Magnetoeleastic waves in nanoscale waveguides and piezoelectric/magnetostrictive bilayer transducers

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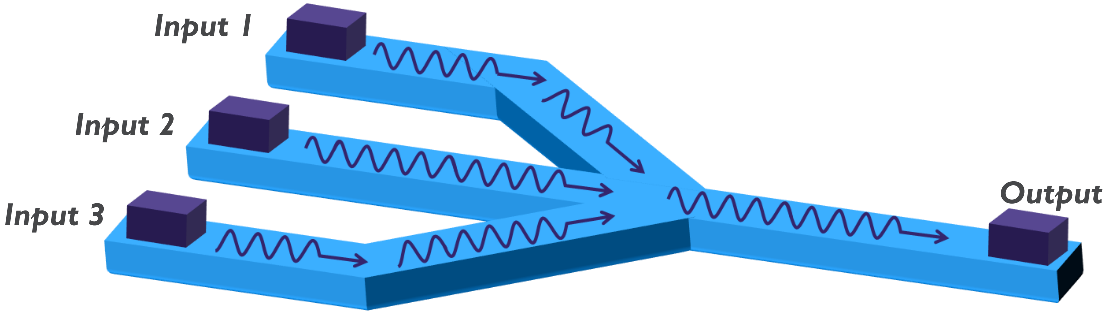
Logic circuits based on wave-based majority gates



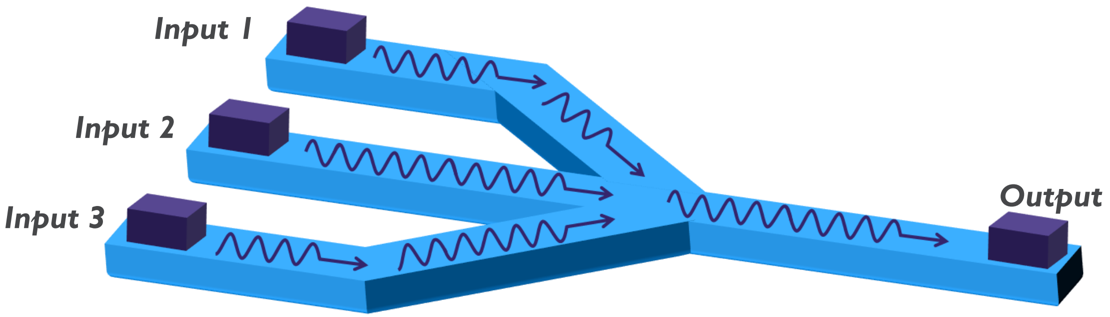
Wave computing:
Information encoded in the wave's phase or amplitude

Logic table

I_1	I_2	I_3	O
0	0	0	0
0	0	1	0
0	1	1	1
1	1	1	1

Computation by interference
Natural logic gate: majority gate

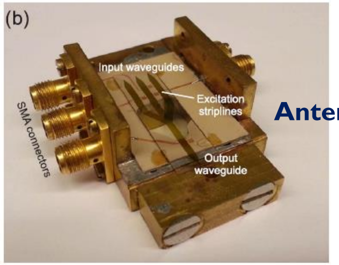
Spin-wave majority gate demonstrated to work properly



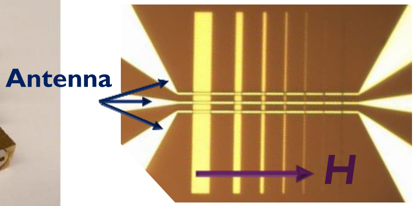
Logic table

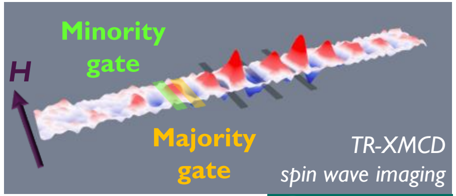
I_1	I_2	I_3	O
0	0	0	0
0	0	1	0
0	1	1	1
1	1	1	1

Experimental demonstration of Majority Gates



T. Fisher et al., APL, vol.110, pp. 152401 (2017)





Max Planck Institute for Intelligent Systems

G. Talmelli et al., accepted in **Science Advances**, 2020

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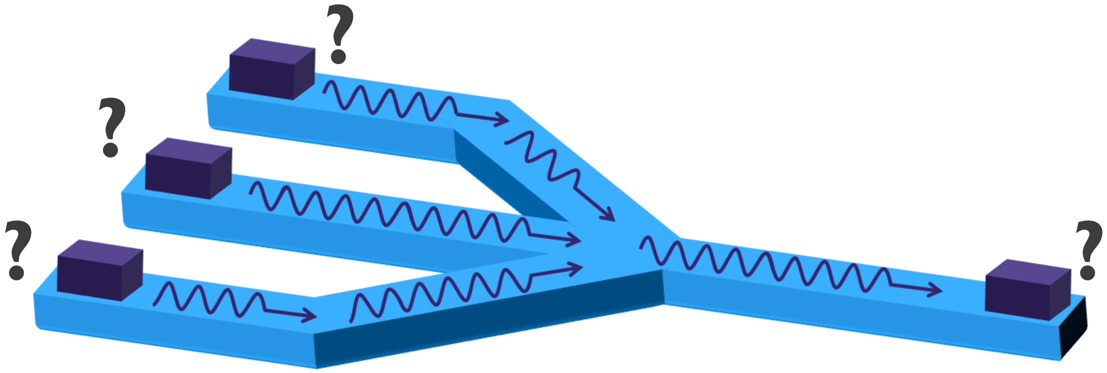
Next steps

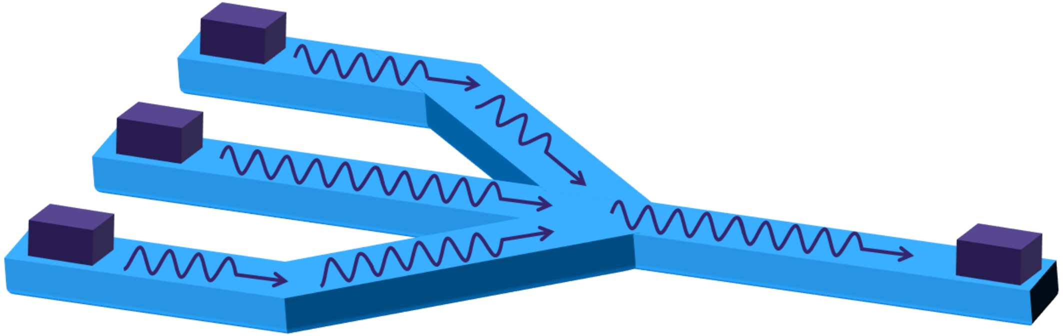
1. Energy efficient magnetoelectric transducer



Next steps and challenges

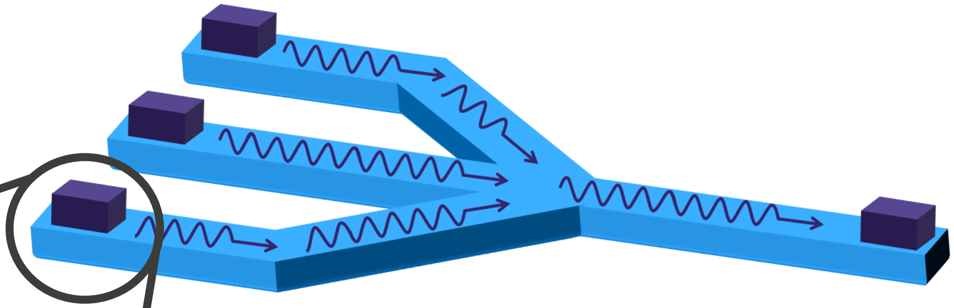
1. *Energy efficient magnetoelectric transducer*

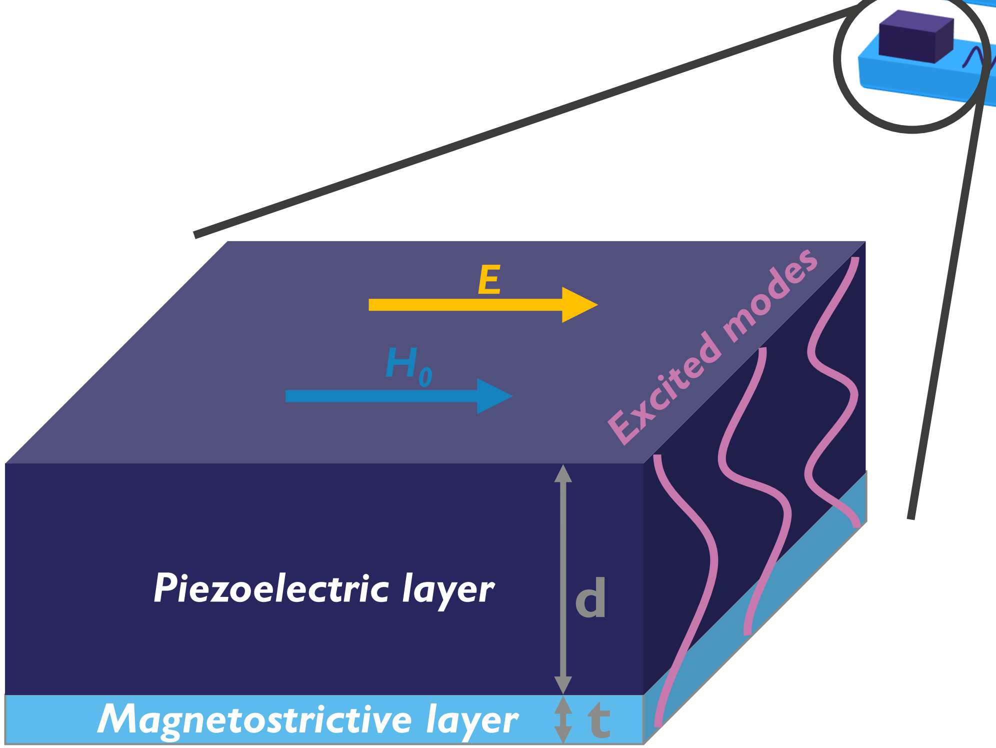
2. *Magnetoelastic waves in nanoscale waveguide*



Magnetoelectric transducer

Simplified transducer model





Assumptions

1. Free top and bottom surface
2. Only variation in thickness direction
3. Magnetic layer much thinner than piezoelectric layer
4. Linear magnetization dynamics

F. Vanderveken et al., *Theoretical description of power transfer in a magneto-acoustic resonator*, arXiv:2204.03072

Theoretical approach

1. Determine differential equations in piezoelectric and magnetostrictive layer

2. Determine boundary and continuity conditions

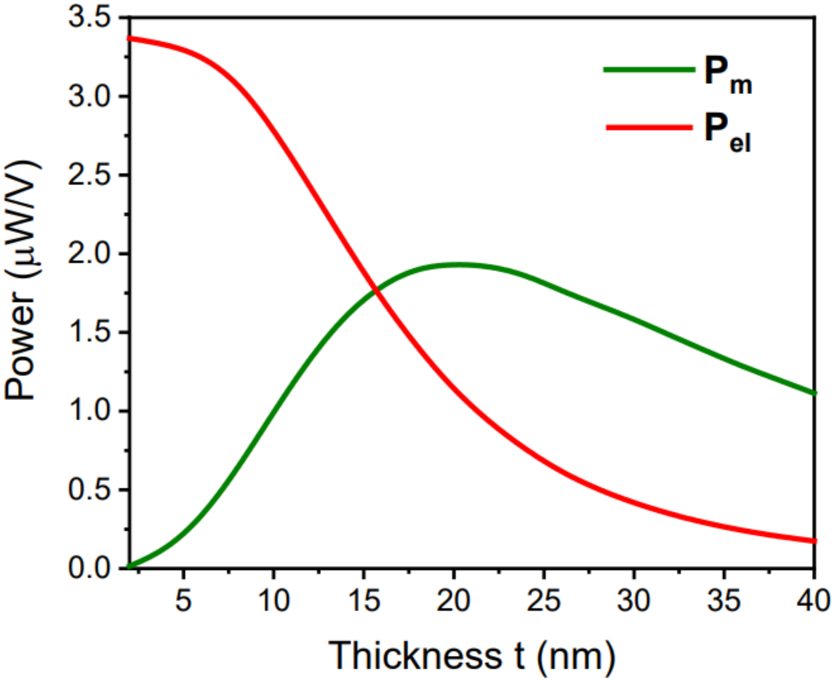
3. Solve boundary value problem

4. Calculate magnetic P_m and elastic power P_{el} based on this solution

5. Determine efficiency: $P_m/(P_m+P_{el})$

F. Vanderveken et al., *Theoretical description of power transfer in a magneto-acoustic resonator*, arXiv:2204.03072

Increasing magnet layer thickness reduces strain amplitude



200 nm ScAlN – t nm CoFeB

Strain amplitude determined by the losses

Elastic power

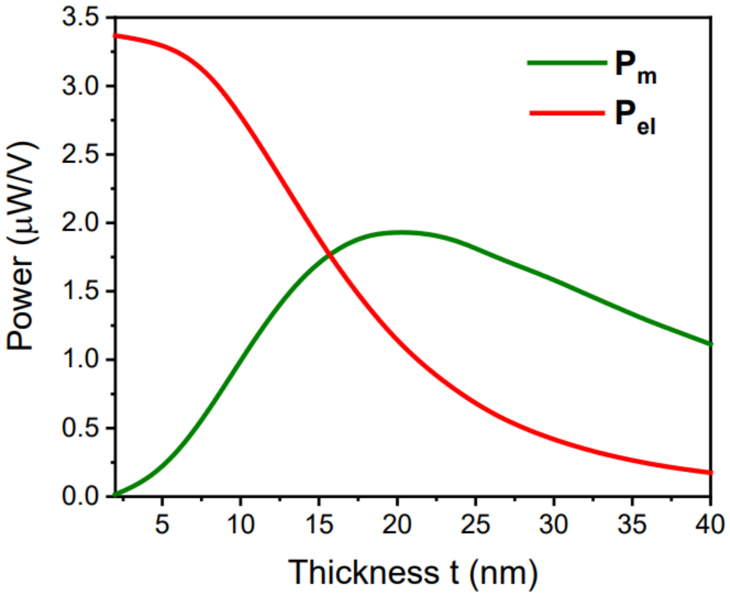
- $P_{el} \sim S^2$ → elastic power decreases

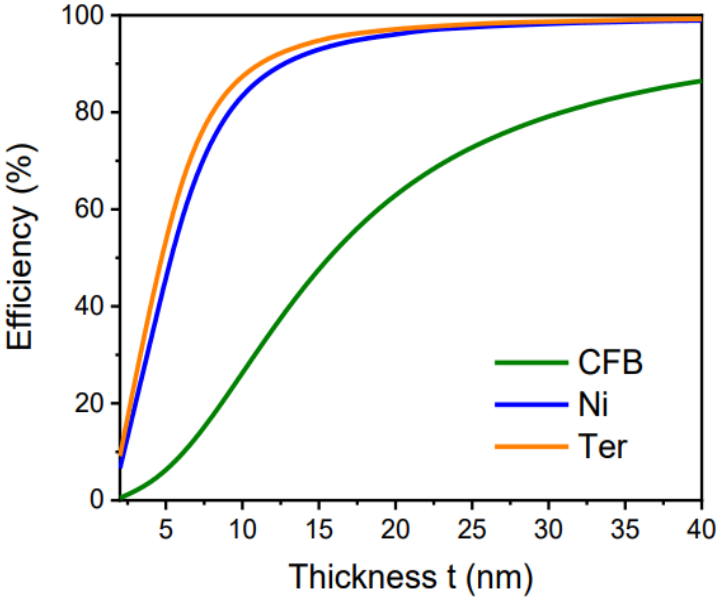
Magnetic power

- $P_m \sim tS^2$ → Two counteracting effects

F. Vanderveken et al., *Theoretical description of power transfer in a magneto-acoustic resonator*, arXiv:2204.03072

Increasing magnet layer thickness improves the efficiency



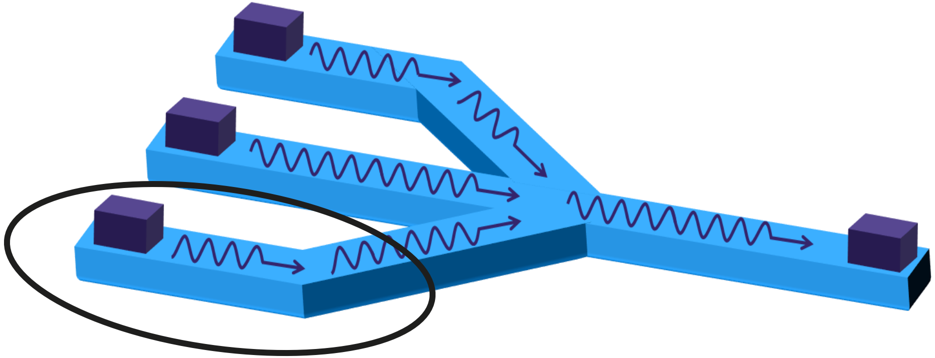


$$FoM = \frac{B^2 H_0}{M_s \alpha (2H_0 + M_s)}$$

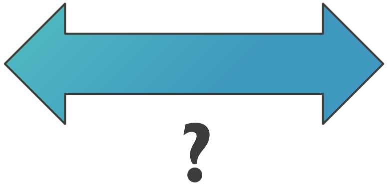
F. Vanderveken et al., *Theoretical description of power transfer in a magneto-acoustic resonator*, arXiv:2204.03072

Confined magnetoelastic waves

Piezoelectric resonator generates magnetoelastic waves



Elastic waves



Spin waves

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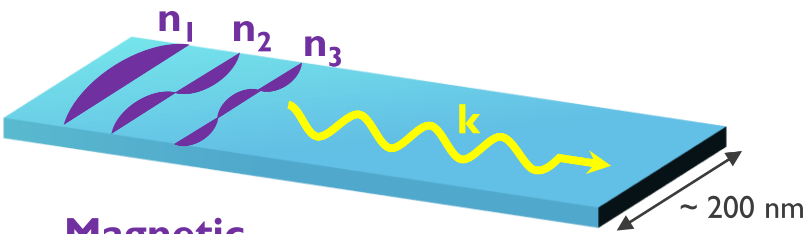
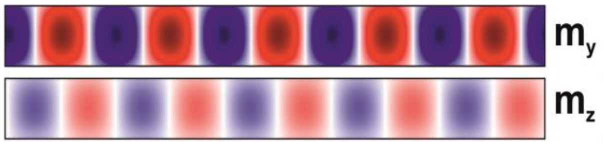
Magnetic and elastic modes have different **mode profile**

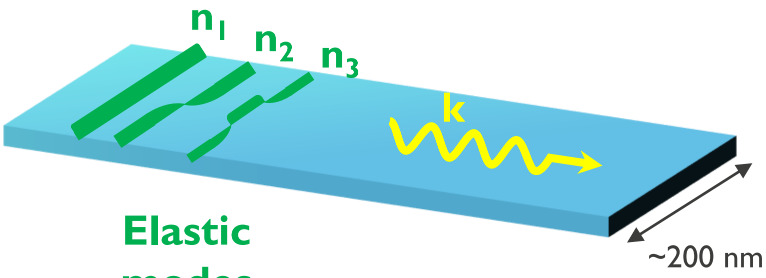
Magnetic system



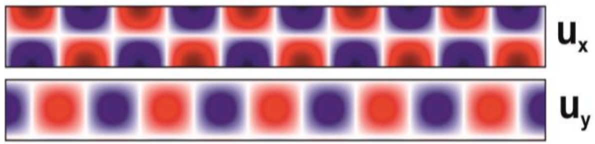
Magnetic modes



Elastic system



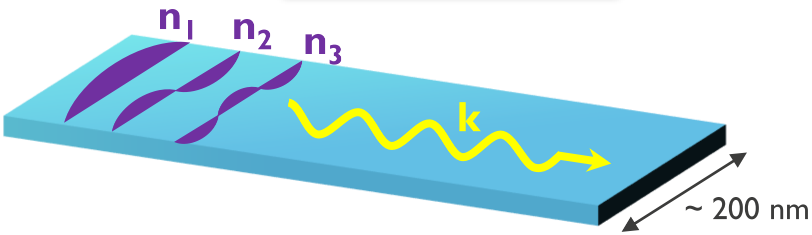
Elastic modes



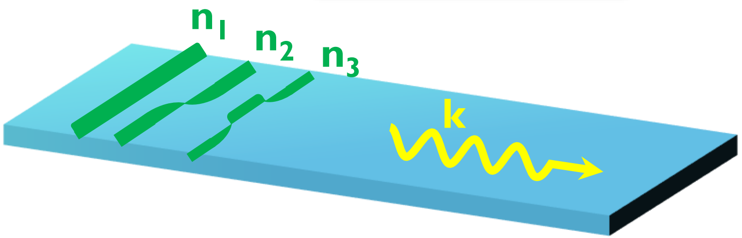
*Different **mode profile***

Magnetic and elastic modes have different **dispersion relation**

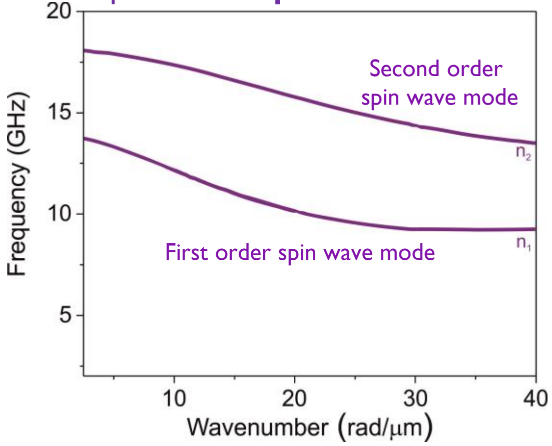
Magnetic system



Elastic system

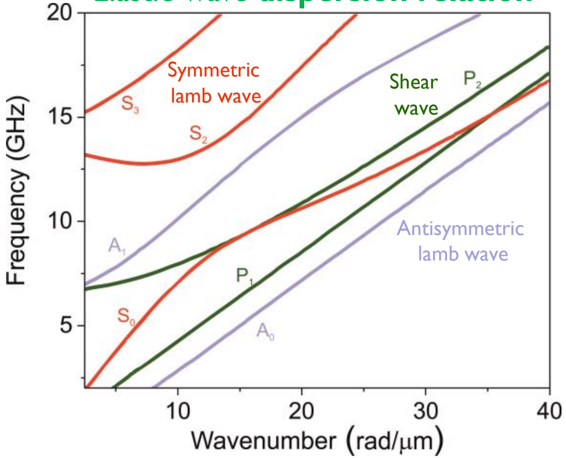


Spin-wave **dispersion relation**

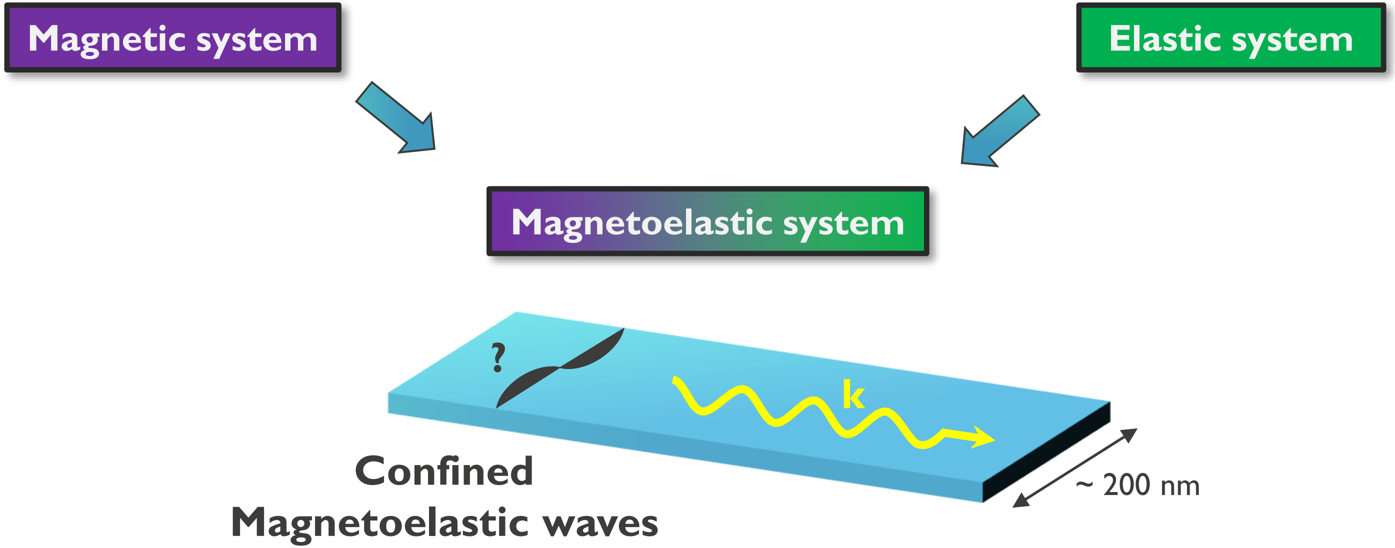


*Different **dispersion relation** and **mode profile***

Elastic-wave **dispersion relation**



What happens if we combine confined magnetic and elastic waves?



Does confinement alter the magnetoelastic coupling?

Do all elastic modes interact with all magnetic modes?

New developed numerical solver

Micromagnetic solvers exist

MuMax3

Magnetization

$$\dot{\boldsymbol{m}} = -\gamma_0 \boldsymbol{m} \times \boldsymbol{H}_{\text{eff}} + \alpha \boldsymbol{m} \times \dot{\boldsymbol{m}}$$

Landau-Lifshitz-Gilbert equation

F. Vanderveken, et al., *Finite difference magnetoelastic simulator*, Open Research Europe 1 (2021)

Elastodynamics is crucial to simulate magnetoelastic waves

Displacement

Elastodynamic equation

$$\rho \ddot{\boldsymbol{u}} + \eta \dot{\boldsymbol{u}} = \boldsymbol{f}_{\text{tot}}$$

Magnetization

Landau-Lifshitz-Gilbert equation

MuMax3

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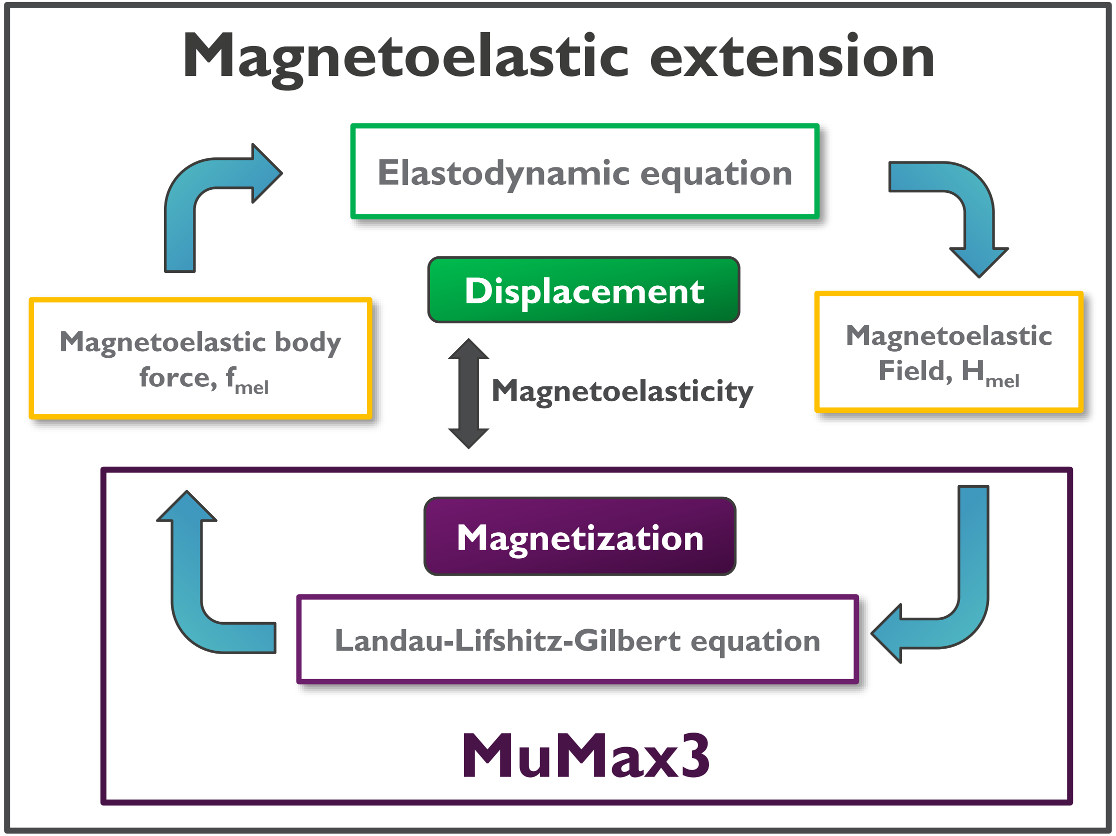
F. Vanderveken, et al., *Finite difference magnetoelastic simulator*, Open Research Europe 1 (2021)

Novel mumax3 extension



F. Vanderveken, et al., *Finite difference magnetoelastic simulator*, Open Research Europe 1 (2021)

Magnetoelastic waves

CoFeB parameters used for simulations

Magnetic parameters

M_s = 1.2 MA/m

A_{ex} = 18 pJ/m

α = 0.004

$\mu_0 H_{ext}$ = 5 mT

Elastic parameters

C_{11} = 283 Gpa

C_{12} = 166 GPa

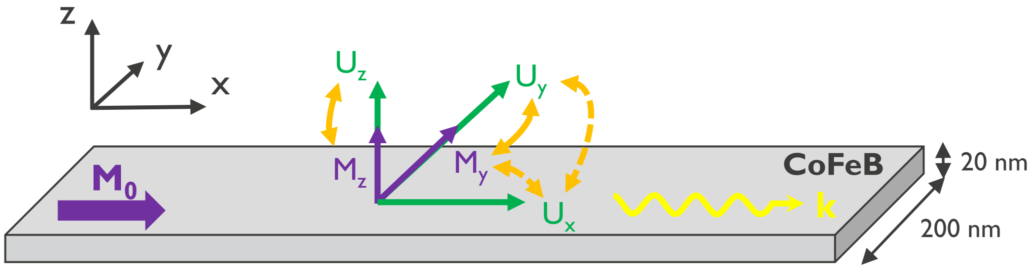
C_{44} = 58 GPa

Rho = 8 kg/m^3

Magnetoelastic coupling

B_1 = -8.8 MJ/m

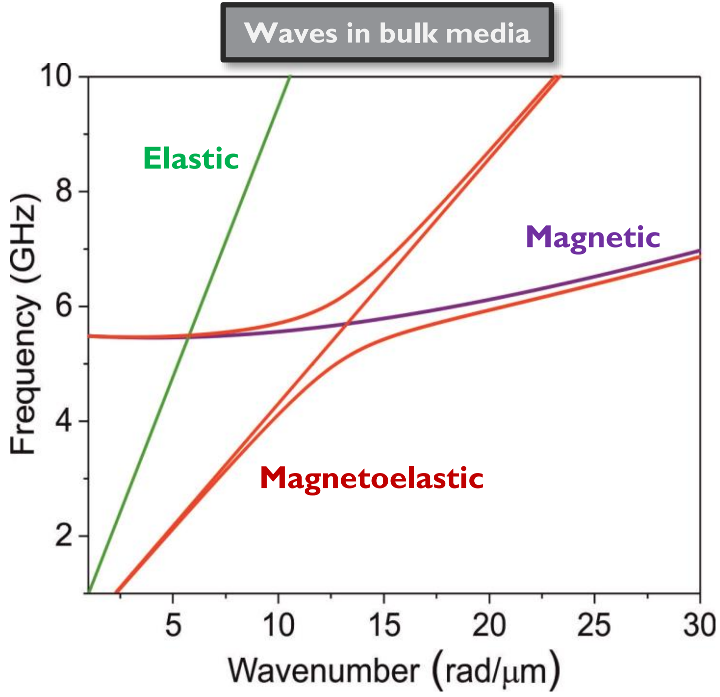
B_2 = -8.8 MJ/m



G. Yu, et al., Appl. Phys. Lett. 106, 72402 (2015).
A. Conca, et al., Appl. Phys. Lett. 104, 182407 (2014).
R.-C. Peng, et al., Sci. Rep. 6, 27561 (2016).
M. Gueye, et al., J. Phys. D: Appl. Phys 49, 145003 (2016).

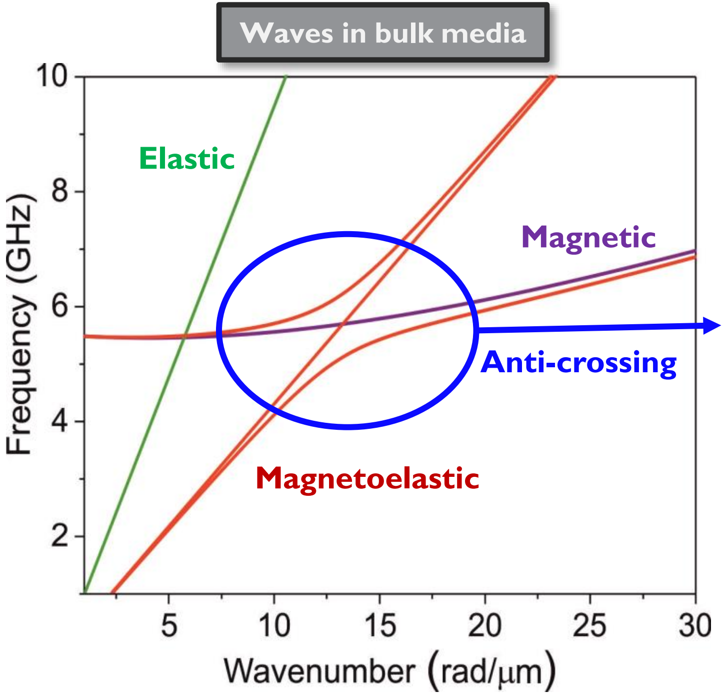
F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

Dispersion relations



F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

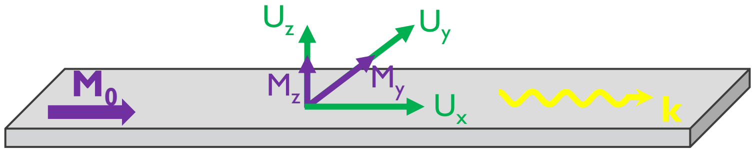
Dispersion relations



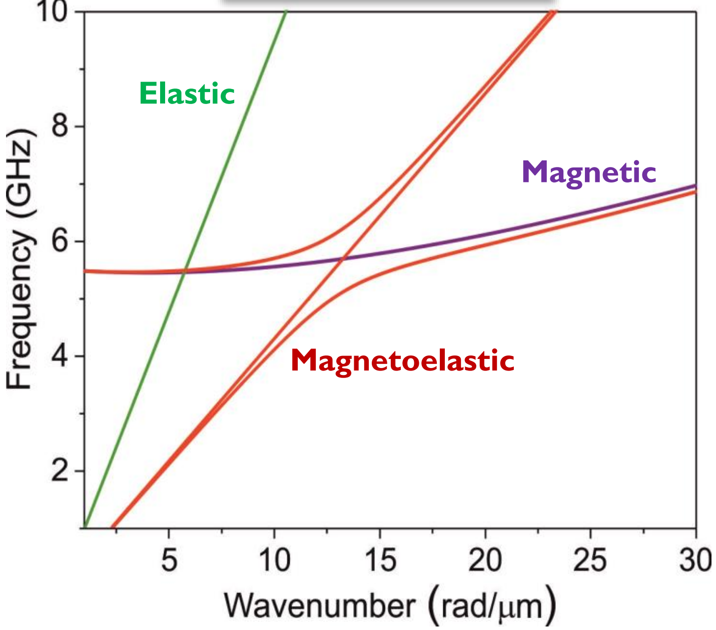
strong interaction between the elastic and magnetic wave

F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

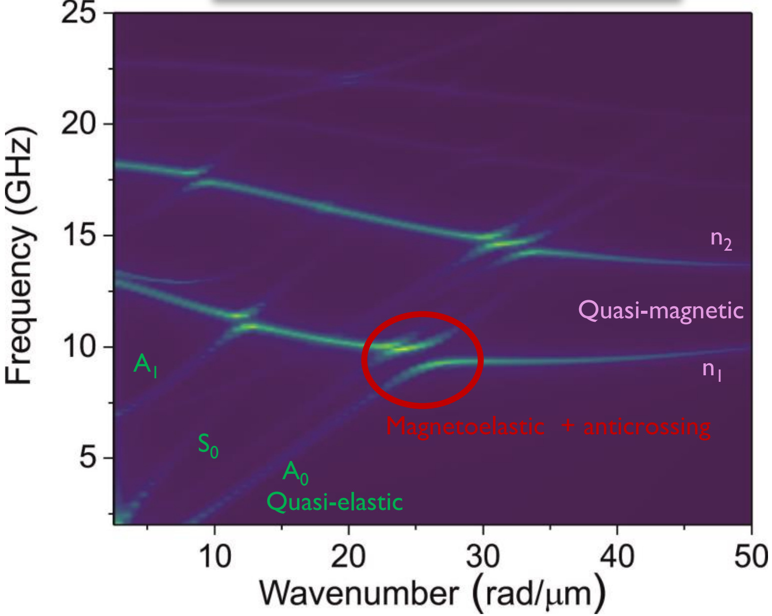
Dispersion relations



Waves in bulk media



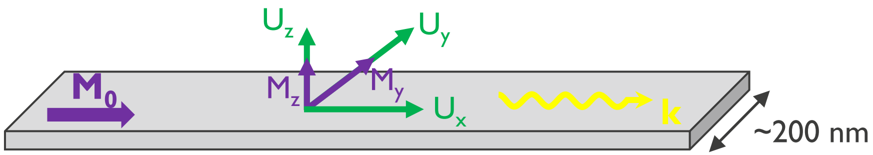
Waves in nanoscale waveguide

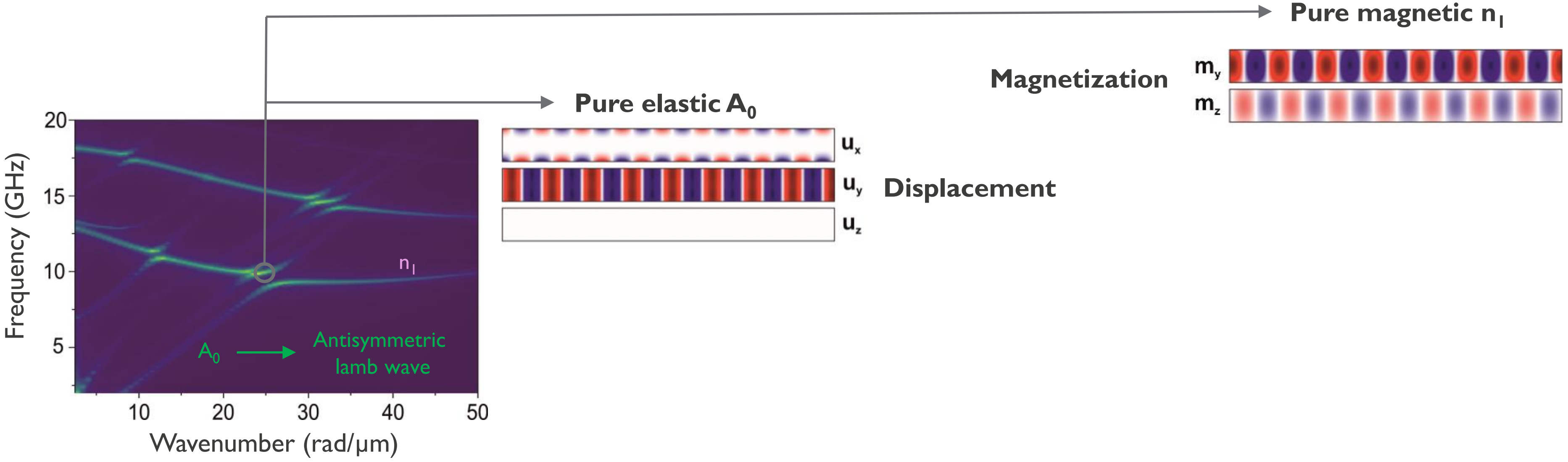


Many magnetic and elastic modes in scaled waveguide
→ Multiple interaction points with varying strength

F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

Mode profiles of confined waves

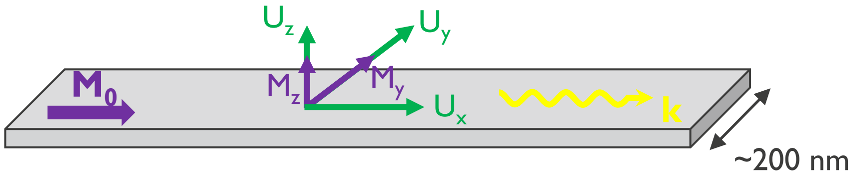


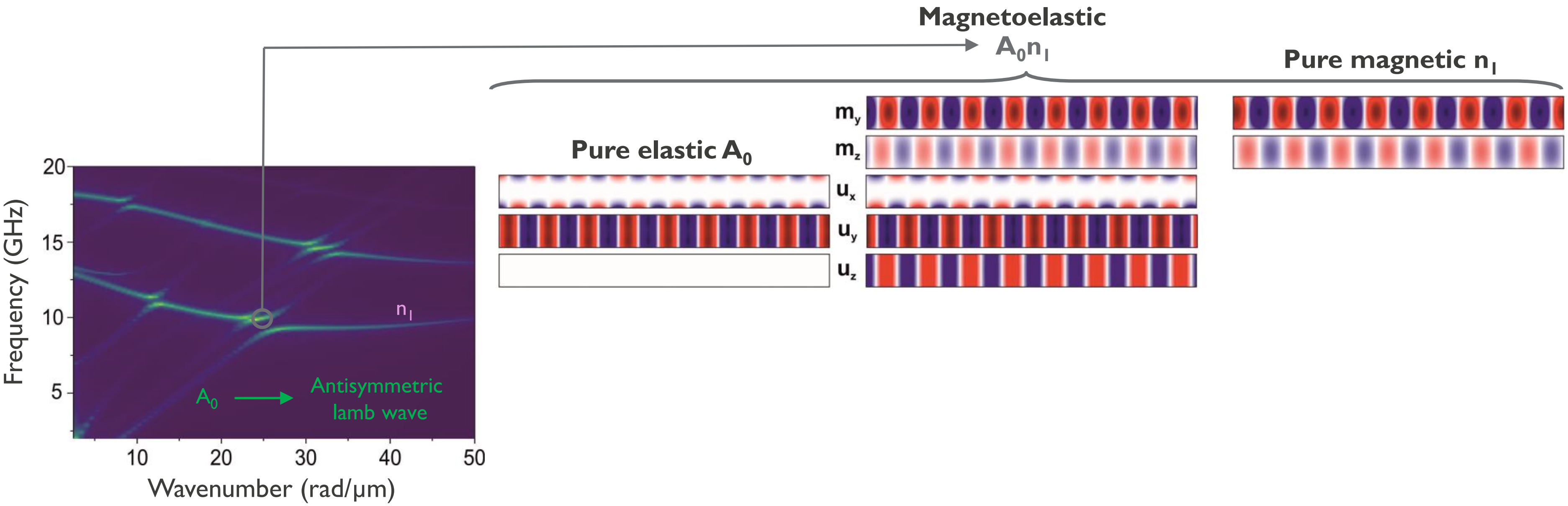


F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

Mode profiles of magnetoelastic waves

Magnetoelastic regime

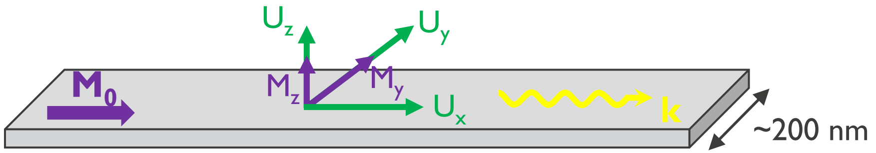


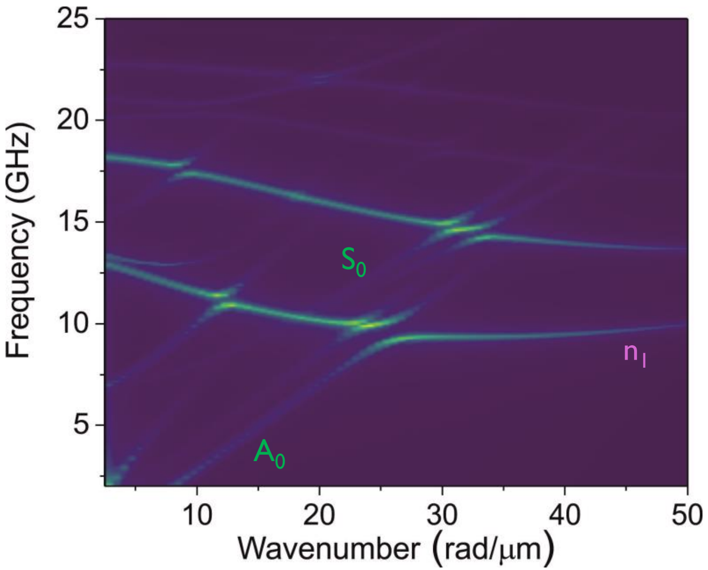


Magnetoelastic coupling does not strongly affect mode profiles

F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

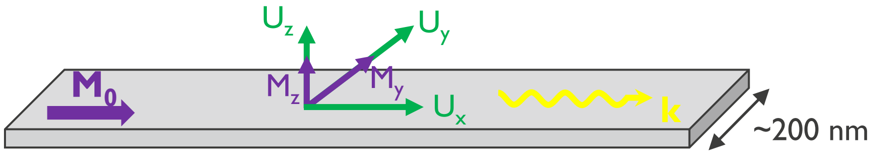
Mode dependent coupling

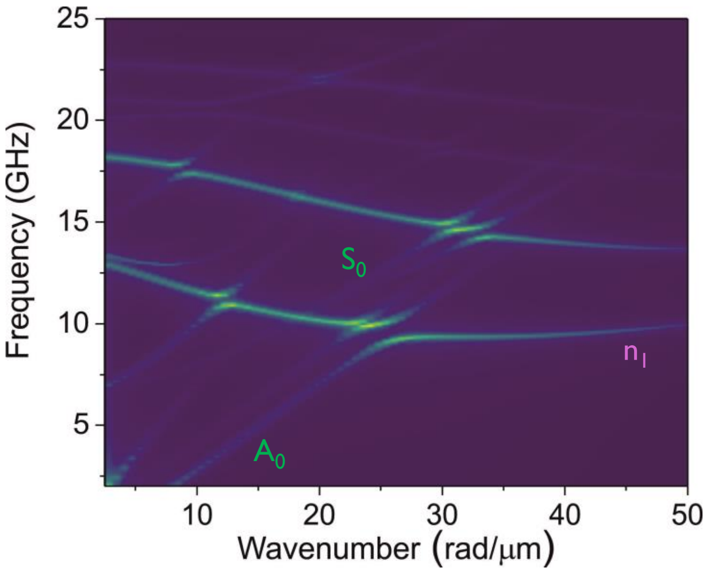




F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

Mode dependent coupling





Does elastic mode couple with magnetic mode?

Magnetic subsystem

Eigenmode excitation determined by overlap integral

$$\int \boldsymbol{m} \cdot \boldsymbol{h}_{mel} \, dV$$

Magnetization mode profile

Magnetoelastic field

Overlap integral explains mode coupling

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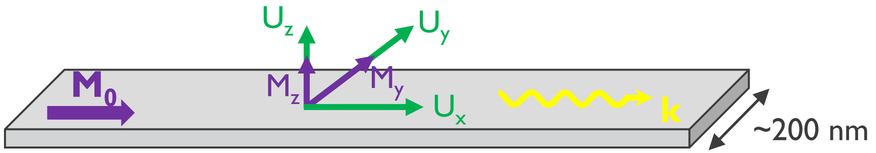
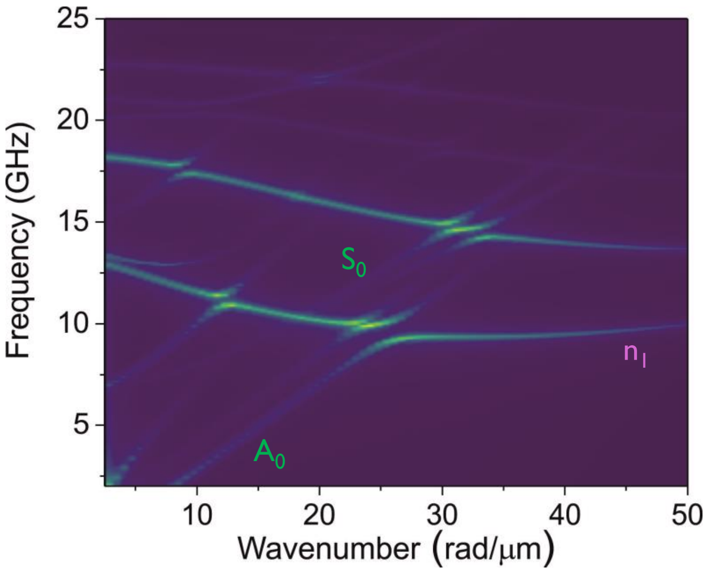
F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

Mode dependent coupling





Does elastic mode couple with magnetic mode?

Magnetic subsystem

Elastic subsystem

Eigenmode excitation determined by overlap integral

$$\int \boldsymbol{m} \cdot \boldsymbol{h}_{mel}\, dV$$

Magnetization mode profile

Magnetoelastic field

$$\int \boldsymbol{u} \cdot \boldsymbol{f}_{mel}\, dV$$

Displacement mode profile

Magnetoelastic body force

Overlap integral explains mode coupling

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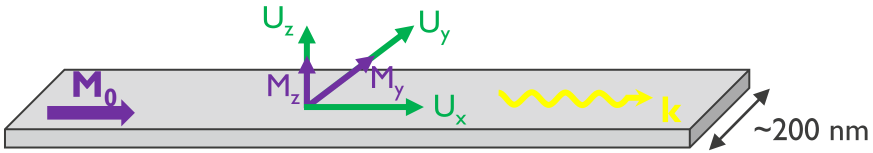
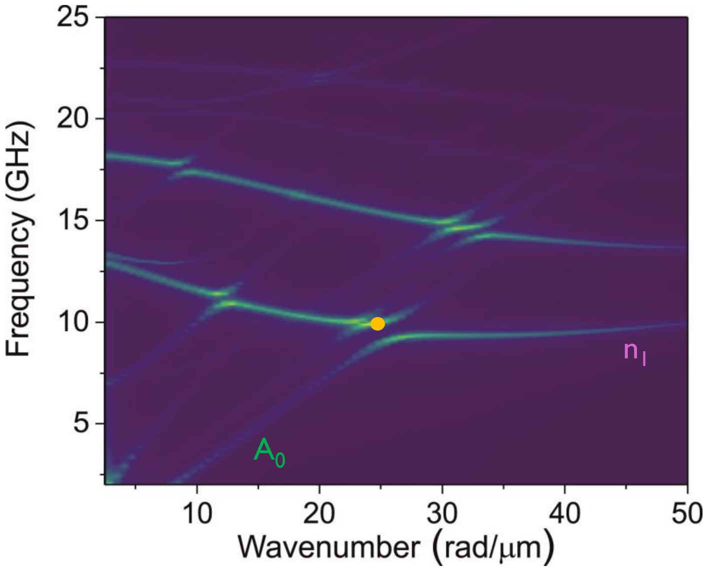
F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

Mode dependent coupling

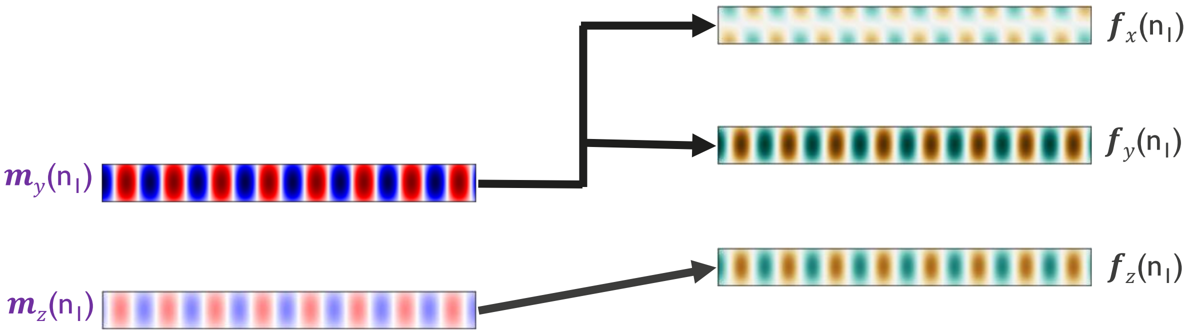
Strong coupling



Coupling between A_0 and n_I



$$\int \boldsymbol{m}\cdot\boldsymbol{h}_{mel}\,dV \qquad \int \boldsymbol{u}\cdot\boldsymbol{f}_{mel}\,dV$$

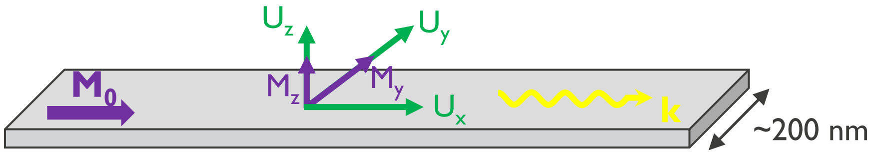


Magnetoelastic force: $\mathbf{f}_{\text{mel}} = B_2 \begin{bmatrix} \frac{\partial m_y}{\partial y} \\ ik_x m_y \\ ik_x m_z \end{bmatrix}$

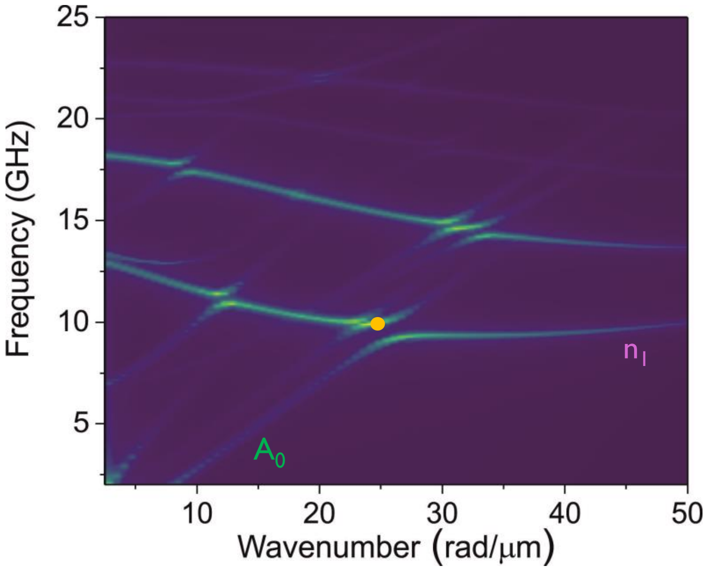
F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

Mode dependent coupling

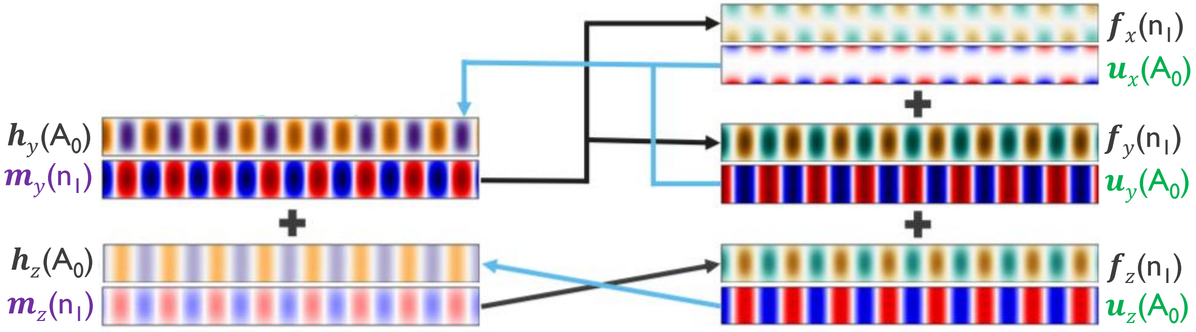
Strong coupling



Coupling between A_0 and n_I



$$\int \boldsymbol{m} \cdot \boldsymbol{h}_{mel}\, dV \qquad \int \boldsymbol{u} \cdot \boldsymbol{f}_{mel}\, dV$$



Magnetoelastic field: $$\mathbf{h}_{\mathrm{mel}} = -\frac{1}{\mu_0 M_s}\begin{bmatrix} 2B_1 i k_x u_x \\ B_2\left(\frac{\partial u_x}{\partial y} + i k_x u_y\right) \\ B_2 i k_x u_z \end{bmatrix}$$

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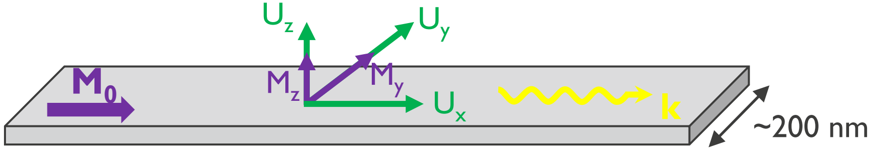
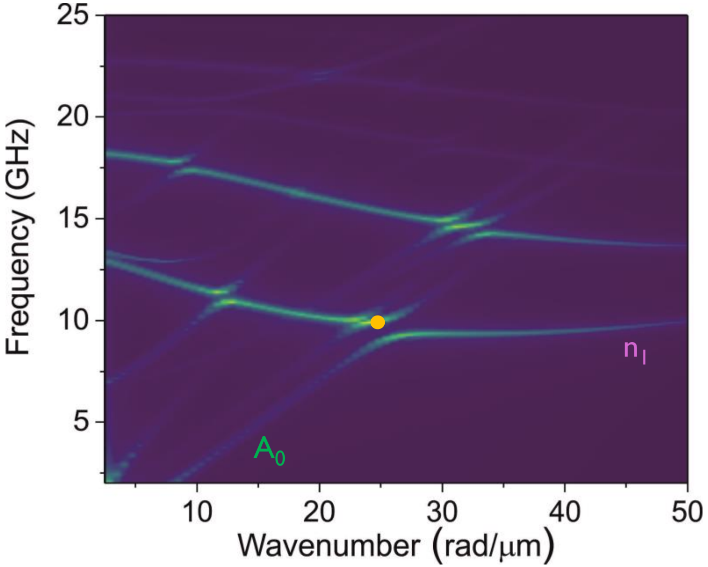
F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

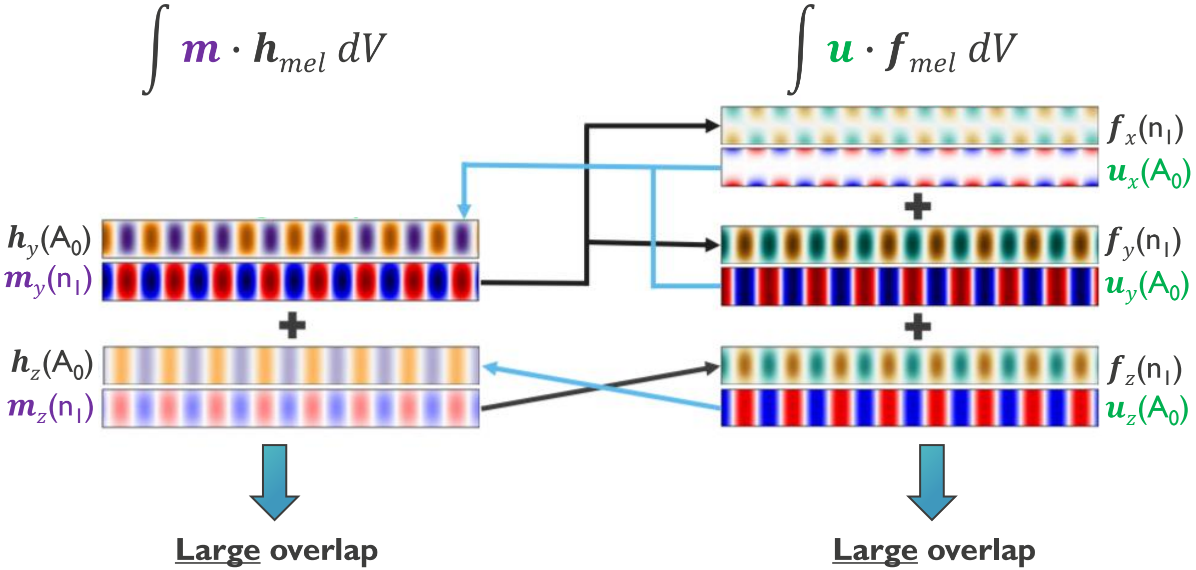
Mode dependent coupling

Strong coupling



Coupling between A_0 and n_1



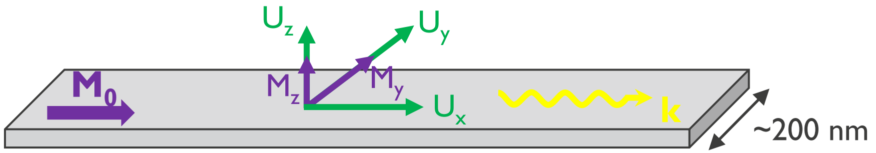


Strong coupling between elastic and magnetic modes with the same symmetry

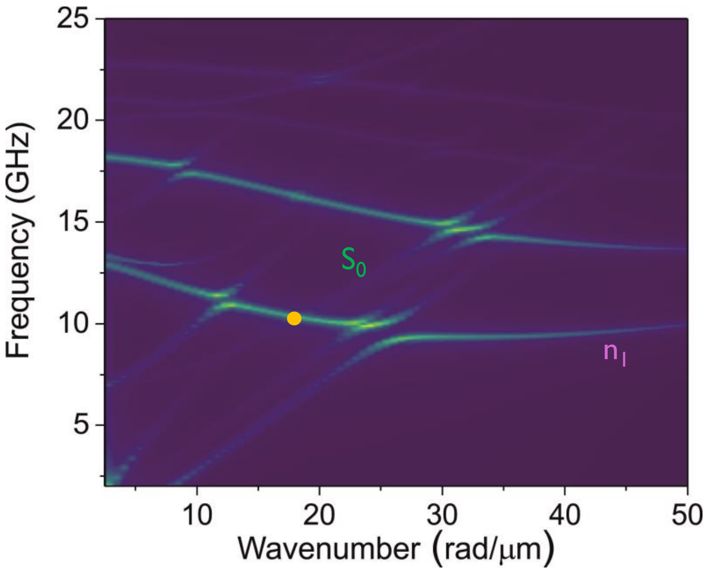
F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

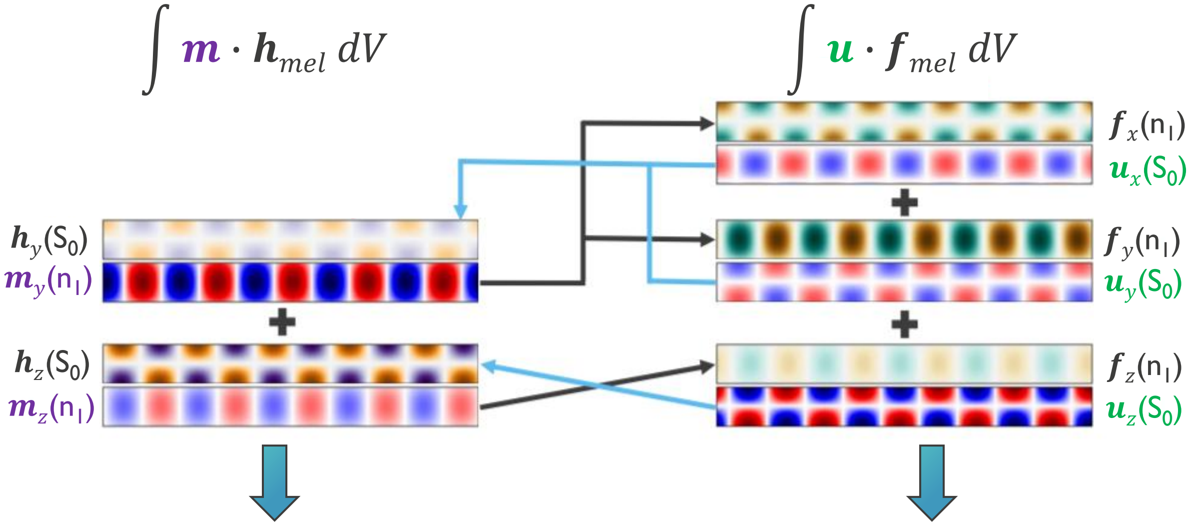
Mode dependent coupling

Weak coupling



Coupling between A_0 and n_I





No coupling between elastic and magnetic modes with the opposite symmetry

F. Vanderveken, et al., Phys. Rev. B 103, 054439 (2021).

Summary

Summary

Magnetoelectric transducer and confined magnetoelastic waves

- Analytical model to calculate **transducer efficiency**
- **New mumax3 extension** developed
- ***Mode profiles*** of the magnetization and displacement are quasi ***unaffected*** by the magnetoelastic coupling
- ***Strong magnetoelastic coupling*** *between elastic and magnetic* ***modes with the same symmetry***

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- *Florin Ciubotaru*
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- *Bart Soree*

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