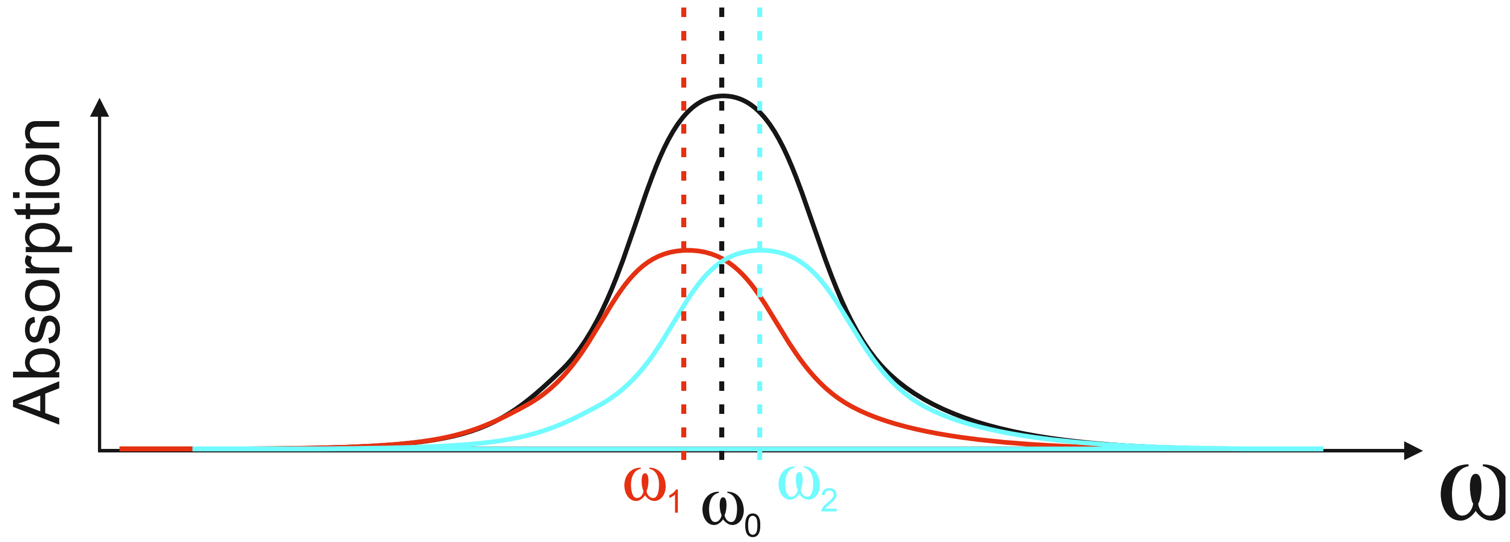
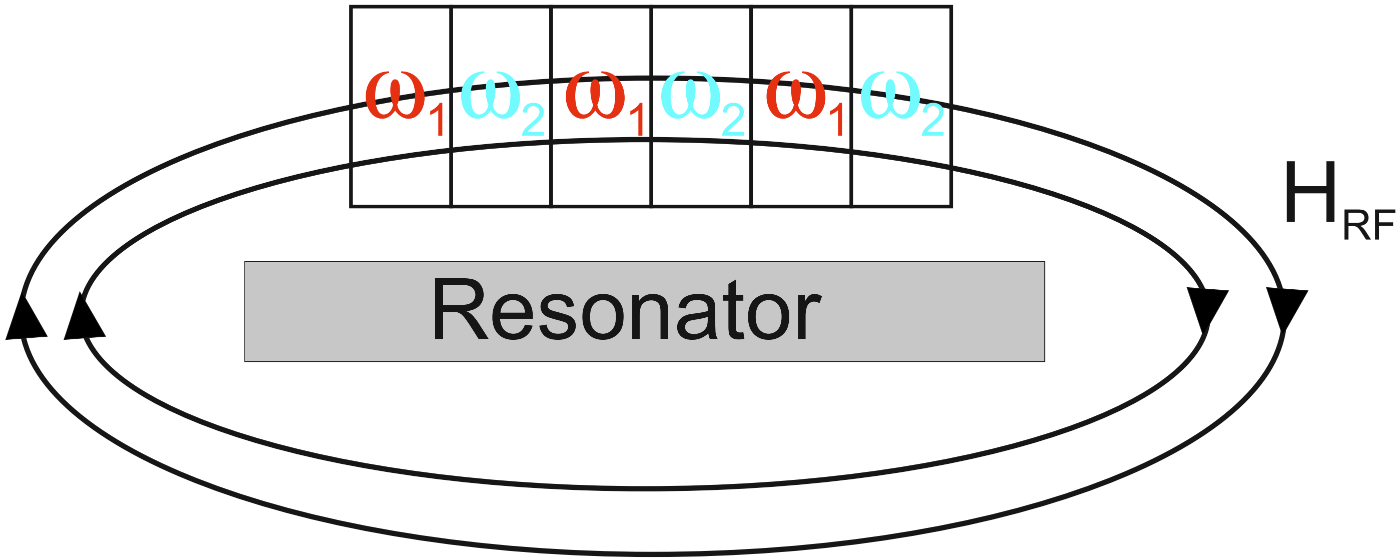
– In a Gedankenexperiment we use material that has different regions with different resonance frequencies but narrow linewidth



YIG, linewidth, and Gilbert damping

What is important?

- We couple this material to a nice superconducting resonator
- For different frequencies or fields different parts of the material are on resonance with long respective magnon lifetimes

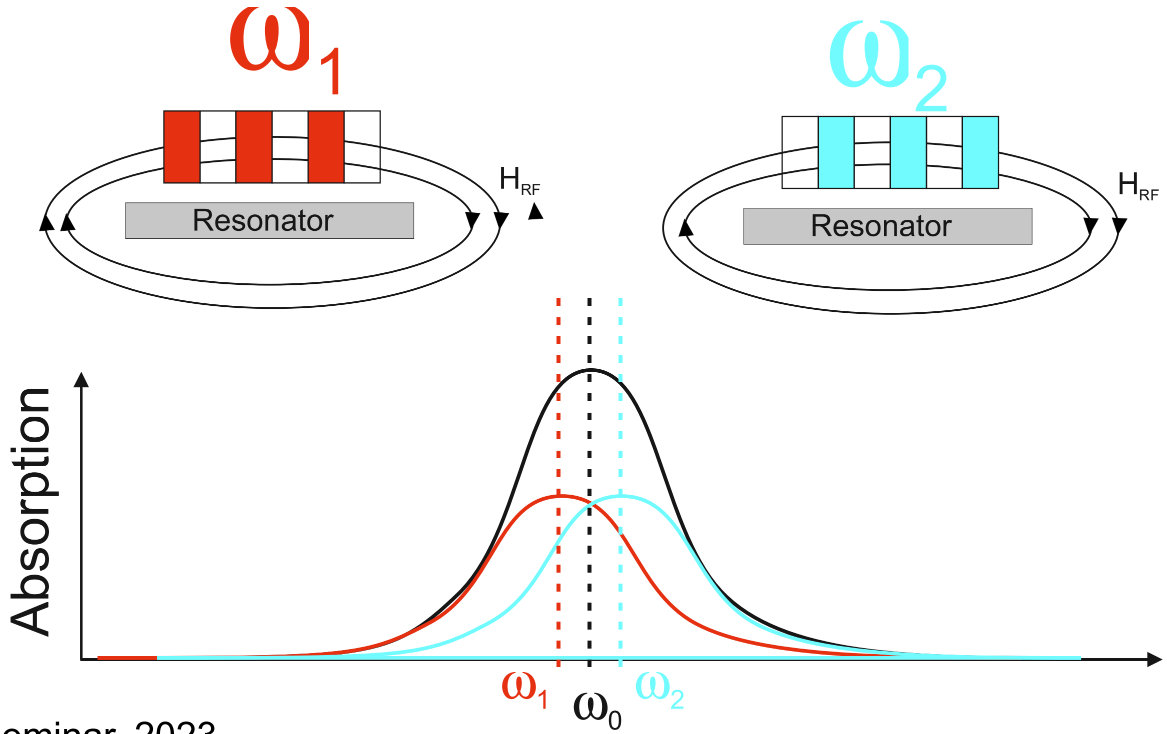


- Fine??? No!!!

YIG, linewidth, and Gilbert damping

What is important?

- Not only the lifetime counts
- Mode overlap is also important
- Separate resonating regions reduce the mode overlap at a given frequency



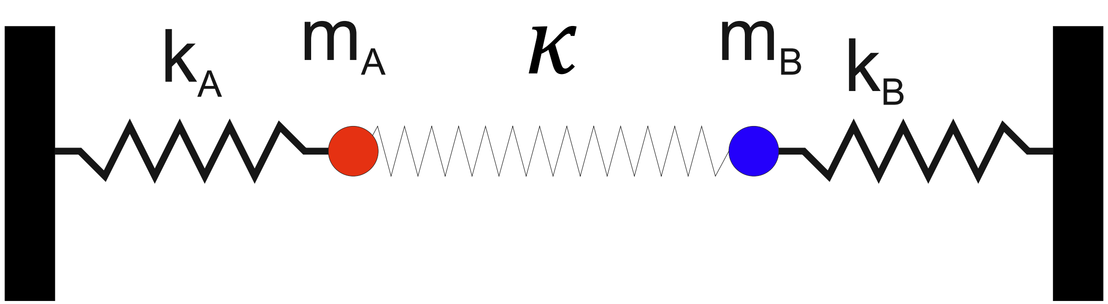
Strong coupling: A (different) introduction

Two coupled oscillators?

- A very useful example is based on two coupled mechanical oscillators
- The equations of motion are simple:

$$m_A \ddot{x}_A + k_A x_A + \kappa(x_A - x_B) = 0$$

$$m_B \ddot{x}_B + k_B x_B - \kappa(x_A - x_B) = 0$$



Strong coupling: A (different) introduction

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Two coupled oscillators?

– This equation system has solutions for

$$\omega_\pm^2 = \frac{1}{2}\left[\omega_A^2 + \omega_B^2 \pm \sqrt{(\omega_A^2 - \omega_B^2) + 4g\omega_A\omega_B}\right]$$

$$\omega_A = \sqrt{(k_A + \kappa)/m_A} \quad and \qquad \omega_B = \sqrt{(k_B + \kappa)/m_B}$$

$$\mathrm{g} = \frac{\sqrt{\kappa/m_A}\sqrt{\kappa/m_B}}{\sqrt{\omega_A\omega_B}}$$

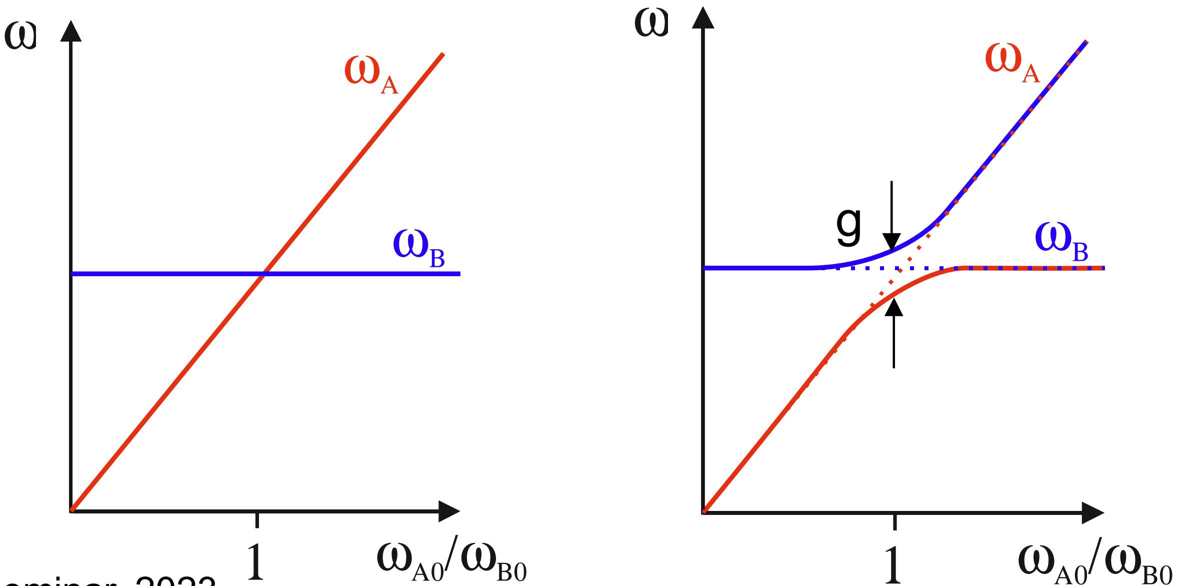
$\mathrm{g} = \omega_+ - \omega_-$ is the coupling strength

Note that ω_A and ω_B both contain κ

Strong coupling: A (different) introduction

The anticrossing?

- We consider a system in which one of the oscillators remains at its frequency while the other one changes its spring constant
- Without coupling (left) the two curves cross
- With coupling (right) a gap opens and the curves no longer cross (anticrossing or avoided crossing)
- The size of the gap g shows the strength of the coupling
- What is the nature of these two modes?



Adapted from:
L. Novotny, Am. J. Phys. **78**, 1199 (2010)

Strong coupling: A (different) introduction

Acoustic and optical phonons

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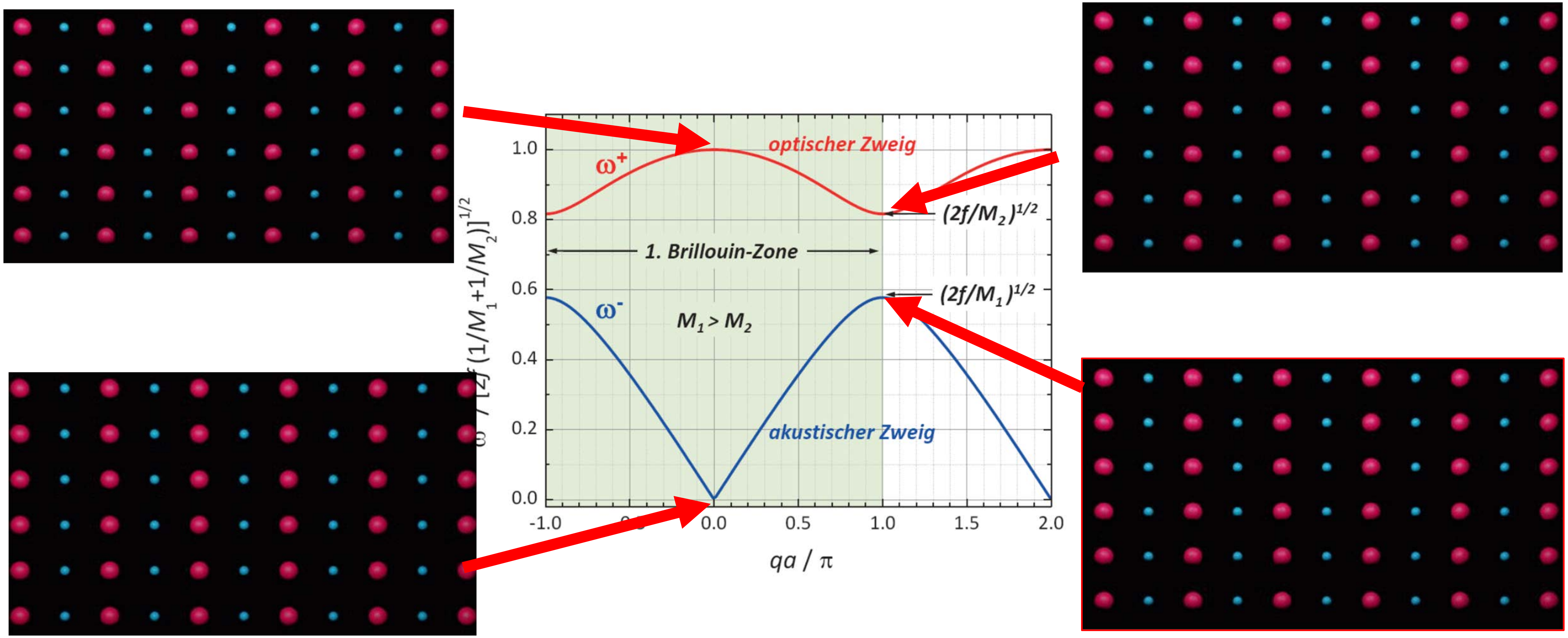
– Coupling only



Strong coupling: A (different) introduction

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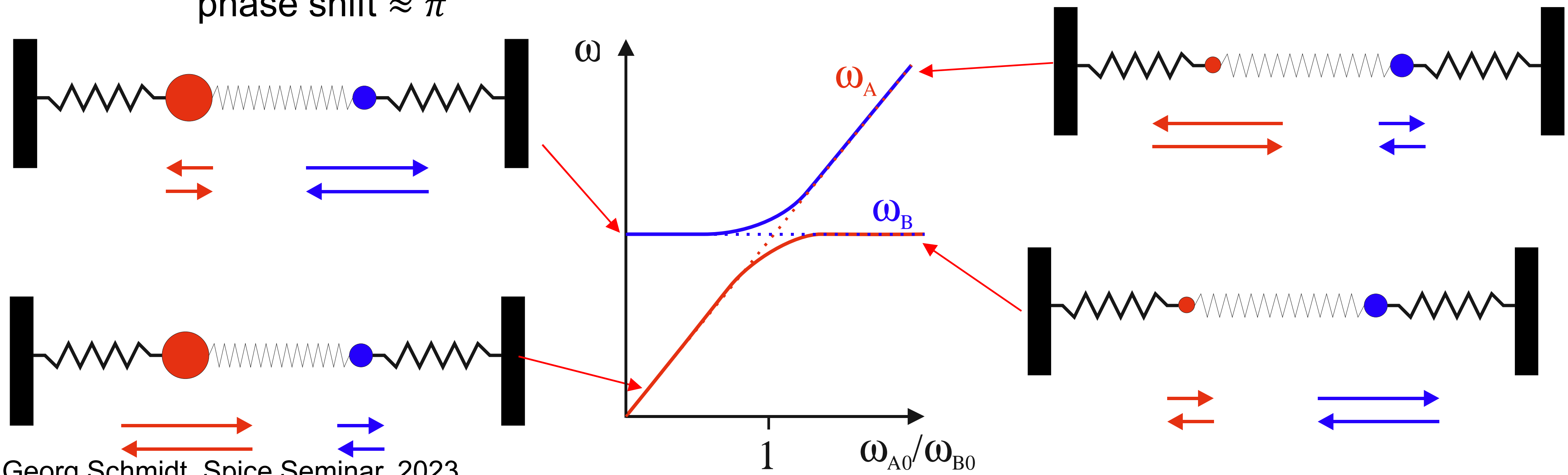
How do the oscillations look?

- When the two resonance frequencies are different we only have one oscillator on resonance
- The other one follows a forced oscillation
- If the forcing oscillator is at lower frequency, the forced oscillator has only a small phase shift
- If the forcing oscillator is at higher frequency, the forced oscillator has a phase shift $\approx \pi$

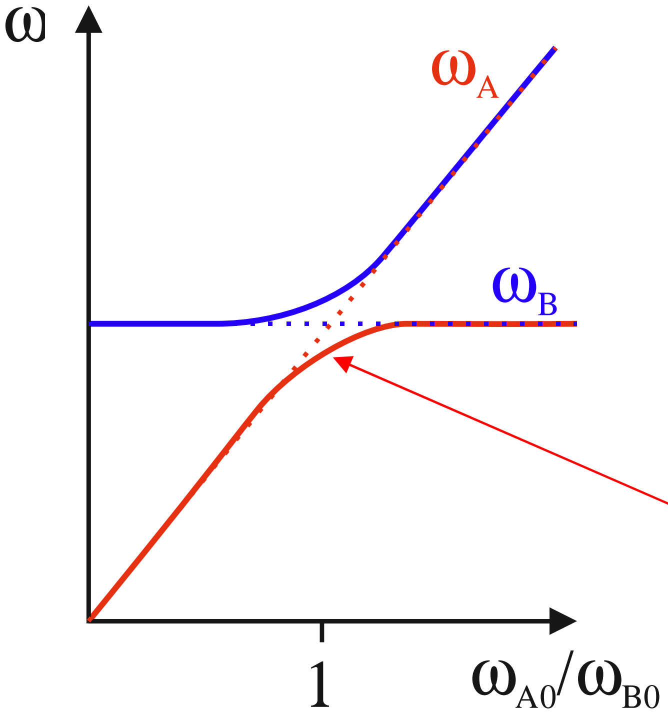


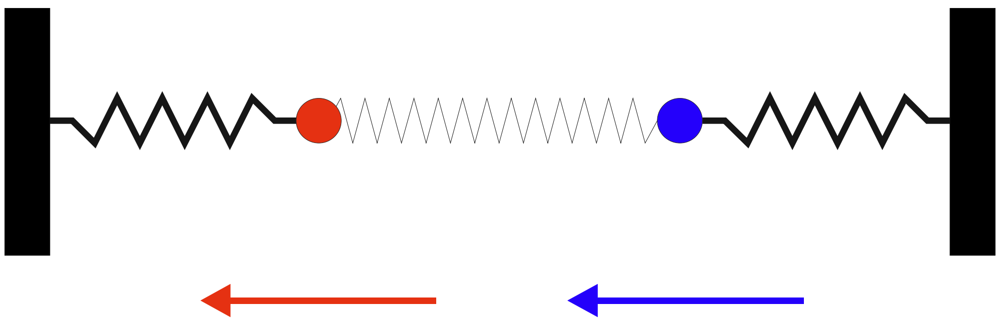
Strong coupling: A (different) introduction

What if the two frequencies are degenerate?

– For $k_A = k_B$ and $m_A = m_B$ we observe two Eigenmodes

– Eigenmode 1:
  - Both oscillators in phase (90°-90°) with the same amplitude
  - The coupling spring sees no deformation $\omega = \sqrt{k/m}$





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Strong coupling: A (different) introduction

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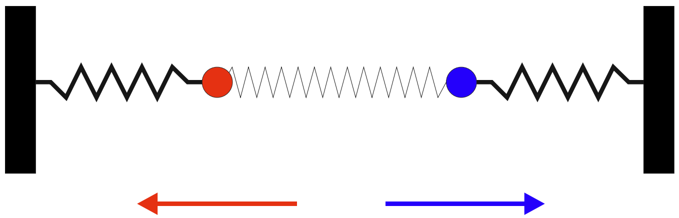
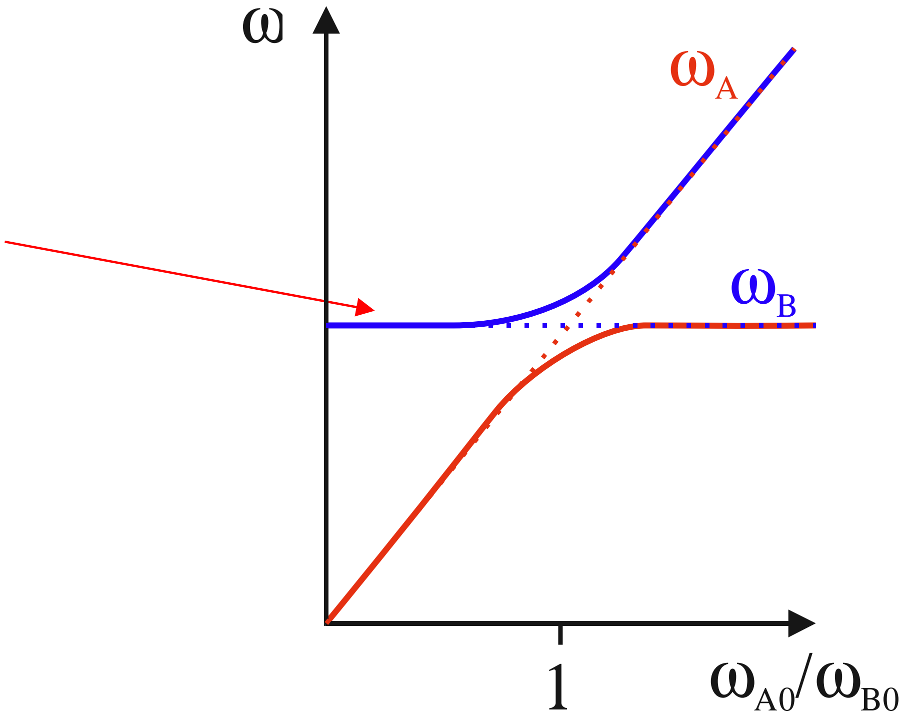
What if the two frequencies are degenerate?

- For $k_A = k_B$ and $m_A = m_B$ we observe two Eigenmodes
- Eigenmode 2:
  - Both oscillators with phase shift 180° (90°+90°) with the same amplitude
  - The coupling spring is deformed in phase with the other spring $\omega = \sqrt{(k+\kappa)/m}$

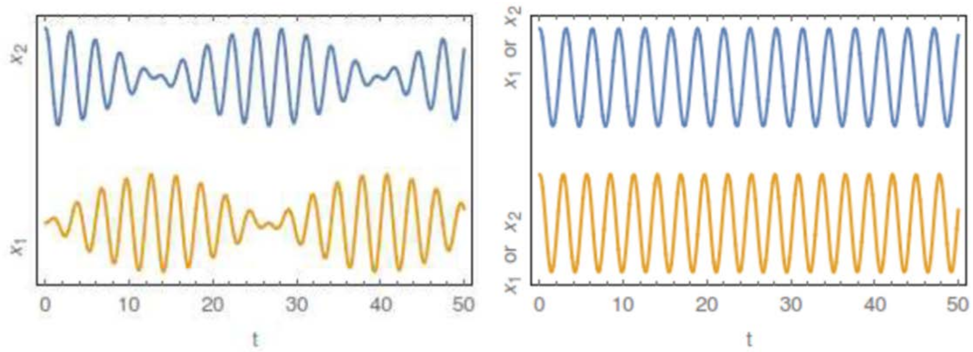




Strong coupling: A (different) introduction

Consequence

- The two Eigenmodes are measured on resonance
- These are the only states at these frequencies where no!!! energy is transferred
- In a mixed state (one side only excited) energy transfer happens at the coupling frequency (this is what we need)
- Observation of beating pattern at frequency g



Behavior starting from $x_1 = 1, x_0 = 0$ Normal mode behavior

Figure 2. Motion of masses and normal modes for $k = 0.5$ and $\kappa = 4$

From Matthew D. Schwartz, lecture on waves, Harvard University

Strong coupling: A (different) introduction

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Damping kicks in

- When we add the damping we get additional terms

$$\gamma_A \dot{x}_A \text{ and } \gamma_B \dot{x}_B$$

- We find that the splitting gets smeared out by the resonance line broadening

- In order to distinguish the lines it is necessary that

$$\mathrm{g} > \frac{\gamma_A}{m_A} + \frac{\gamma_B}{m_B}$$

or

$$\frac{g}{\gamma_A/m_A+\gamma_B/m_B} > 1$$

- We consider this a satisfactory condition for strong coupling

Strong coupling: A (different) introduction

The cooperativity

– Another important parameter is the so called cooperativity

$$\frac{g^2}{\gamma_A/m_A \times \gamma_B/m_B}$$

– In the strong coupling regime this is always >1
– Attention: Cooperativity >1 is not sufficient for strong coupling

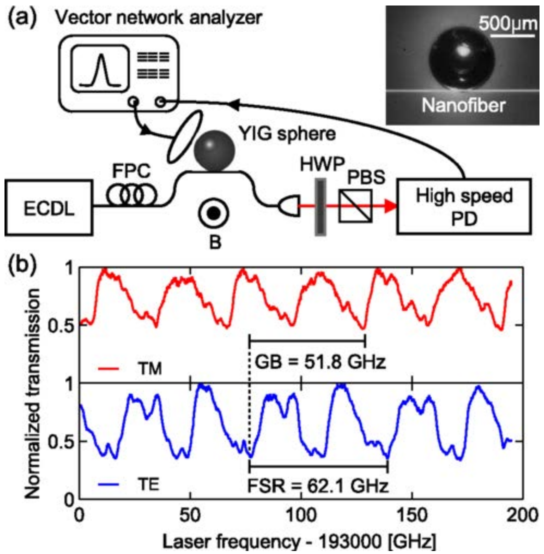
– In the end the first definition (satisfactory condition) was that g is larger than the arithmetic mean of the two linewidths
– The cooperativity compares the coupling strength to the geometric mean of the two linewidths

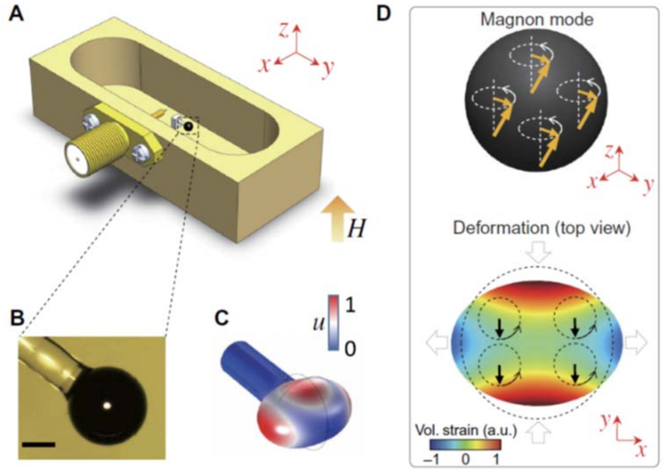
Now let's get down to business

Our target

– Investigate strong coupling of magnons with
  - Light
  - Phonons
  - Microwaves

A. Osada et al., Phys. Rev. Lett. 116, 223601 (2016)





X. Zhang et al., Sci. Adv. 2016; 2 : e1501286

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And do all this with high Q micromagnets

Coupling to cavity photons

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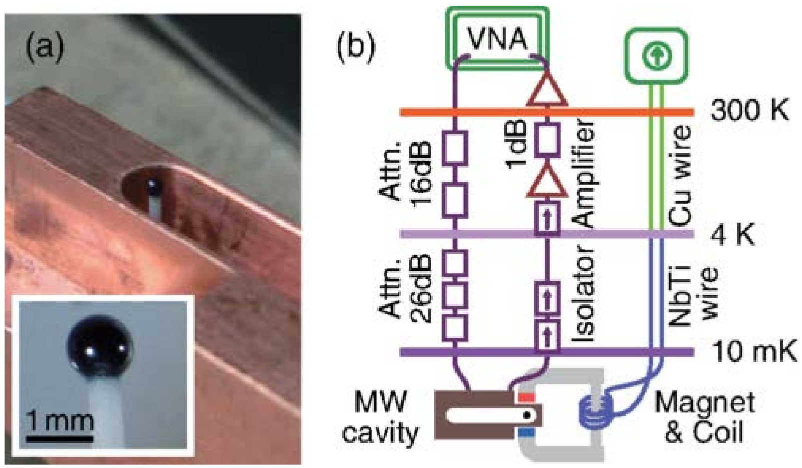
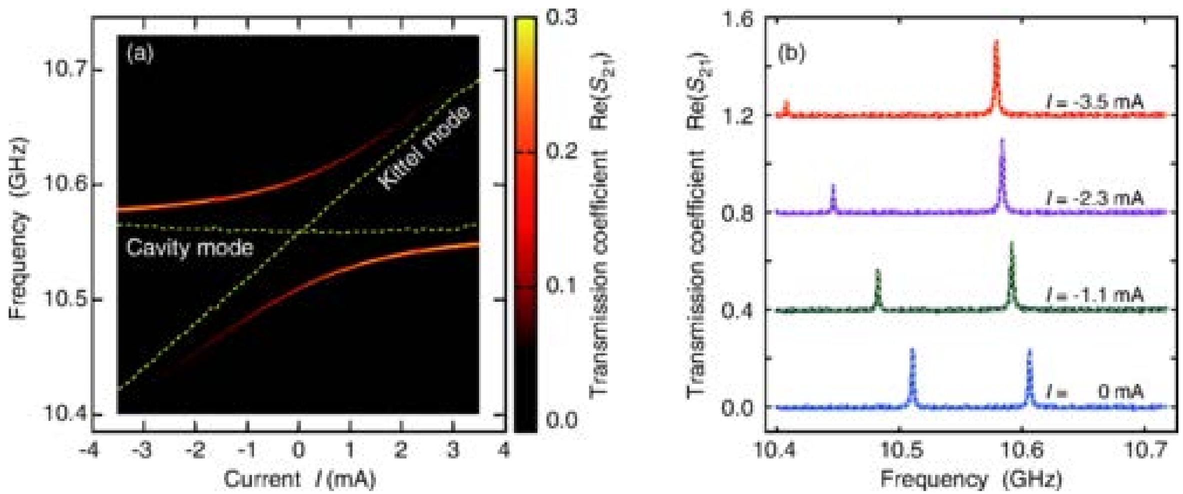
What cavity size?

- For high cooperativity, a large overlap of the mode volume is needed
- Hollow cavities work nicely with YIG spheres but are way too big for micromagnets
- What about superconducting resonators?

Y. Tabuchi et al. PRL 113, 083603 (2014)

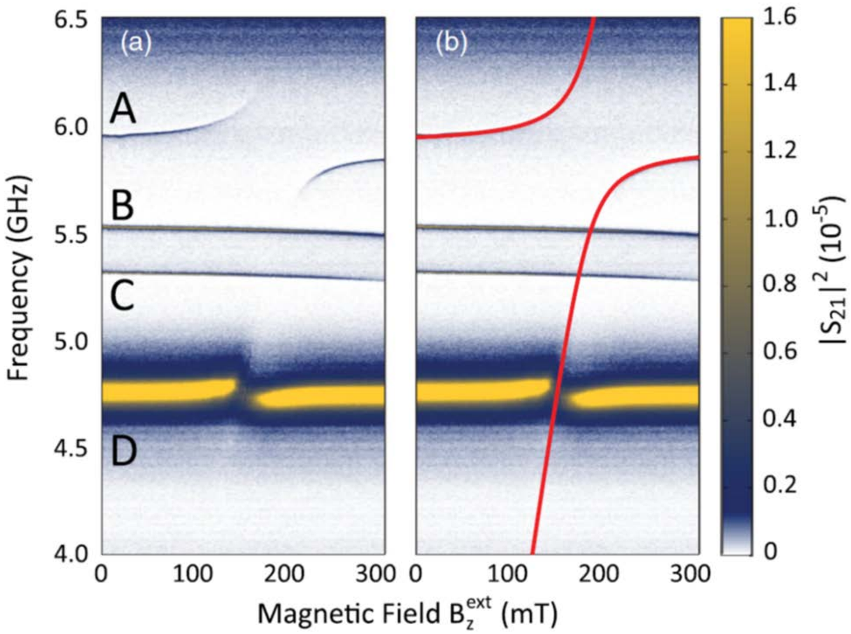


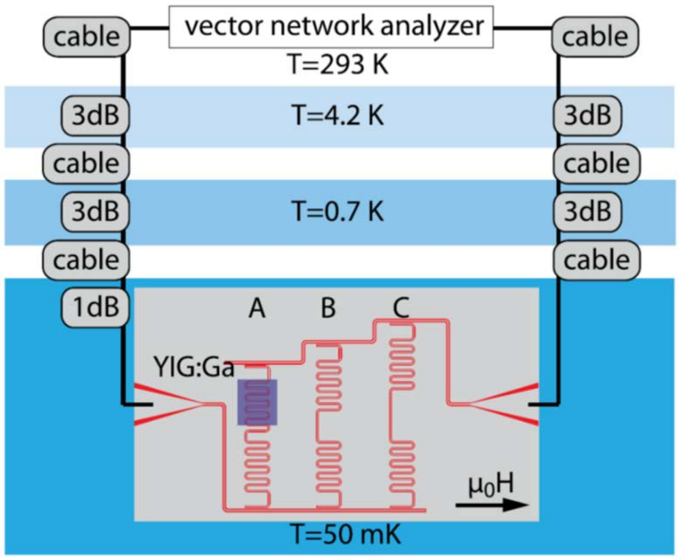


Coupling to cavity photons

What cavity size?

- What about superconducting resonators
- Superconducting λ/4 resonator still pretty large (λ @cm at 4 GHz)
- Scalable only within limits





H. Hübl et al. PRL 111, 127003 (2013)

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Coupling to cavity photons

What cavity size?

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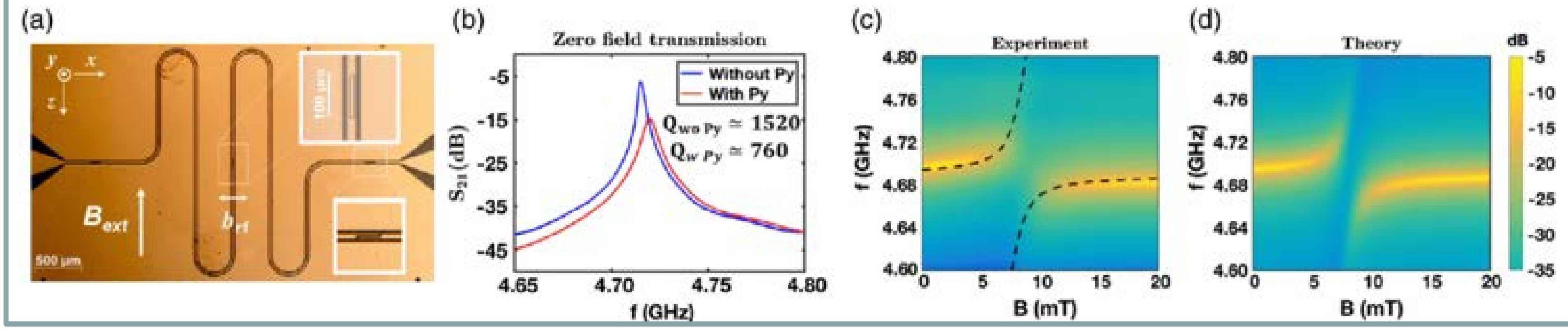
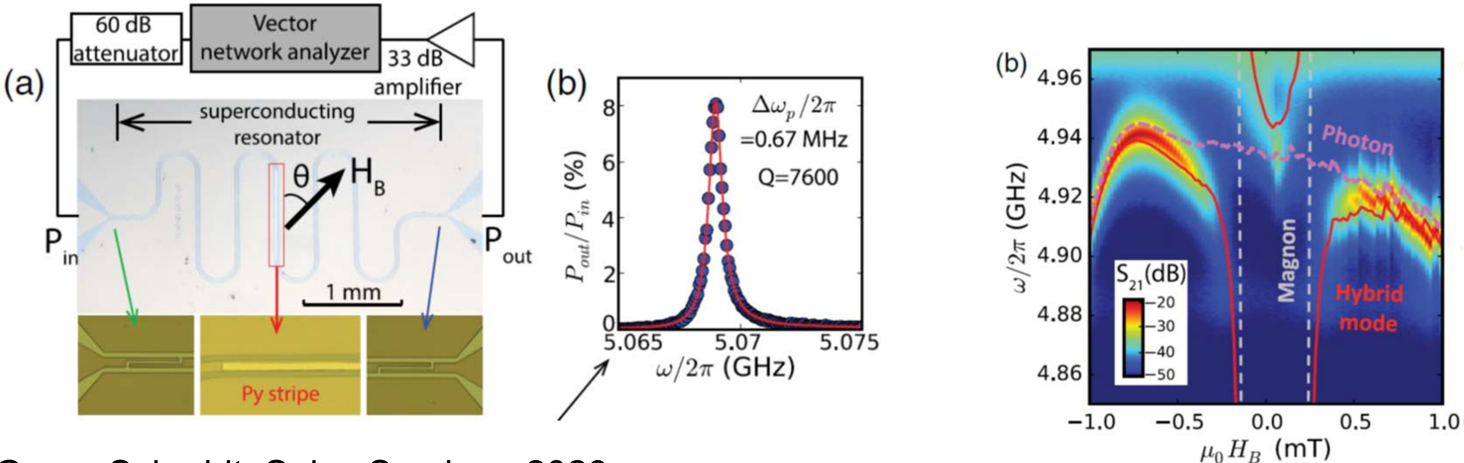
- For λ/4 resonators
  - Demonstration of strong coupling for Py magnets down to 0.1 mm size



Hou et al., PRL 123, 107702 (2019)



Li et al., PRL 123, 107701 (2019)

Coupling to cavity photons

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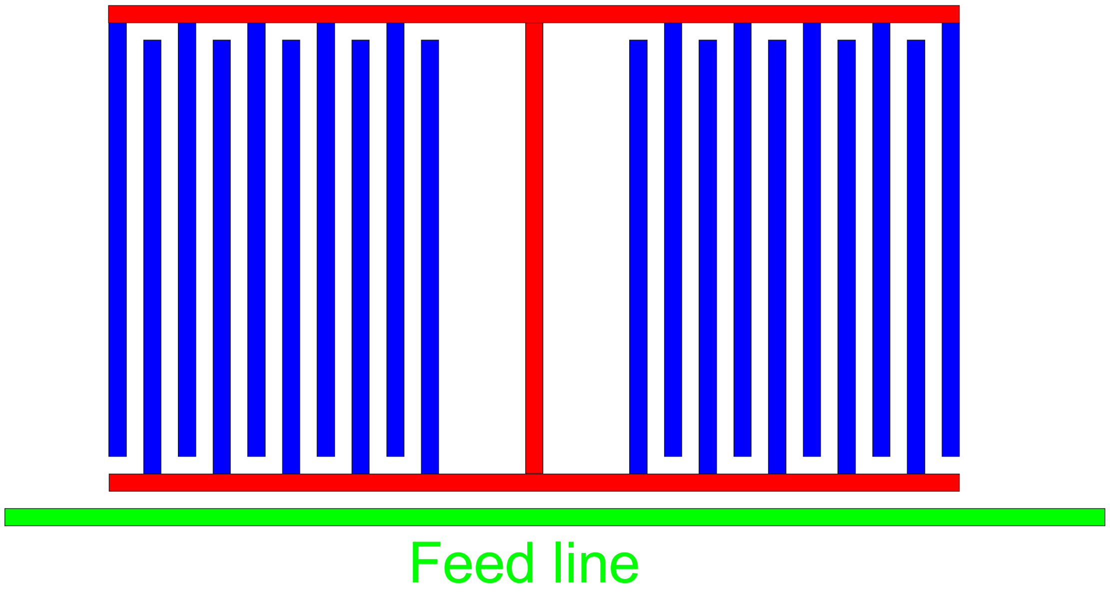
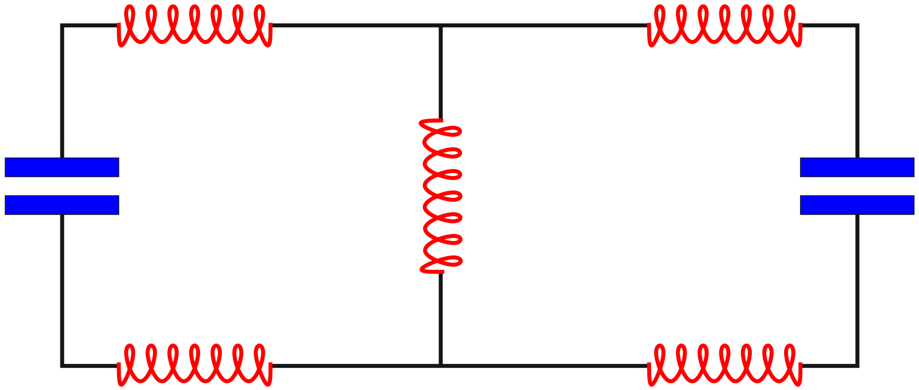
What cavity size?

- Better choice: Superconducting LC resonator (lumped element)
- Magnetic field can be concentrated around an inductive element





Coupling to cavity photons

What cavity size?

- Demonstration of coupling of a Py stripe with LC-resonator
- 40x2x10nm Py element
- High cooperativity but no strong coupling (Py has large linewidth)

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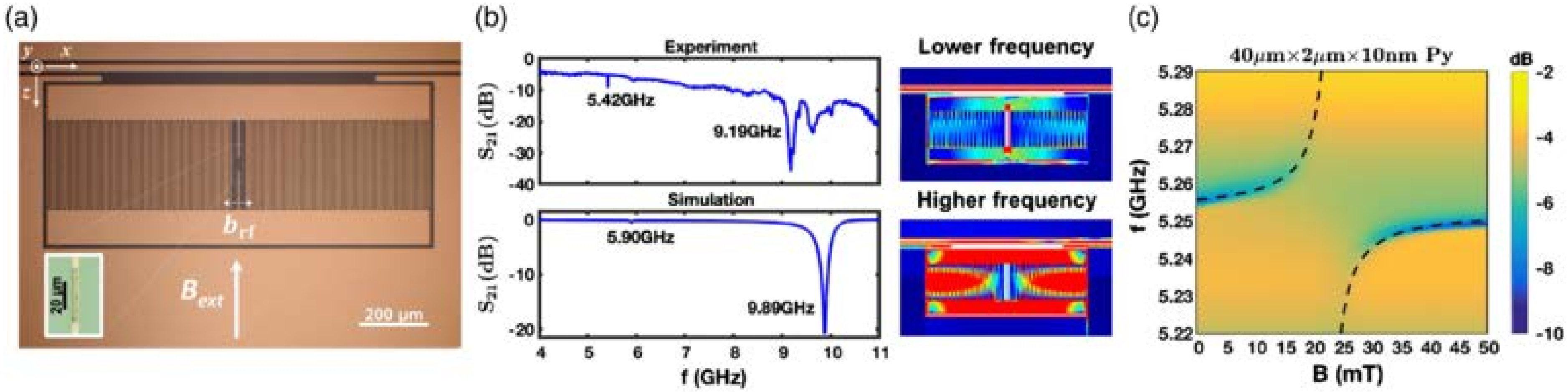
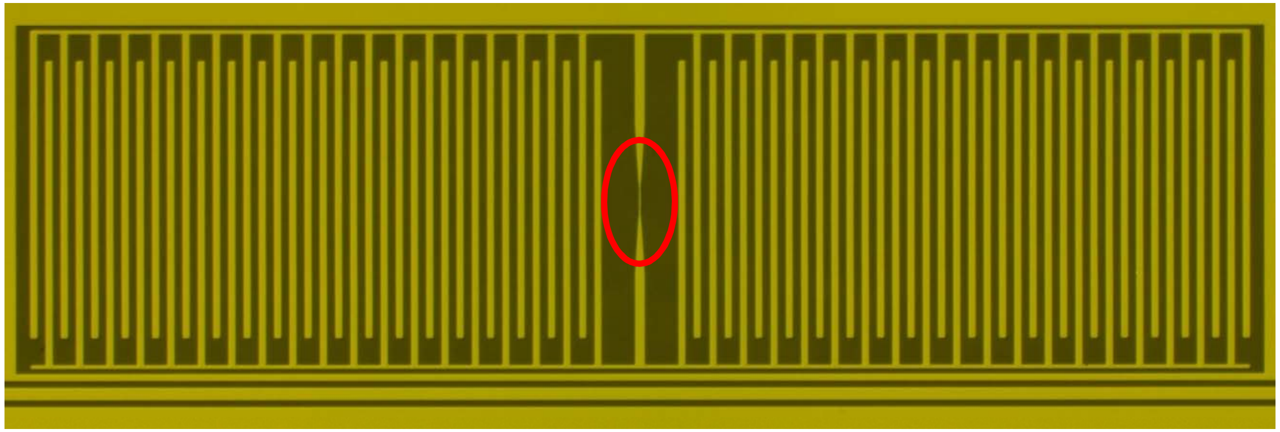


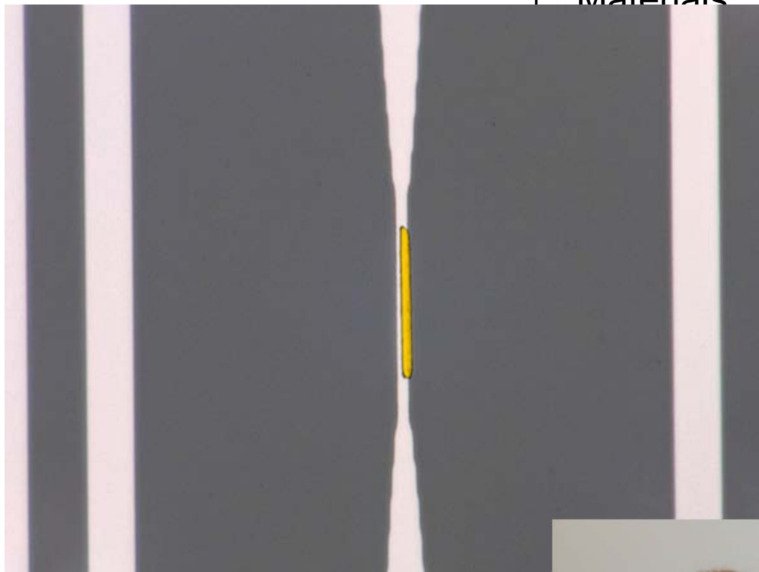
Hou et al., PRL 123, 107702 (2019)

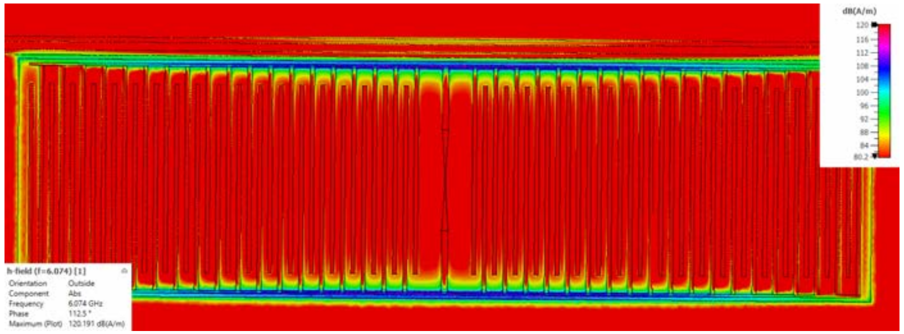
New resonator design

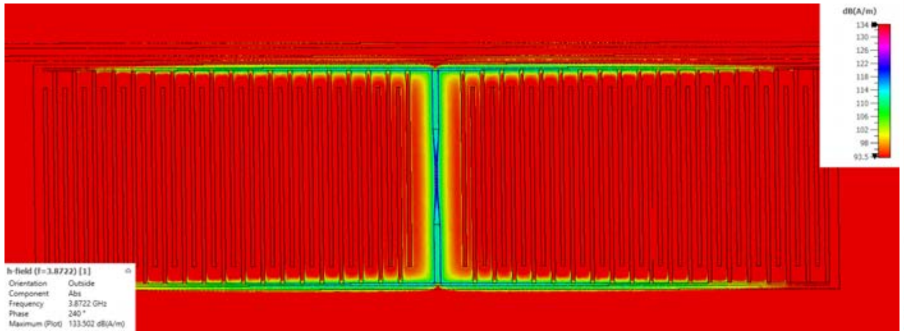
Modified lumped element resonator

- Central inductance more narrow to localize the magnetic field
- Py structure of 30 µm x 2 µm x 50 nm (1st try)
  Work by Philipp Geyer







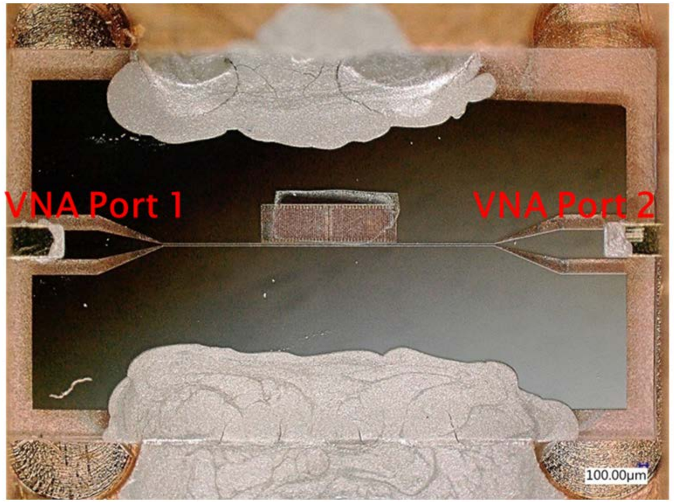


P. Geyer

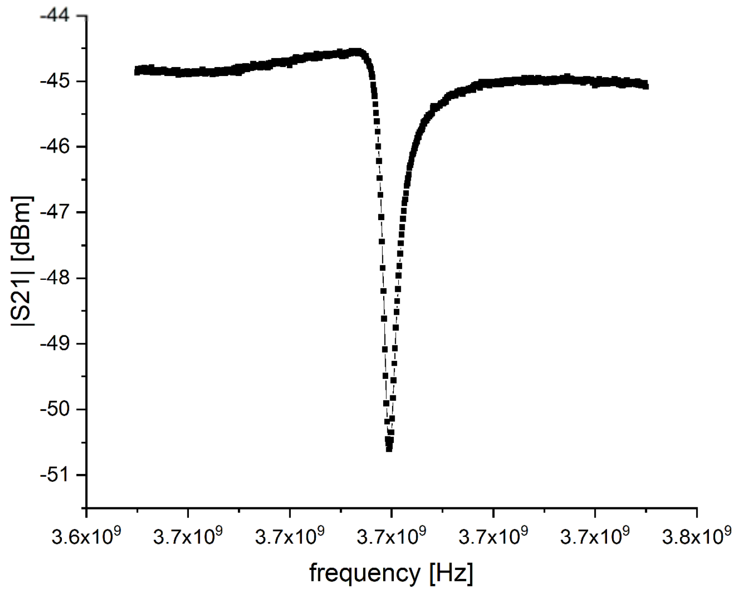
New resonator design

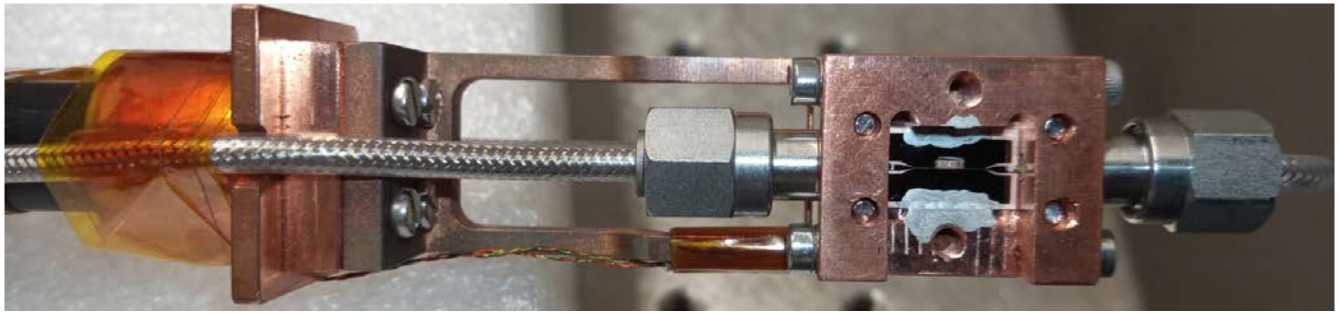
Modified lumped element resonator

- Setup developed with support from Hans Hübl
- Resonance frequency ~3.7 GHz



Q > 1000
T≈ 1.5 K



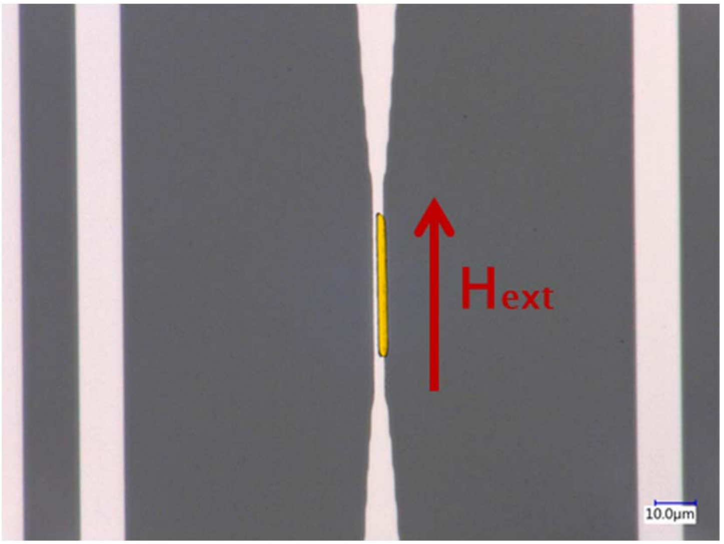


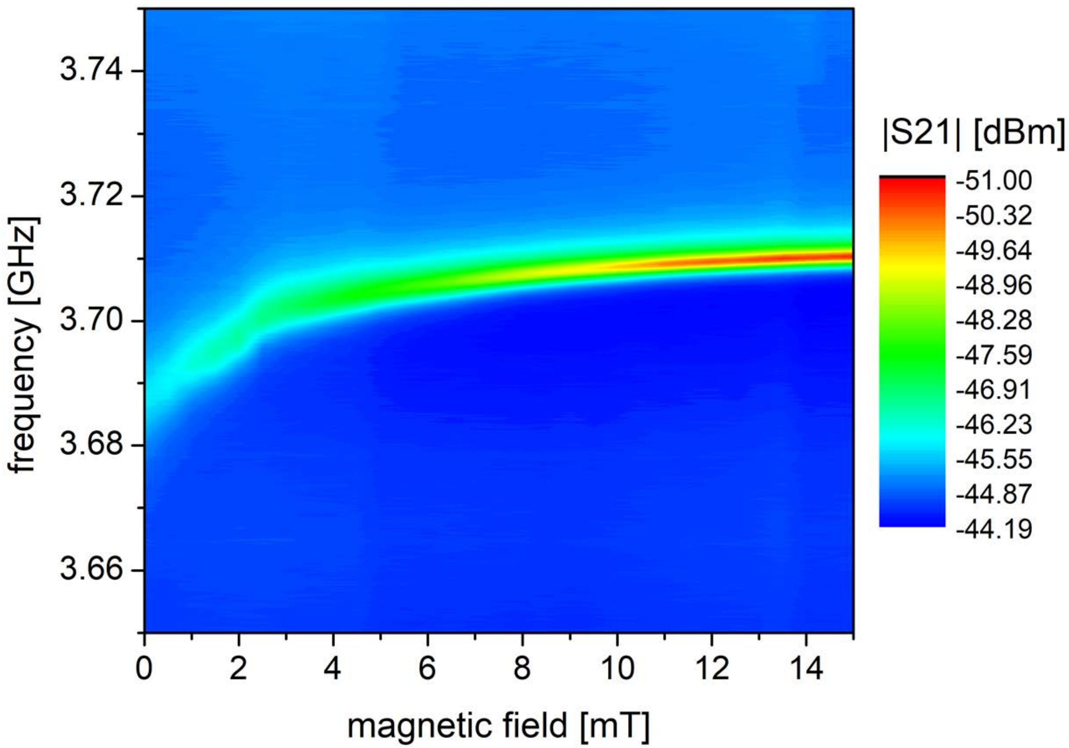
First results

Easy axis

- No FMR at resonator frequency
- Even zero field resonance out of range

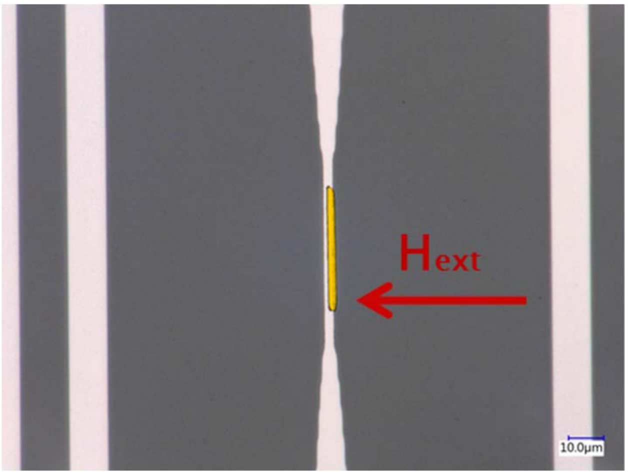
Nanostructured Materials

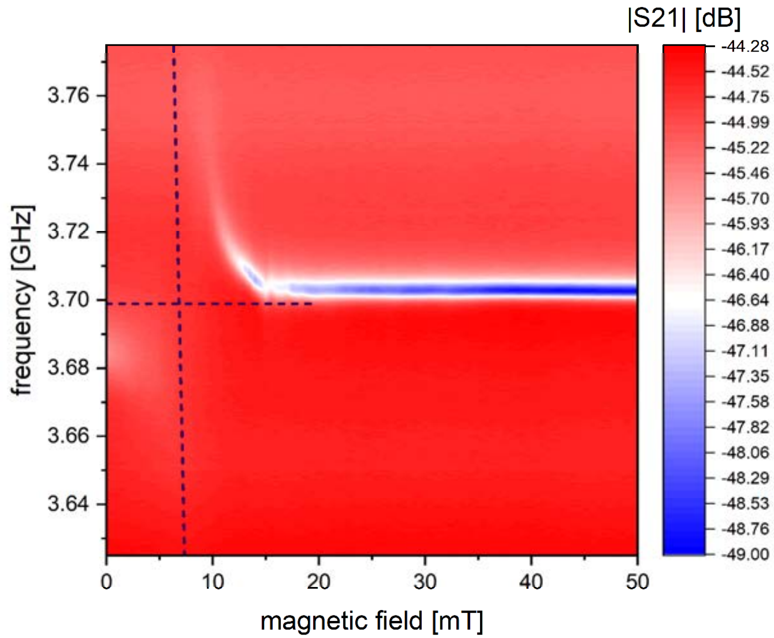




First results
Hard axis

- Clear avoided crossing
- However, wrong dispersion direction
- Origin???
- Numbers: $\frac{\Delta\omega_{FMR}}{2\pi} \approx 250\ MHz$ (conservative estimate), $\frac{\Delta\omega_{Cav}}{2\pi} \approx 1.5\ MHz$, $\frac{g}{2\pi} \approx 100\ MHz$
- No strong coupling ($\Delta\omega_{FMR} > g$)
- Cooperativity: $\frac{g^2}{\Delta\omega_{FMR}\,\Delta\omega_{Cav}} \approx 27$



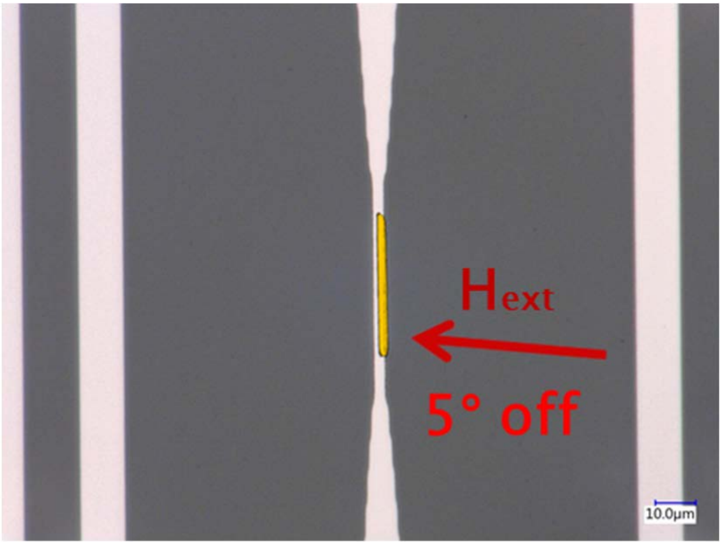


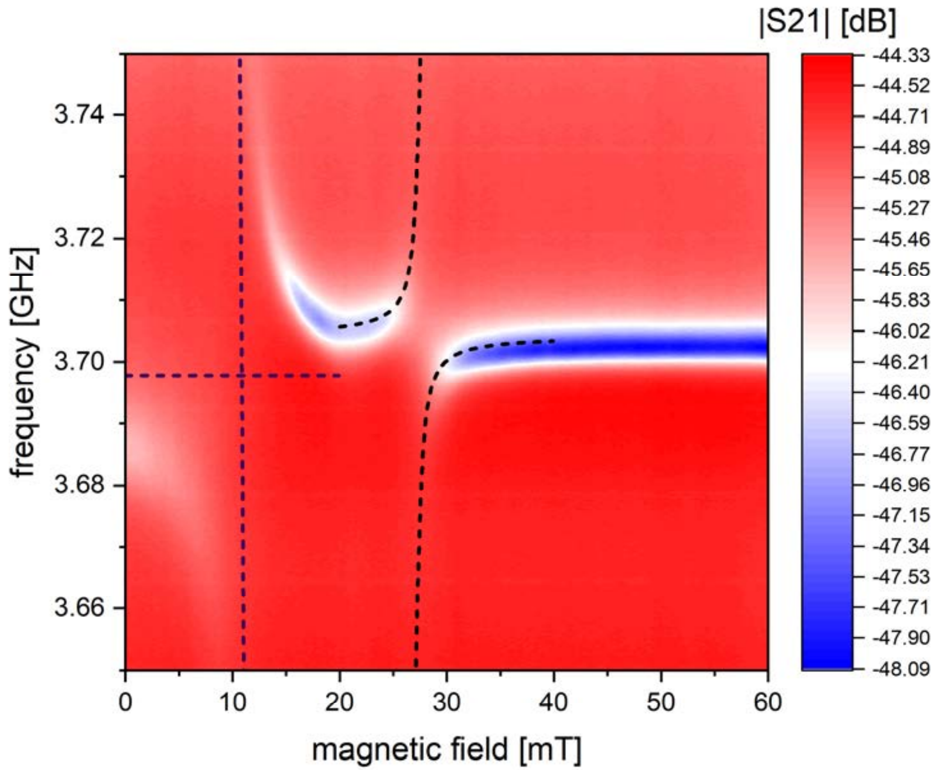
First results

Tilted field

- Second avoided crossing appears
- Second crossing has "correct" dispersion
- Can be explained by micromagnetic simulations

Nanostructured Materials

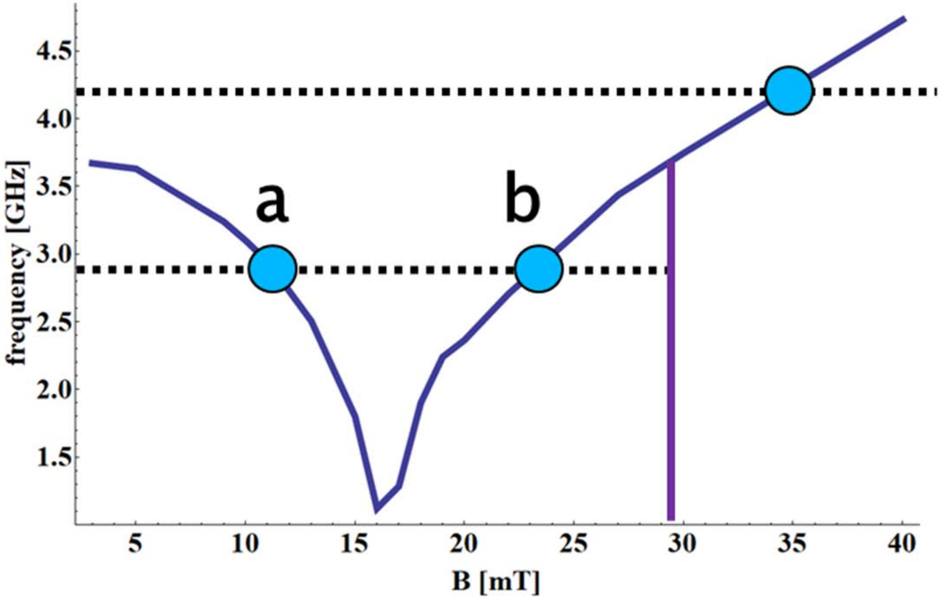


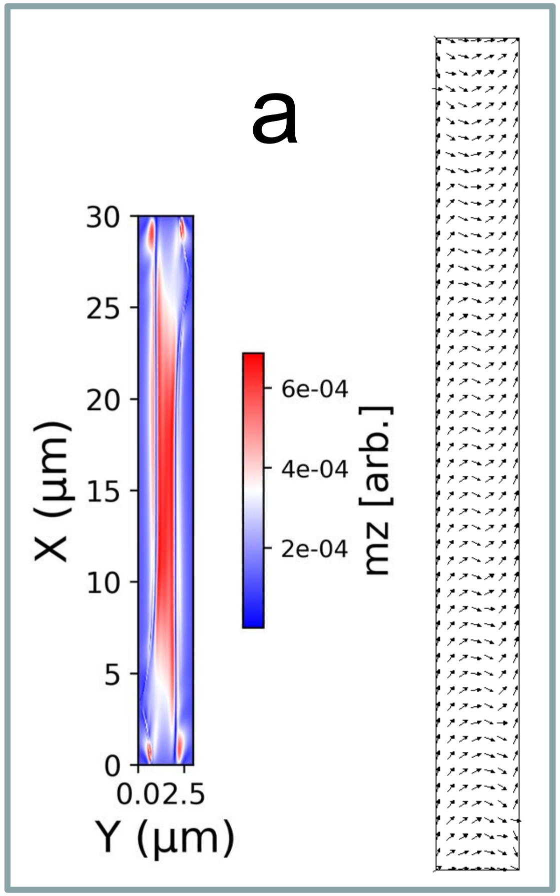


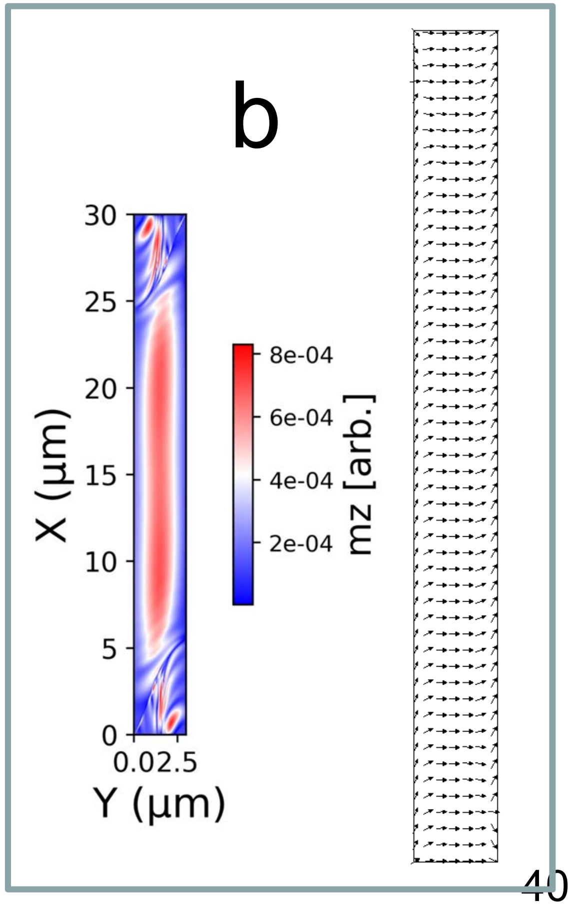
Explanation

Unsaturated state

- Close to hard axis the magnet is not saturated
- Resonance field H_{eff} is determined by external field and demagnetizing field
- At low fields H_{demag} and H_{ext} compensate each other
- Saturated state has resonance beyond cavity frequency







Moving towards YIG

Issues

- Nanopatterning of YIG non-trivial
- GGG substrate is detrimental for low temperaure measurements
- GGG substrate is also not suitable for superconductong resonators

- Needed
  - Nanopatterned YIG
  - Ideally
    - Either without substrate or
    - On a subtrate other than GGG

P. Trempler

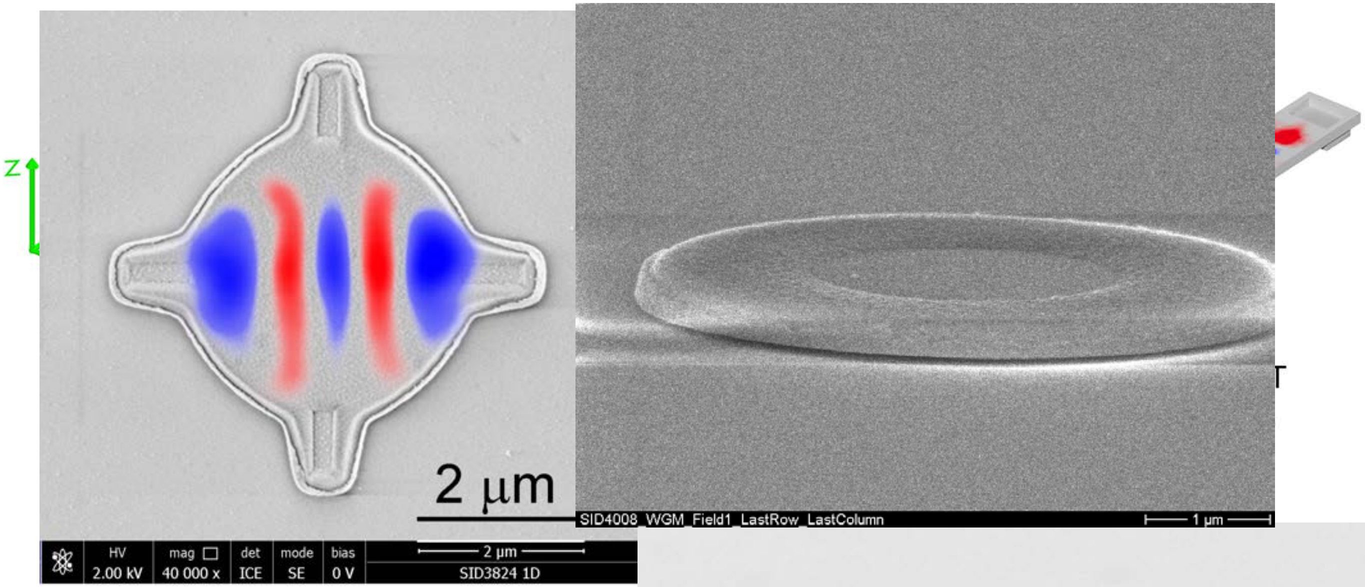
New YIG fabrication process

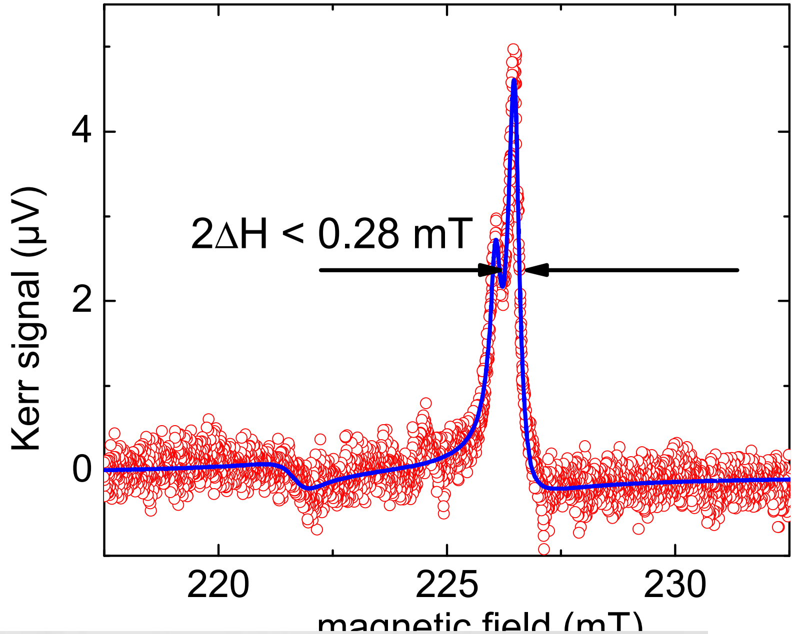
Allows high Q free standing 3D structures

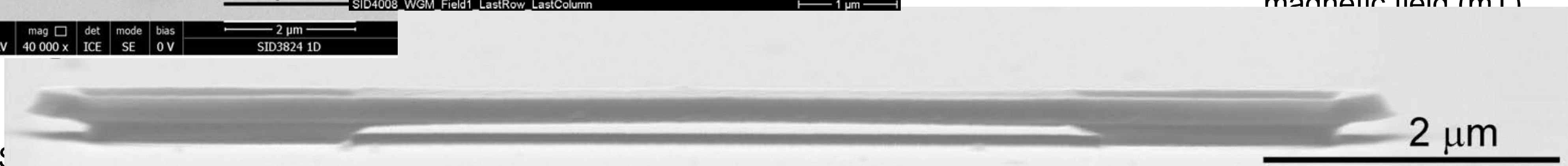
Nanostructured Materials

- E-beam lithography and PLD
- Subsequent lift-off and annealing
- Damping $\alpha = 2 \times 10^{-4}$

F. Heyroth, GS et al. PR Appl. 12, 054031 (2019)





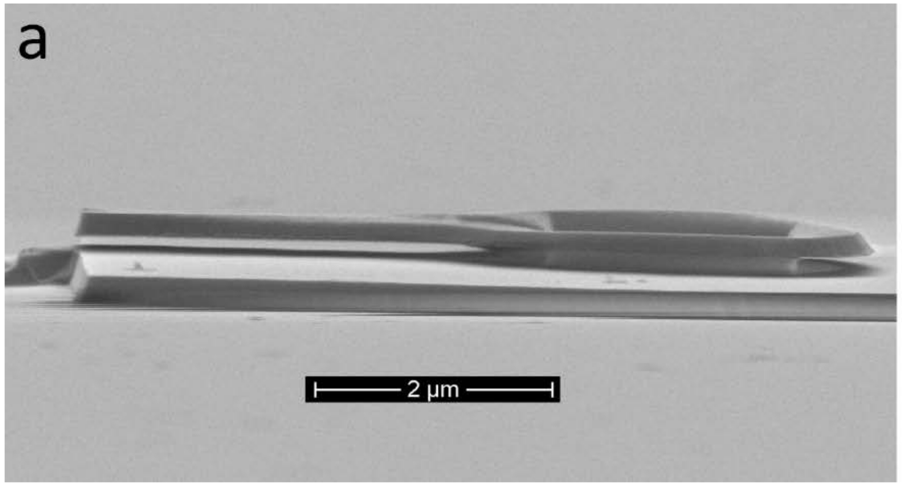


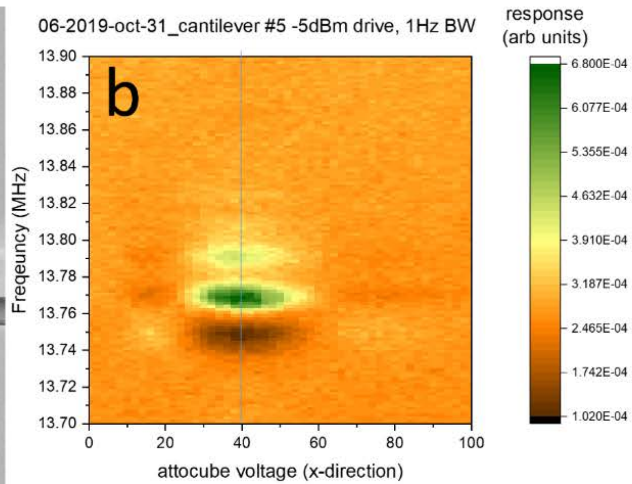
Possible applications (first trials)

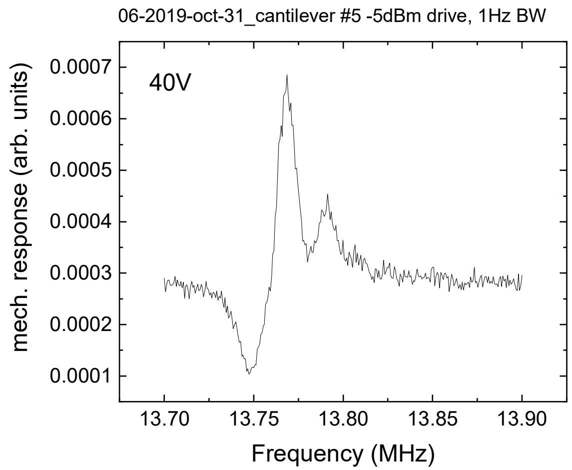
Mechanical oscillations (Hans Hübl, WMI)

- Cantilever (single side clamped beam) fabricated from bridge
- Excitation by piezoactuation
- Measurement of mechanical vibration by optical interferometry
- Result:
  - Mechanical oscillation at 13.75 MHz
  - Q-factor ~550

Nanostructured Materials



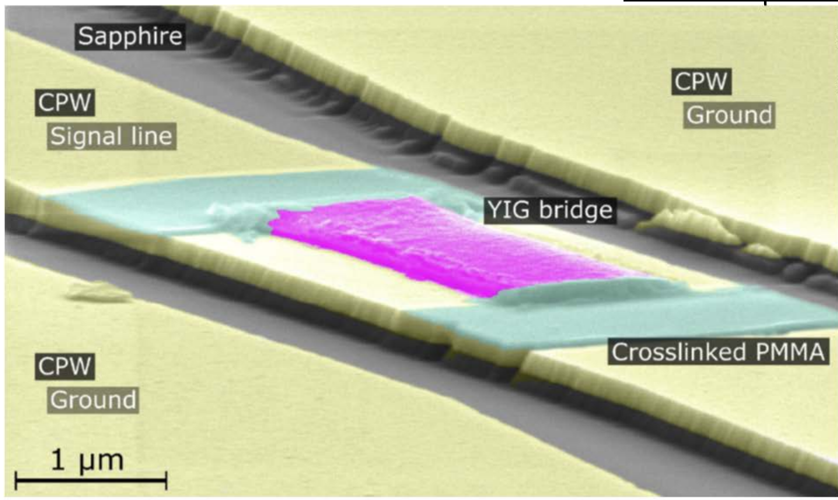


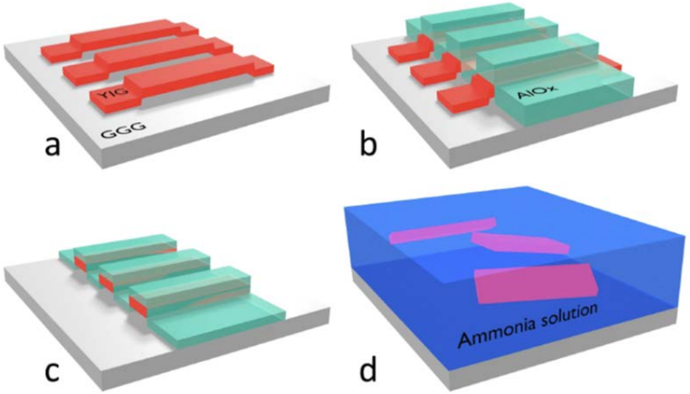


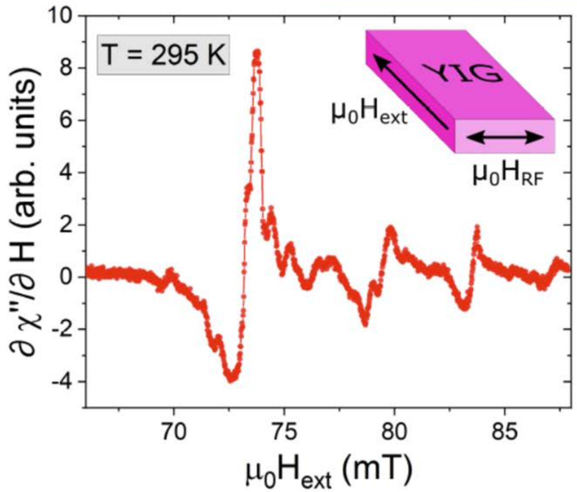
Getting onto other substrates

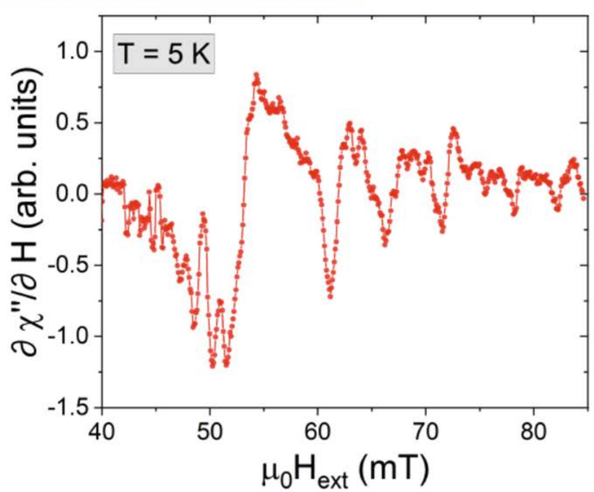
Route 1

- Drop casting
  - make lots of bridges
  - Mask them
  - Remove the feet and get them into solution
  - Drop cast and use single structure







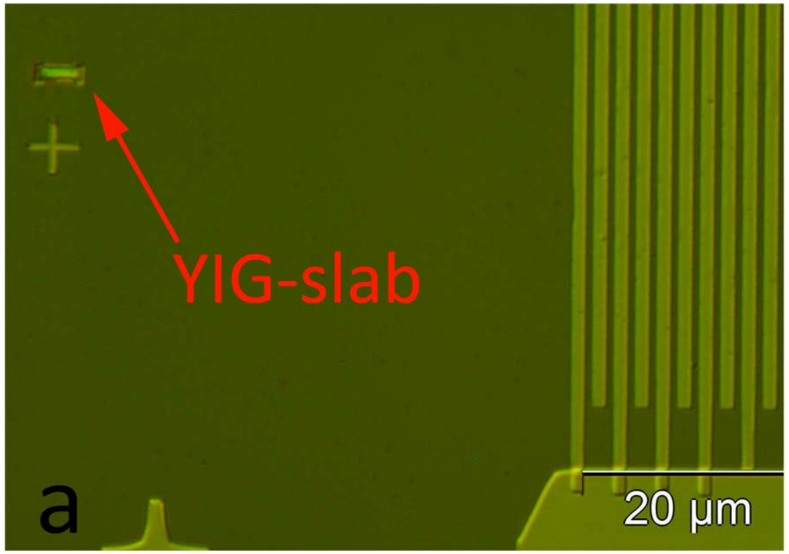


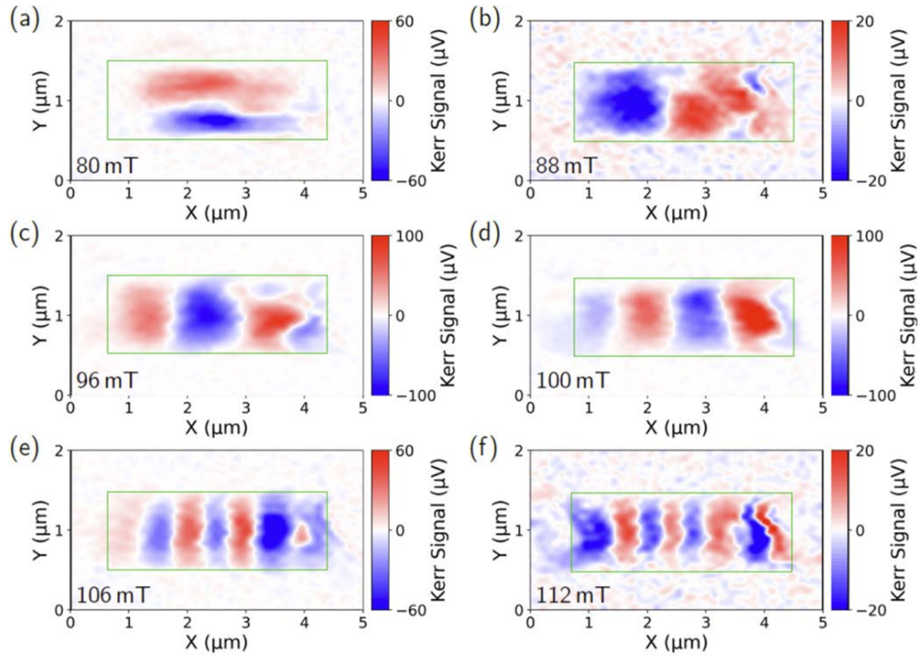
P. Trempler, et al. Appl. Phys. Lett., **117**, 232401 (2020)

More fun

Magnon excitation by surface acoustic waves (SAW)

- Fabricate interdigitated transducer on $LiNbO_3$
- Drop cast YIG nanoslabs on the sample untol you find something suitable
- Fix the slab to the surface
- Start shaking and look with TR-MOKE

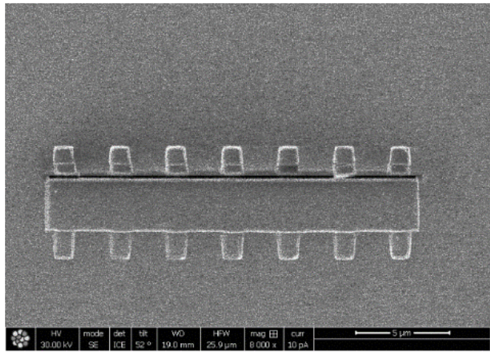




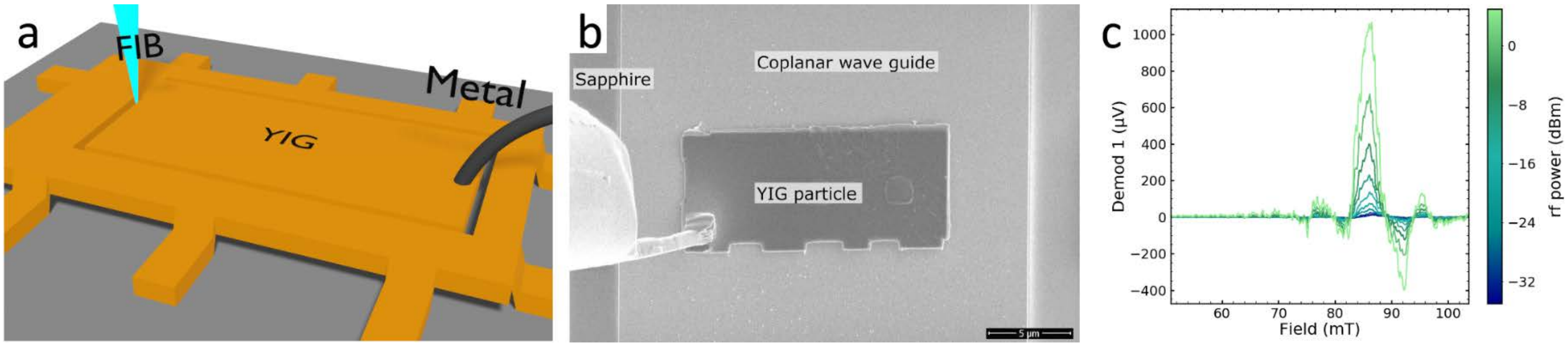
Collaboration with G. Woltersdorf and R. Dreyer, MLU

Route 2

FIB transfer



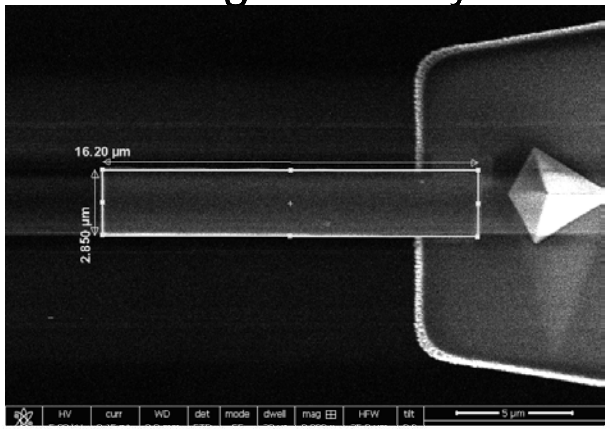
- Larger stuctures possible
- Precisely placeable
- New process:
  - Structure with multiple feet (centipede) allows for larger YIG areas
  - Structure can be detached and transferred using focused ion beam
  - Using a few tricks the magnetic properties are preserved

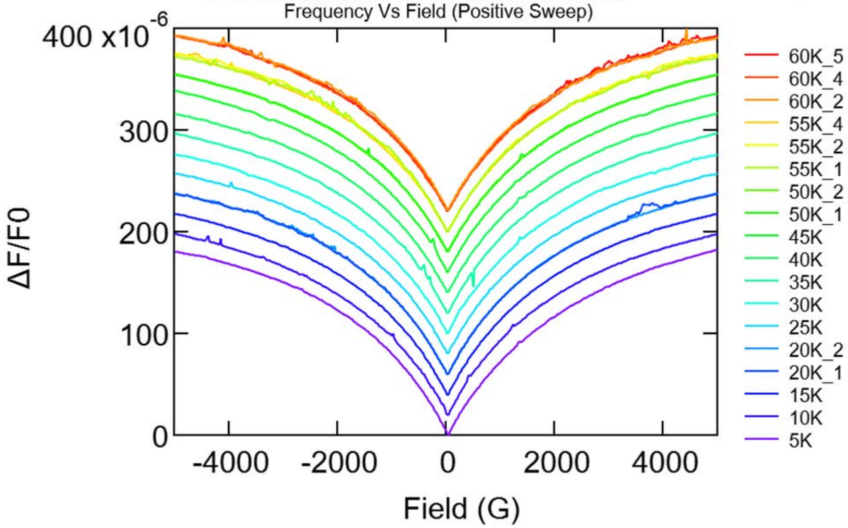


Magnetometry

– YIG slab transferred to AFM cantilever can be used for cantilever magnetometry

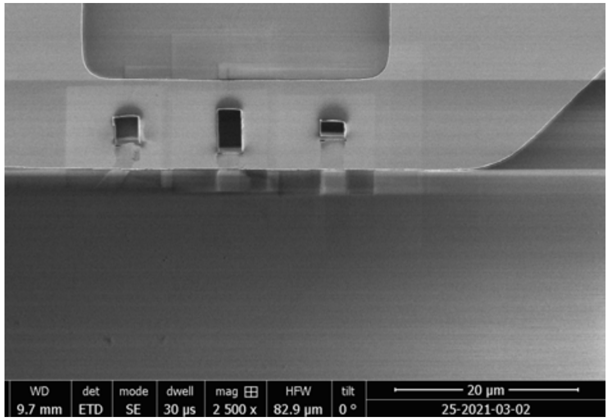
OSU
(F. Rodriguez, P.C. Hammel)

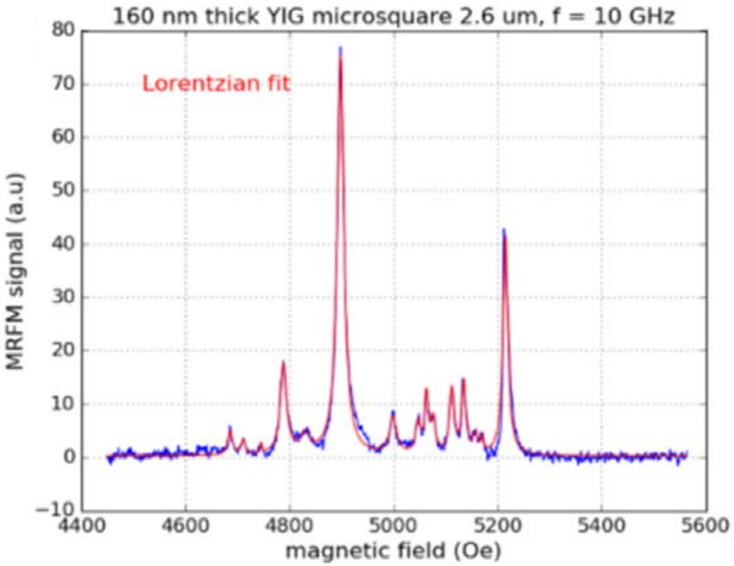




Magnetic resonance force microscopy

– MRFM on transferred YIG slabs





CEA Grenoble
(G. deLoubens, I. Ngouagnia and M. Fontaine)

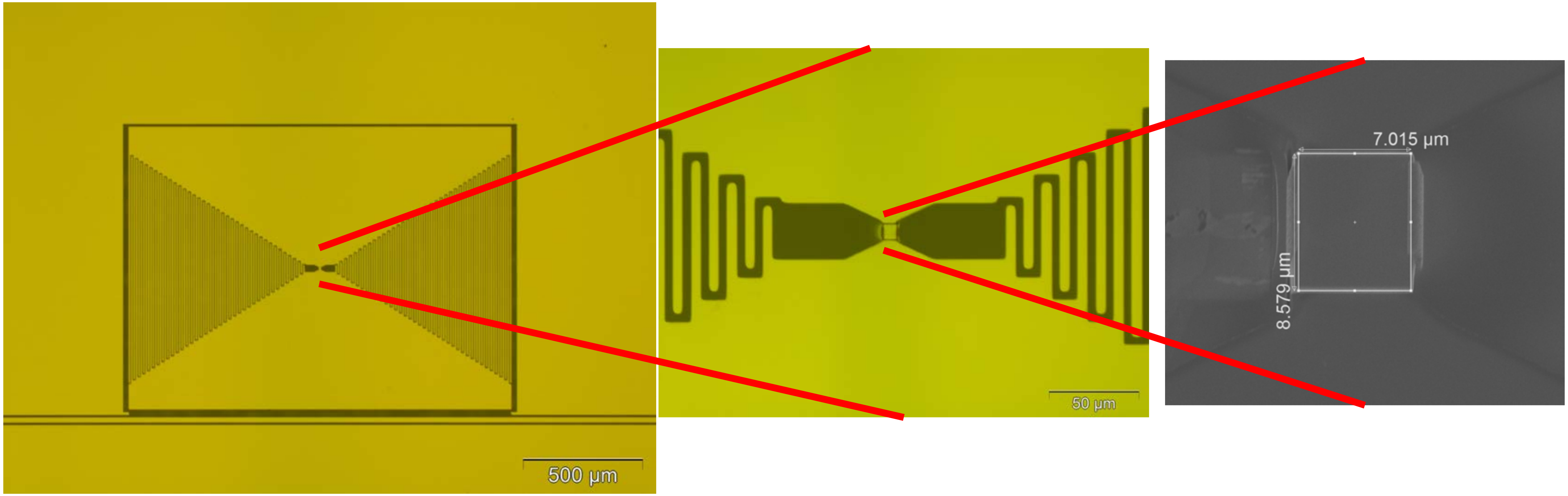
Nanostructured Materials

YIG on LC resonator

Resonator adapted to sample

- Small area inductance
- YIG transferred by FIB

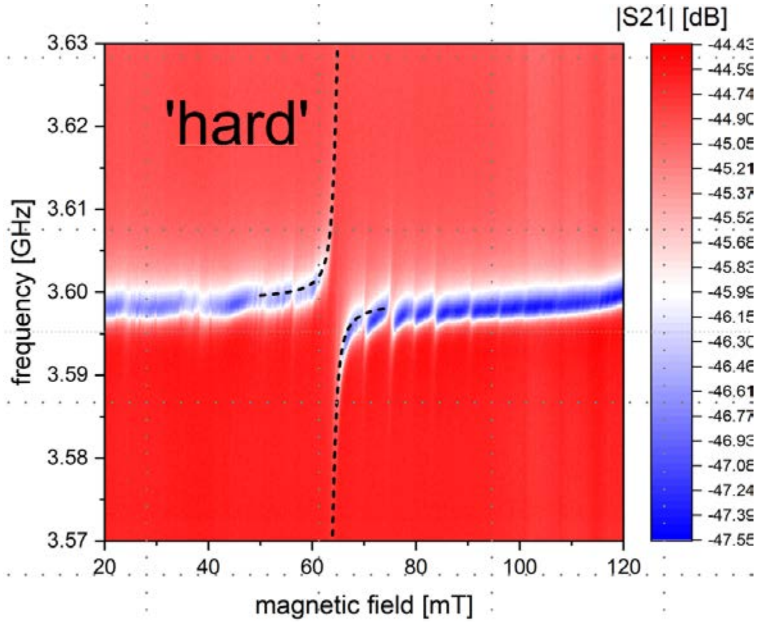
Nanostructured Materials

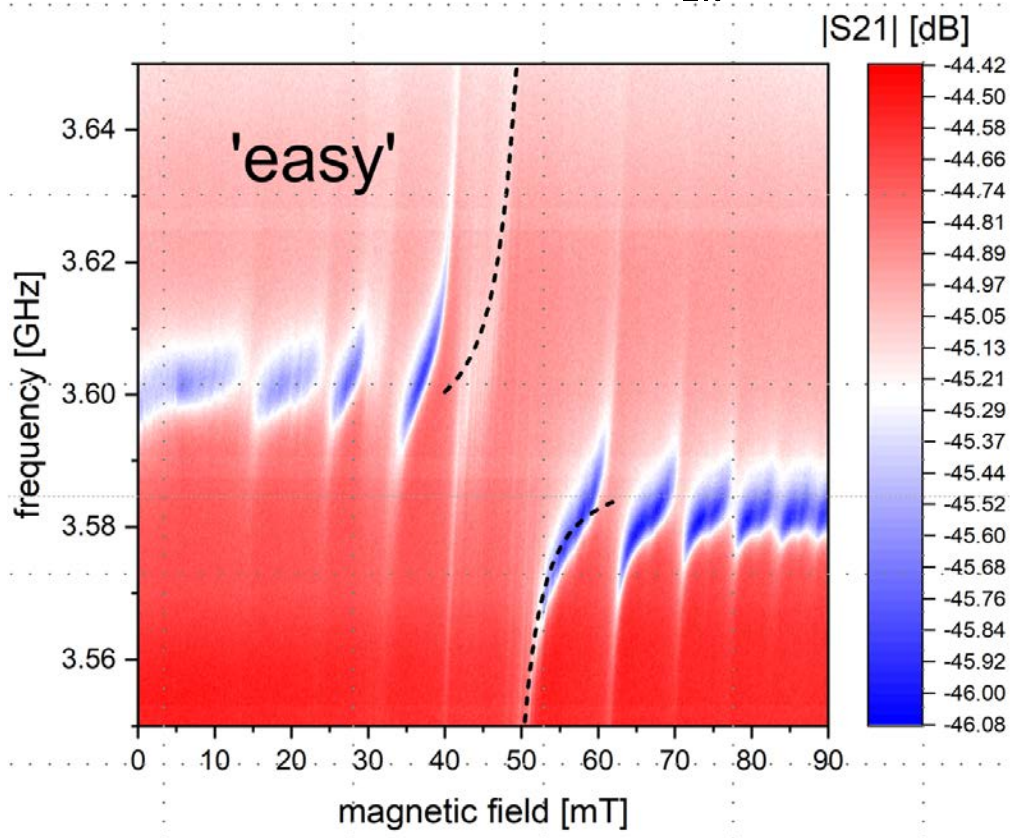


YIG on LC resonator

FIB prepared YIG

- Multiple resonances detected along hard and easy axis
- Numbers: $\frac{\Delta\omega_{FMR}}{2\pi} \approx 11\ MHz$ (estimate), $\frac{\Delta\omega_{Cav}}{2\pi} \approx 1.3\ MHz$, $\frac{g}{2\pi} \approx 53.8\ MHz$
- Strong coupling regime ($g > \Delta\omega_{FMR} > \Delta\omega_{Cav}$), Coupling per Spin: $\frac{g_{Spin}}{2\pi} \approx 63\ Hz$ for M_{sat}=140 kA/m
- Cooperativity: $\frac{g^2}{\Delta\omega_{FMR}\,\Delta\omega_{Cav}} \approx 202$





Nanostructured Materials

Conclusion

- LC resonators suitable for downscaling of coupling experiments
- No strong coupling achieved with Py
- New process allows to transfer small YIG structures
- Strong coupling demonstrated
- Cooperativity >200 achieved

- Where are the limits???
  (Collaborations to find out are welcome)