Magneto-Acoustic Waves in Magnetic Thin Films

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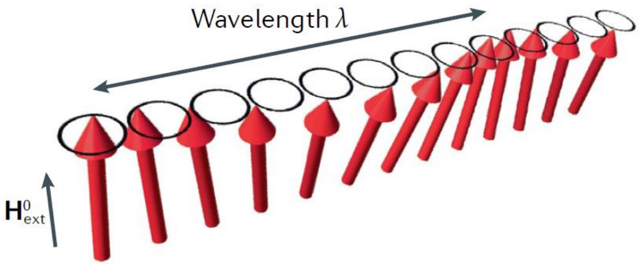
… and many more

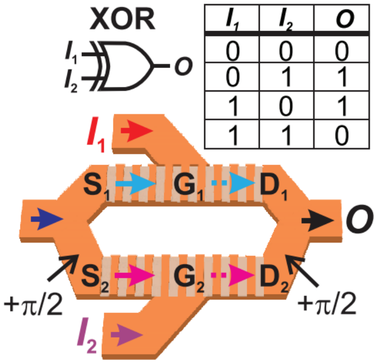
Contents

- **Introduction**
- Symmetry of the magneto-acoustic interaction
- Origin of the magneto-acoustic interaction
- Non-reciprocal magneto-acoustics
- Non-linear magneto-acoustics

Spinwaves and soundwaves for applications

Spinwaves for information processing

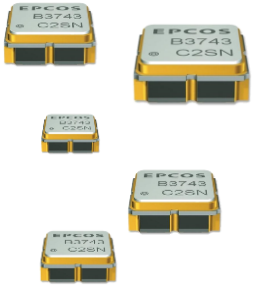




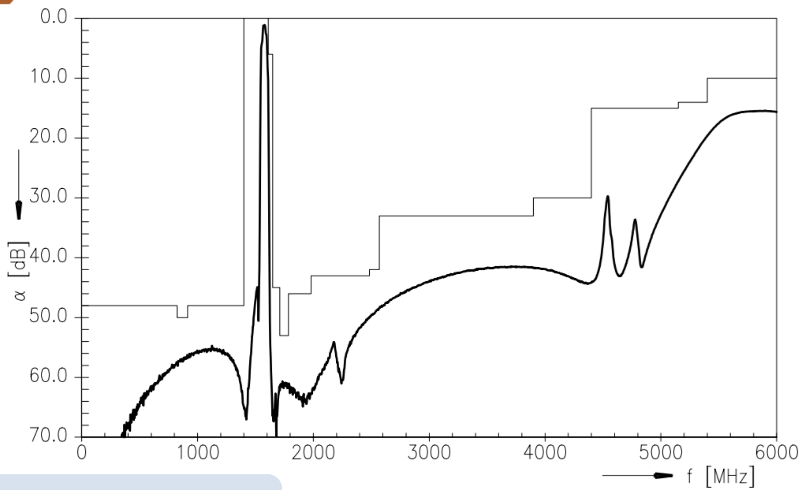
Chumak et al J. Phys. D: Appl. Phys. **50,** 244001 (2017)

P. Pirro et al., Nat Rev Mater **6**, 1114 (2021)

Soundwaves for mobile communication

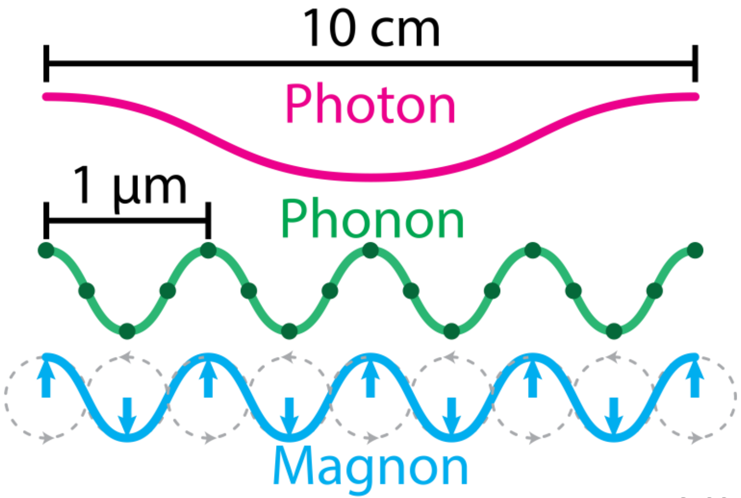


Acoustic filters (data: GPS filter Epcos B9080, footprint 2 mm²)



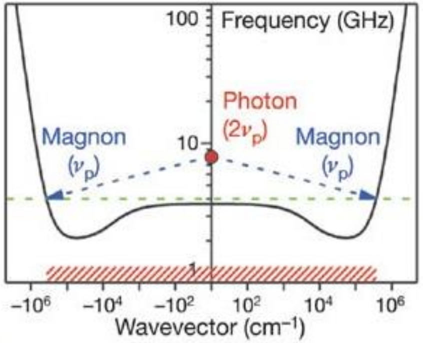
$4.5 billion (2020)

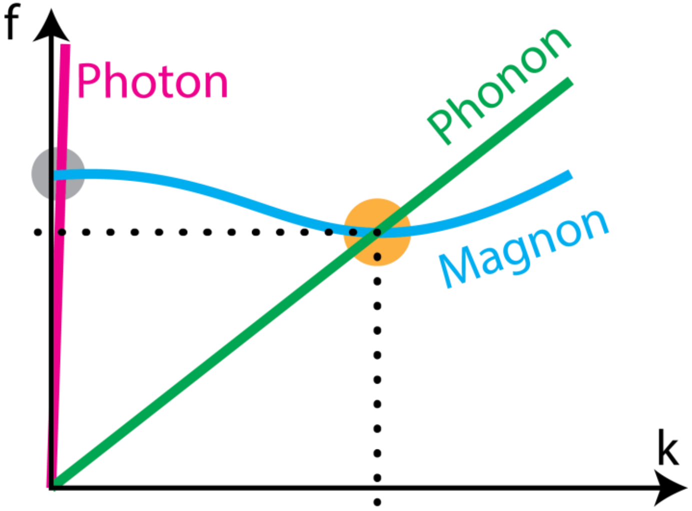
Why magneto-acoustic waves?



$f \approx \mathrm{GHz}$

Miniaturize non-reciprocal microwave devices





Control spin-waves with $k_{SW} \neq 0$

Demokritov et al., Nature **443**, 430 (2006)

Bozhko *et al.*, Phys. Rev. Lett. **118**, 237201 (2017)

Brief history of sound and spin

Interaction of Spin Waves and Ultrasonic Waves in Ferromagnetic Crystals*

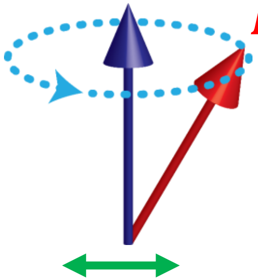
C. KITTEL
Department of Physics, University of California, Berkeley, California
(Received January 9, 1958)

Phys. Rev. **110**, 836 (1958)

Magnetoelastic free energy contribution: $m_z \approx 1 \gg m_x, m_y$

$$f_{\mathrm{ME}} = b_1 \left[\varepsilon_{xx} m_x^2 + \varepsilon_{yy} m_y^2 + \varepsilon_{zz} m_z^2\right] + 2b_2\left[\varepsilon_{xy} m_x m_y + \varepsilon_{xz} m_x m_z + \varepsilon_{yz} m_y m_z\right]$$

Pure strain — Shear strain



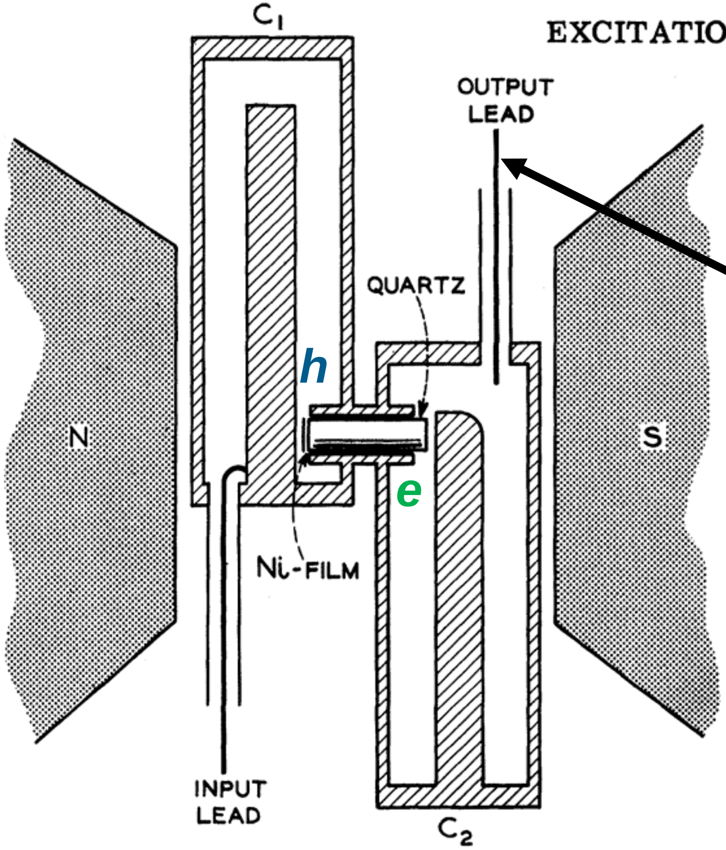
$$\mu_0 \boldsymbol{H}_{\mathrm{ME}} = -\nabla_{\boldsymbol{m}} f_{\mathrm{ME}} \approx 2b_2 \begin{pmatrix} \varepsilon_{xz} \\ \varepsilon_{yz} \\ 0 \end{pmatrix}$$

$b_2 \approx 10\ \mathrm{T}$
$\varepsilon \approx 10^{-3}$
$\mu_0 H_{\mathrm{ME}} \approx 10\ \mathrm{mT}$

$$\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma\mu_0\, \boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}} \qquad \boldsymbol{H}_{\mathrm{eff}} = \boldsymbol{H}_0 + \boldsymbol{H}_{\mathrm{ME}} + \cdots$$

Dreher, MW *et al.*, Phys. Rev. B **86**, 134415 (2012)

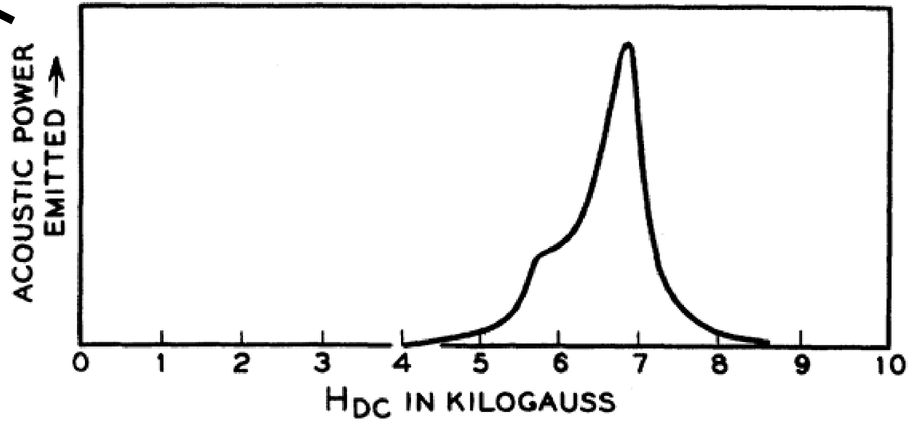
Brief history of sound and spin



EXCITATION OF HYPERSONIC WAVES BY FERROMAGNETIC RESONANCE

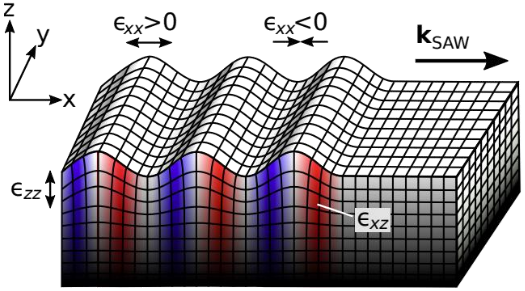
H. Bömmel and K. Dransfeld
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received June 18, 1959)

Phys. Rev. Lett. **3**, 83 (1959)



FMR ↔ Soundwave ↔ E-Field

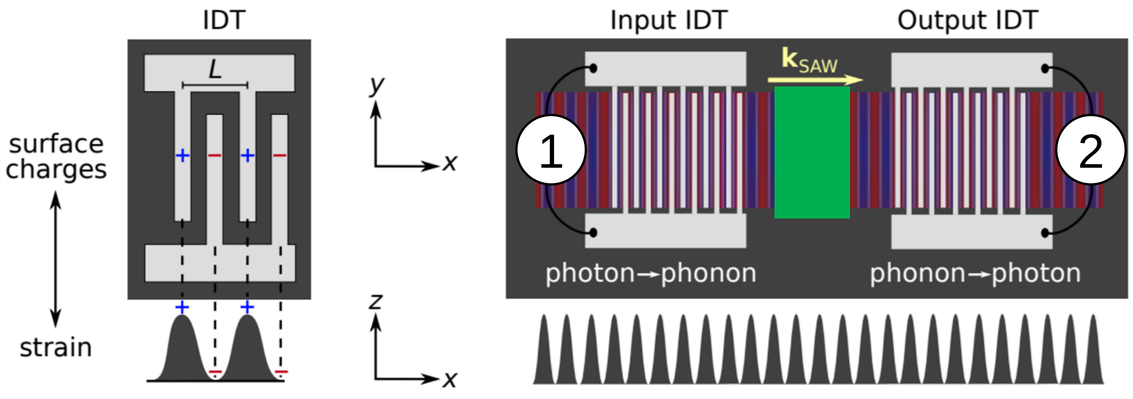
Brief history of sound and spin

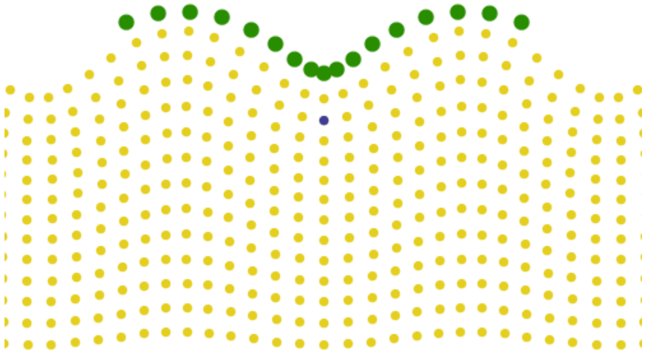


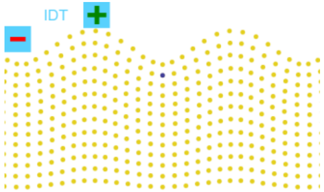
Surface Acoustic Wave (SAW)

Macroscopic: Earthquake

Microscopic: Mobile communication



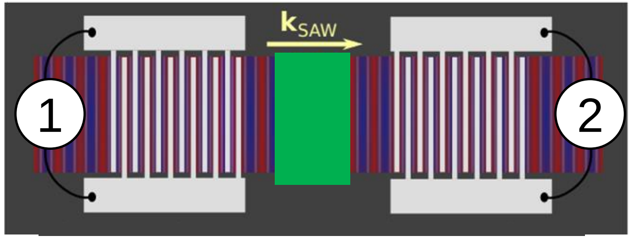




Interdigital transducer (IDT)

Spinwave ↔ Soundwave ↔ E-Field

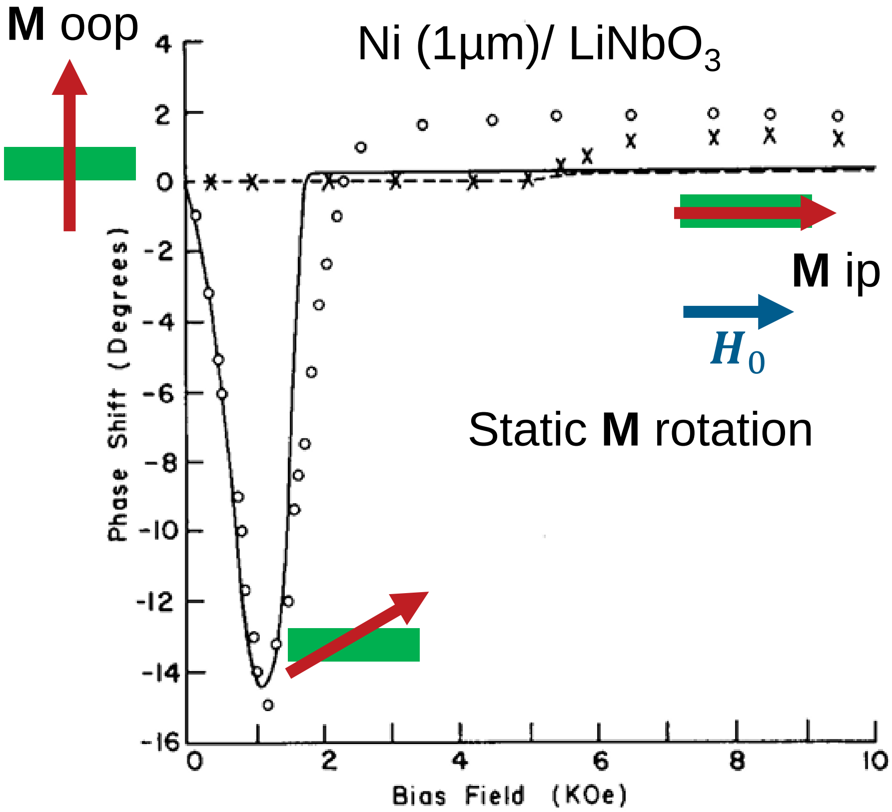
Brief history of sound and spin



$f_{SAW} \approx 100\ \mathrm{MHz} \ll f_{FMR} \approx 1\ \mathrm{GHz}$

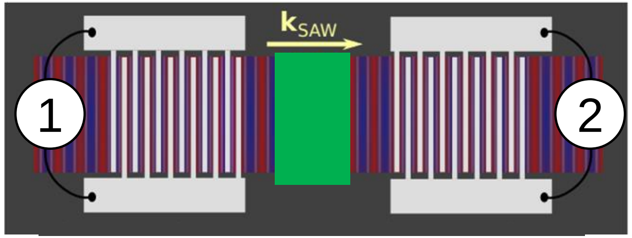
ΔE-Effect: c=c(**M**)

Thick Ni film with perpendicular magnetic anisotropy

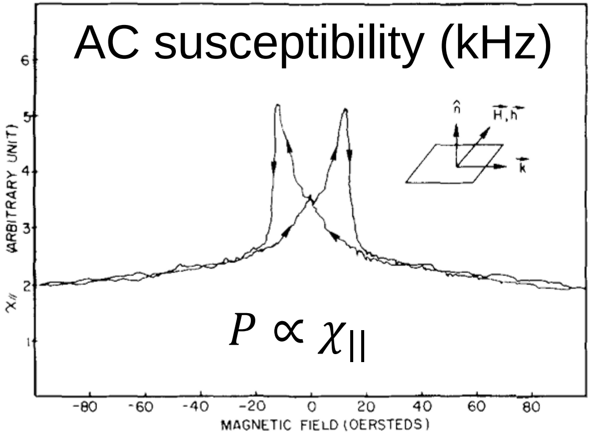


Ganguly *et al.*, JAP **47**, 2696 (1976)

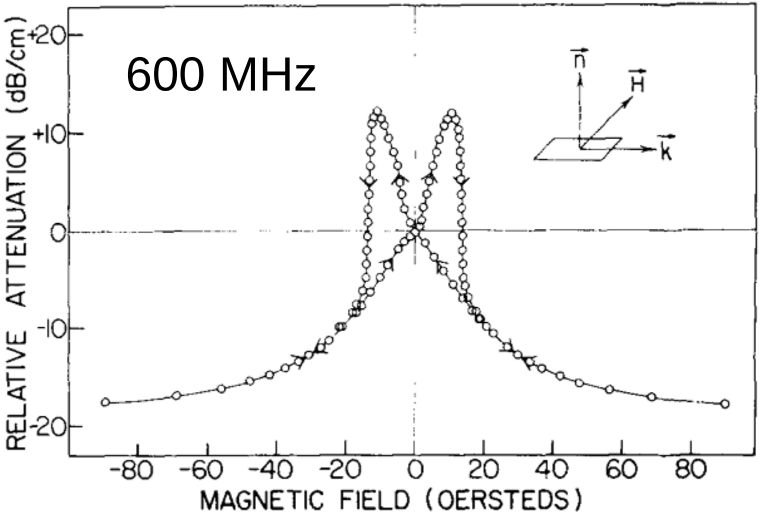
Brief history of sound and spin



$f_{SAW} \approx 600$ MHz



In-plane anisotropy Ni (0.2µm)/ $LiNbO_3$

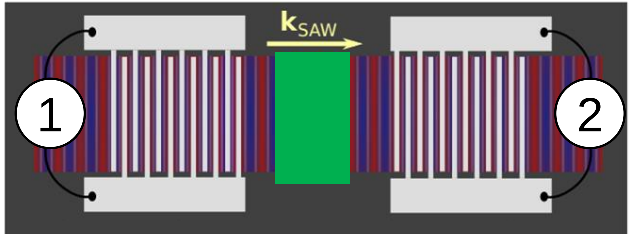


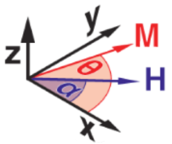
SAW absorption mimics low-frequency susceptibility $\chi_{||}$

SAW generates magneto-elastic “tickle-field” ***h***

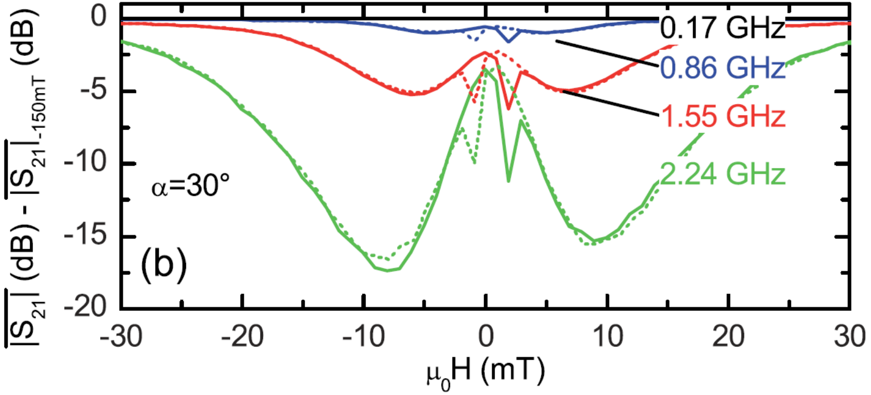
Feng *et al.*, JAP **53**, 177 (1982)

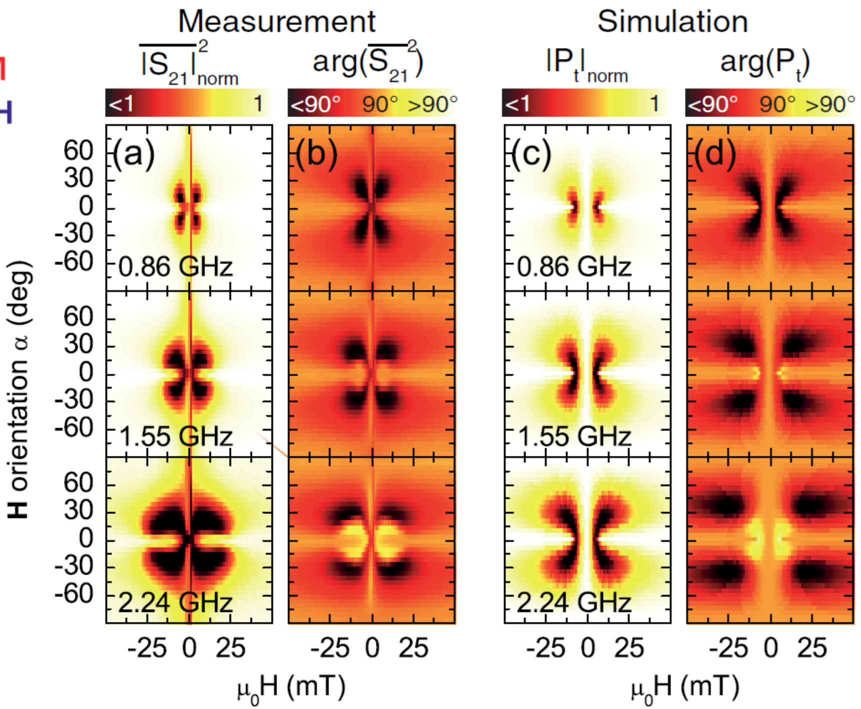
Brief history of sound and spin





$f_{\mathrm{SAW}} \approx 1\ \mathrm{GHz} = f_{\mathrm{FMR}}$





Acoustically driven magnetic resonance

MW *et al.*, Phys. Rev. Lett. **106**, 117601 (2011)

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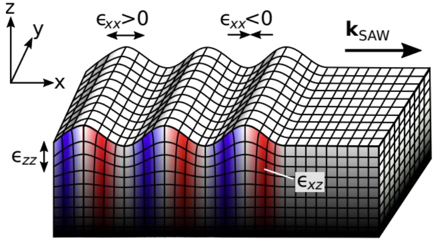
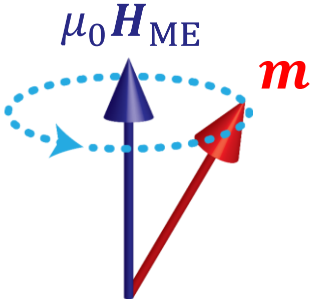
Symmetry of the magneto-acoustic interaction

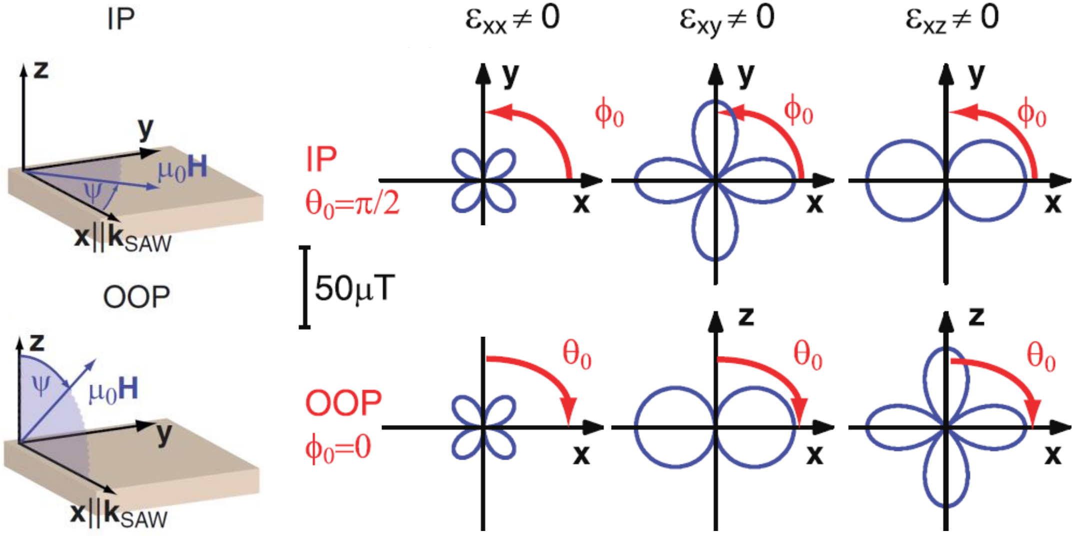
$$f_{\mathrm{ME}} = b_1 \varepsilon_{xx} m_x^2 + 2b_2\left[\varepsilon_{xy} m_x m_y + \varepsilon_{xz} m_x m_z\right]$$



$$\mu_0 \boldsymbol{H}_{\mathrm{ME}} = -\nabla_{\boldsymbol{m}} f_{\mathrm{ME}}$$



$$\boldsymbol{\tau} = \boldsymbol{m} \times \mu_0 \boldsymbol{H}_{\mathrm{ME}}$$

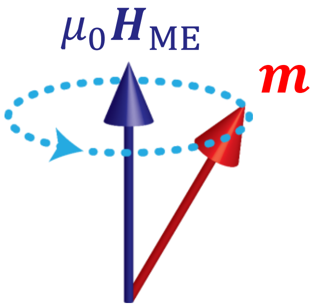


Dreher, MW *et al.*, Phys. Rev. B **86**, 134415 (2012)

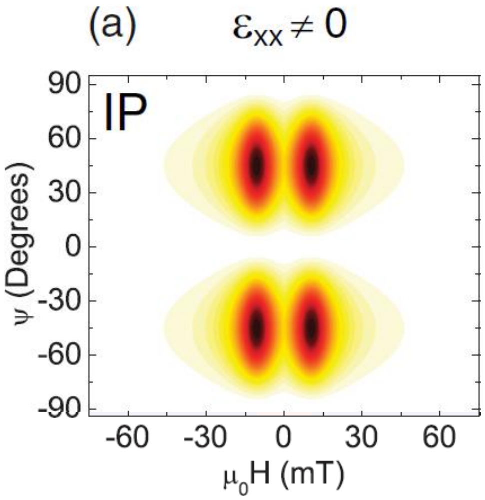
Symmetry of the magneto-acoustic interaction

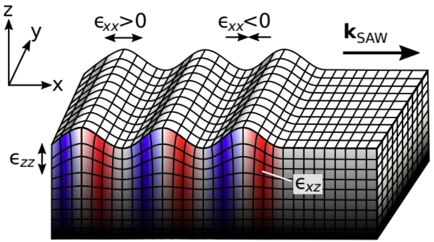
$$f_{\mathrm{ME}} = b_1 \varepsilon_{xx} m_x^2 + 2b_2\left[\varepsilon_{xy} m_x m_y + \varepsilon_{xz} m_x m_z\right]$$

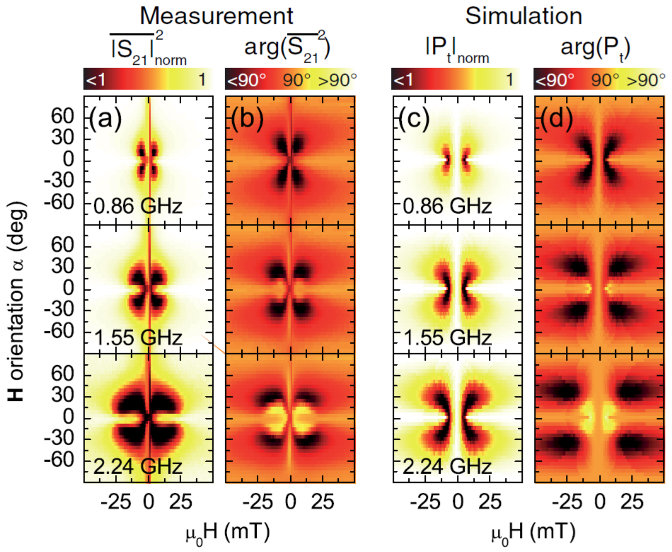
$$\mu_0 \boldsymbol{H}_{\mathrm{ME}} = -\nabla_{\boldsymbol{m}} f_{\mathrm{ME}}$$



$$\boldsymbol{\tau} = \boldsymbol{m} \times \mu_0 \boldsymbol{H}_{\mathrm{ME}}$$

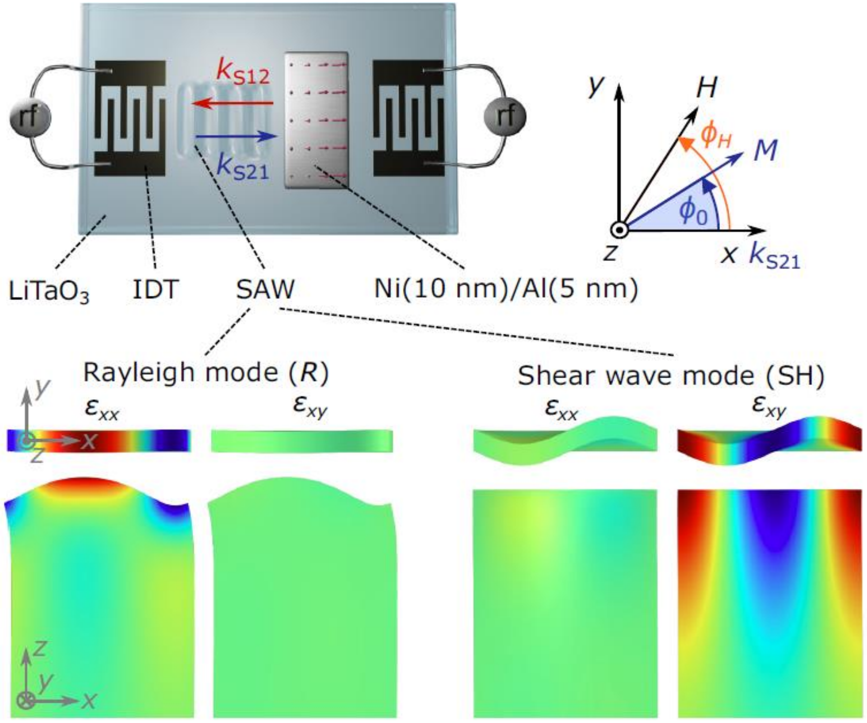


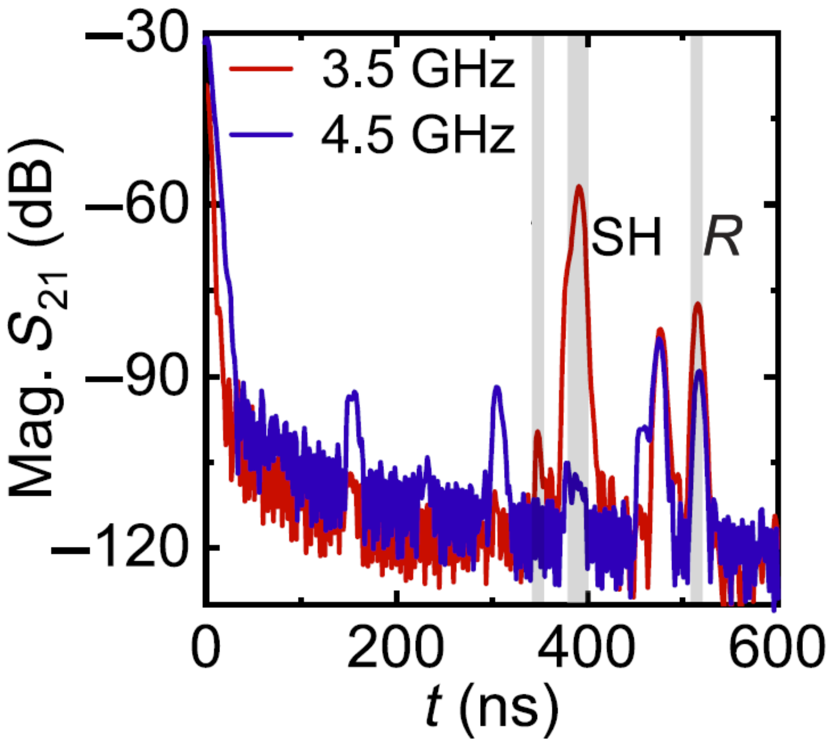




Dreher, MW *et al.*, Phys. Rev. B **86**, 134415 (2012)

Symmetry of the magneto-acoustic interaction

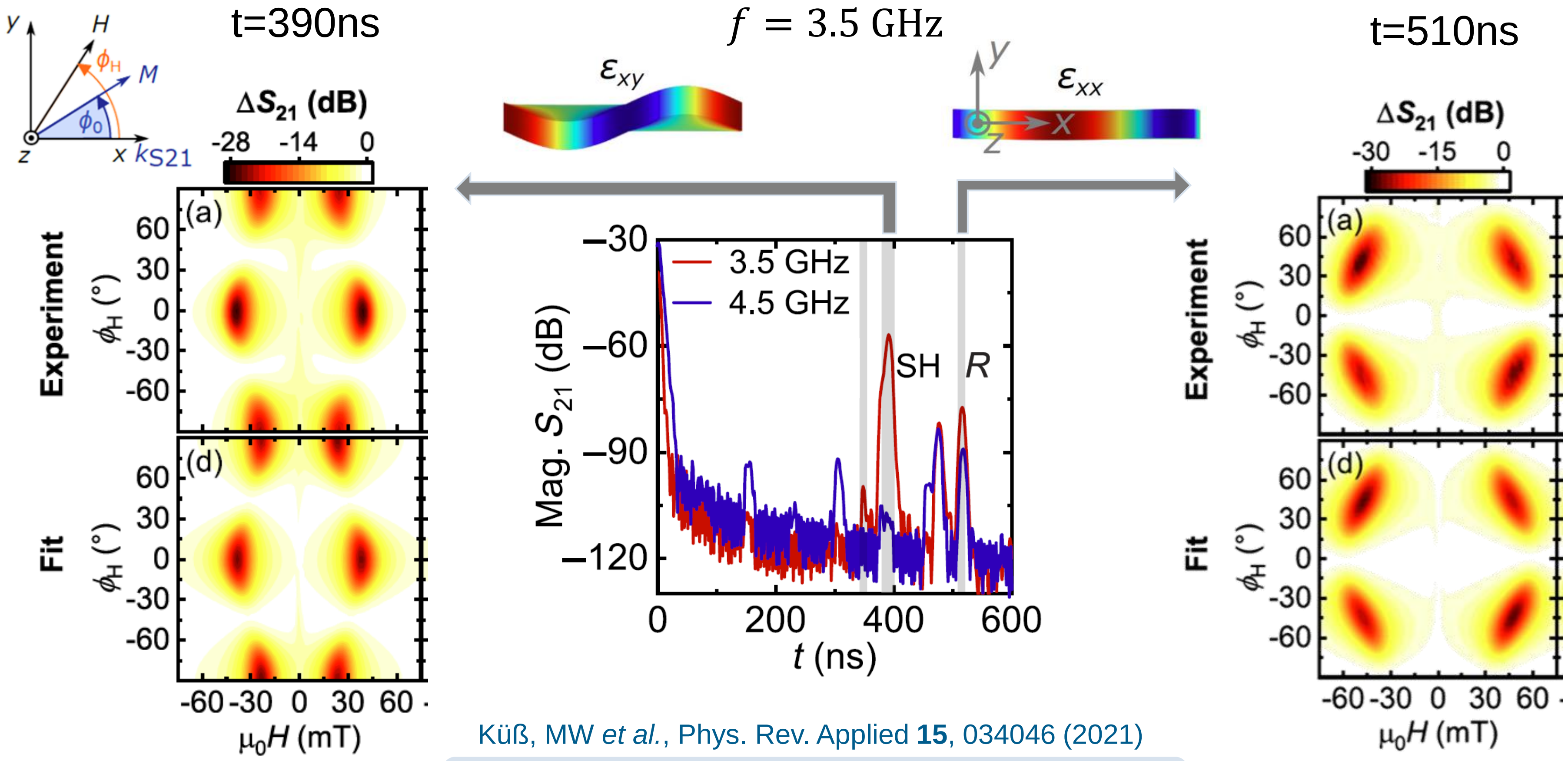




$$v_{\mathrm{R}} = 3105\,\frac{\mathrm{m}}{\mathrm{s}}$$

$$v_{\mathrm{SH}} = 4075\,\frac{\mathrm{m}}{\mathrm{s}}$$

Symmetry of the magneto-acoustic interaction

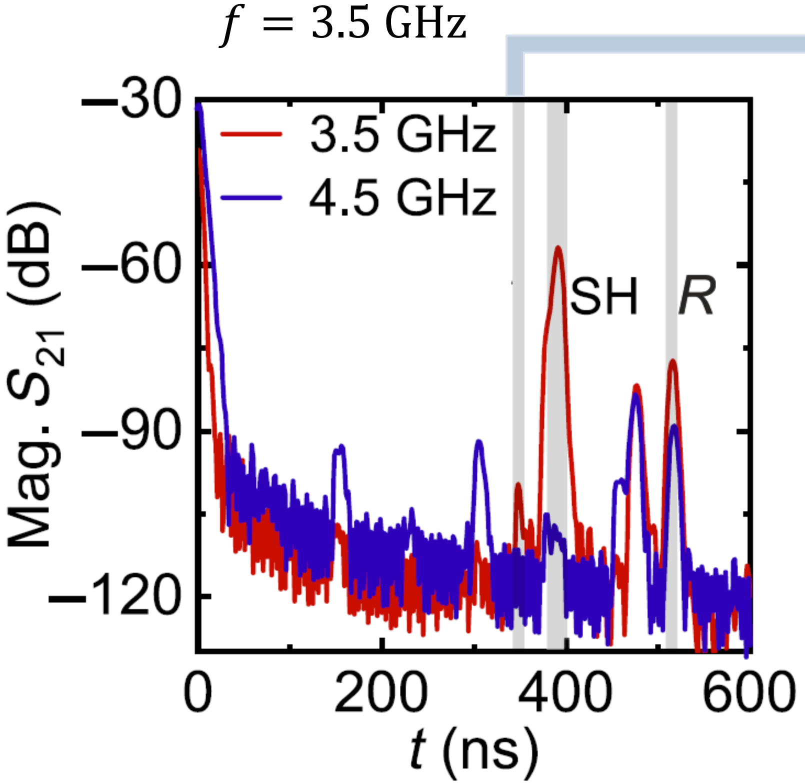


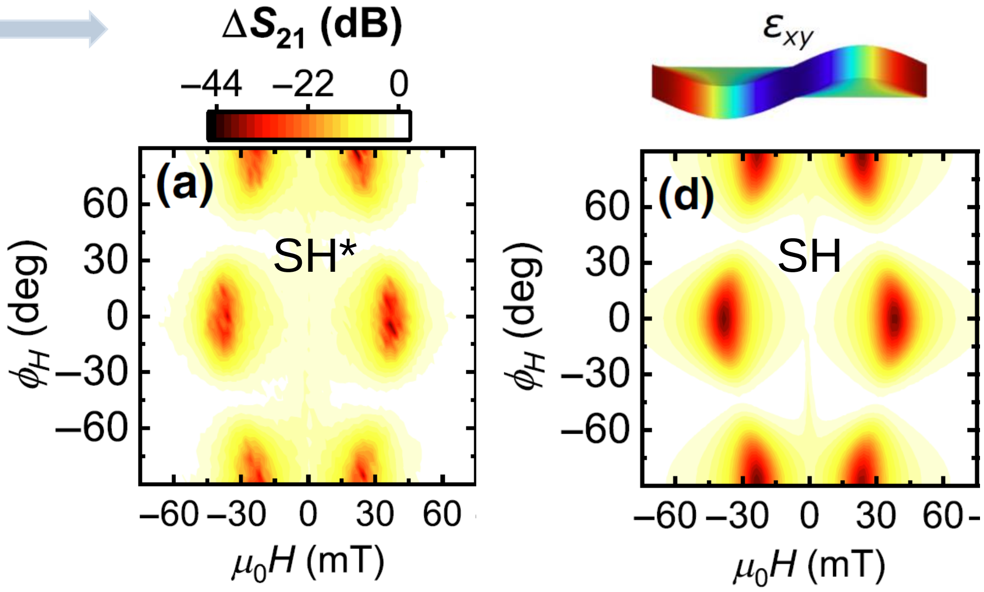
Küß, MW *et al.*, Phys. Rev. Applied **15**, 034046 (2021)

$\mu_0 h \propto \varepsilon_{xz} \cos(2\phi_0)$

$\mu_0 h \propto \varepsilon_{xx} \sin\phi_0 \cos\phi_0$

Symmetry of the magneto-acoustic interaction





Symmetry of unknown SAW-mode can be determined

Küß, MW *et al.*, Phys. Rev. Applied **15**, 034046 (2021)

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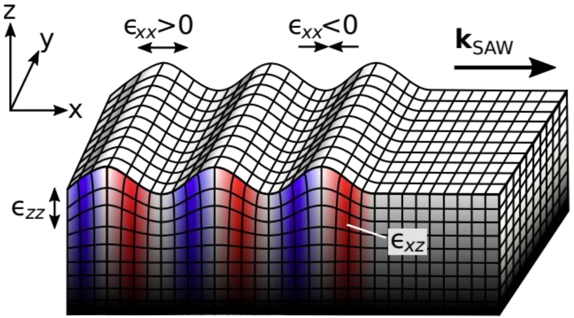
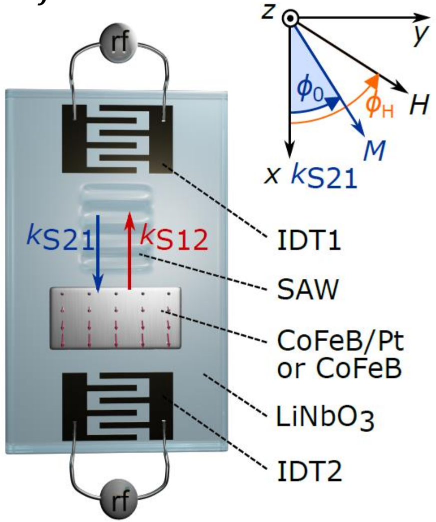
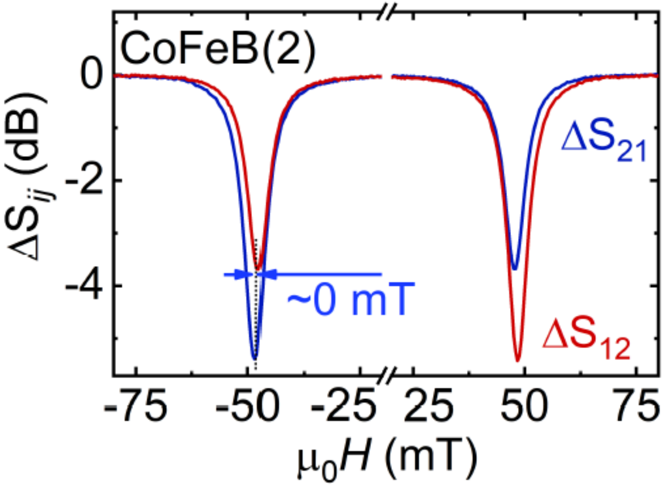
Magneto-acoustic coupling

Rayleigh-SAW:



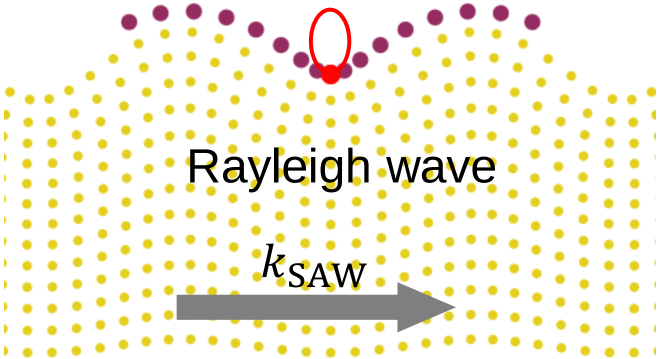
$f \approx 7$ GHz





Origin of amplitude non-reciprocity?
Are magneto-acoustic waves chiral?

Magneto-acoustic coupling

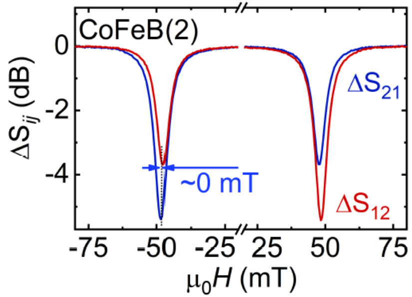


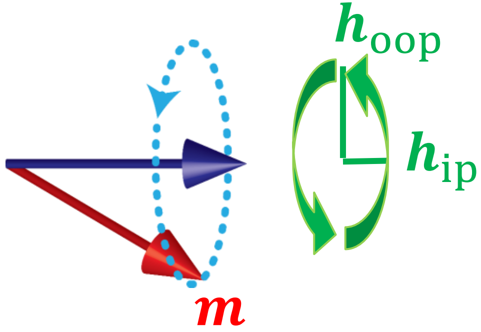
$$\varepsilon_{xx} = \frac{\partial u_x}{\partial x} \qquad \varepsilon_{xz} = \frac{1}{2}\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right)$$

$$\mu_0 h_{\mathrm{ip}} = 2\, b\, \varepsilon_{xx} \sin\phi_0 \cos\phi_0$$

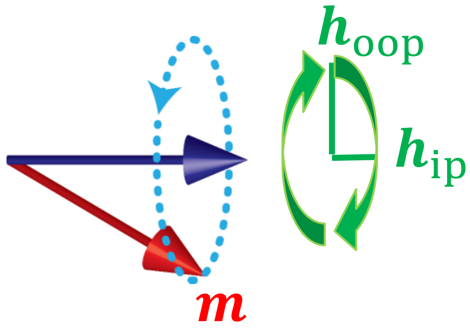
$$\mu_0 h_{\mathrm{oop}} = 2\, b\, \varepsilon_{xz} \cos\phi_0$$

Elliptically polarized driving field

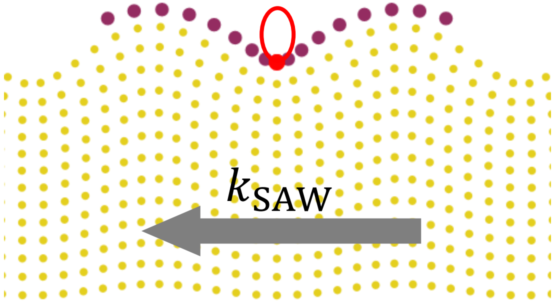




Good coupling



Poor coupling



Case closed?

Magneto-elasticity and magneto-rotation

$$\varepsilon_{xz} = \frac{1}{2}\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right) \rightarrow 0 \text{ in thin film limit}$$

Maekawa, Tachiki, AIP Conference Proceedings **29**, 542 (1976)

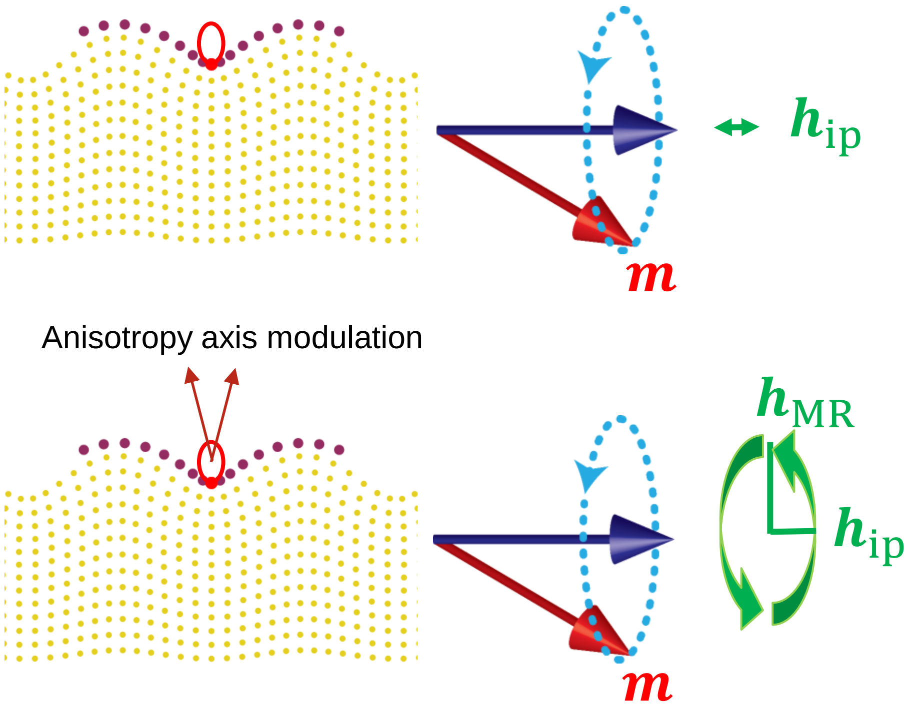
$$\mu_0 h_{oop} = 2\, b\, \varepsilon_{xz} \cos\phi_0 \rightarrow 0$$

$$\omega_{xz} = \frac{1}{2}\left(\frac{\partial u_x}{\partial z} - \frac{\partial u_z}{\partial x}\right) \neq 0 \text{ in thin film limit}$$

Magneto-rotation

$$\mu_0 h_{\mathrm{MR}} = -\frac{1}{2}\mu_0 M_{\mathrm{eff}} \omega_{xz} \cos\phi_0$$

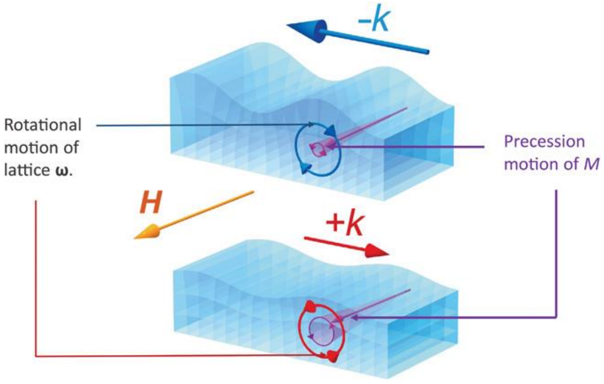
(does not require magneto-elastic medium!)

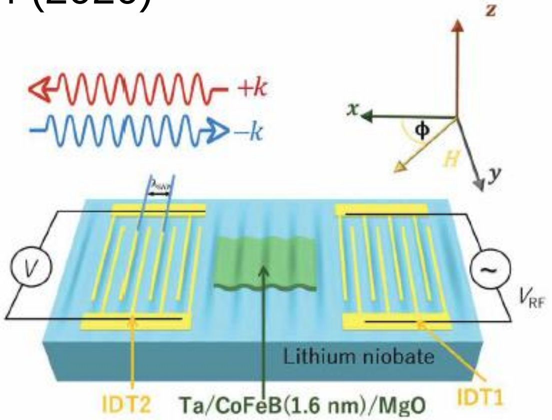


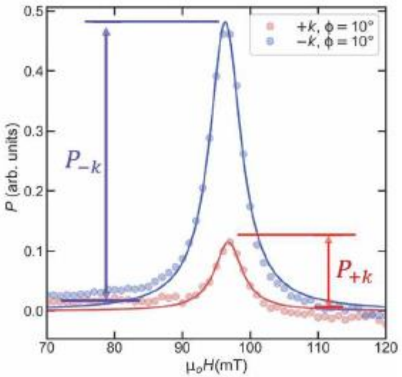
Magneto-rotation

Xu *et al.*, Science Advances **6**, eabb1724 (2020)

$f \approx 6$ GHz



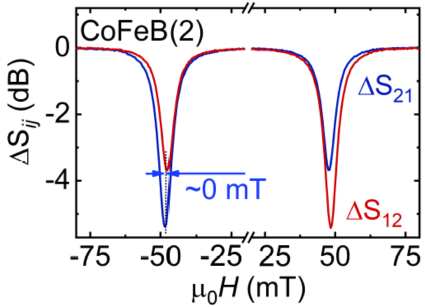




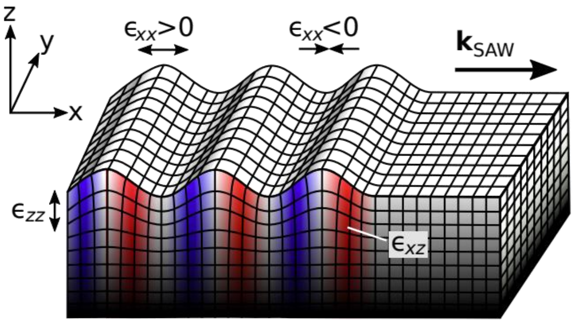
$$\mu_0 h_{\mathrm{ME}} = 2\, b\, \varepsilon_{xz} \cos \phi_0$$

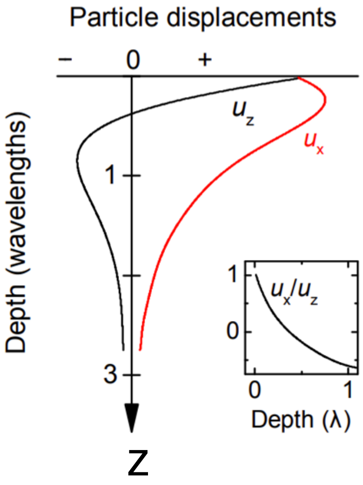
$$\mu_0 h_{\mathrm{MR}} = -\frac{1}{2} \mu_0 M_{\mathrm{eff}} \omega_{xz} \cos \phi_0$$

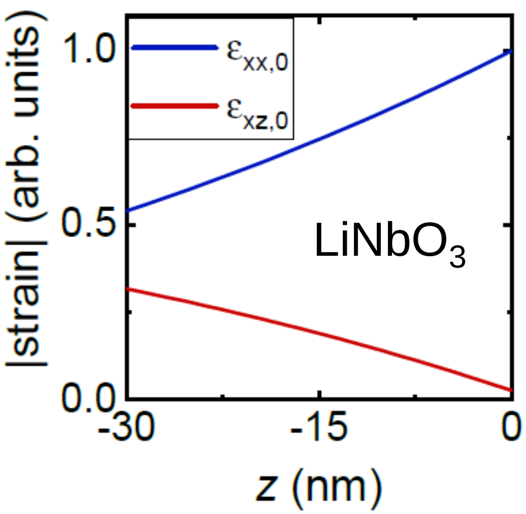
(only) magneto-rotation or (also) magneto-elasticity?

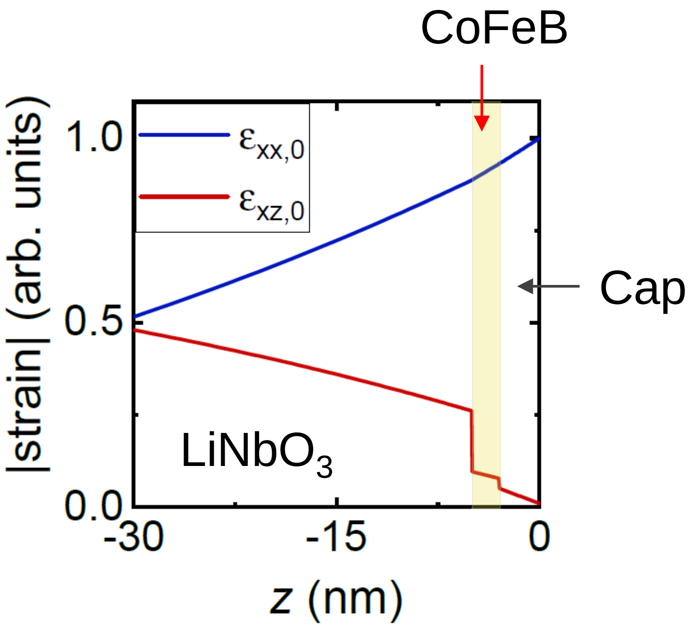


Finite element modeling of strains









ε_{xz}=0 for free $LiNbO_3$ surface

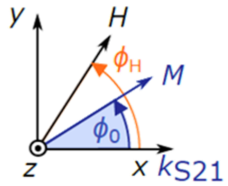
$\varepsilon_{xz} \neq 0$ in CoFeB

Quantitative Analytical Model (Rayleigh SAW)

From FEM

$$b_{xx} = b_1 \frac{\epsilon_{xx,0}}{|u_{z,0}||k|} \qquad b_{xz} = b_2 \frac{\epsilon_{xz,0}}{|u_{z,0}||k|} \qquad |u_{z,0}(x)| = \sqrt{\frac{1}{R\omega W}}\sqrt{P_{\mathrm{SAW}}(x)}$$

$$\mathbf{h}(x,t) = \begin{pmatrix} \tilde{h}_1 \\ \tilde{h}_2 \end{pmatrix} \sqrt{\frac{k^2}{R\omega W}}\sqrt{P_{\mathrm{SAW}}(x)}\, \mathrm{e}^{i(kx-\omega t)} \qquad \begin{pmatrix} \tilde{h}_1 \\ \tilde{h}_2 \end{pmatrix} = \begin{pmatrix} 2\frac{b_{xz}}{\mu_0}\cos\phi_0 \\ 2\frac{b_{xx}}{\mu_0}\cos\phi_0 \sin\phi_0 \end{pmatrix}$$



$$P_{\mathrm{abs}} = P_0 \left\{ 1 - \exp\left\{ -C \, \mathrm{Im}\left[\begin{pmatrix} \tilde{h}_1 \\ \tilde{h}_2 \end{pmatrix}^{*} \bar{\chi} \begin{pmatrix} \tilde{h}_1 \\ \tilde{h}_2 \end{pmatrix} \right] \right\} \right\} \qquad C = \frac{1}{2}\mu_0 V_0 \left(\frac{k^2}{RW}\right)$$

$$\bar{\chi}^{-1} = \frac{1}{M_s}\begin{pmatrix} \chi^I_{11} & \chi^I_{12} \\ \chi^I_{21} & \chi^I_{22} \end{pmatrix} \qquad G_0 = \frac{1 - e^{-|k|d}}{|k|d}$$

$$\chi^I_{11} = H\cos(\phi_0 - \phi_{\mathrm{H}}) + \frac{2A}{\mu_0 M_s}k^2 + M_s G_0 - H_k + H_{\mathrm{ani}}\cos^2(\phi_0 - \phi_{\mathrm{ani}}) - i\frac{\alpha\omega}{\mu_0\gamma}$$

$$\chi^I_{12} = -\chi^I_{21} = i\left(\frac{\omega}{\mu_0\gamma} + \frac{2D_{\mathrm{eff}}}{\mu_0 M_s}k\sin(\phi_0)\right)$$

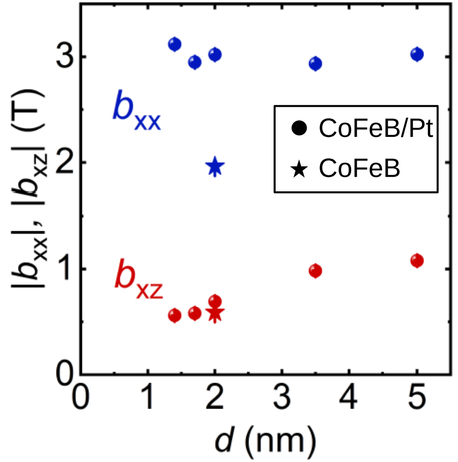
$$\chi^I_{22} = H\cos(\phi_0 - \phi_{\mathrm{H}}) + \frac{2A}{\mu_0 M_s}k^2 + M_s(1 - G_0)\sin^2(\phi_0) + H_{\mathrm{ani}}\cos(2(\phi_0 - \phi_{\mathrm{ani}})) - i\frac{\alpha\omega}{\mu_0\gamma}$$

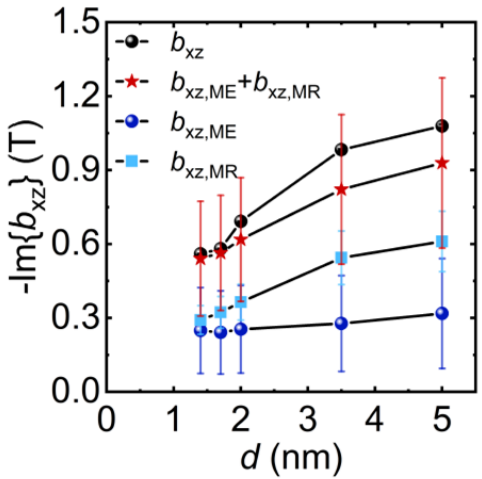
Model considers:
- Dipolar
- Exchange
- DMI
- Anisotropy
- Damping

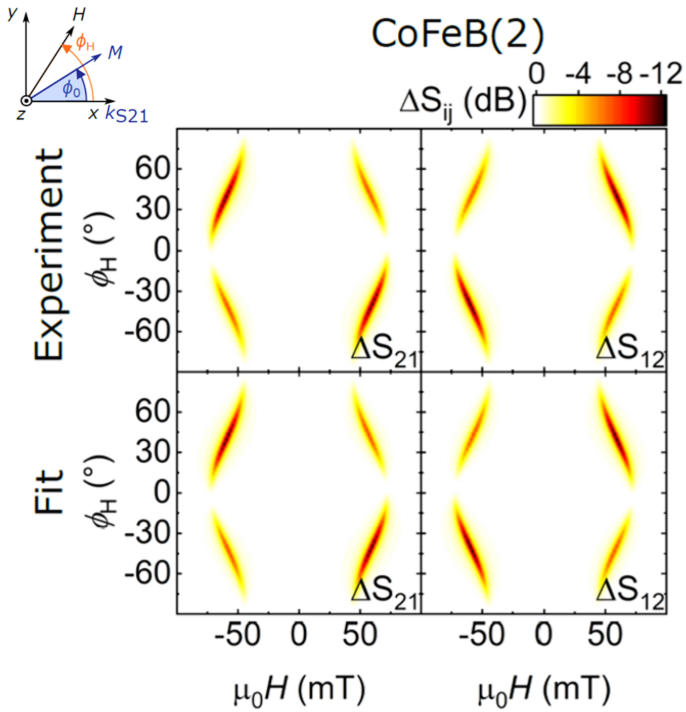
Küß, MW *et al.* PRL **125**, 217203 (2020)

P. G. Gowtham, JAP **118**, 233910 (2015)

Quantitative modeling







Küß, MW *et al.* PRL **125**, 217203 (2020)

Magneto-elastic:

$$\varepsilon_{xz} = \frac{1}{2}\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right)$$

$$b_{xz,\mathrm{ME}} = b_2 \varepsilon_{xz}$$

Magneto-rotation:

$$\omega_{xz} = \frac{1}{2}\left(\frac{\partial u_x}{\partial z} - \frac{\partial u_z}{\partial x}\right)$$

$$b_{xz,\mathrm{MR}} = -\frac{1}{2}\mu_0 M_{\mathrm{eff}} \omega_{xz}$$

Contents

- Introduction
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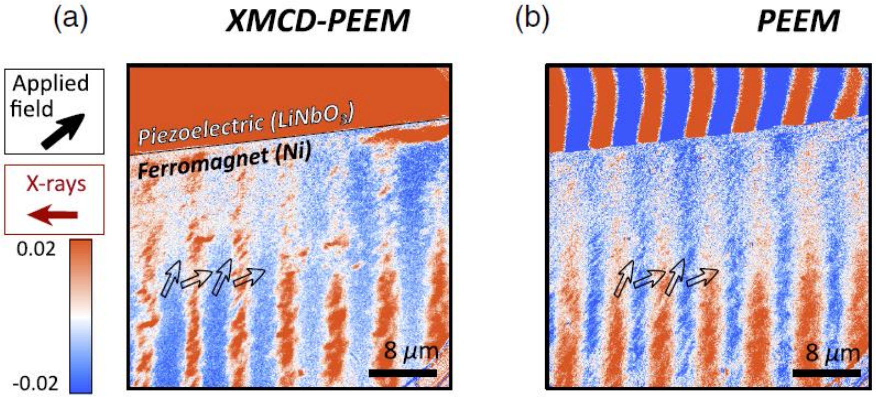
Sound-spin-waves

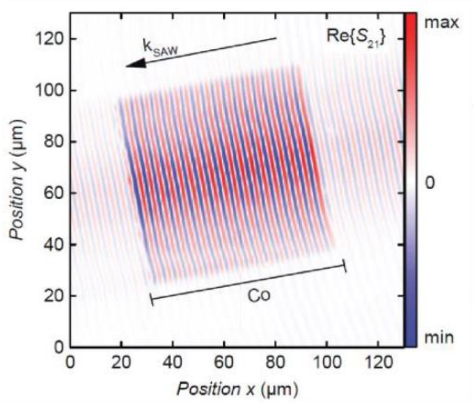
$f = 500$ MHz



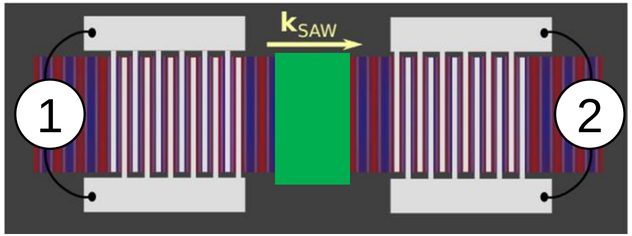
Casals *et al.*, Phys. Rev. Lett. **124**, 137202 (2020).

$k_{SAW} = k_{SW}$

FR-MOKE

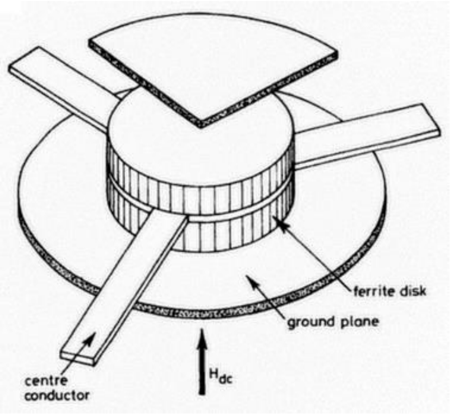


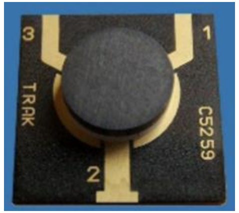
Liensberger, MW *et al.*, IEEE Mag. Lett. **10**, 5503905 (2019).

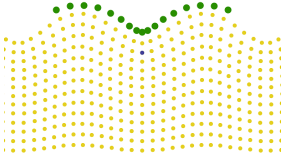


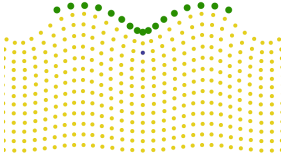
We do not excite FMR $(k = 0)$ but spin waves

Non-reciprocal microwave devices



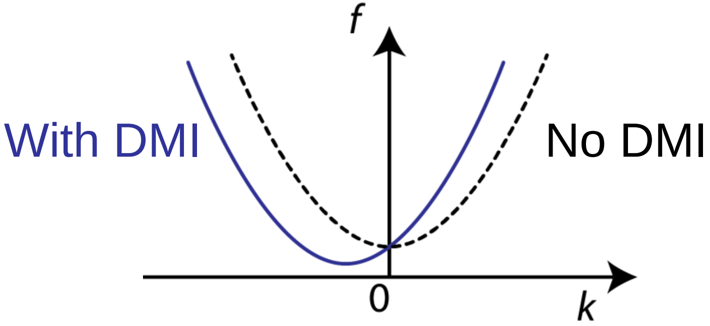






How to improve non-reciprocity of magneto-acoustic devices?

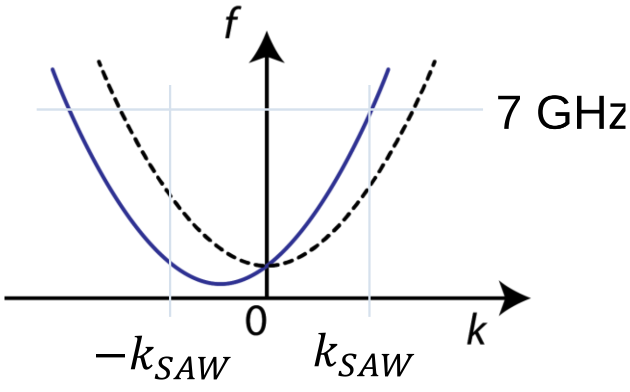
Non-reciprocal spin wave dispersion

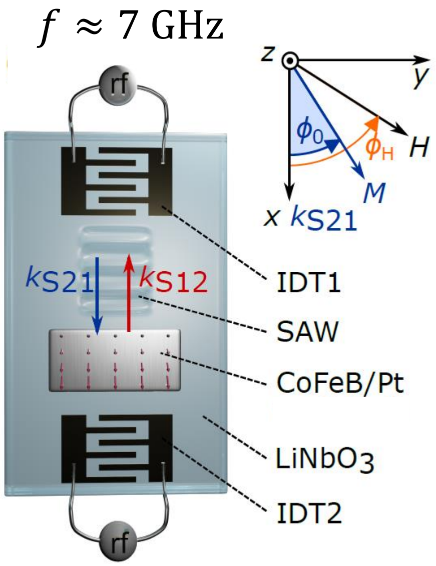


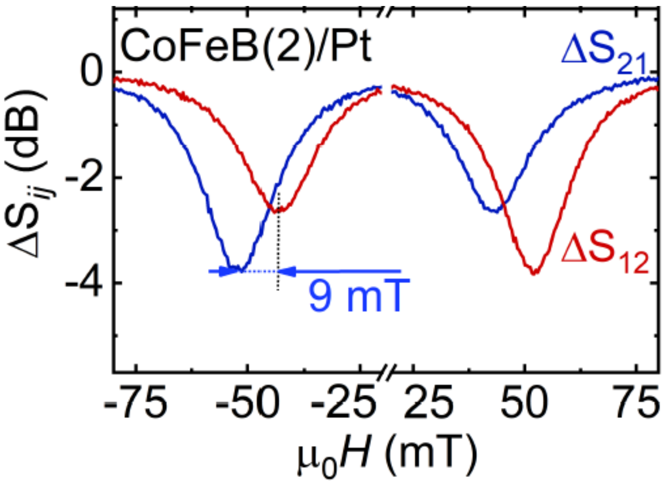
Moon *et al.*, PRB **88**, 184404 (2013)

Nembach, MW *et al.*, Nat Phys **11**, 825 (2015)

Non-reciprocal spin wave dispersion



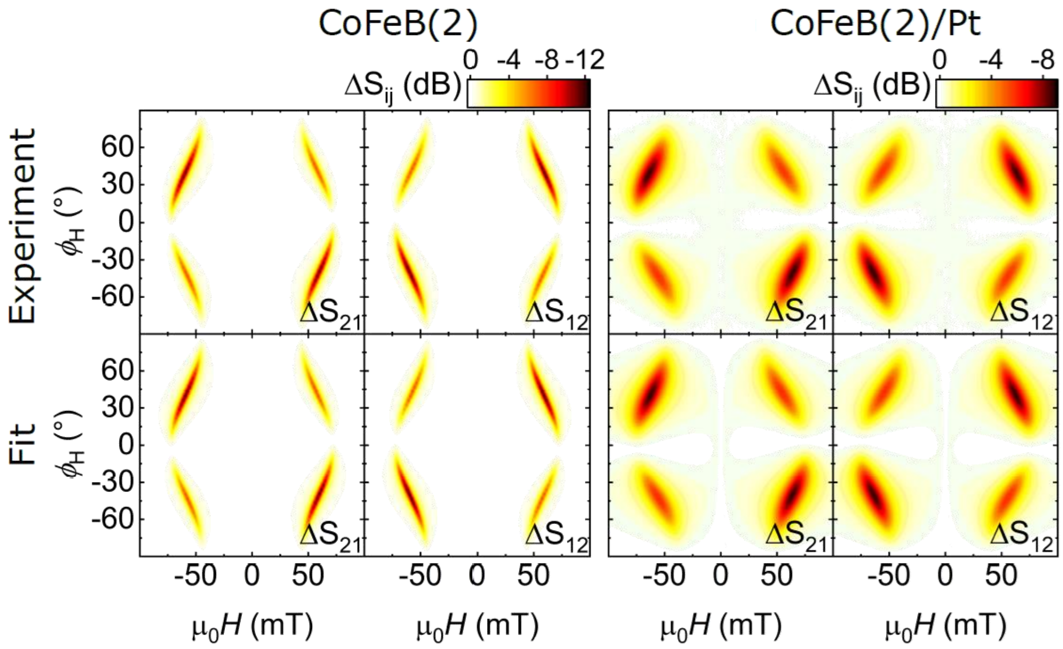


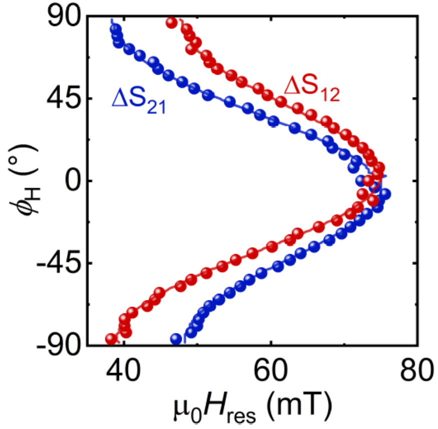


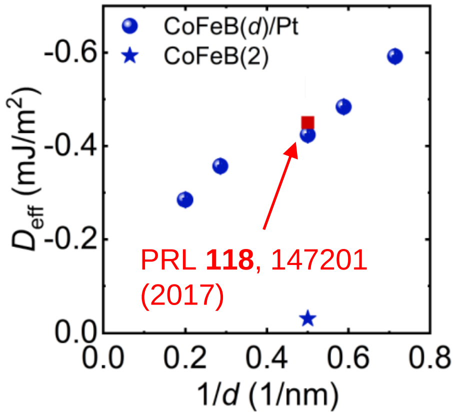
$$f = \frac{\mu_0 \gamma}{2\pi}\sqrt{H_{11}H_{22}} - \frac{\gamma}{\pi M_s} D_{\text{eff}}\, k \sin(\phi_0)$$

Spin-wave frequency non-reciprocity due to DMI

$$f = \frac{\mu_0 \gamma}{2\pi}\sqrt{H_{11} H_{22}} - \frac{\gamma}{\pi M_s} D_{\text{eff}}\, k \sin(\phi_0)$$

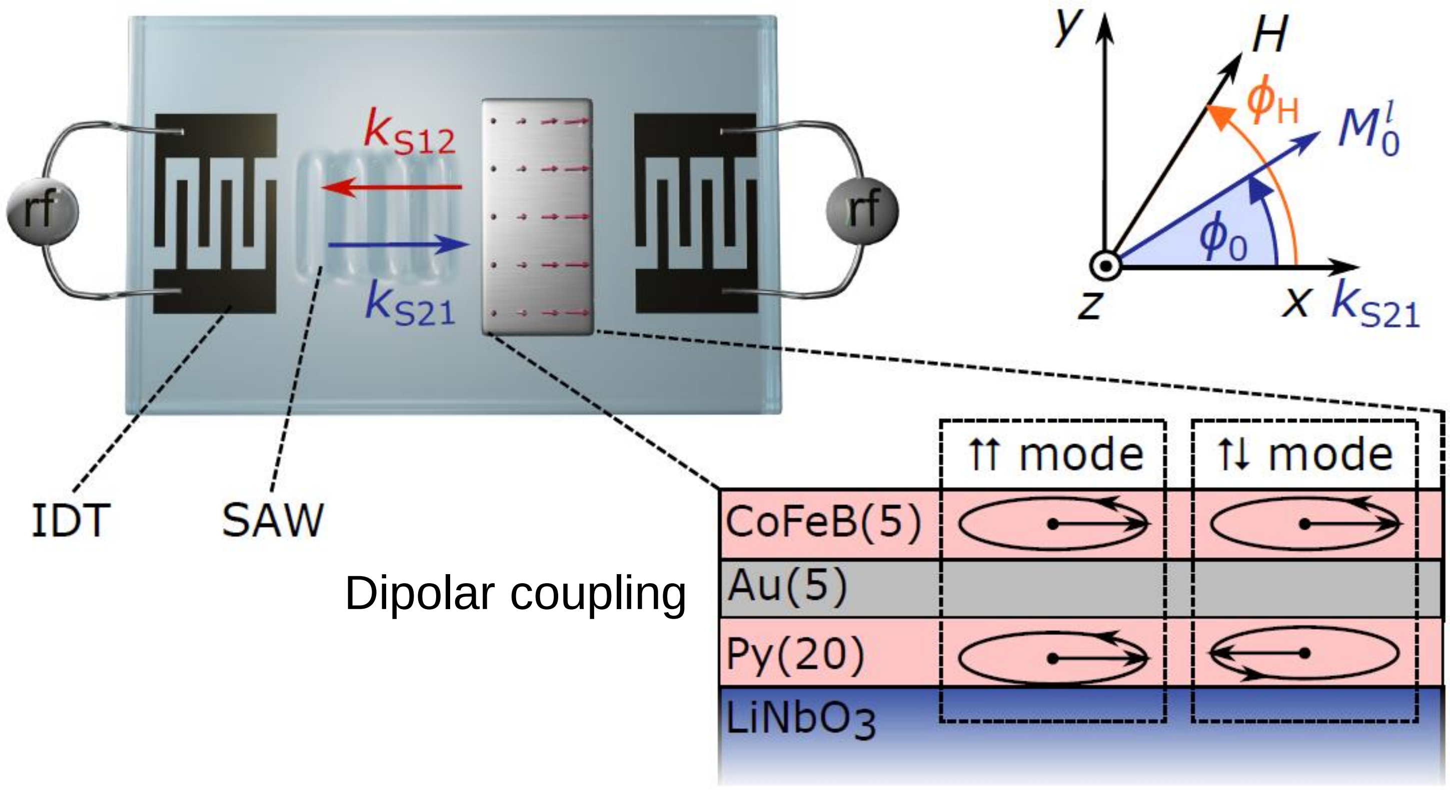






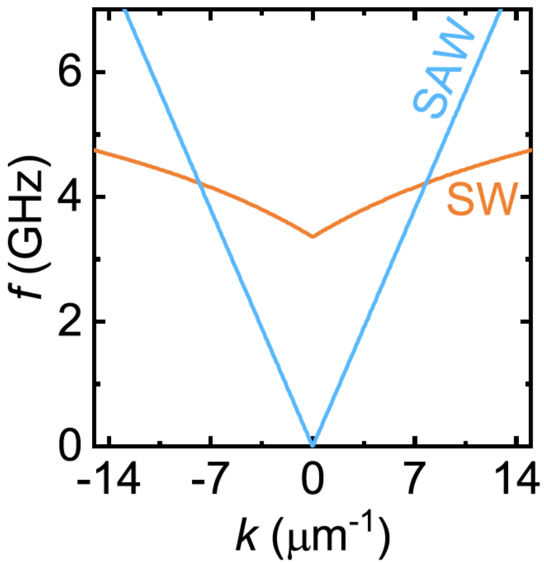
Küß, MW *et al.* PRL **125**, 217203 (2020)

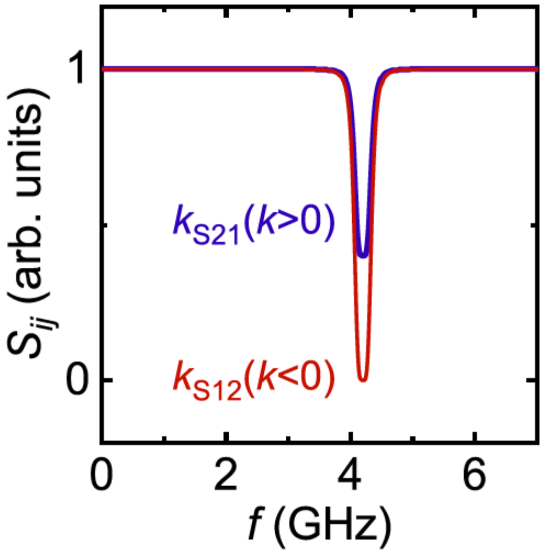
Magneto-elastic waves in bilayers

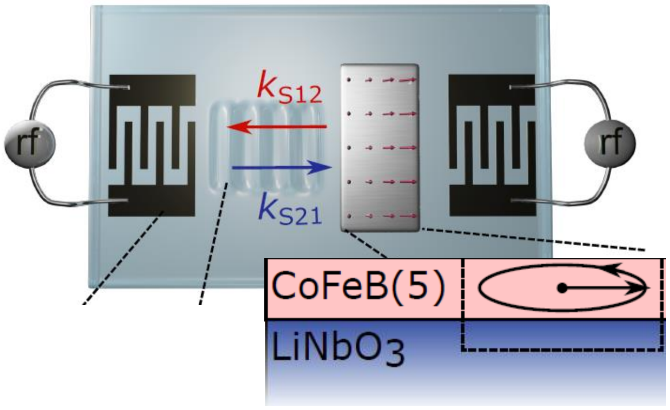


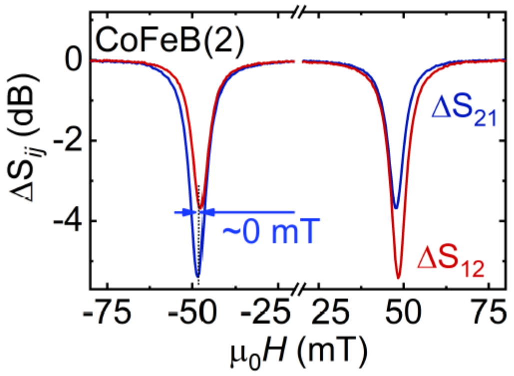
Dipolar coupling

Single layer

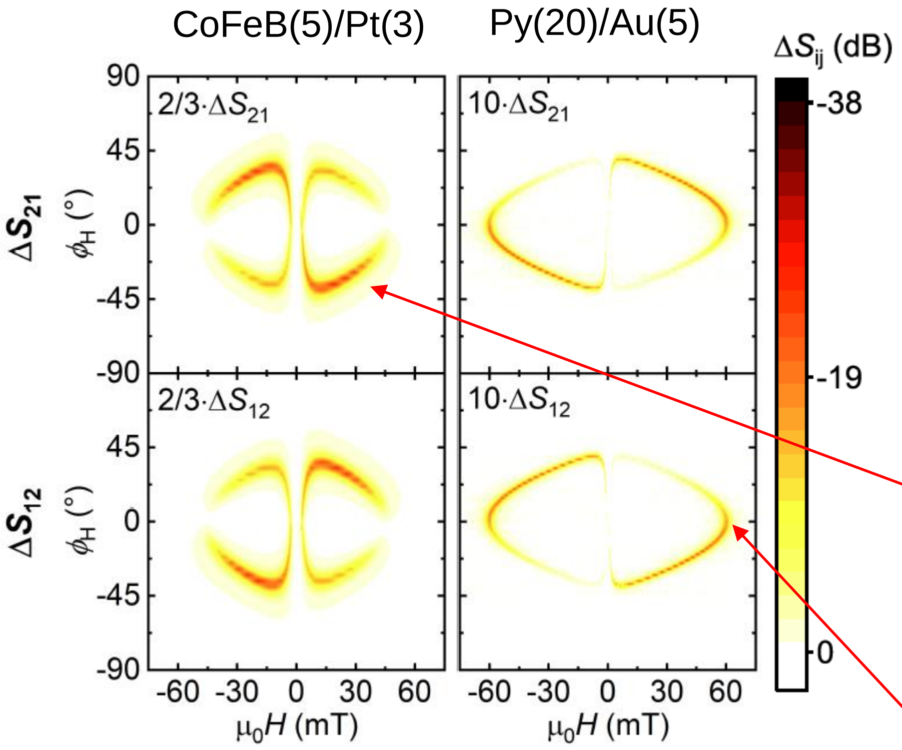


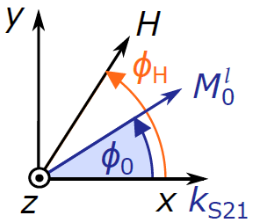


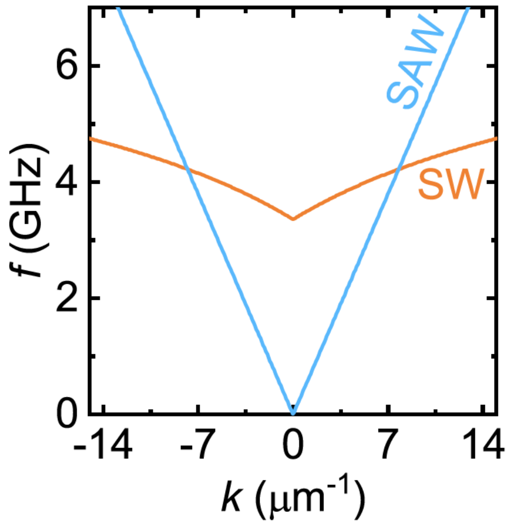




Single layers







magneto-elastic

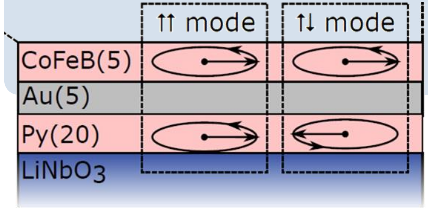
$$\mu_0 h_{\mathrm{ip}} = 2 b_{xx} \sin\phi_0 \cos\phi_0$$

$$\mu_0 h_{\mathrm{oop}} = 2 b_{xz} \cos\phi_0$$

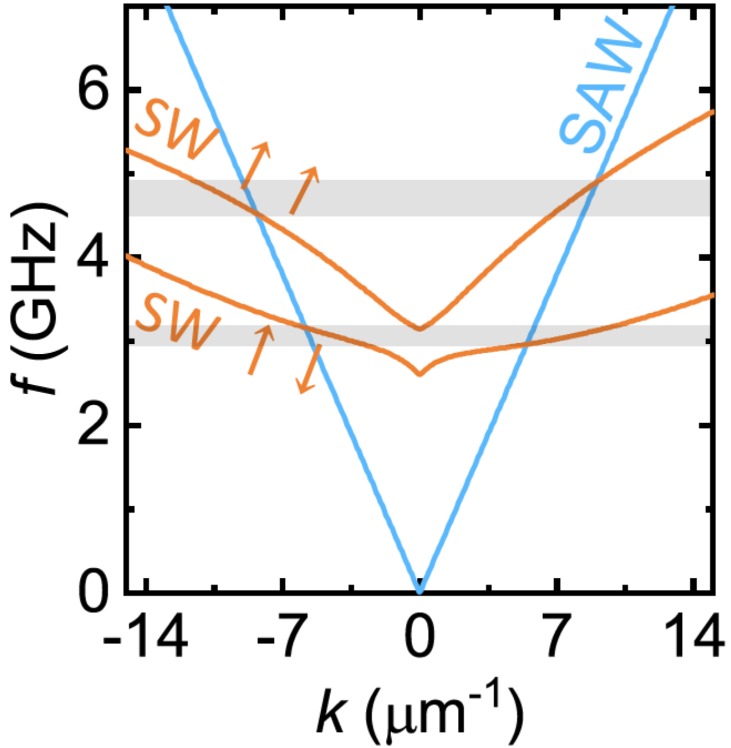
magneto-rotation

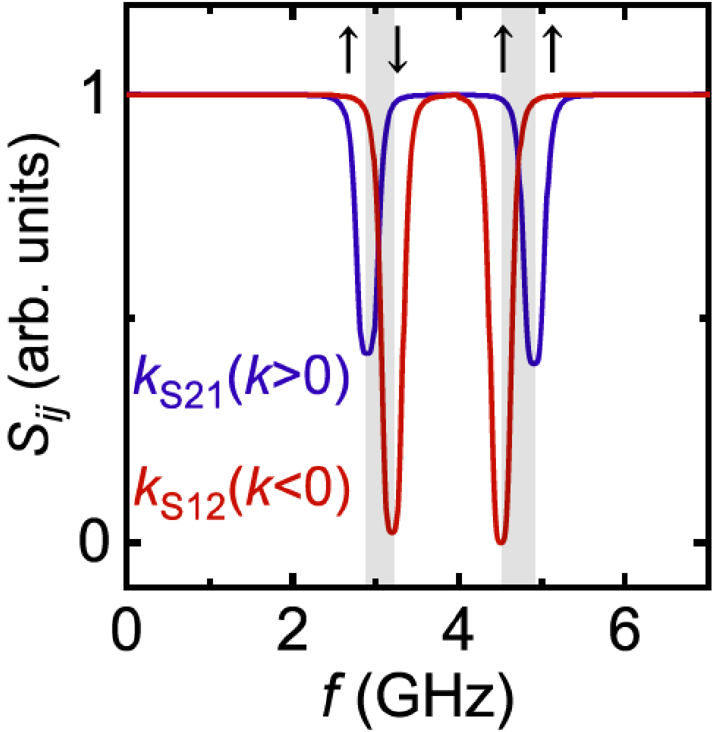
Küß, MW *et al.*, Phys. Rev. Applied **15**, 034060 (2021).

Bilayer expectations



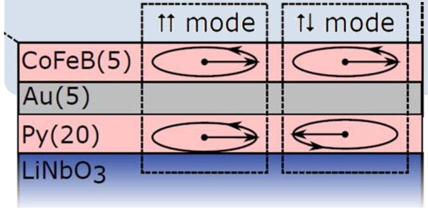
Bilayer spin wave dispersion: Gallardo *et al.*, Phys. Rev. Applied **12**, 034012 (2019).

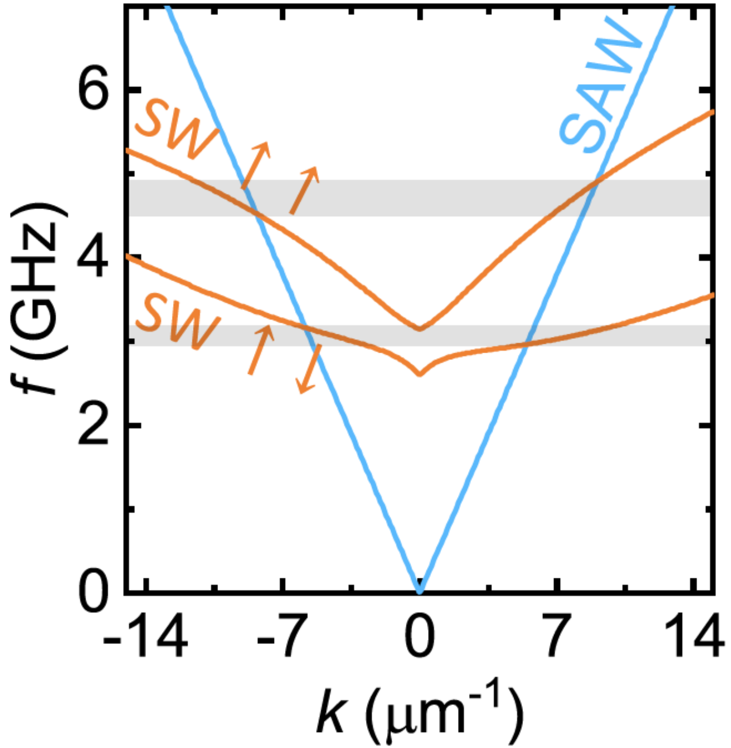


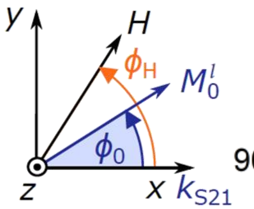


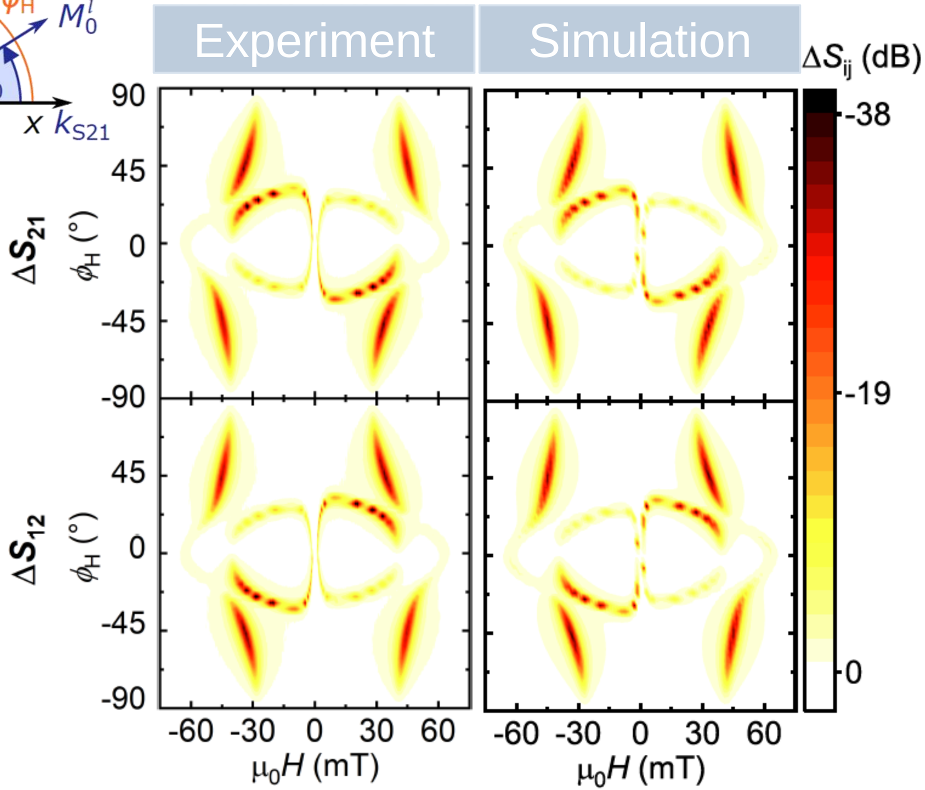
Küß, MW *et al.*, Phys. Rev. Applied **15**, 034060 (2021).

Bilayer experiment & simulation



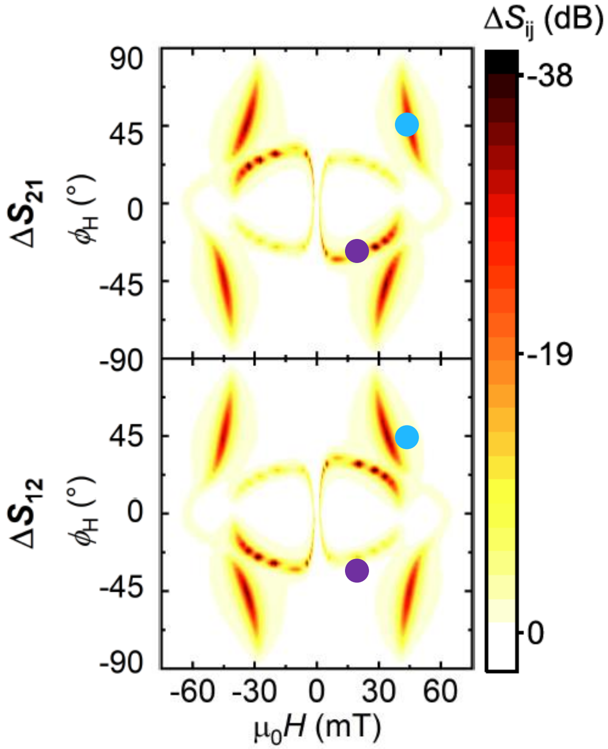


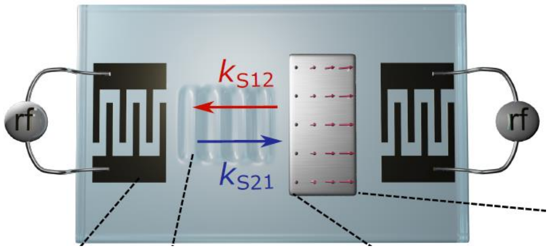


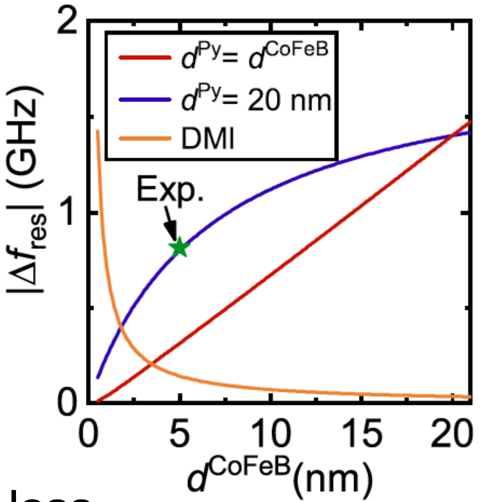


Küß, MW *et al.*, Phys. Rev. Applied **15**, 034060 (2021).

Optimizing non-reciprocity







Non-reciprocity
$\Delta S > 35\ \mathrm{dB}$

Magneto-acoustic insertion loss
$\Delta IL \approx 1\ \mathrm{dB}$

Achievable SAW insertion loss $IL_0 < 4\ \mathrm{dB}$ [APL **110**, 073105 (2017)]

Küß, MW *et al.*, Phys. Rev. Applied **15**, 034060 (2021).

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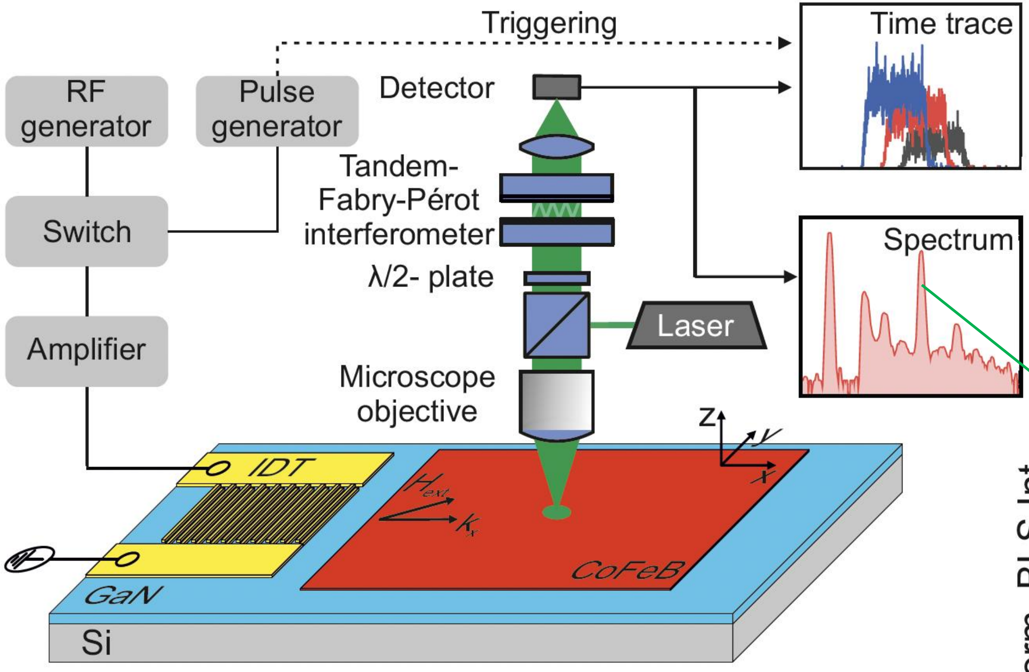
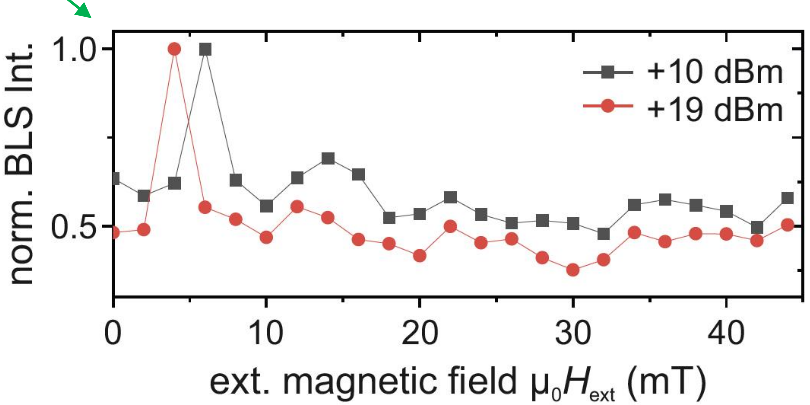
Non-linear magneto-acoustics

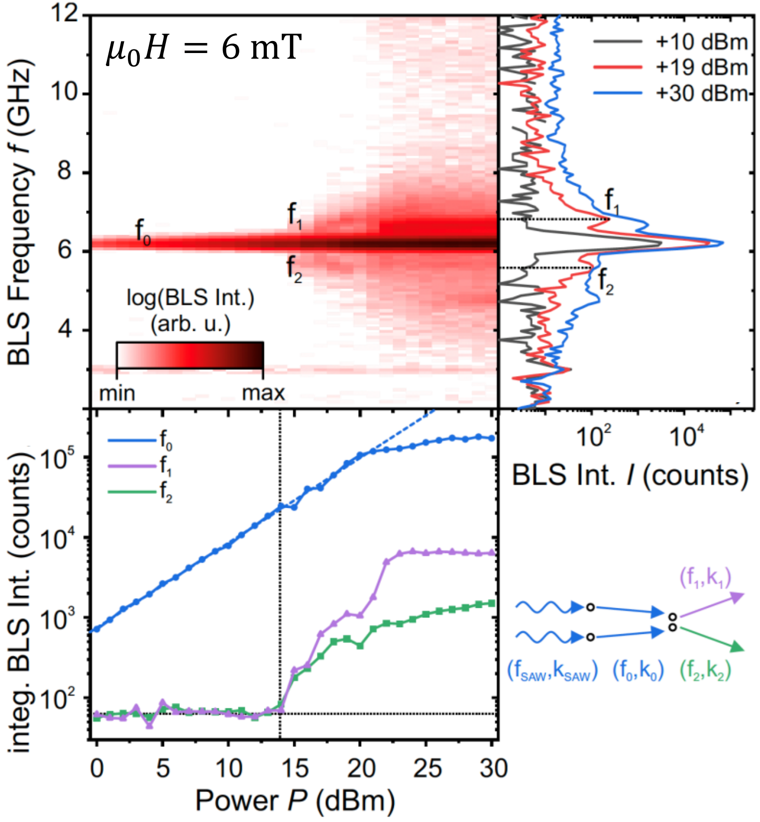


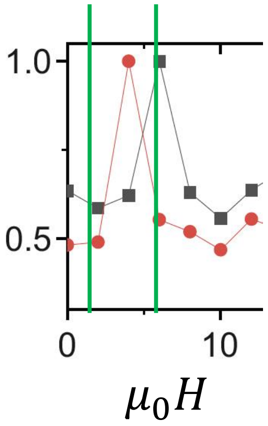
Microfocused Brillouin Light-Scattering

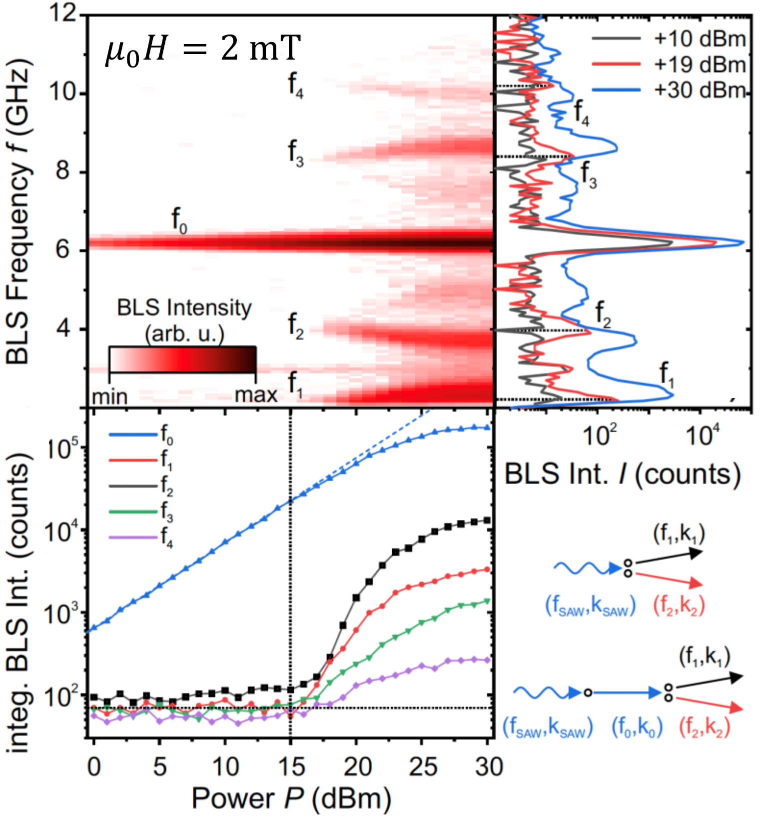
Magnon signal at $f_{SAW} \approx 6\ \mathrm{GHz}$



Non-linear magneto-acoustics







Theory: R. Verba, Institute of Magnetism, Kyiv, Ukraine

Geilen, MW *et al.*, arXiv:2201.04033 (2022)

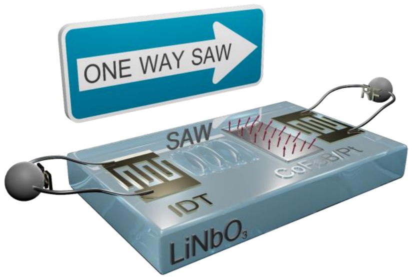
Summary

Magneto-acoustic interaction due to
- Magneto-elasticity
- Magneto-rotation

Acoustic spin-wave spectroscopy
- High wave-vectors
- High sensitivity

Küß, MW *et al.* Phys. Rev. Lett. **125**, 217203 (2020)

Open positions (PhD & postdoc)



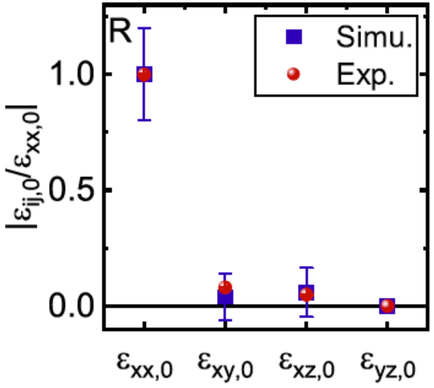
Strong non-reciprocity
- Miniaturized device with low insertion loss
- Established technological platform

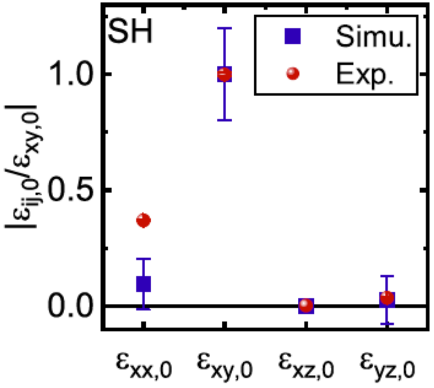
Küß, MW *et al.*, Phys. Rev. Applied **15**, 034060 (2021)

Symmetry of magneto-acoustic interaction can be controlled by choice of SAW-mode
Küß, MW *et al.*, Phys. Rev. Applied **15**, 034046 (2021)

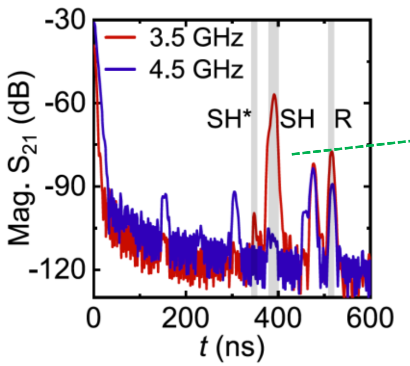
Nonlinear magneto-acoustics (Geilen, MW *et al.*, arXiv:2201.04033 (2022))

Extracted strain components

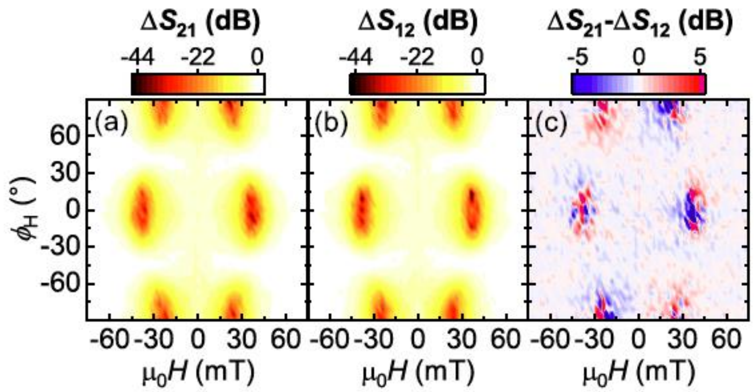




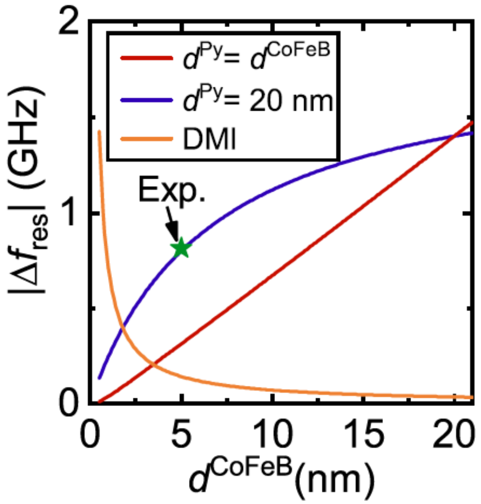
- Good agreement
- Magneto-elastic symmetry can be used to determine strain components

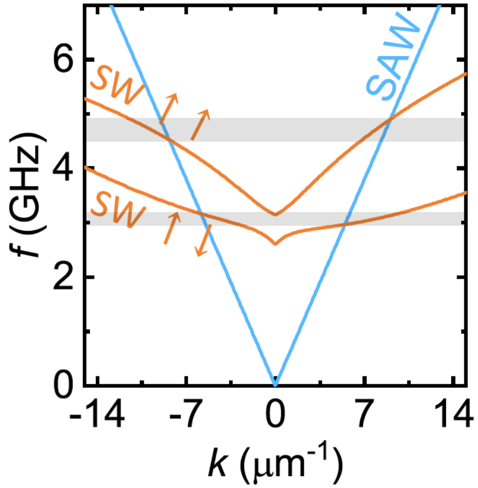


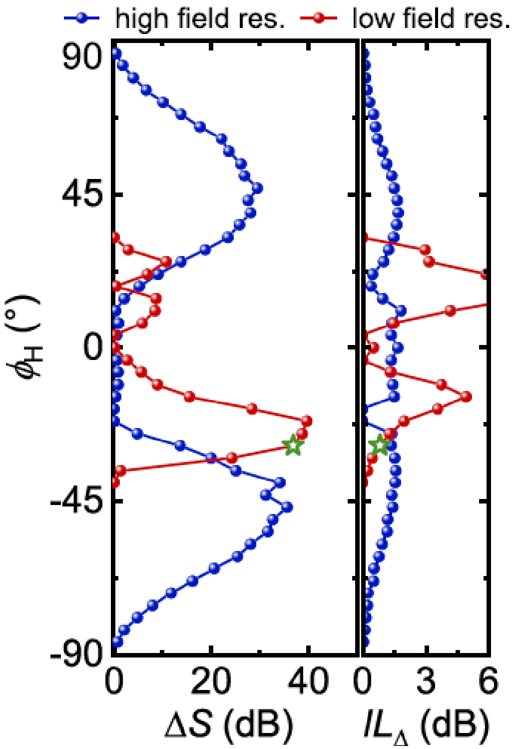
Unknown mode SH* has shear horizontal symmetry

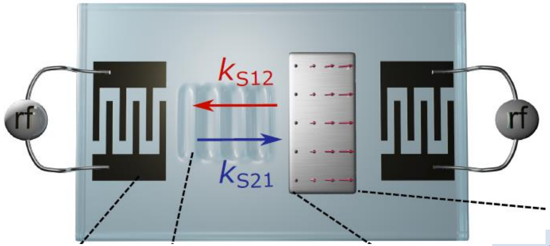


Optimizing non-reciprocity









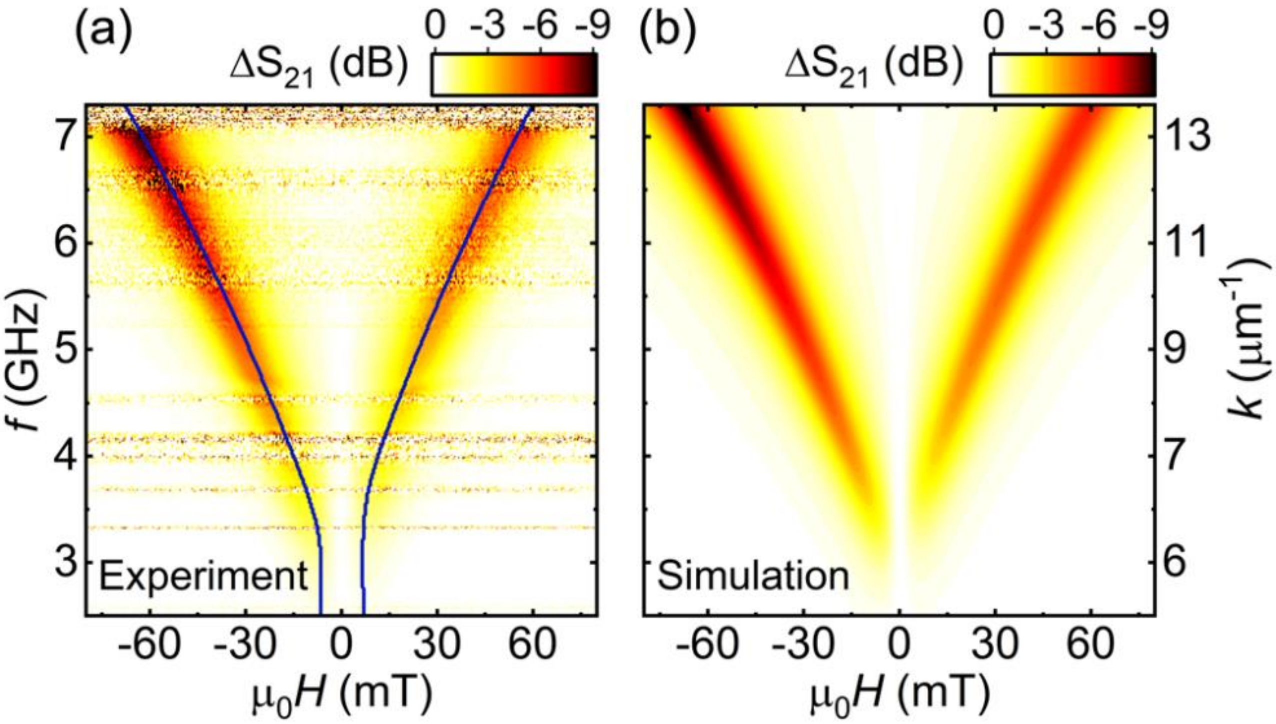
Achievable SAW insertion loss $IL_0 \approx 4\ \mathrm{dB}$ [APL **110**, 073105 (2017)]

Fit results

	CoFeB(1.4)/Pt	CoFeB(1.7)/Pt	CoFeB(2)/Pt	CoFeB(3.5)/Pt	CoFeB(5)/Pt	CoFeB(2)
l_{f} (μm)	1250	1250	1250	750	750	1250
f (GHz)	6.87	6.87	6.88	6.88	6.77	6.9
M_{s} (kA/m)	1320	1306	1262	1534	1504	1125
ϕ_{ani} (°)	88.8	90.5	87.7	83.9	83.2	88.9
$\mu_0 H_{\mathrm{ani}}$ (mT)	8.4	7.2	7.1	4.2	4.8	6.0
H_{k} (kA/m)	837.9 ± 0.07	772.4 ± 0.05	659.5 ± 0.05	629.3 ± 0.1	483.8 ± 0.2	505 ± 0.01
D_{eff} (μJ/m^2)	-592 ± 1.1	-484 ± 0.7	-424 ± 0.7	-357 ± 1.3	-285 ± 2.3	-32 ± 0.1
α (10^{-3})	55.3 ± 0.05	45.8 ± 0.03	37.6 ± 0.03	20.7 ± 0.04	17.8 ± 0.05	10.7 ± 0.01
$-b_{xx}$ (T)	3.119 ± 0.001	2.948 ± 0.001	3.021 ± 0.001	2.936 ± 0.002	3.025 ± 0.003	1.963 ± 0.001
$-b_{xz}$ (T)	$i0.560$	$i0.581$	$i0.692$	$i0.983$	$i1.079$	$i0.589$
Error(b_{xz}) (T)	$\pm i0.001$	$\pm i0.0019$	$\pm i0.0019$	$\pm i0.004$	$\pm i0.007$	$\pm i0.001$

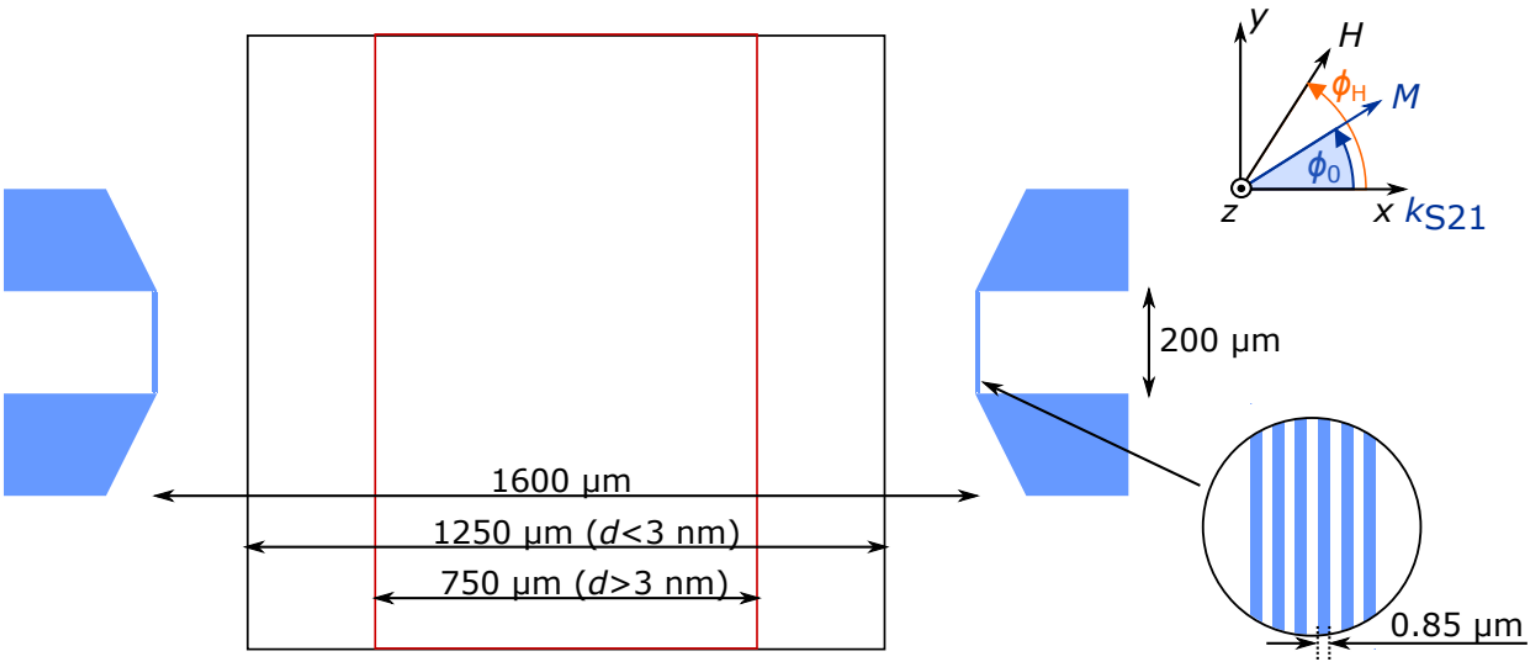
Küß, MW *et al.* PRL **125**, 217203 (2020)

Broadband SAW spectroscopy



Küß, MW *et al.* PRL **125**, 217203 (2020)

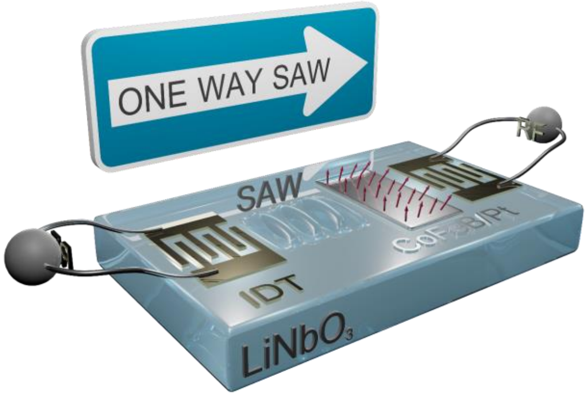
Sample layout



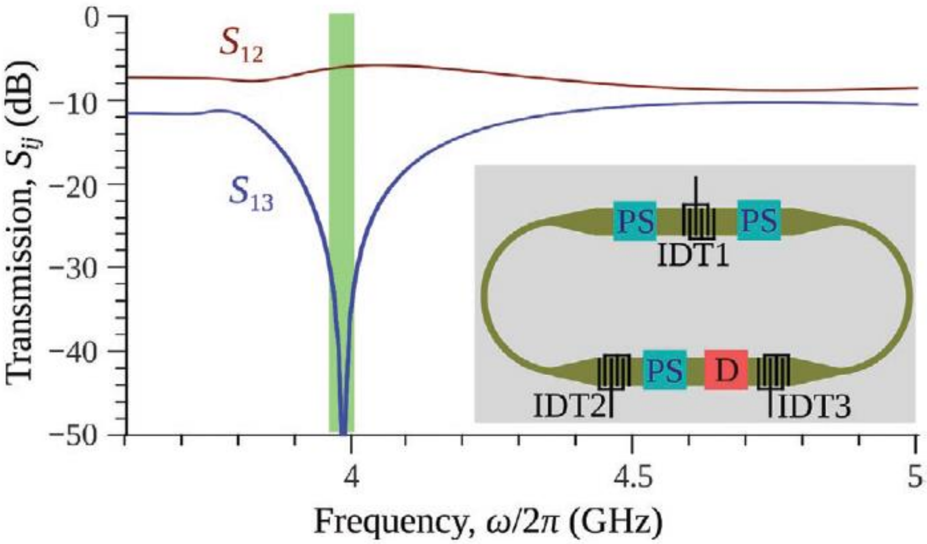
Küß, MW *et al.* PRL **125**, 217203 (2020)

Proposed applications

Isolators

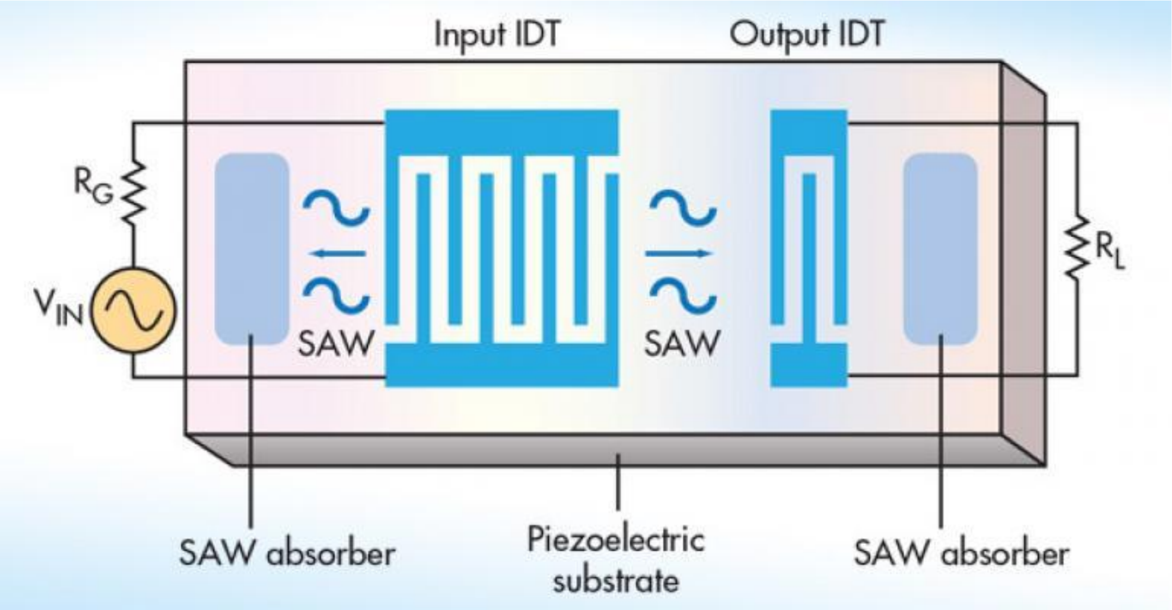


Circulators



R. Verba et al., Advanced Electronic Materials **7**, 2100263 (2021).

SAW filter


Input IDT
Output IDT
R_G
V_{IN}
R_L
SAW
SAW
SAW absorber
Piezoelectric substrate
SAW absorber