Photon-magnon interaction in ferromagnets of different sizes

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Quantum
Materials and Devices

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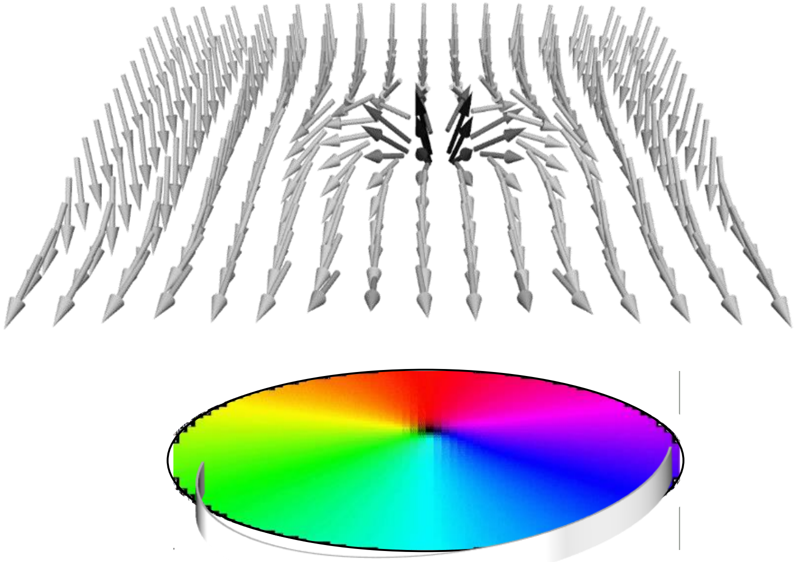
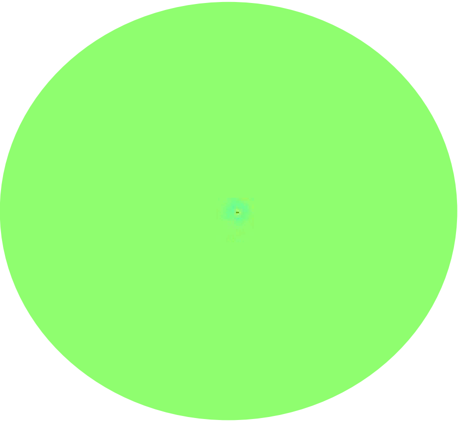
Zaragoza

INMA
INSTITUTO DE NANOCIENCIA
Y MATERIALES DE ARAGÓN

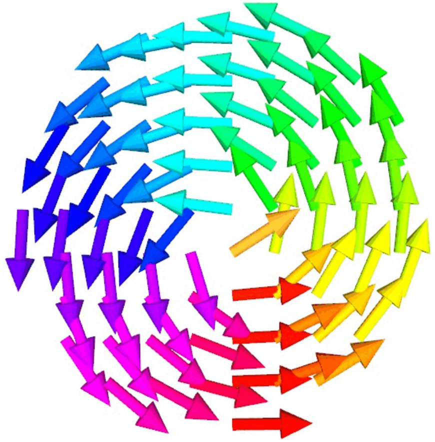
Motivation

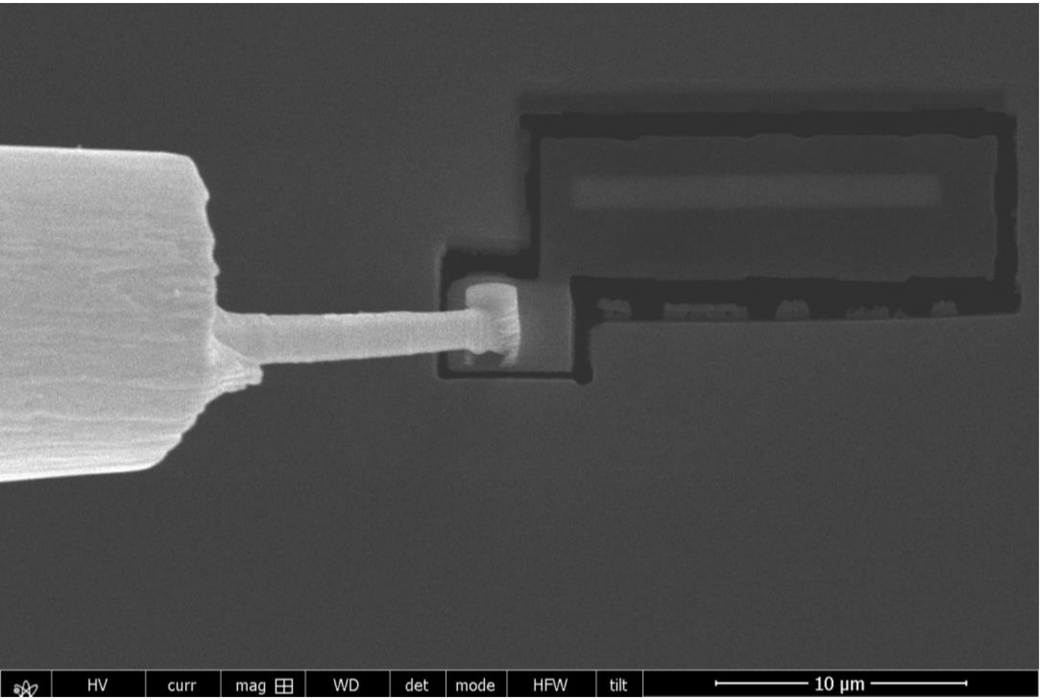


Spin wave generation



Frequency tunable and mobile



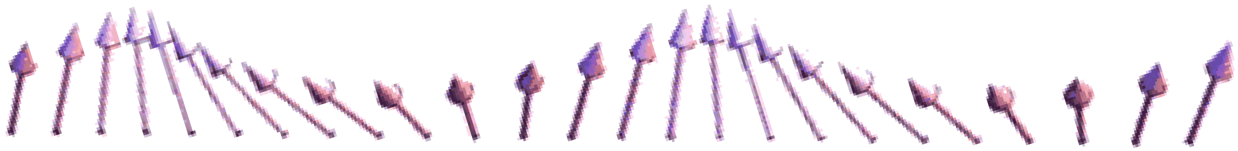


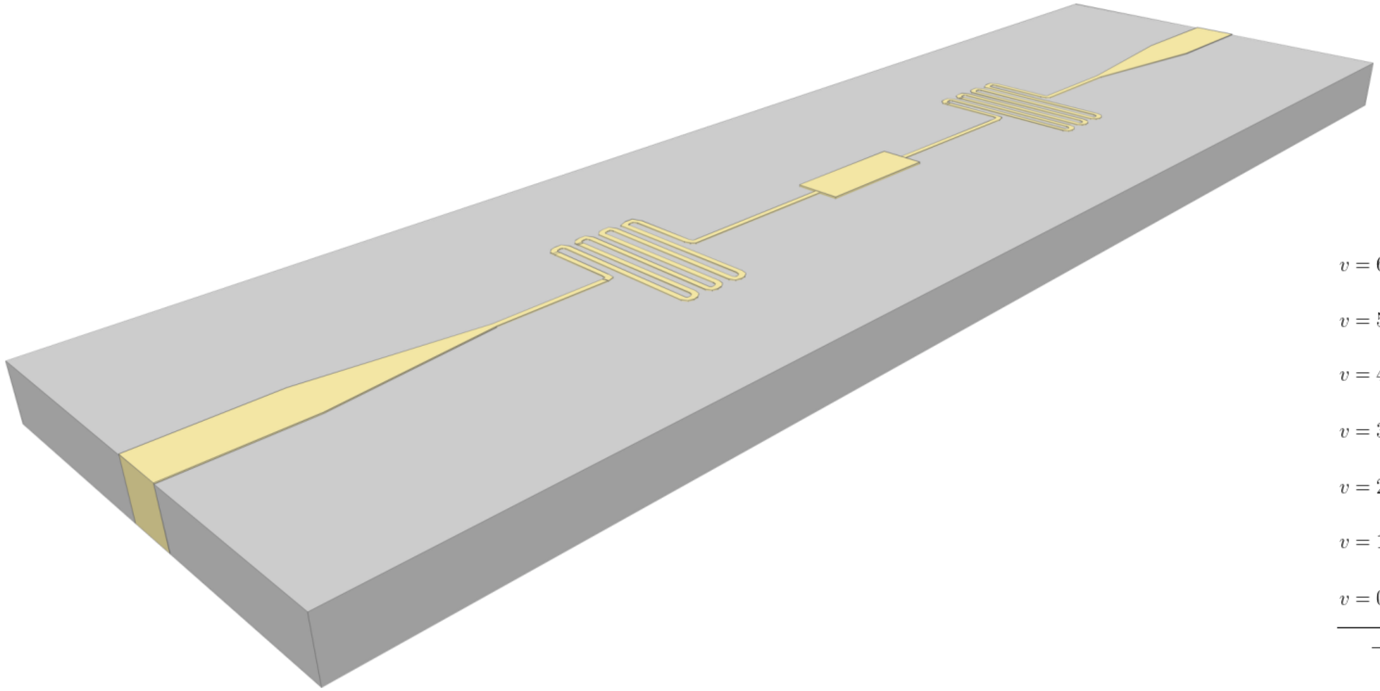
Outline

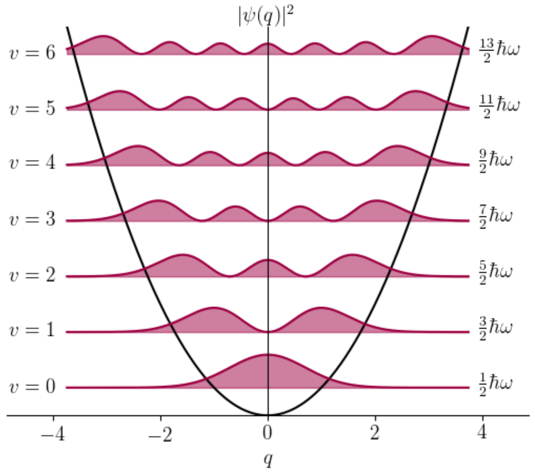
- ☐ Introduction
- ☐ Theoretical Framework
- ☐ Experimental Work
- ☐ Results and Analysis
- ☐ Ongoing Work
- ☐ Conclusions

Introduction

Magnons as quasiparticles

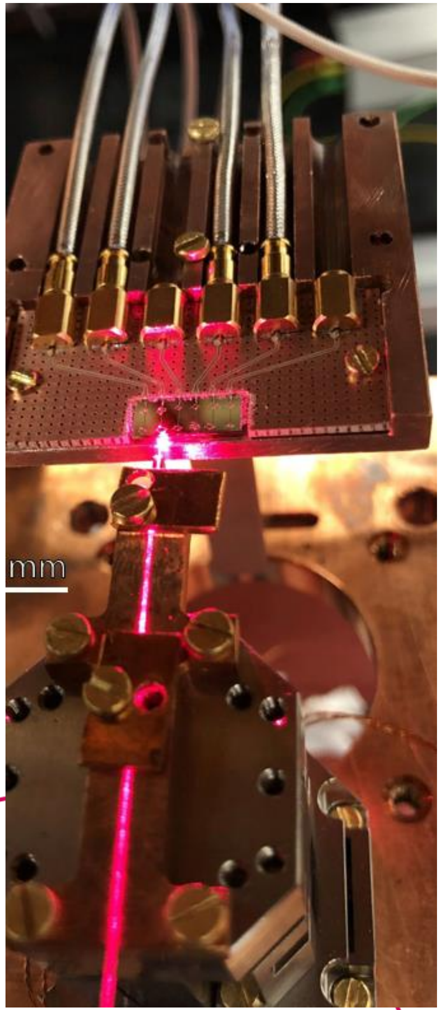






Introduction

Applications of Magnonic Sytems – Quantum Computation



Photon microwave transducer to optical domain

Arnold, G., Wulf, M., Barzanjeh, S. *et al.* **Converting microwave and telecom photons with a silicon photonic nanomechanical interface**. *Nat Commun* **11**, 4460 (2020).

Dark Matter detectors

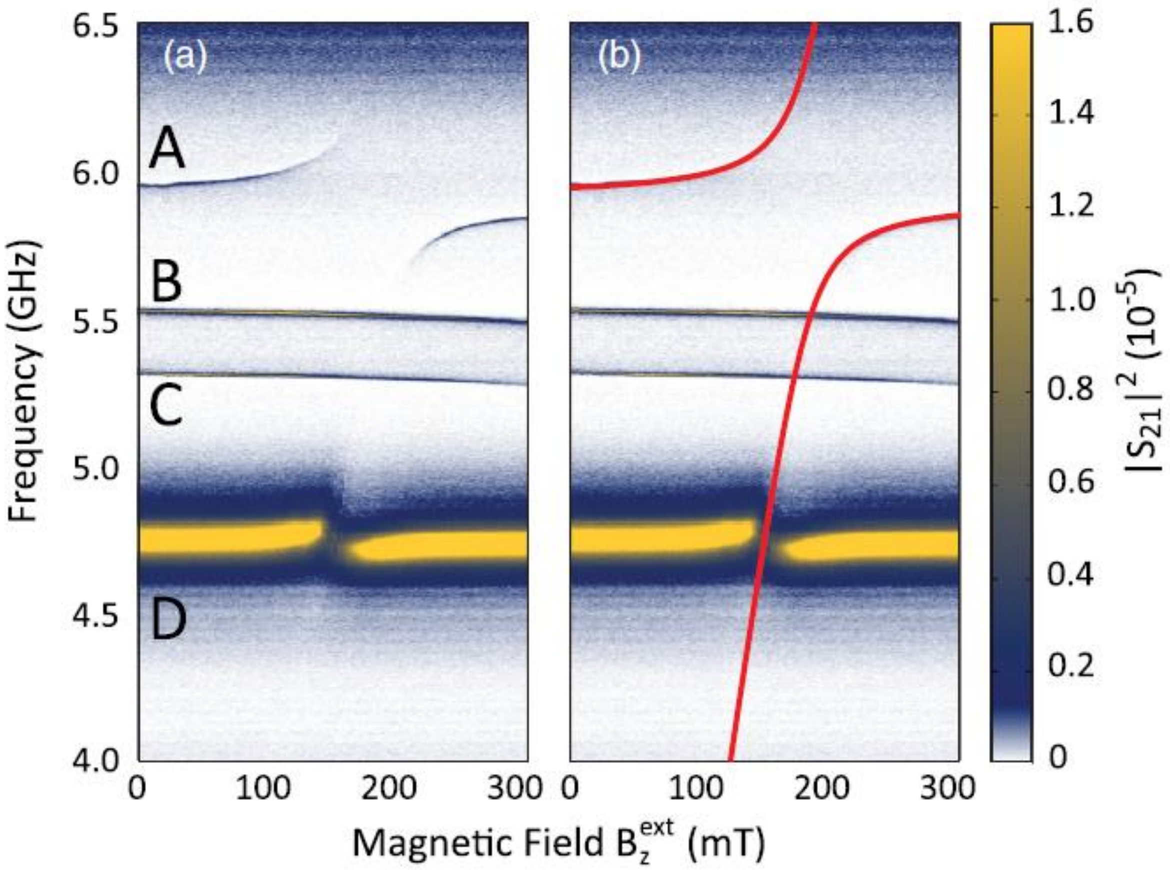
T. Trickle, Z. Zhang, and K. M. Zurek,
Detecting Light Dark Matter with Magnons
Phys. Rev. Lett. 124, 201801 (2020)

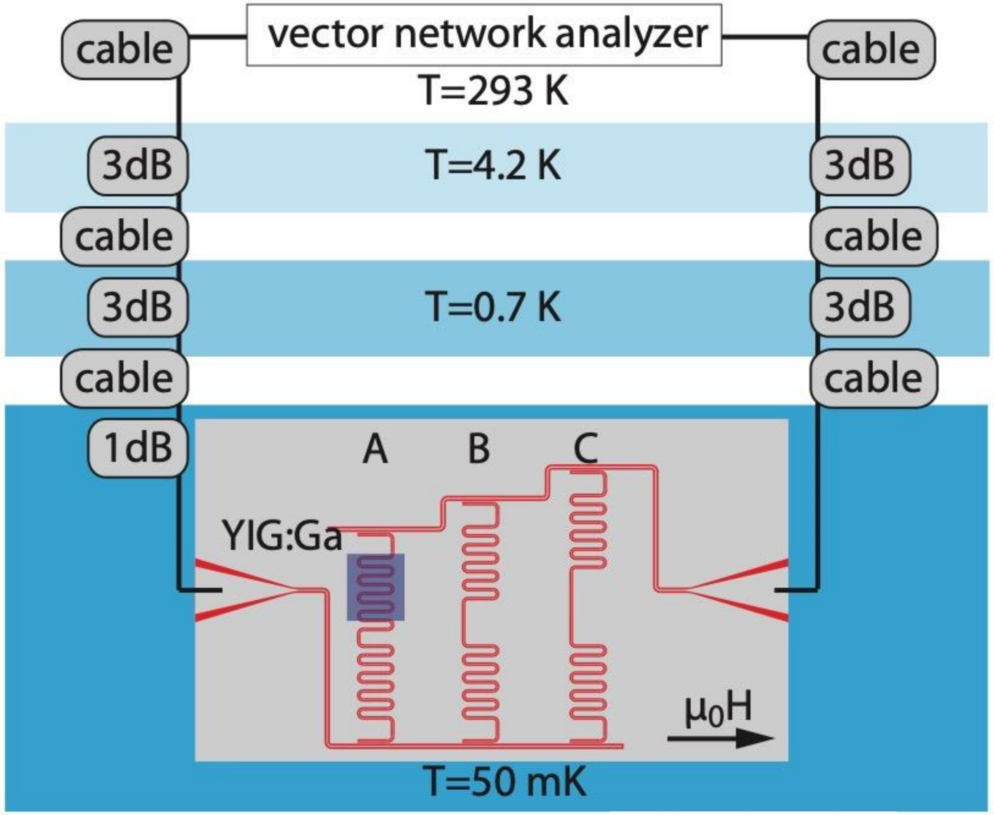
Introduction

Magnons as quasiparticles

PRL **111,** 127003 (2013) PHYSICAL REVIEW LETTERS week ending 20 SEPTEMBER 2013

High Cooperativity in Coupled Microwave Resonator Ferrimagnetic Insulator Hybrids

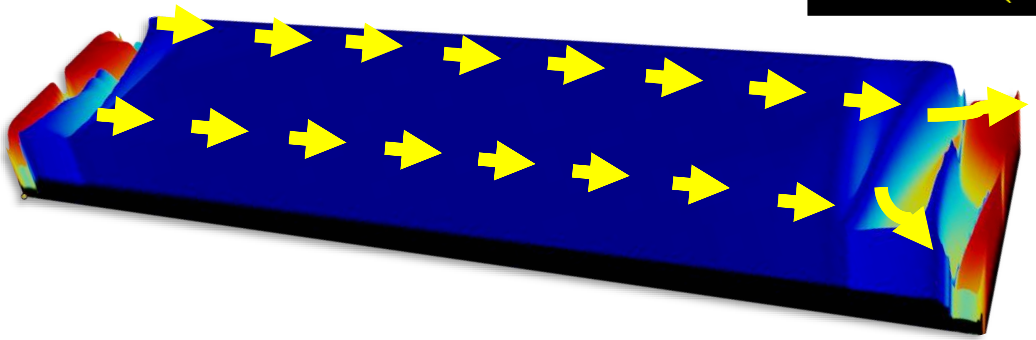


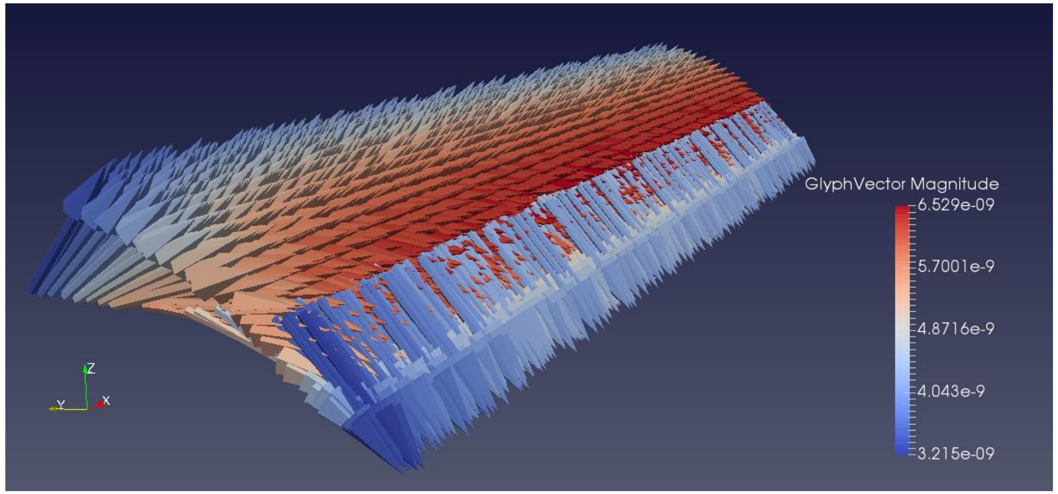


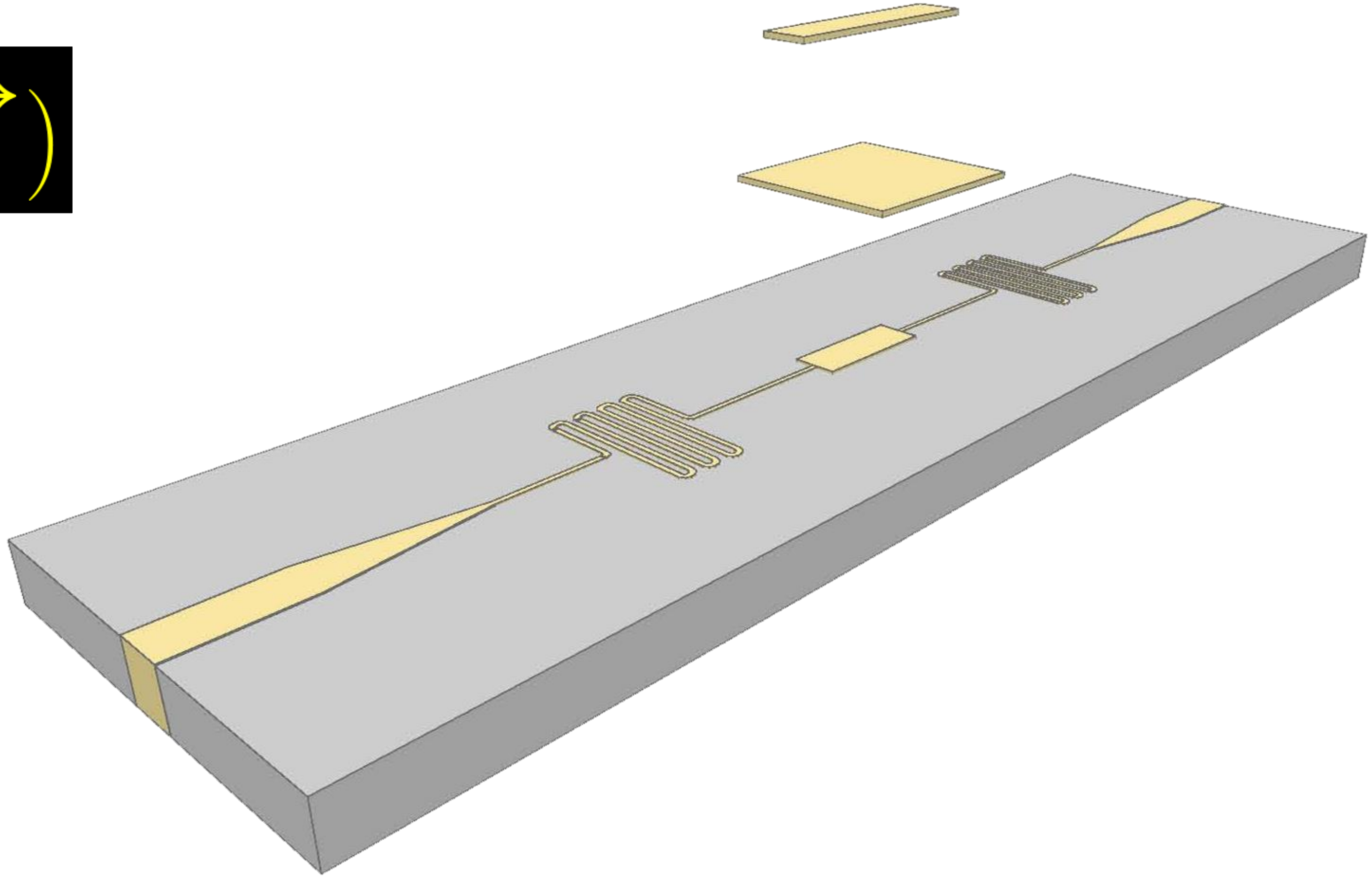
Theoretical Framework

Shaped ferromagnets

$$\vec{M}\left(\vec{r}\right)$$

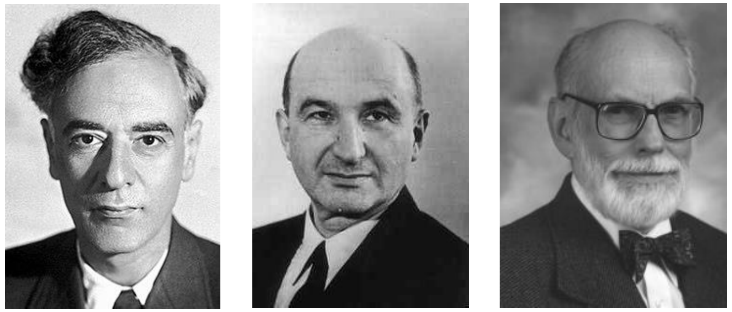






Theoretical Framework

Magnon-photon coupling in ferromagnets

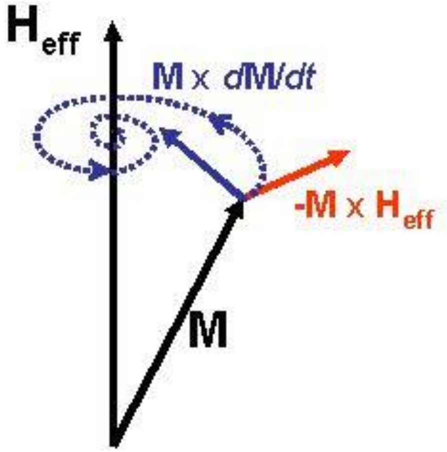


Rotation of the magnetization in response to torques

mumax^3

GPU-accelerated micromagnetism

$$\frac{\partial \vec{m}}{\partial t} = \vec{\tau}$$



$$\vec{\tau}_{LL} = \gamma_{LL} \frac{1}{1+\alpha^2} \left(\vec{m} \times \boxed{\vec{B}_{\text{eff}}} + \alpha \left(\vec{m} \times \left(\vec{m} \times \boxed{\vec{B}_{\text{eff}}} \right) \right) \right)$$

Dipolar term + Bext + magnetic exchange

T. L. Gilbert, **Lagrangian formulation of the gyromagnetic equation of the magnetization field,** Phys. Rev. **100**, 1243–1243 (1955).

Arne Vansteenkiste, Jonathan Leliaert, Mykola Dvornik, Mathias Helsen, Felipe Garcia-Sanchez, and Bartel Van Waeyenberge,
The design and verification of MuMax3, AIP Advances 4, 107133 (2014)

Theoretical Framework

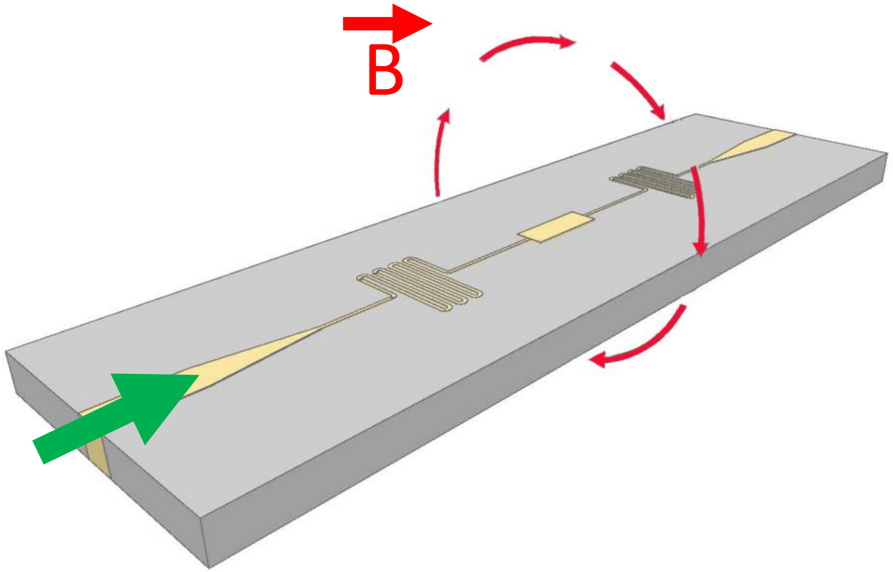
Magnon-photon coupling in ferromagnets

$$f = \gamma \cdot \sqrt{(B_{dc} + (N_y - N_x) \cdot M_{\text{sat}} \cdot \mu_0) \cdot (B_{dc} + (N_z - N_x) \cdot M_{\text{sat}}) \cdot \mu_0}$$

3D MLSI 3D-MLSI
Current distribution simulation for superconducting multi-layered structures

mumax^3
GPU-accelerated micromagnetism

$$g = \frac{B_{rms}}{2} \sqrt{\frac{\Delta f \chi V_{mag.system}}{h}}$$



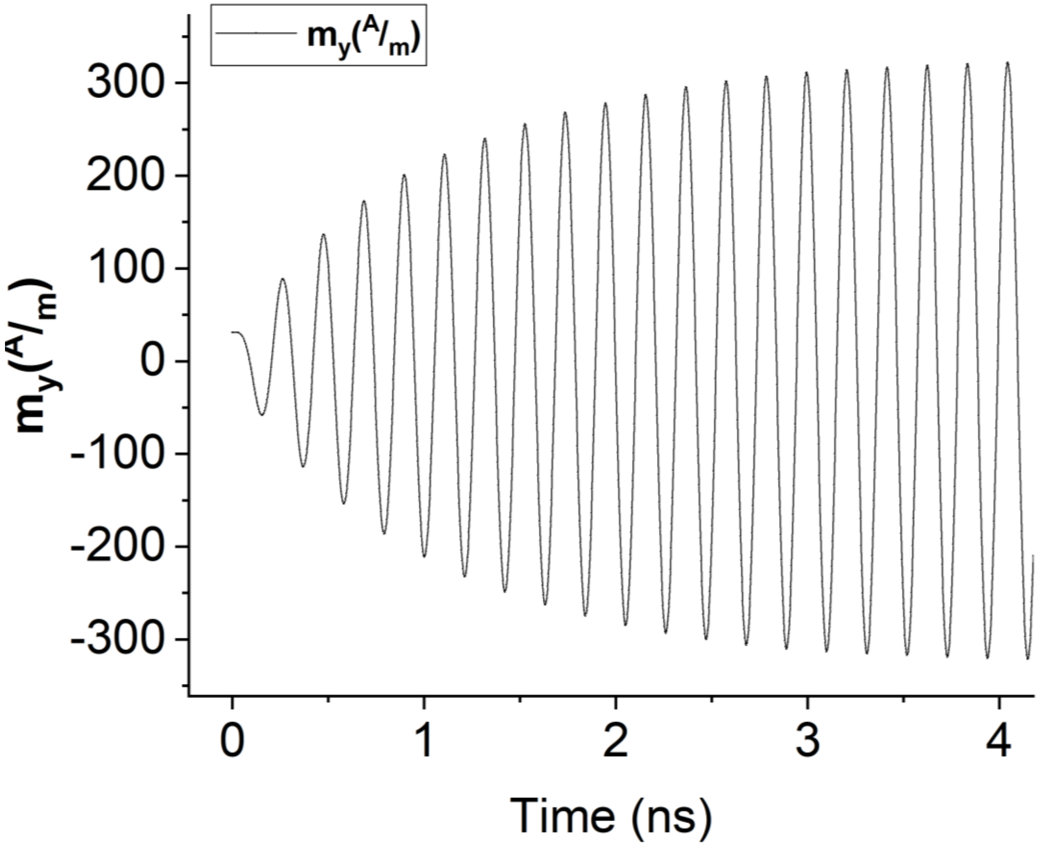
Arne Vansteenkiste, Jonathan Leliaert, Mykola Dvornik, Mathias Helsen, Felipe Garcia-Sanchez, and Bartel Van Waeyenberge, **The design and verification of MuMax3**, AIP Advances 4, 107133 (2014)

Theoretical Framework

Shaped ferromagnets

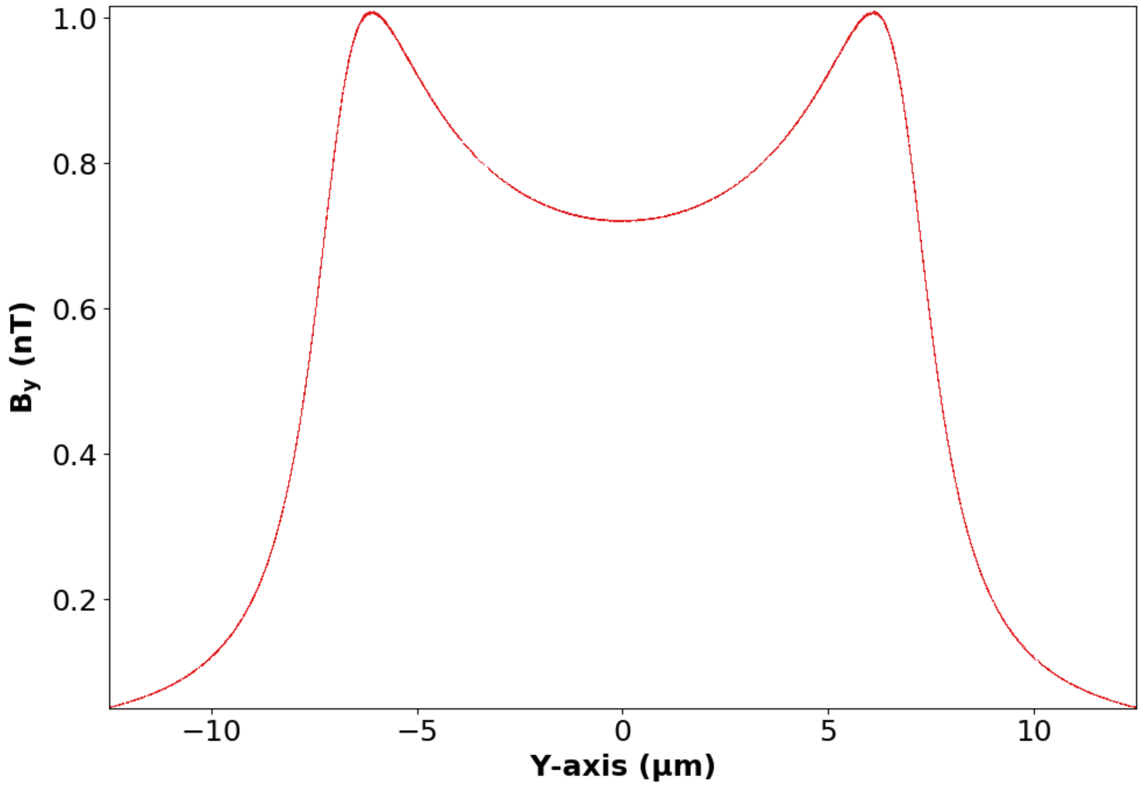
mumax^3

GPU-accelerated micromagnetism



3D-MLSI

Current distribution simulation for superconducting multi-layered structures



Experimental Work

Materials

26 55.845

Fe

Iron

[Ar] $3d^6 4s^2$

+

28 58.693

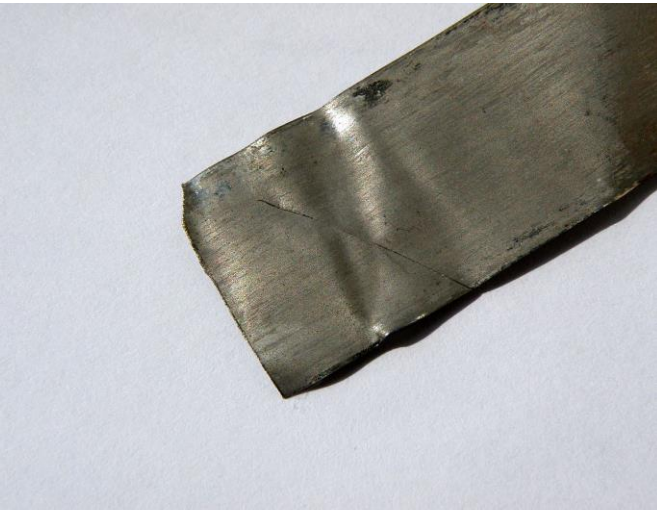
Ni

Nickel

[Ar] $3d^8 4s^2$

=

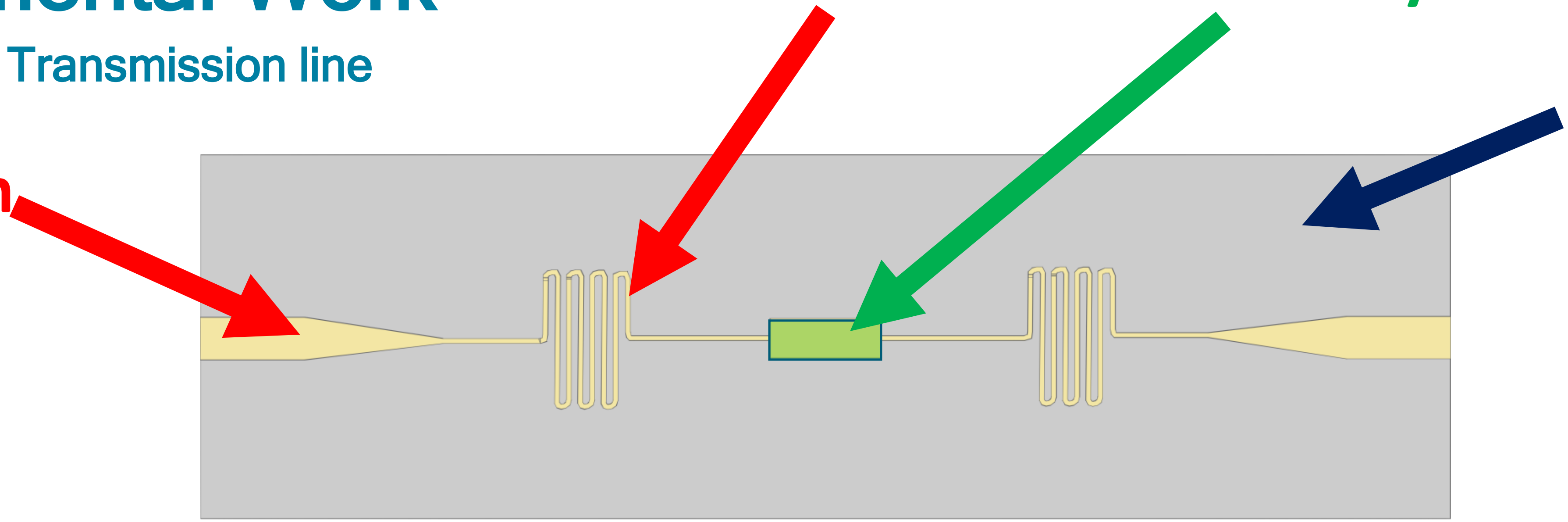
LOW magneto-crystalline anisotropy



Permalloy

Experimental Work

Chip and Transmission line



Niobium

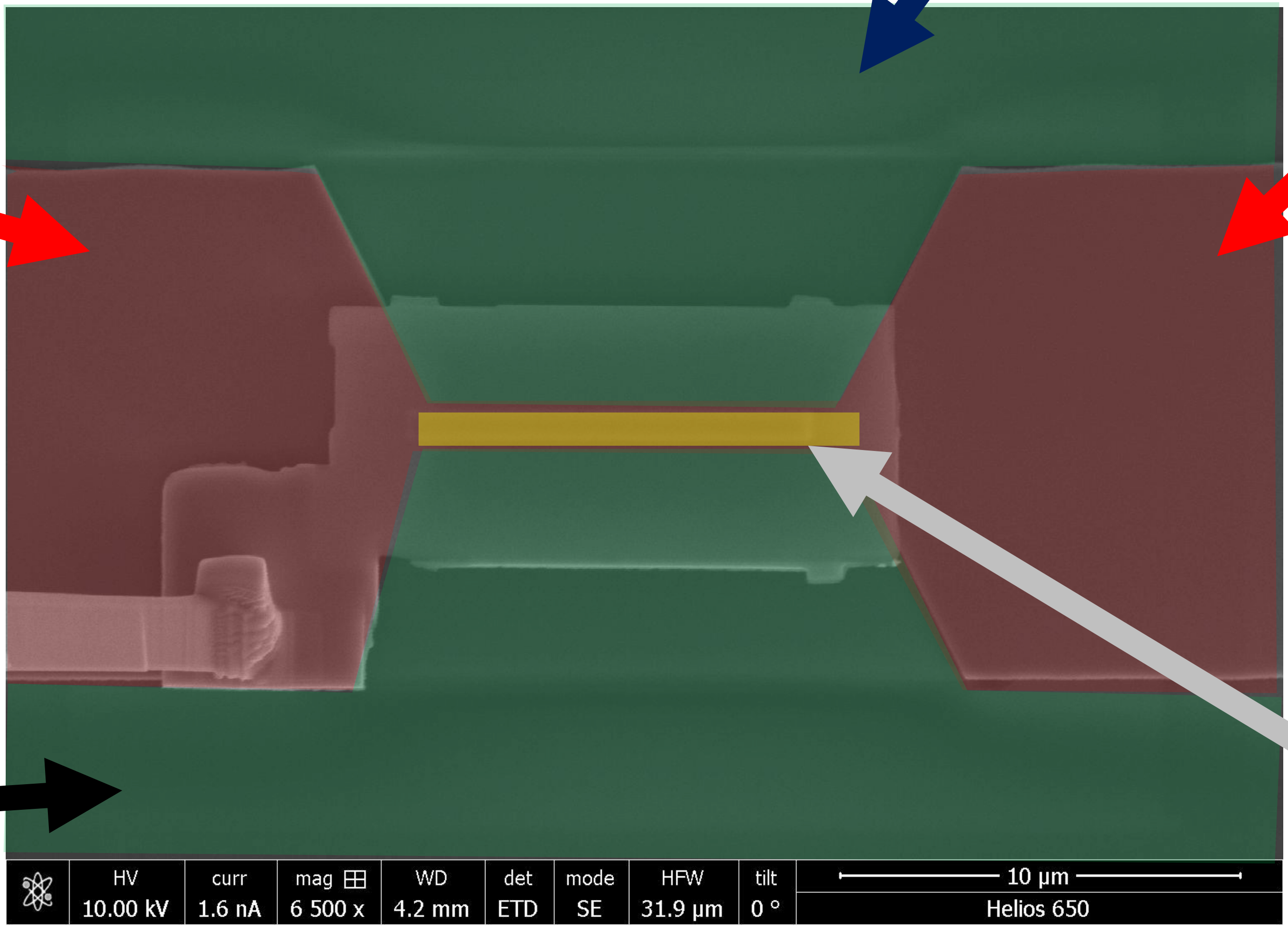
Niobium

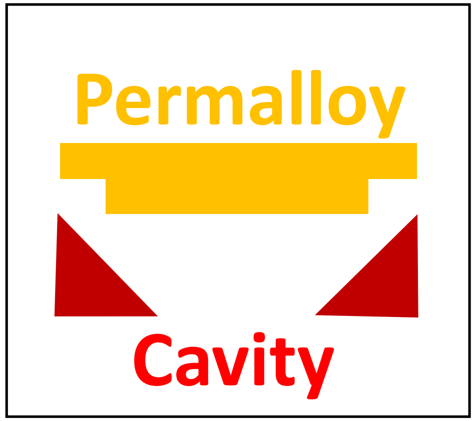
Permalloy

Sillicon

Experimental Work

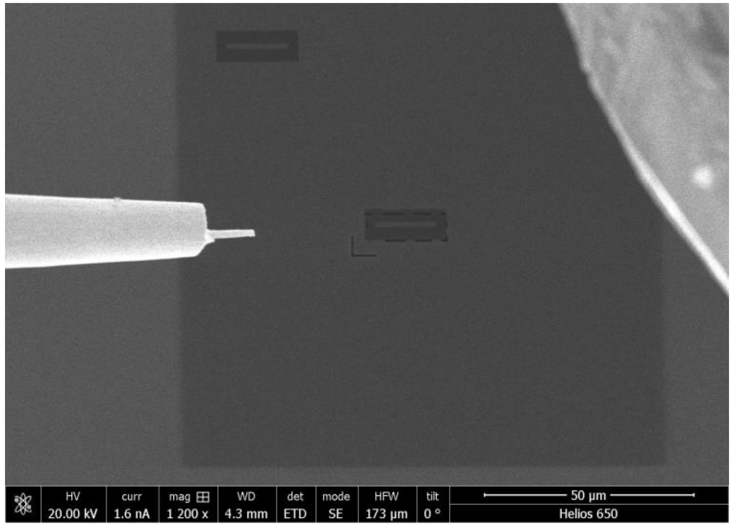
Cavity detail

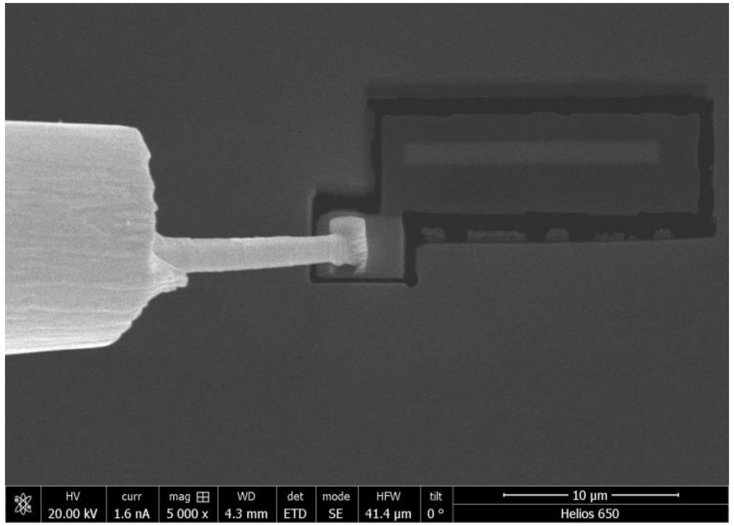


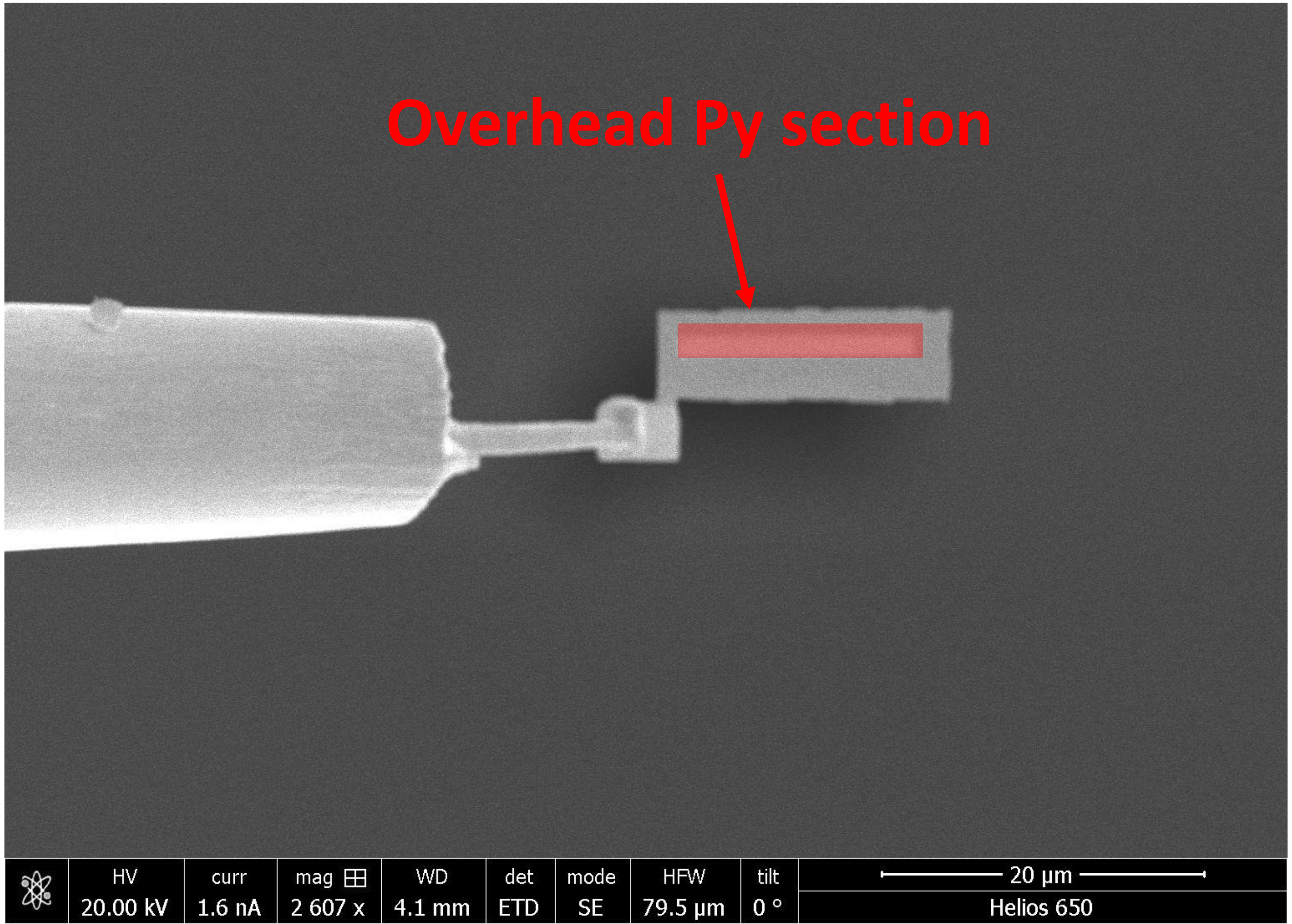


Experimental Work

Fabrication Process - Slab cut

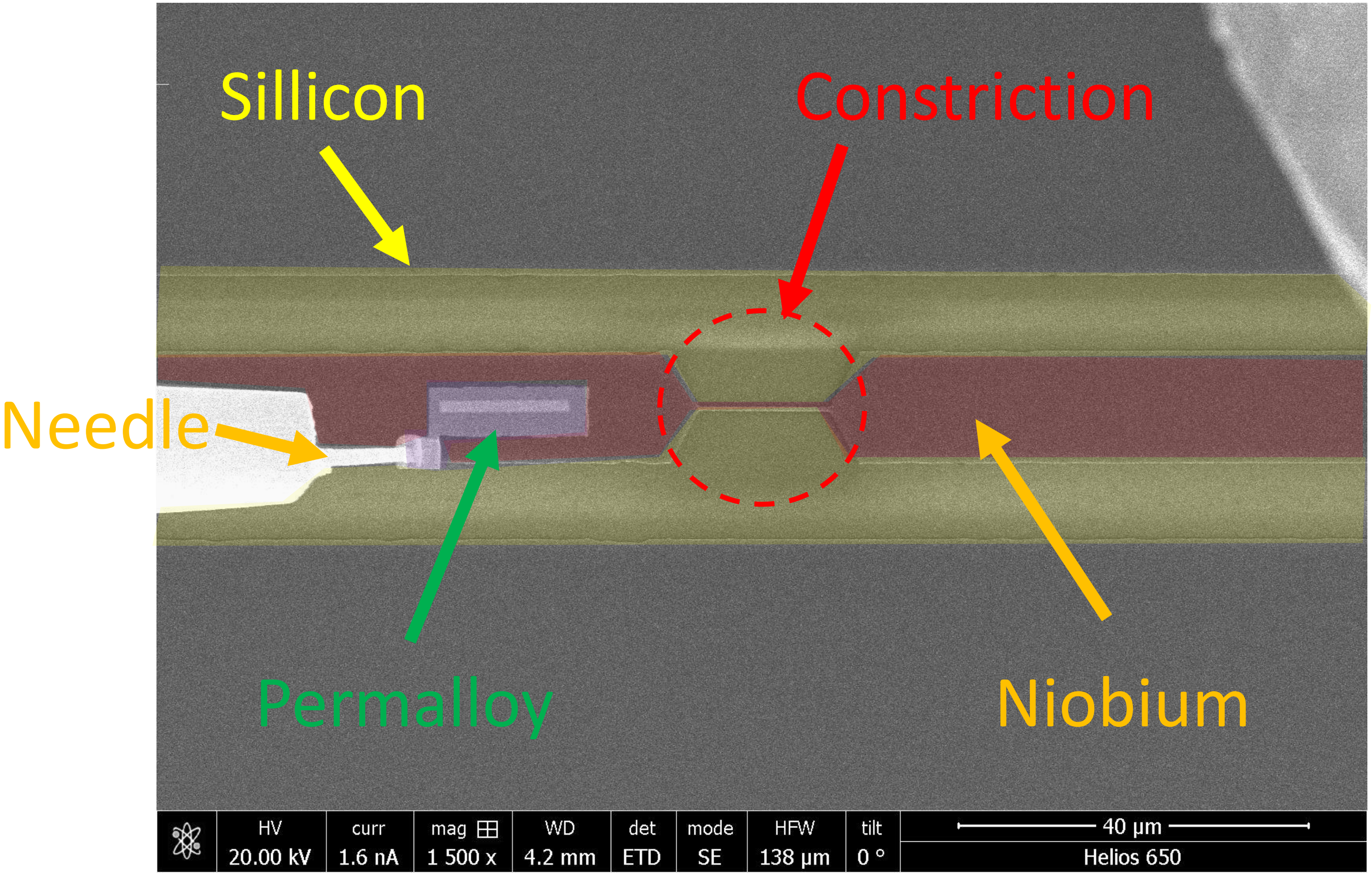


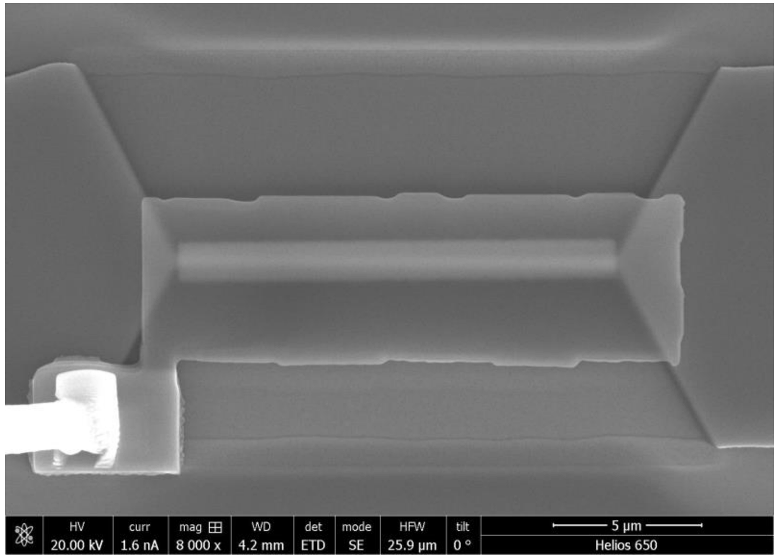


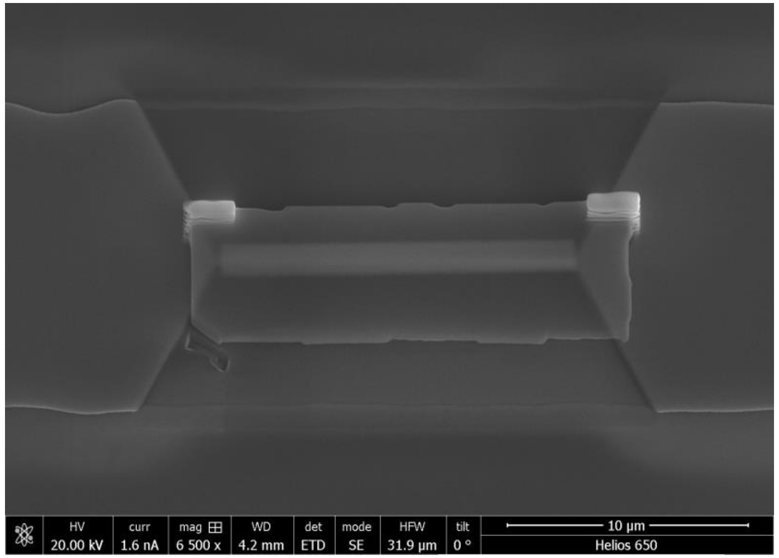


Experimental Work

Fabrication Process - Slab deposition





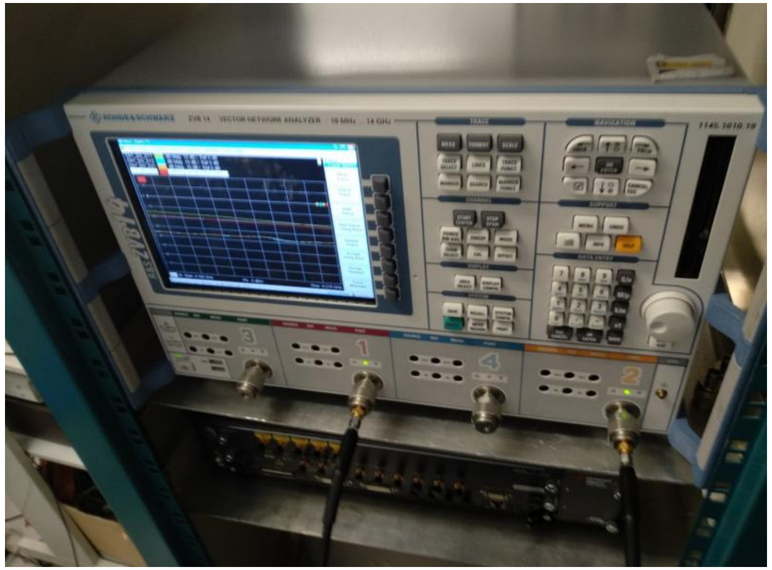


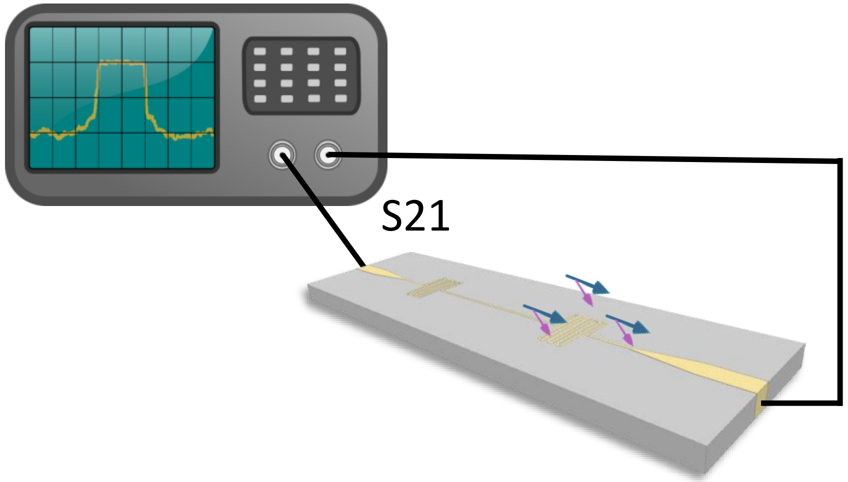
Experimental Work

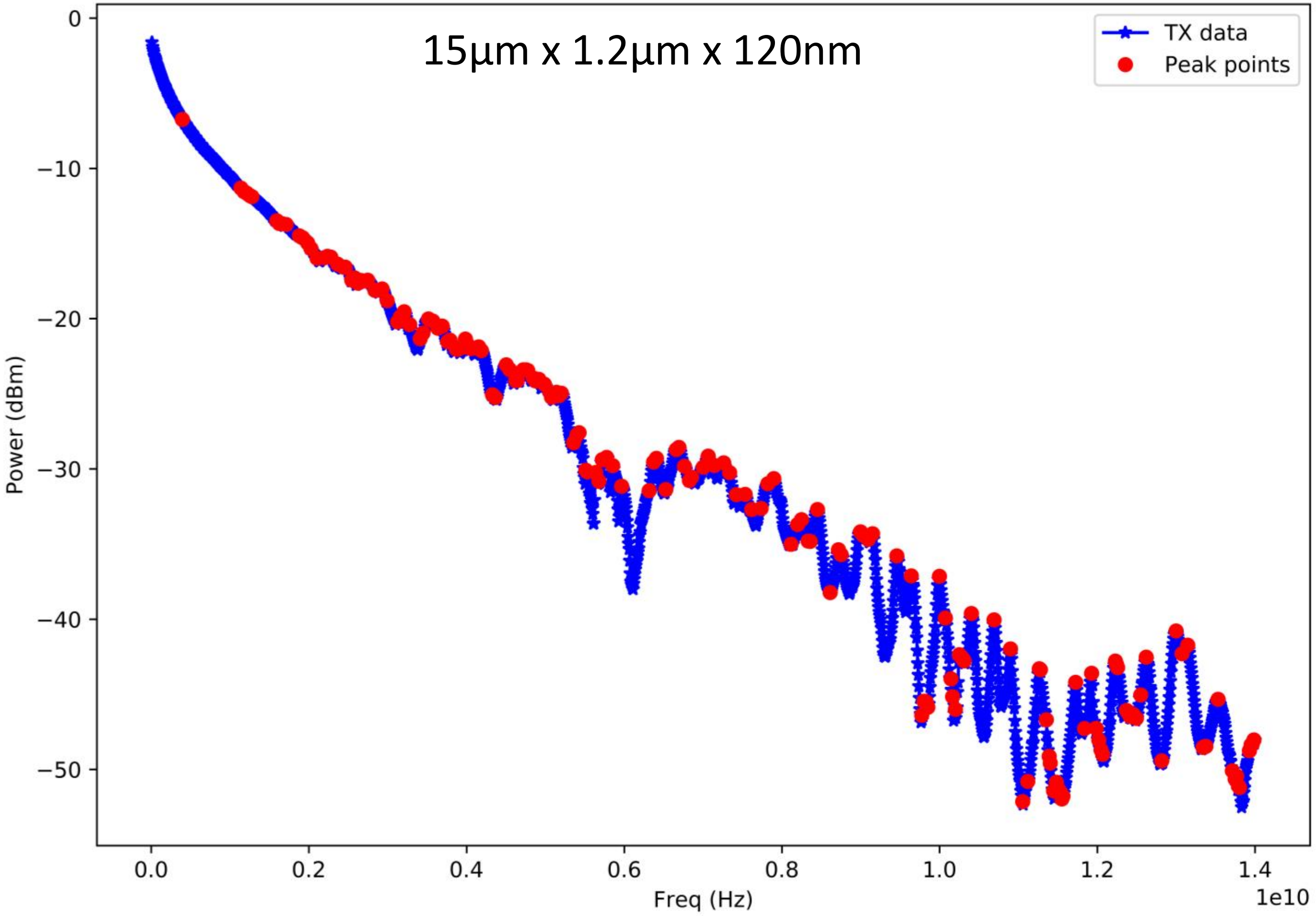
Fabrication Process – Cooling system

Experimental Work

Laboratory devices



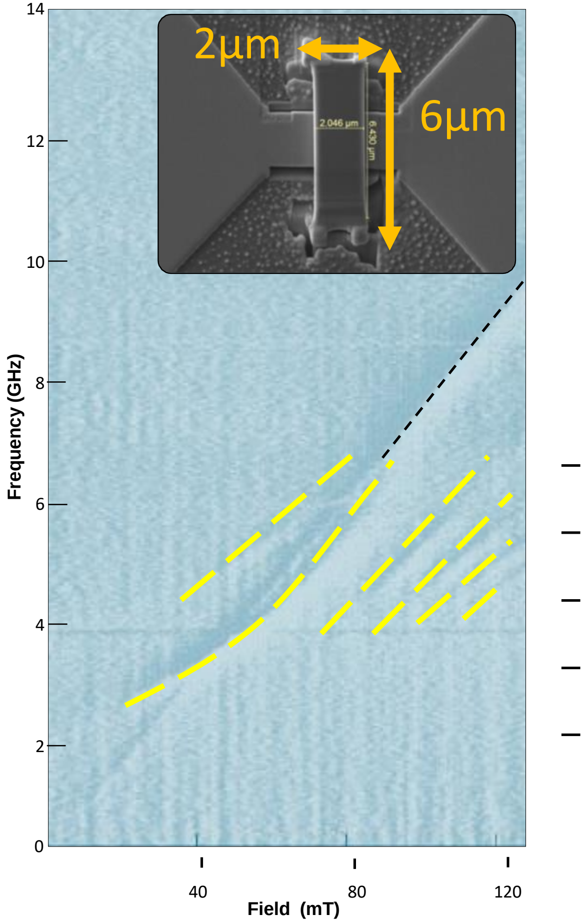


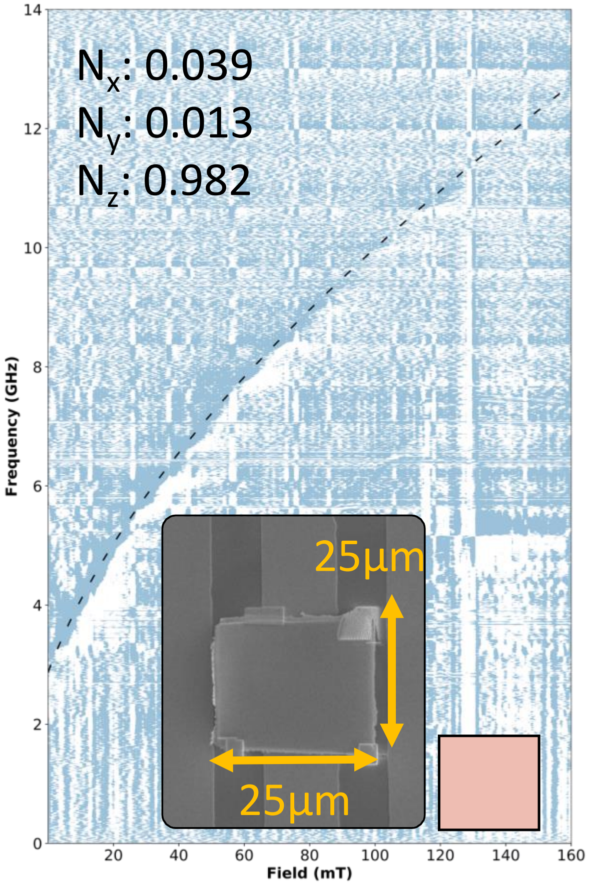


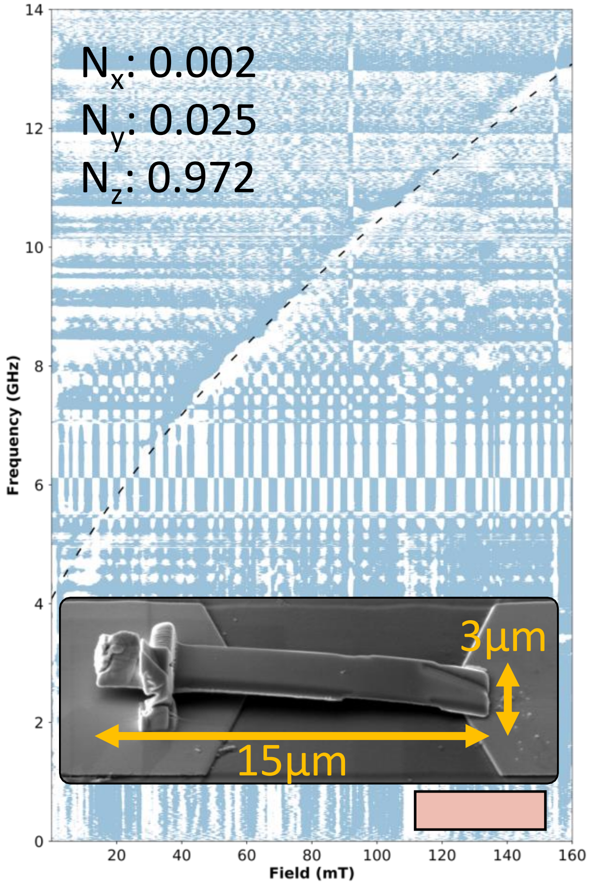
Experimental Work

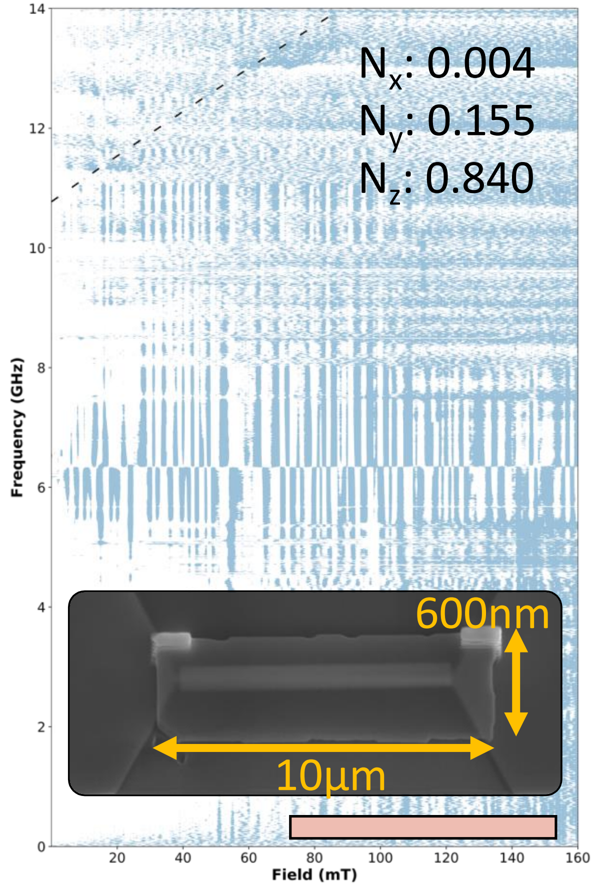
B_{ext} →

Transmission lines





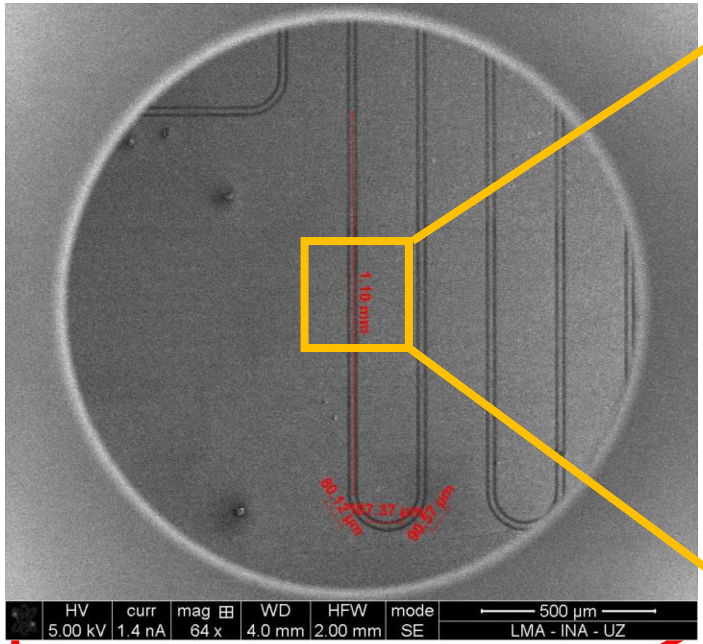


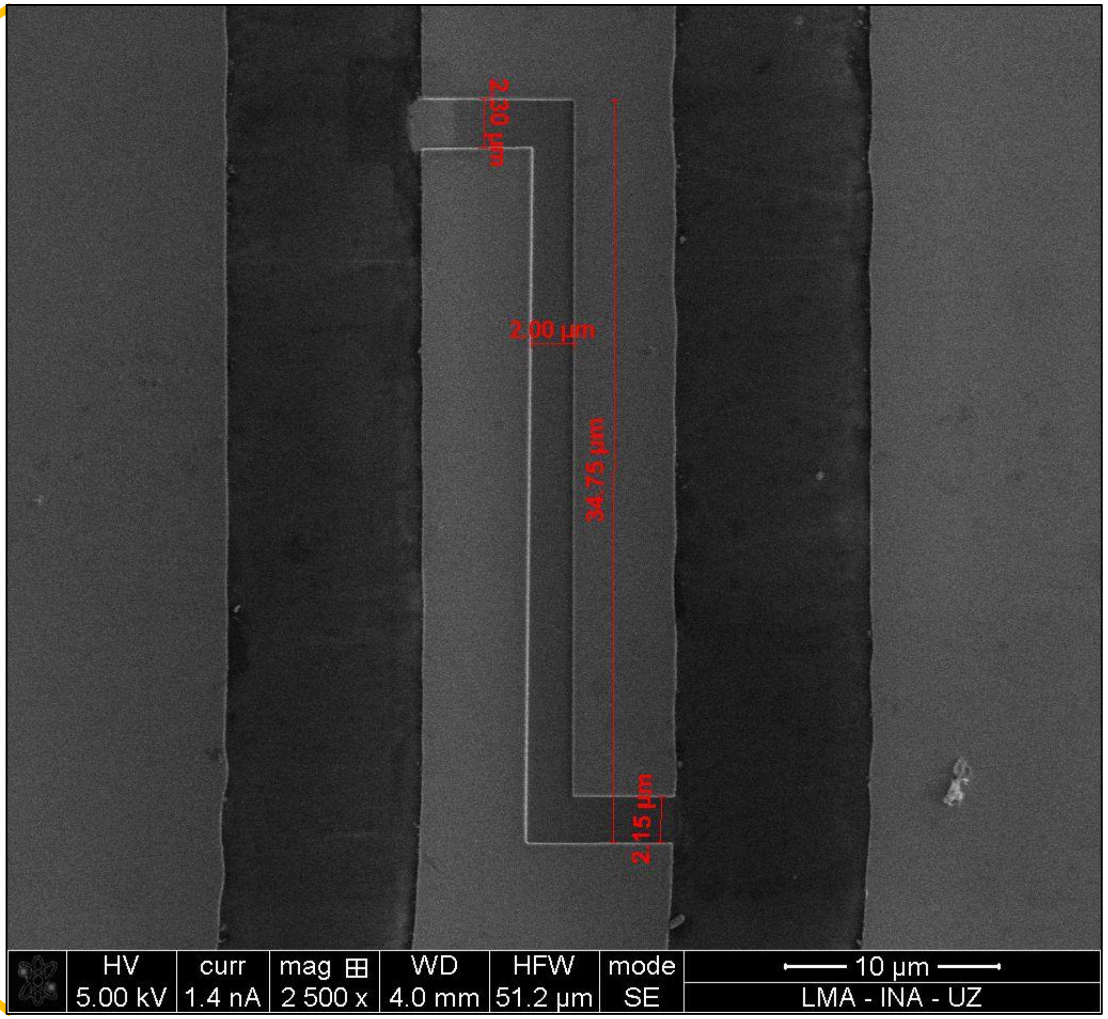


S. Martinez-Losa del Rincon, I. Gimeno, J. Perez-Bailon, V. Rollano, F. Luis, D. Zueco, M. J. Martinez-Perez, **Measuring the magnon-photon coupling in shaped ferromagnets: tuning of the resonance frequency**, Phys. Rev. Applied 19, 014002 (2023)

Experimental Work

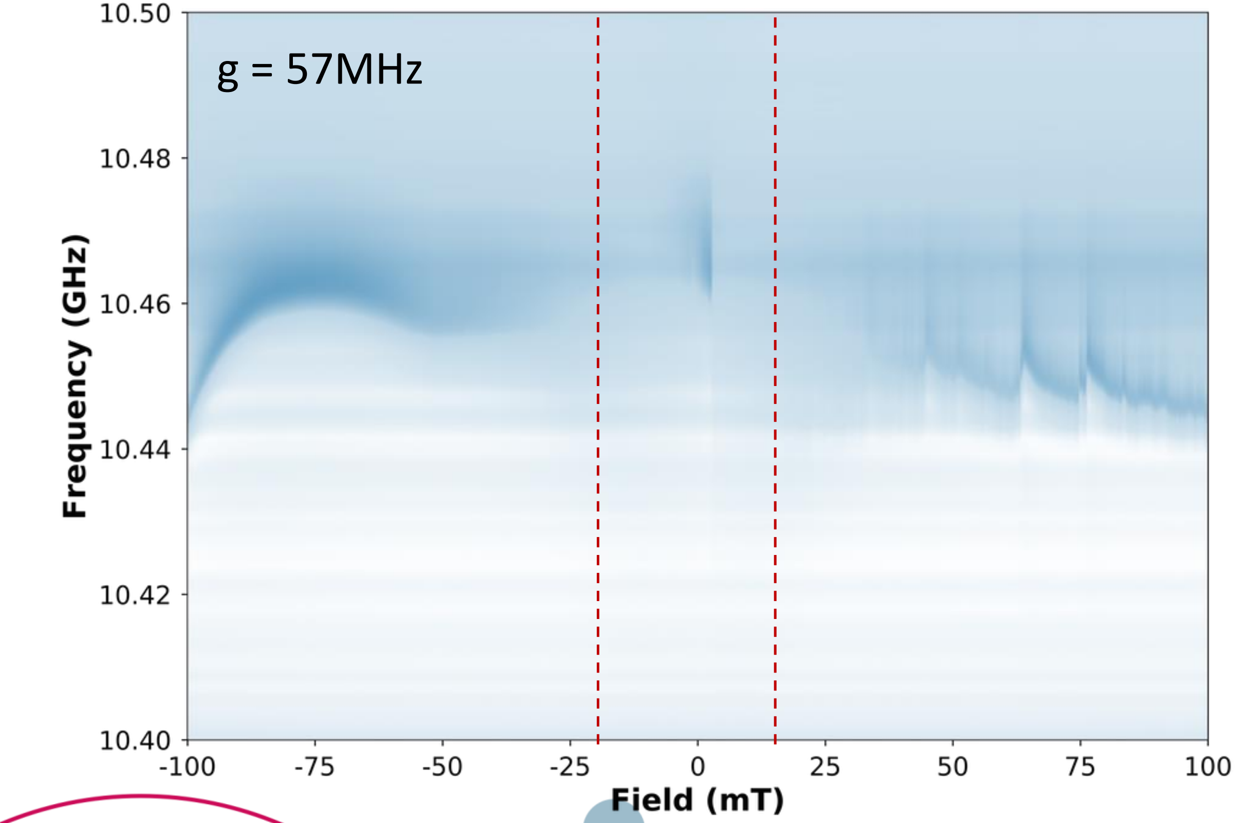
From CPW to Resonator

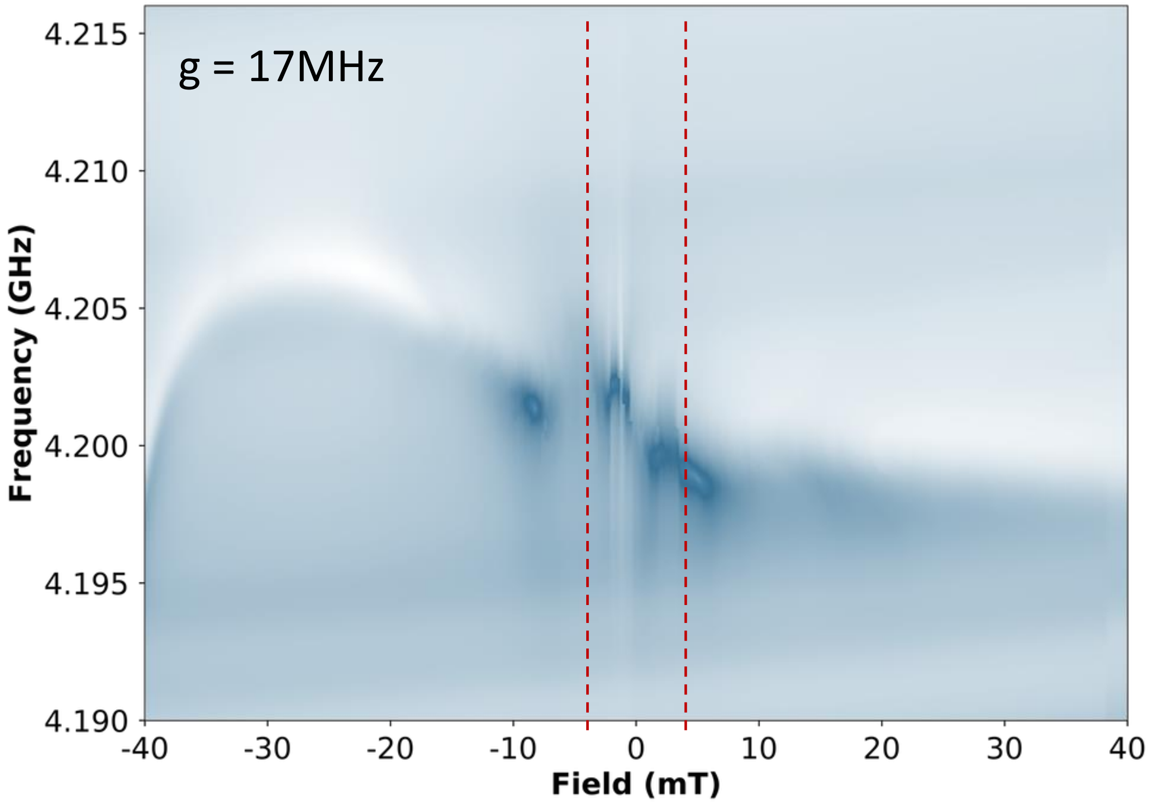




Experimental Work

Resonators



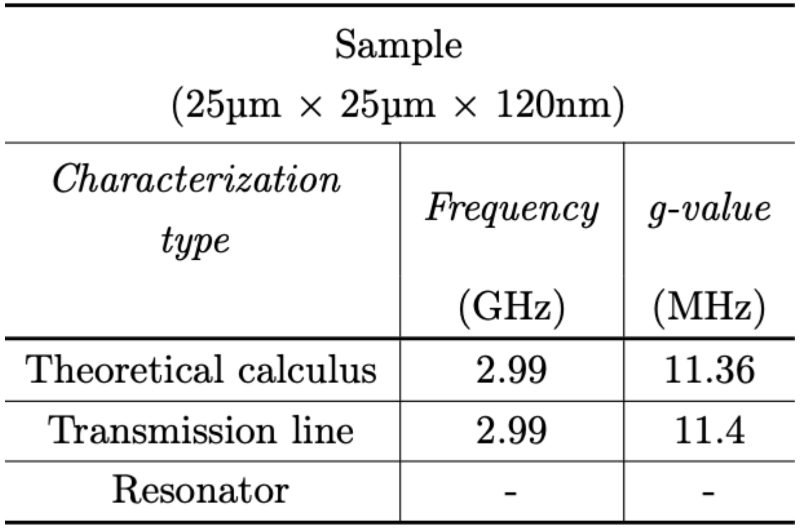


10µm x 600nm x 120nm

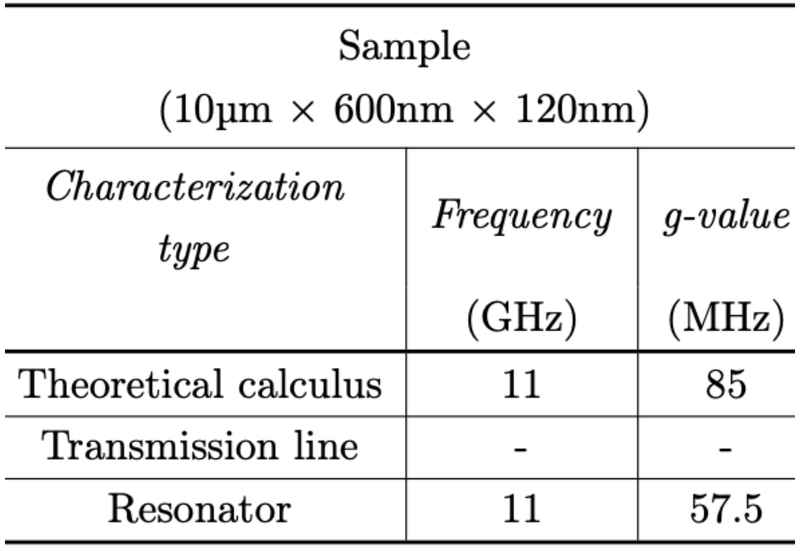
15µm x 3µm x 60nm

Results and Analysis

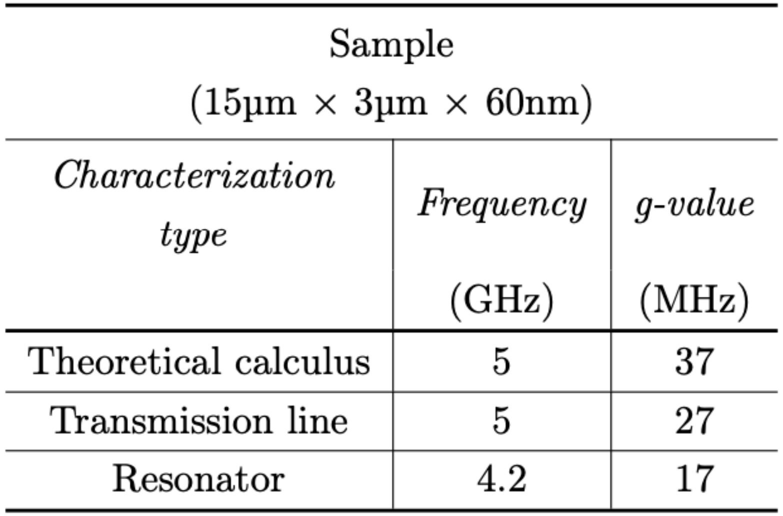
Coupling values summary



Sample (25µm × 25µm × 120nm)		
Characterization type	*Frequency* (GHz)	*g-value* (MHz)
Theoretical calculus	2.99	11.36
Transmission line	2.99	11.4
Resonator	-	-



Sample (10µm × 600nm × 120nm)		
Characterization type	*Frequency* (GHz)	*g-value* (MHz)
Theoretical calculus	11	85
Transmission line	-	-
Resonator	11	57.5



Sample (15µm × 3µm × 60nm)		
Characterization type	*Frequency* (GHz)	*g-value* (MHz)
Theoretical calculus	5	37
Transmission line	5	27
Resonator	4.2	17

Ongoing Work

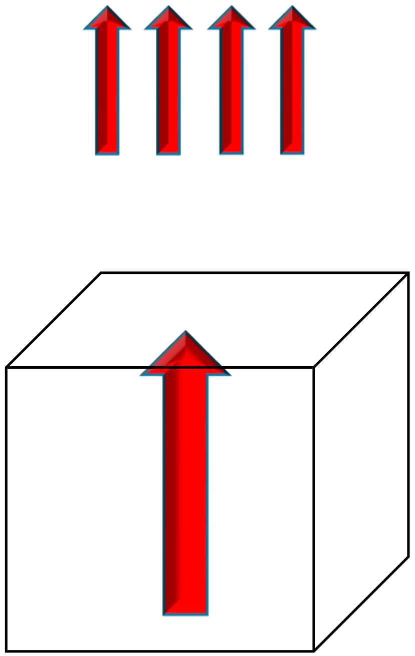
mumax^3

GPU-accelerated micromagnetism

+

Cavity

Ongoing Work

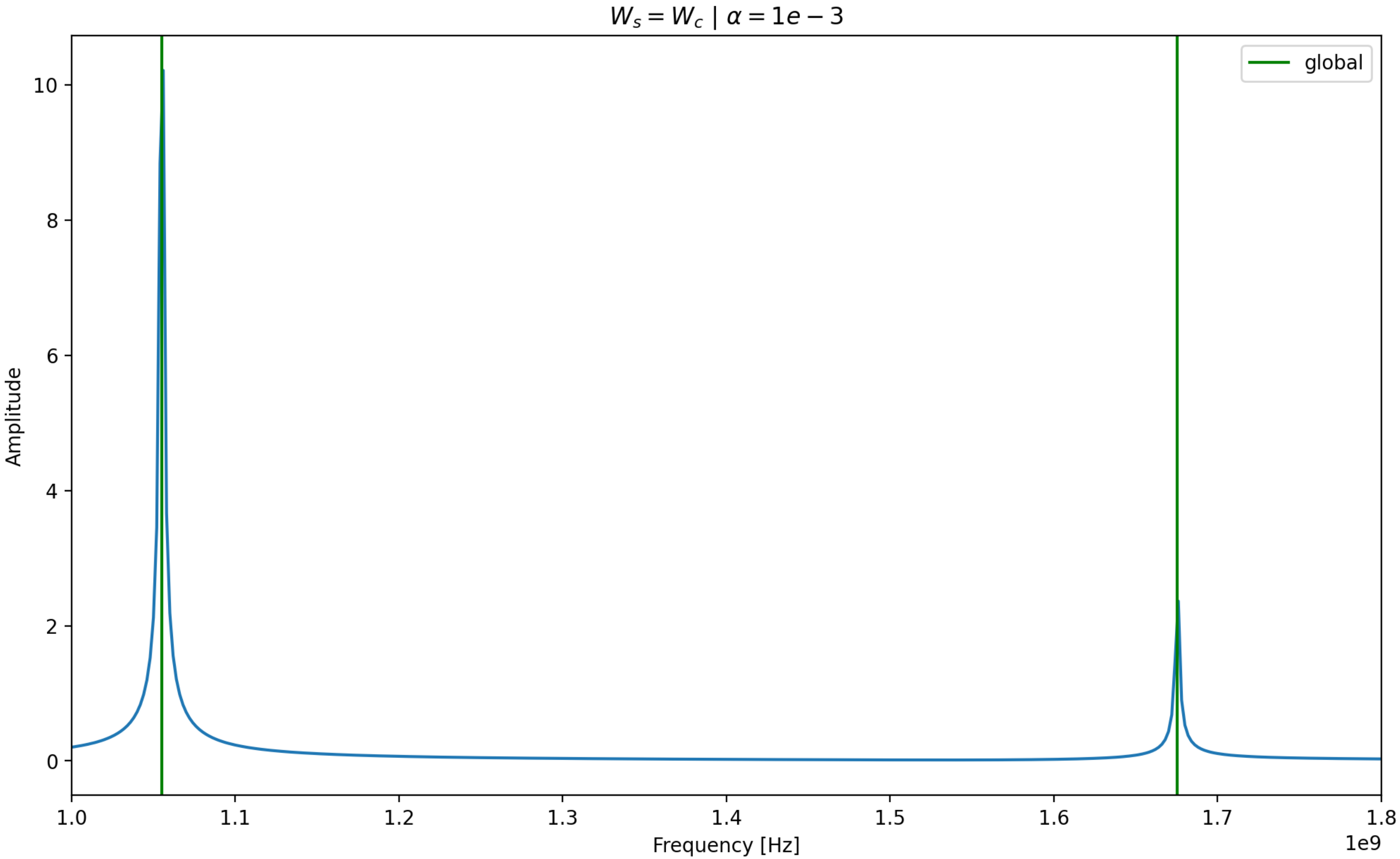


$$\vec{B}_{\text{eff}}\left(\vec{r}_i,t\right)=\vec{B}-\overset{\text{Extra term}}{\boxed{\vec{b}_{rms}\left(\vec{r}_i\right)\Gamma(t)}}$$

$$\Gamma(t)=\frac{2\gamma}{\hbar}\sum_i\vec{b}_{\text{rms}}(\vec{r}_i)\int_0^t\sin(\omega_c(\tau-t))\vec{S}_i(\tau)\delta\tau$$

J. Román-Roche, F. Luis, and D. Zueco, **Photon Condensation and Enhanced Magnetism in Cavity QED**, Phys. Rev. Lett. 127, 167201 (2021)

Ongoing Work



Conclusions

- CPW and resonators with ferromagnetic materials creates different states of matter
- Demonstrated performance in nanoscale and mesoscale of quantum phenomena
- Reuse of samples to make resonators
- Magnons are just more than quasiparticles

Supervisors

Theoretical colleagues

Thank you