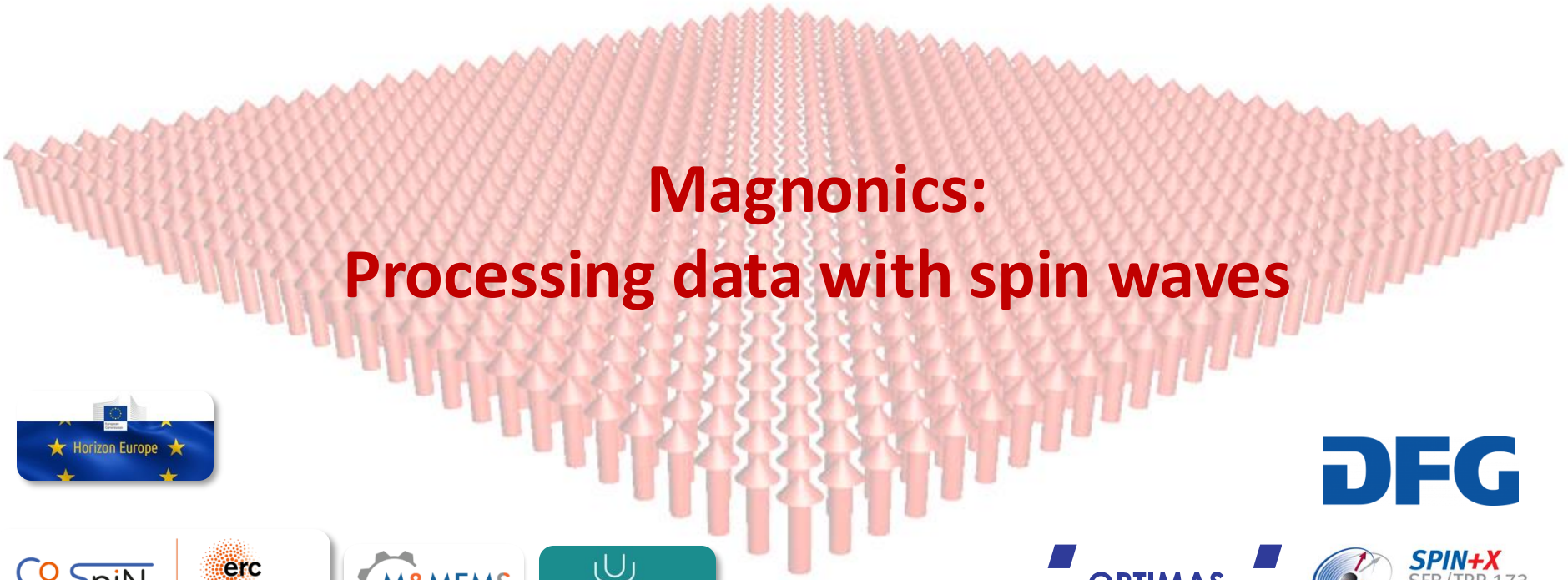
AG MAGNETISMUS
TU KAISERSLAUTERN



Magnonics:
Processing data with spin waves

Horizon Europe

DFG

CoSpiN

erc
European Research Council

M&MEMS

SPIDER

OPTIMAS
light-spin-matter

SPIN+X
SFB/TRR 173
Kaiserslautern • Mainz

Spin physics in Kaiserslautern

Laboratory for Advanced Spin Engineering
LASE









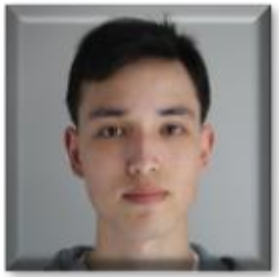
Research team *Nanoscaled Magnonic Hybrids*







Jun. Prof. Philipp Pirro
Dr. Björn Heinz
Dr. Mateusz Zelent
Dr. Mujin You
Dr. Anna Friedel




PhD students:
David Breitbach,
Akira Lentfert,
Abbas Koujok,
Felix Kohl,
Hanadi Mortada



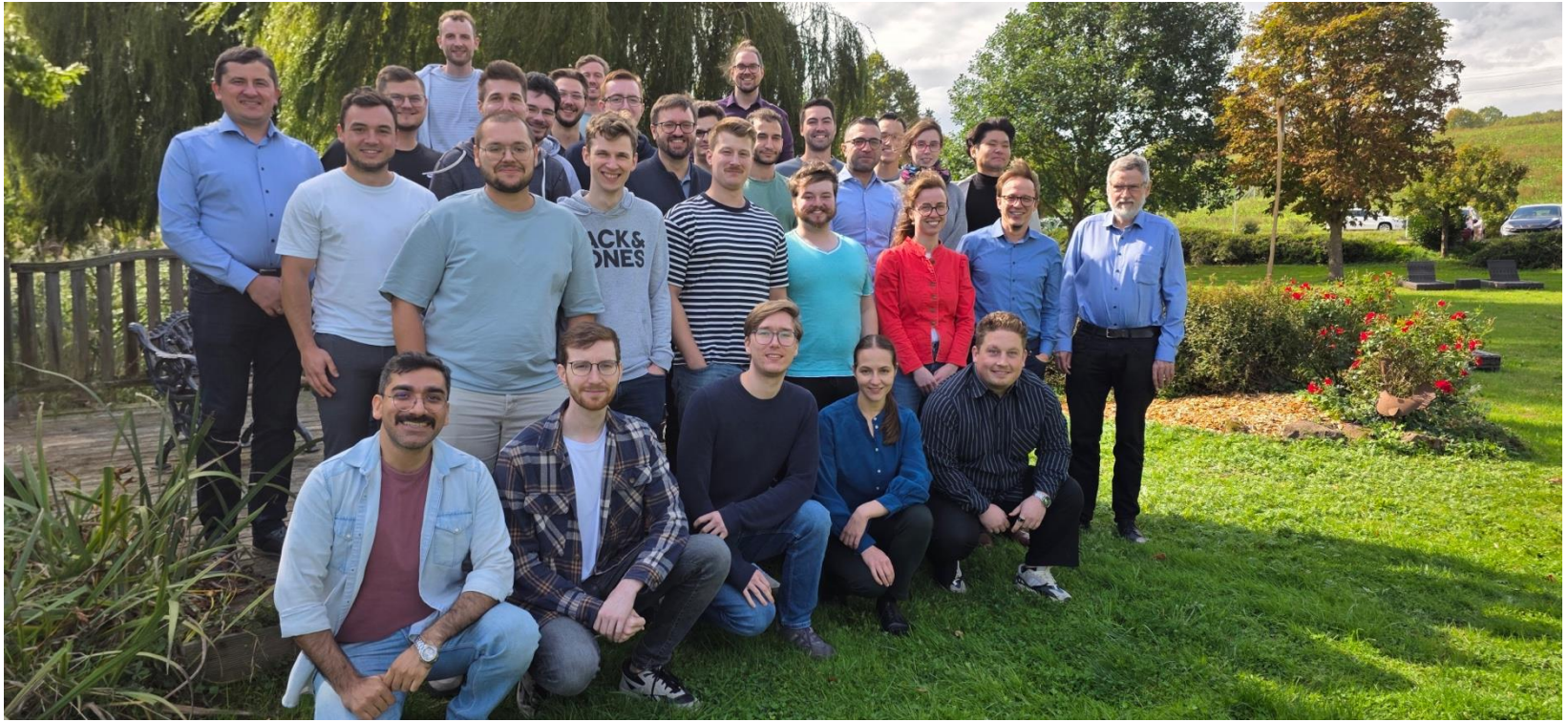


PhD students:
Javad Kamali,
Moritz Bechberger,
Matthias Wagner



Master student:
Tim Vogel

Magnonics in Kaiserslautern



Together with the groups “Applied Spintronic Phenomena” (Prof. M. Weiler) and “Magnetism” (Prof. B. Hillebrands)

Outline

- **Basics of spin waves**
  - Classical spin wave theory (micromagnetic model)
  - Spin-wave detection, manipulation and generation
- **Magnon signal processing and computing**
  - **Linear** magnonics for
    - Signal processing
    - Logic devices: interference-based approaches
  - **Nonlinear** magnonic elements

Our field: magnonics



Electronics
Carrier of information: **charge** of the electron

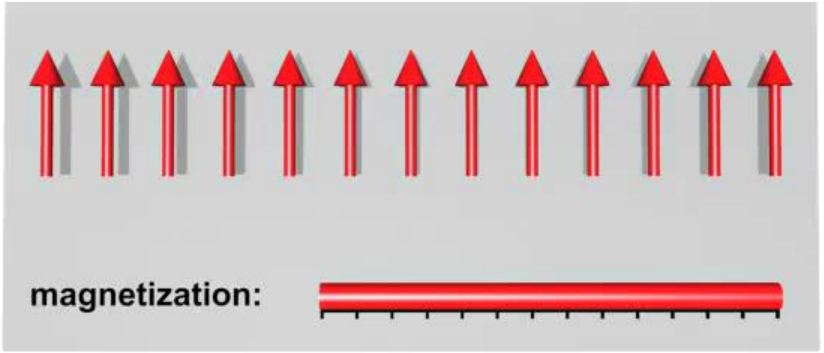
- **Magnonics** is subfield of **Spintronics**: use of **spin** to create functionalities

Ferromagnetic spin chain

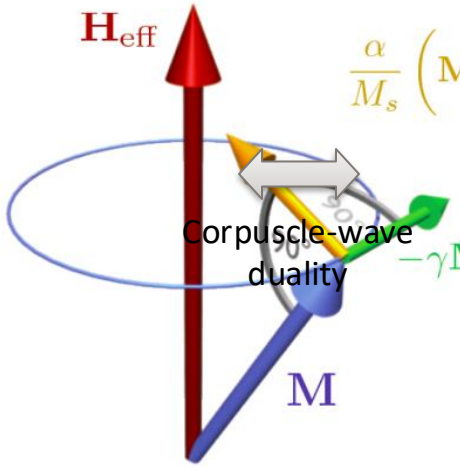
Spin-wave excitation energy (exchange energy) vs. wave vector

Dispersion relation:

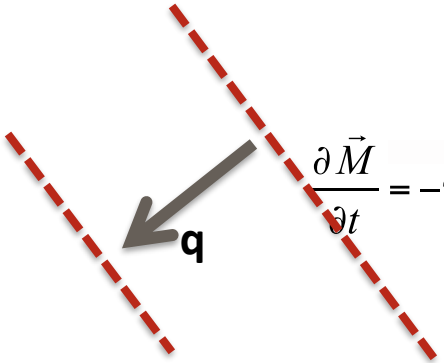
$$E = hf = 4J_{ex}S(1-\cos(ka)) \approx 2J_{ex}Sa^2 k^2$$



Coherent dynamics: spin waves and magnons



Corpuscle-wave duality



$$\frac{\partial\vec{M}}{\partial t}=-\gamma\left(\vec{M}\times\vec{B}_{\text{eff}}\right)+\frac{\alpha\mu_0}{M_s}\left(\vec{M}\times\frac{\partial\vec{M}}{\partial t}\right)$$

MAGNON quasi-particle :

- Energy

$$\varepsilon=\hbar\omega=\frac{\eta}{\hbar}p^2$$

- Quasi-momentum

$$\vec{p}=\hbar\vec{q}$$

- Mass

$$m=\hbar M_S/(4J_{ex})$$

- Spin (in Planck's constant)

$$s=1$$

- Lifetime
  (Yttrium Iron Garnet, $Y_3Fe_5O_{12}$)
  ~ 500 ns !

Example: only exchange interaction considered

Magnetostatic spin-wave description

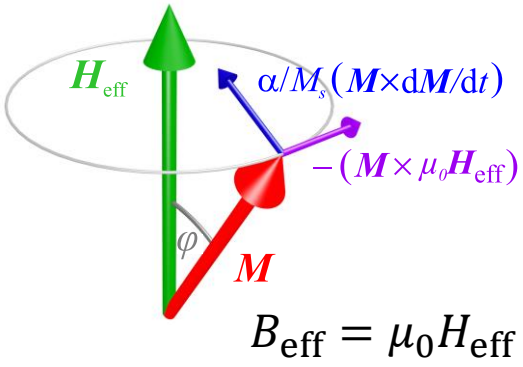
Spin wave: (weak) excitation of the magnetization ***M*** from its ground state described by:

Landau-Lifshitz-Gilbert torque equation

Includes (non-local) interactions

$$\frac{1}{|\gamma|}\frac{d\vec{M}(\vec{r},t)}{dt} = -\vec{M}(\vec{r},t)\times\vec{B}_{eff}(\vec{r},t) + \frac{\alpha}{M_s}\vec{M}(\vec{r},t)\times\frac{d\vec{M}(\vec{r},t)}{dt} + \vec{T}_{STT}$$

Precession — Viscous damping



Additional torque due to spintronic effects

Maxwell equations (magnetostatic limit): „Magnetostatic modes“

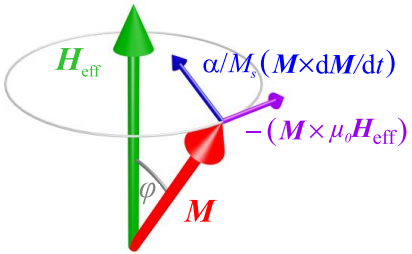
$$\nabla\times\vec{H} = 0 \quad \text{for } k_{\mathrm{SW}} \gg k_{Photon} = \omega/c, \quad j = 0$$

$$\nabla\cdot(\vec{H} + M) = 0$$

Valid for wave vector *k*>500 rad/m for typical ferrite (YIG, ε=10, 10 GHz)

Effective field $B_{eff}=\mu_0 H_{eff}$

$$\frac{1}{|\gamma|}\frac{d\vec{M}(\vec{r},t)}{dt} = -\vec{M}(\vec{r},t)\times\vec{B}_{eff}(\vec{r},t) + \frac{\alpha}{M_s}\vec{M}(\vec{r},t)\times\frac{d\vec{M}(\vec{r},t)}{dt}$$



$$\vec{B}_{\text{eff}} = \mu_0\vec{H}_{\text{eff}} = -\nabla_{\vec{M}}\varepsilon\left(\vec{M}\right)$$

ε: Magnetic energy density

$$= \vec{B}_0 + \vec{b}_0(t) + \int_V \tilde{G}(\vec{r},\vec{r}')\cdot\vec{M}(\vec{r})\,\mathrm{d}\vec{r}'^3 + \frac{\eta}{\gamma M_s}\Delta\vec{M} + \frac{D}{M_s}\left(\hat{z}\times\frac{\partial M}{\partial\hat{x}}\right)$$

Dipolar interaction described by Green's function *G*

Symmetric Heisenberg exchange interaction

Antisymmetric Dzyaloshinskii–Moriya exchange interaction

Contribution to the spin-wave dispersion relation (ferromagnetic ground state):

Geometry dependent, complex contribution

$f \sim k^2$

$f \sim k$

Linearization of the Landau-Lifshitz-equation

$$\frac{1}{|\gamma|}\frac{d\vec{M}(\vec{r},t)}{dt} = -\vec{M}(\vec{r},t)\times\vec{B}_{eff}(\vec{r},t)$$

Neglect damping

$$\vec{M}(\vec{r},t) = \vec{M}_0(\vec{r}) + \vec{m}(\vec{r},t)$$
$$\vec{B}_{eff}(\vec{r},t) = \vec{B}_0(\vec{r}) + \vec{b}(\vec{r},t)$$

Small perturbations of the ground state

$$\frac{1}{|\gamma|}\frac{d\vec{m}(t)}{dt} = -\vec{M}_0\times\vec{B}_0 + \vec{M}_0\times\vec{b}(t) + \vec{m}(t)\times\vec{B}_0 + \vec{m}(t)\times\vec{b}(t)$$

Nonlinear contribution

- Low amplitude spin-waves/non-interacting magnons: neglect the nonlinear contribution
- However: **Nonlinearity is intrinsic**, pronounced nonlinear effects can be realized in any spin-wave system => see later

Solve for spin-wave eigenmodes

1) $\frac{1}{|\gamma|}\frac{d\vec{m}(t)}{dt} \approx -\vec{M}_0 \times \vec{B}_0 + \vec{M}_0 \times \vec{b}(t) + \vec{m}(t) \times \vec{B}_0$ Linearized Landau-Lifshitz-Equation

2) $\vec{M} \times \left[\frac{1}{M_s} \nabla_{\vec{M}} E_{Int} - \frac{2A}{M_s^2} \frac{\partial \vec{M}}{\partial \vec{n}} \right] = 0$ Rado-Weertman boundary condition: at the interfaces, the interface torque must vanish

Interface anisotropy energy

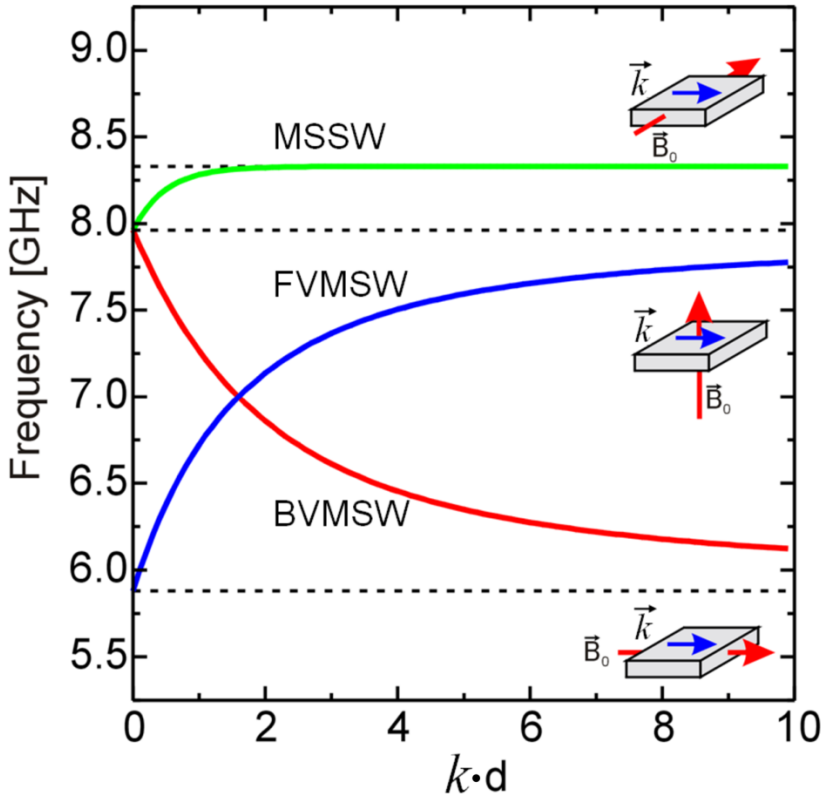
3) Continuous components from Maxwell's equation: $\vec{H} \parallel \text{interface}, \quad \vec{B} \perp \text{interface}$

In general, a numerical solution of the linear equations is needed, e.g. to solve for the spin-wave eigenmodes in magnetic multilayers

=>Numerical tools/eigenmode solver for complex geometries: TetraX, MagnumNP

B. Hillebrands, Phys Rev B 41, 530 (1990).

Dipolar spin waves in thin films



d: film thickness

Magnetostatic Surface Spin Waves (MSSW)

Forward Volume Magnetostatic Spin Waves (FVMSW)

Backward Volume Magnetostatic Spin Waves (BVMSW)

Dispersion relations:

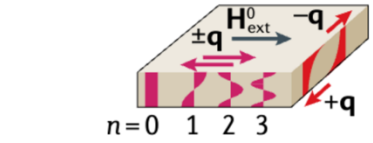
- strongly anisotropic
- not linear in |k|
- Finite gap at k=0

Dispersion relations of spin waves: tunability

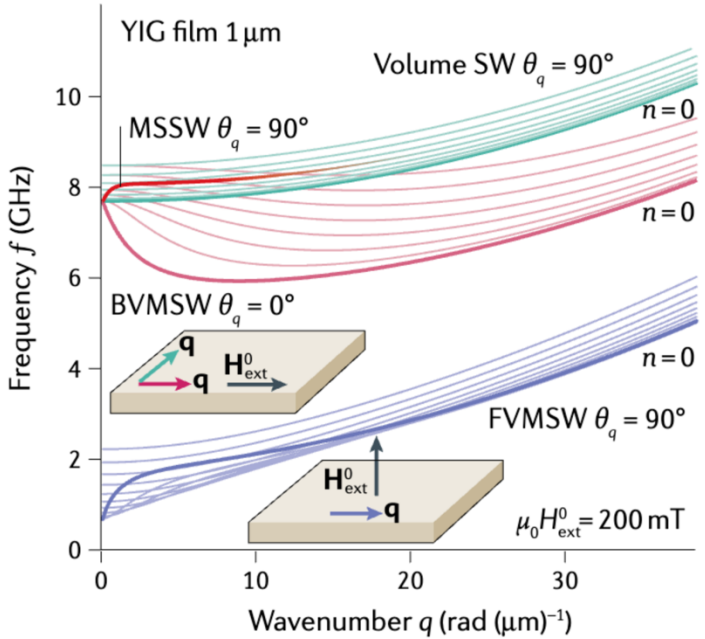
$$\frac{d\vec{M}}{dt} = -\gamma\mu_0 \vec{M} \times \vec{H}_{\text{eff}}$$

$$\vec{H}_{\text{eff}} = \vec{H}_{\text{ext}} + \vec{H}_{\text{dip}} + \vec{H}_{\text{exc}} + \vec{H}_{\text{m-e}} + \cdots$$

- $\vec{H}_{\text{ext}}$: **External field** shifts entire dispersion
- $\vec{H}_{\text{dip}}$: **Dipolar field** leads to anisotropic dispersion relations (wave vector, field direction), chirality
- $\vec{H}_{\text{exc}}$: **Exchange field** leads to $f \propto k^2$ (symmetric) and $f \propto k$ (antisymmetric exchange)
- $\vec{H}_{\text{m-e}}$: **Magneto-elastic field**, strain-based effects, enables coherent magnon-phonon coupling

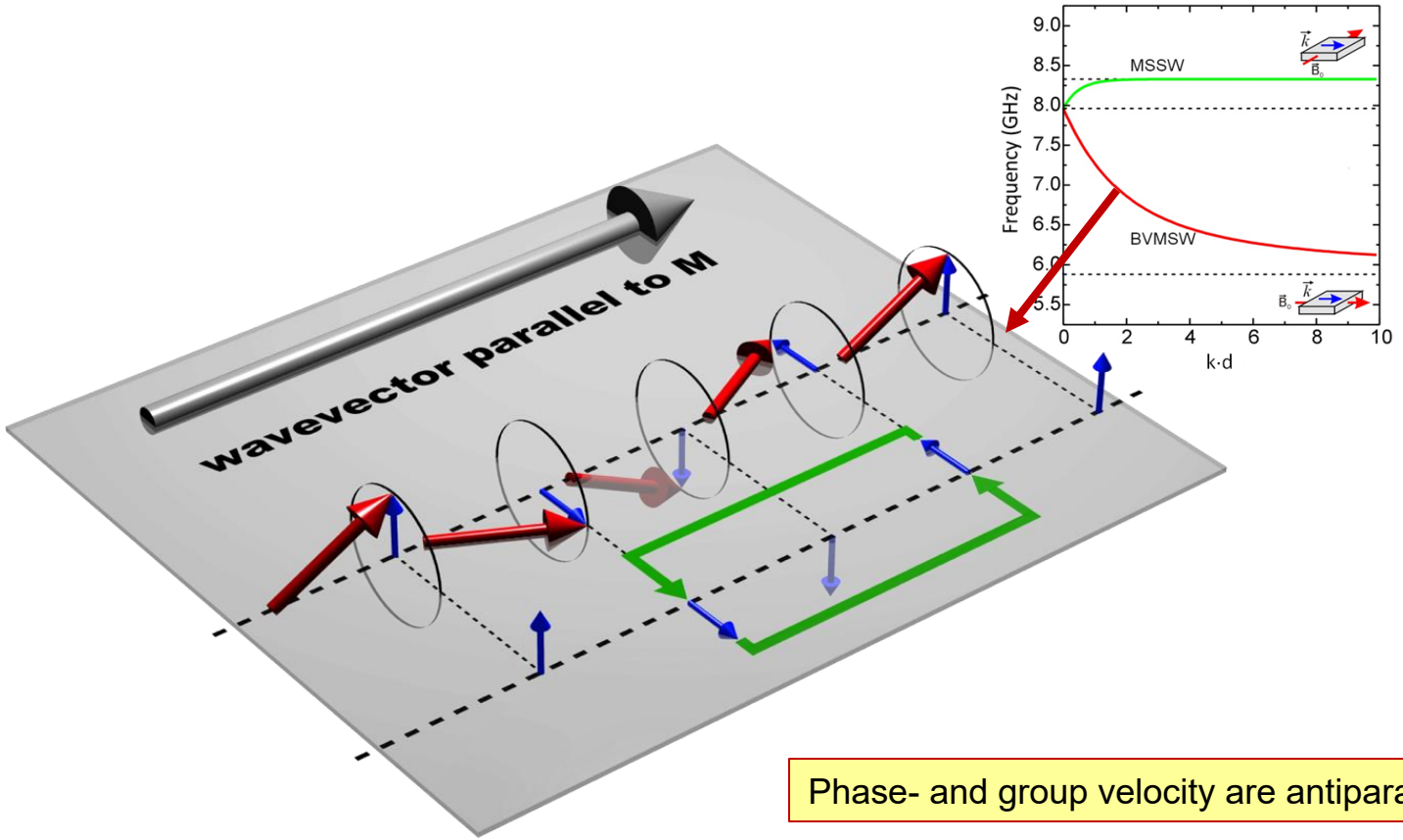


Dipolar spin waves



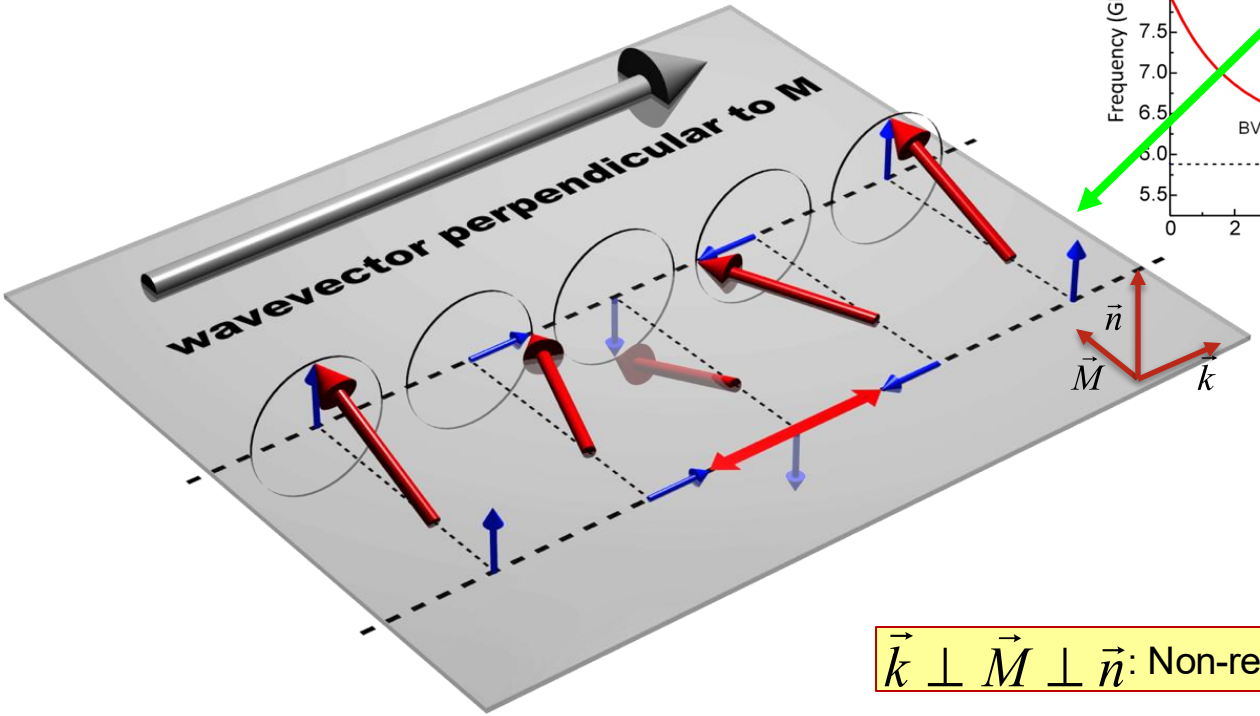
P. Pirro, et al., *Advances in **Coherent** Magnonics*, Nat Rev Mater **6**, 1114 (2021).

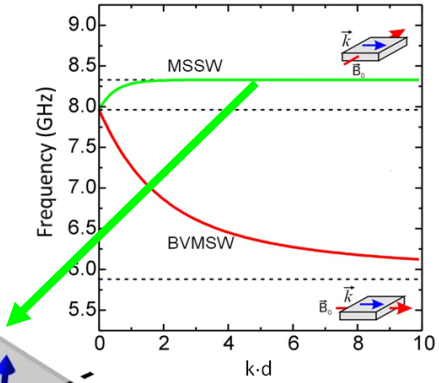
Backward volume magnetostatic spin wave (BVMSW)



Phase- and group velocity are antiparallel

Magnetostatic surface spin wave (MSSW)

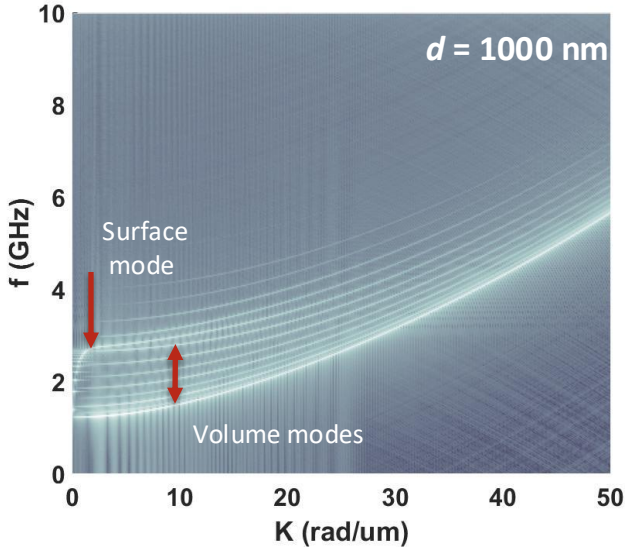


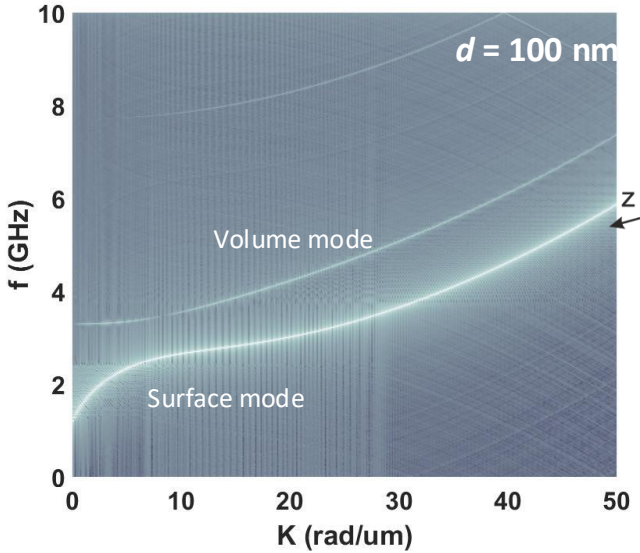


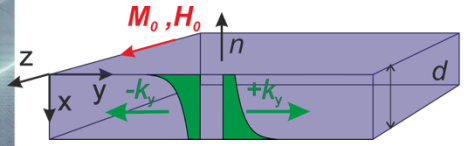
$\vec{k} \perp \vec{M} \perp \vec{n}$: Non-reciprocal effects

Dipole-exchange dispersion relations for films

Film thicknesses influences the volume modes due to quantized exchange energy







Surface mode (MSSW)

Thick films: Hybridization of "dipole" surface mode with exchange volume mode

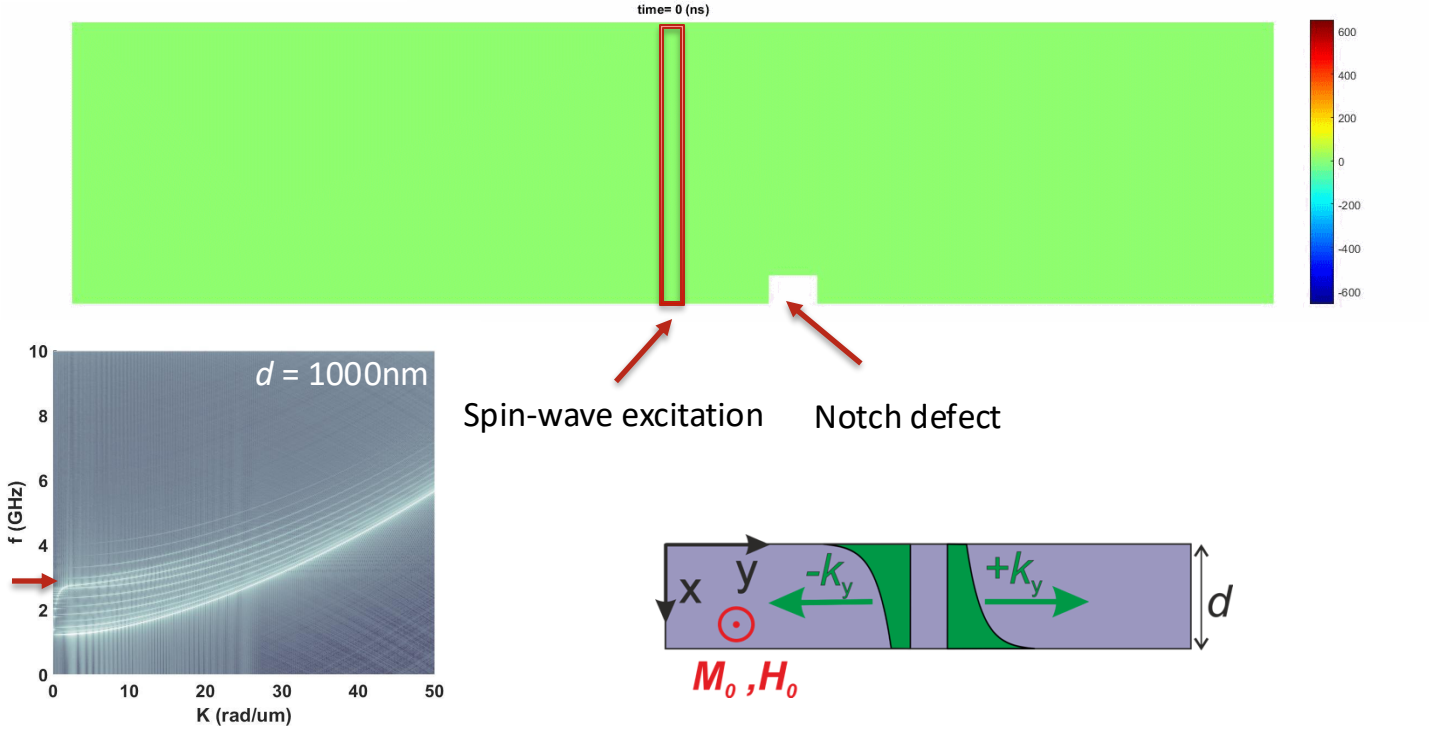
Thin films: "Dipole" surface mode in the **gap** of exchange volume modes

***k*⊥*M*, 10 mT**

Example: spin-wave scattering

10 ns spin-wave pulse

d=1000 nm, *f=3 GHz, k= 20 rad/um*

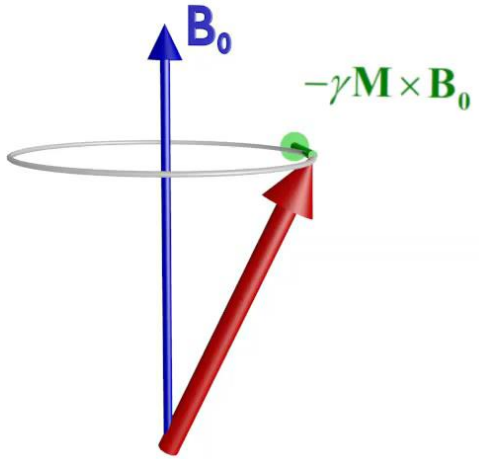


Scattering from surface to volume modes leads to spin-wave reflection, wave vector change …

Damping of spin waves

Landau-Lifshitz-Gilbert torque equation

$$\frac{1}{|\gamma|}\frac{d\vec{M}(\vec{r},t)}{dt} = -\vec{M}(\vec{r},t)\times\vec{B}_{eff}(\vec{r},t) + \frac{\alpha}{M_s}\vec{M}(\vec{r},t)\times\frac{d\vec{M}(\vec{r},t)}{dt}$$



"Viscous damping" (for linear spin waves)

Exponential spin-wave amplitude decay time τ:

$$m(t) \sim m_0 \exp(-t/\tau)$$

$$\tau = \left[\frac{\partial\omega_k}{\partial\omega_H}\cdot\alpha\cdot\omega_k\right]^{-1} = \frac{1}{P_A\cdot\alpha\cdot\omega_k}$$

Note: Not all damping processes can be included into Gilbert damping

Maximum lifetime for spin waves in the GHz regime:

$\tau_{max} \approx 700ns$ High quality Yttrium Iron Garnet (YIG) (bulk samples under certain conditions up to 10 µs)

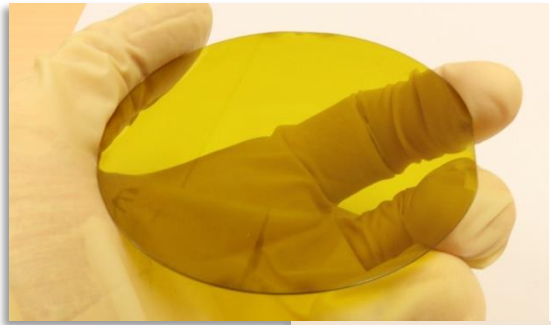
$\tau \leq 10\ ns$ Ferromagnetic metals with lowest damping (e.g., Heusler compounds or CoFeB)

D. Stancil, A. Prabhakar: „Spin waves", Springer

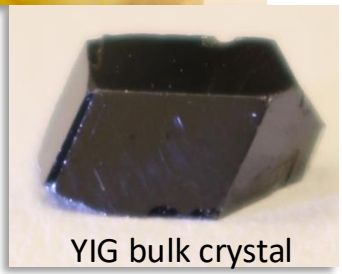
“Gold Standard” material: Yttrium Iron Garnet (YIG, $Y_3Fe_5O_{12}$)

- Room temperature ferrimagnet (T_C = 560 K)
- Cubic crystal
- **Low magnon and phonon damping**

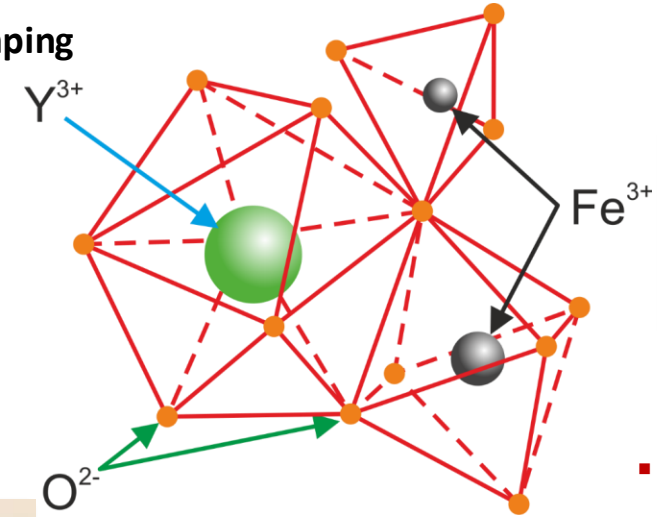
Cherepanov, Kolokolov, L’vov,
The saga of YIG, Phys. Rep. **229**, 81 (1993)



3” YIG wafer
SRC “Carat”
Lviv, Ukraine



YIG bulk crystal



YIG: Electrical insulator
with low spin-orbit coupling

8 octahedral iron atoms (spin 5/2 up)
12 tetrahedral iron atoms (spin 5/2 down)

Magnetic moment of a unit cell is
20 Bohr magnetons μ_B at T=0 K

- Lattice constant 12.376 Å
- Unit cell – 80 atoms

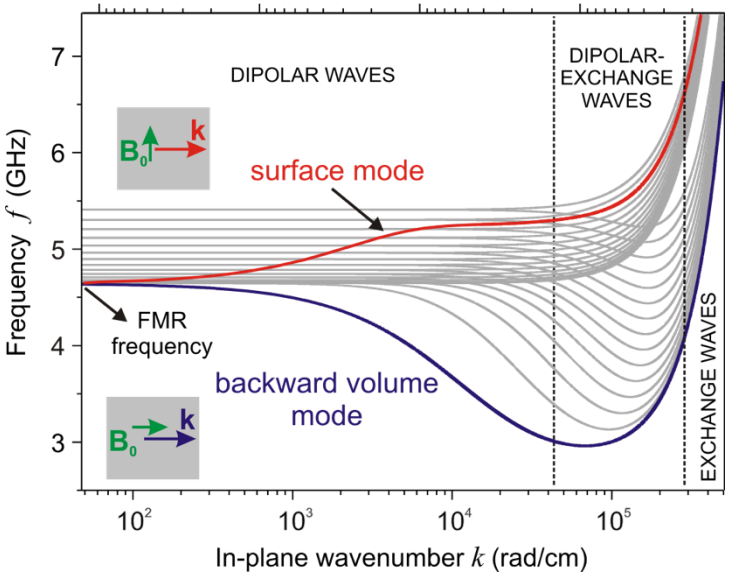
Longest known spin-wave lifetime

LPE grown YIG films with very low damping down to 10 nm thickness:

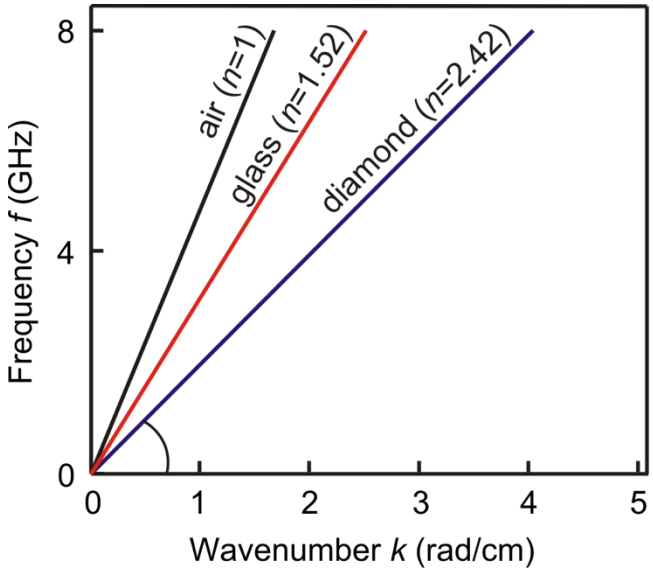
C. Dubs, Phys. Rev. Materials, 4, 024416, (2020).

Magnon versus (MW) photon dispersion relations

Magnons in a YIG film



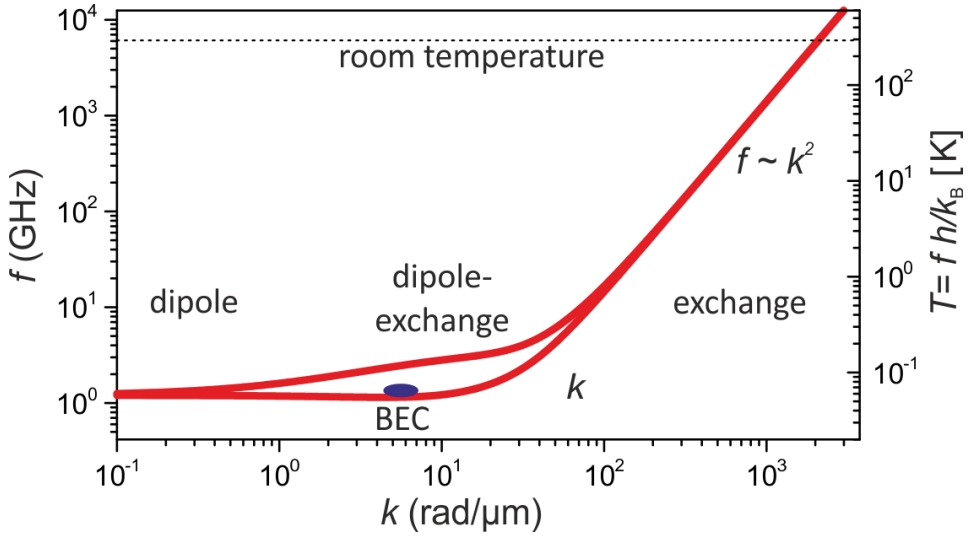
Photons in different media



Magnons: about 10^3-10^5 higher wavenumbers for the same frequency range:

- **Miniaturization** is facilitated
- Magnons travel much **slower** than photons: direct **time resolved investigation** possible

Energy scales for dipole-exchange magnons

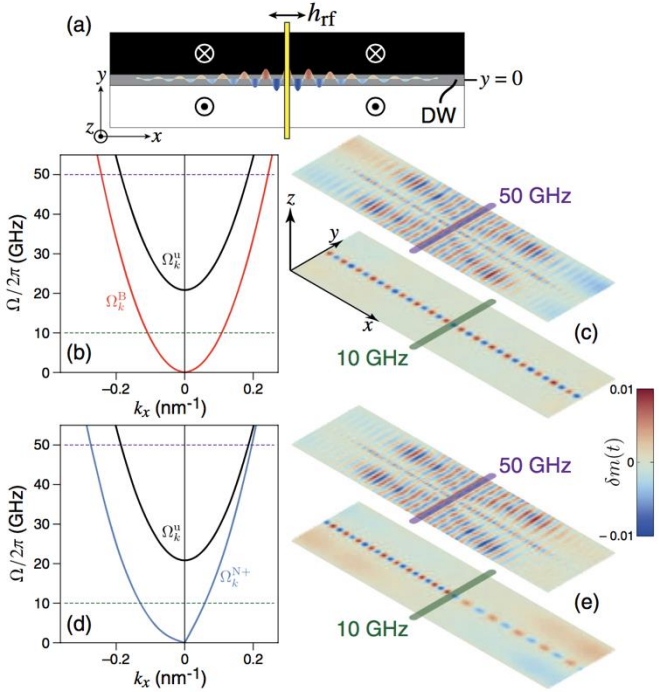


- Magnons used for experiments with coherent waves ($f < 100$ GHz) have energies well below $k_B T$ at room temperature.
- **Quantum magnonics** (low number of thermal magnons in the system) requires cryogenic temperatures (**mK**).

The 2017 Magnetism Roadmap, J Phys D Appl Phys 50, 363001 (2017).

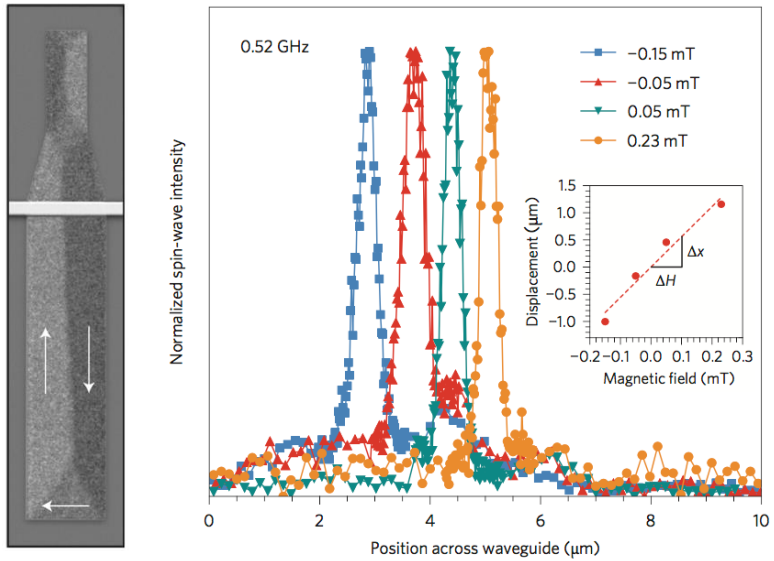
Magnons in different ground states

Magnon dispersion relation in a **magnetic domain wall**



F. García-Sánchez et al., PRL **114**, 247206 (2015).

Reconfigurable magnon transport inside a **Néel domain wall**



K. Wagner et al., Nature Nanotech 11, 432 (2016).

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- **Basics of spin waves**
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Detection of spin waves

- **Brillouin light scattering spectroscopy (BLS)**
- **Inductive microwave techniques**
- Time resolved magneto-optical Kerr effect (MOKE)

} Dipolar and dipolar-exchange spin waves (usually GHz regime)

- Spintronic effects: spin pumping, **inverse spin Hall effect**, rectification effects (AMR, TMR)
- Neutron scattering
- Inelastic tunneling spectroscopy and electron loss spectroscopy

} exchange spin waves (THz regime)

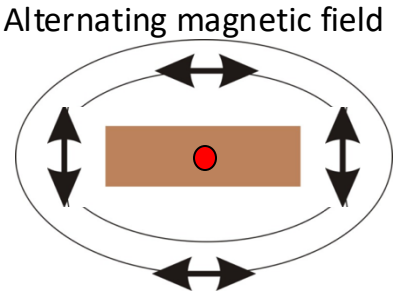
Generation of spin waves

- **Thermal spin waves**

- **Inductive Microwave antennas** (*Oe-field of dynamic current*)

  Direct excitation: $f_{MW} = f_{SW}$

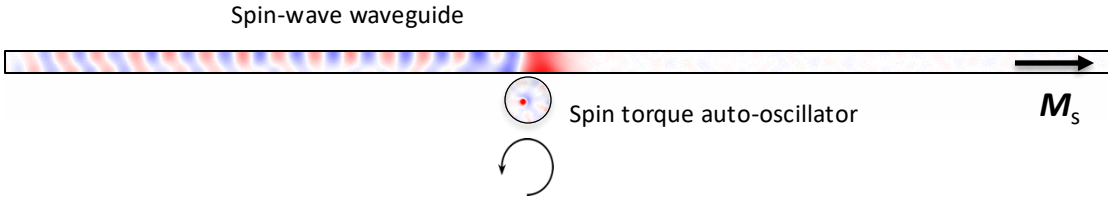
  Parametric excitation $f_{MW} = 2 \cdot f_{SW}$



T. Brächer, P. Pirro, B. Hillebrands. Physics Reports **699**, 1–34 (2017).

- **Spintronic effects:** spin transfer torque, spin Hall effect…

  Auto-oscillations and/or spin-wave amplification



A. Hamadeh, *et al.*, J Appl Phys 132, 183904 (2022).

Brillouin light scattering spectroscopy

Brillouin light scattering process (BLS)

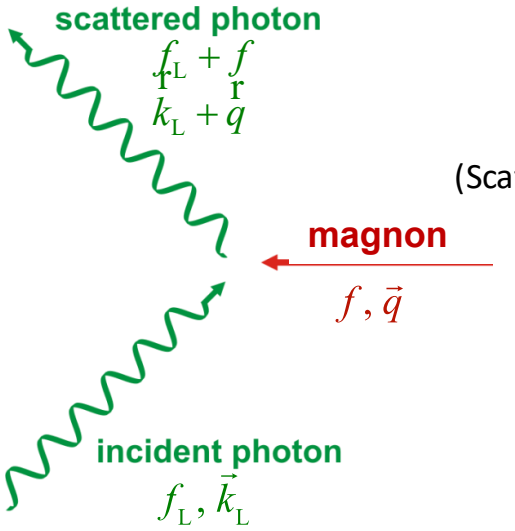
Example: Anti-Stokes process

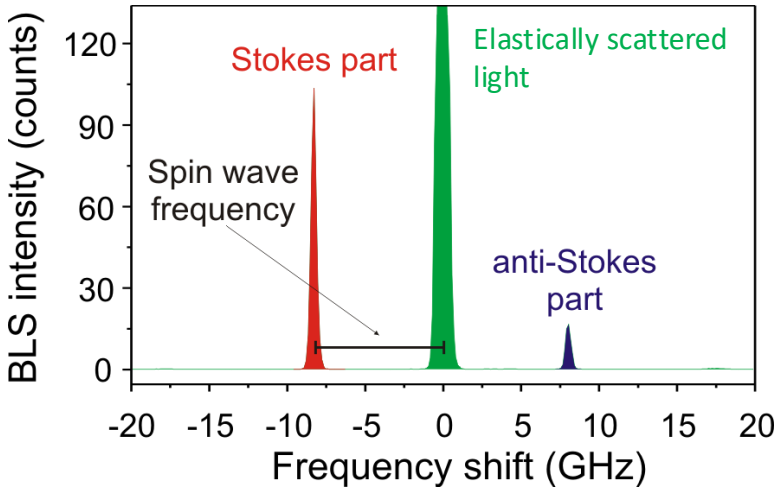
= inelastic scattering of photons from spin waves:

$$f_{\text{scattered L}} = f_{\text{L}} \pm f$$

$$\vec{k}_{\text{scattered L}} = \vec{k}_{\text{L}} \pm \vec{q}$$

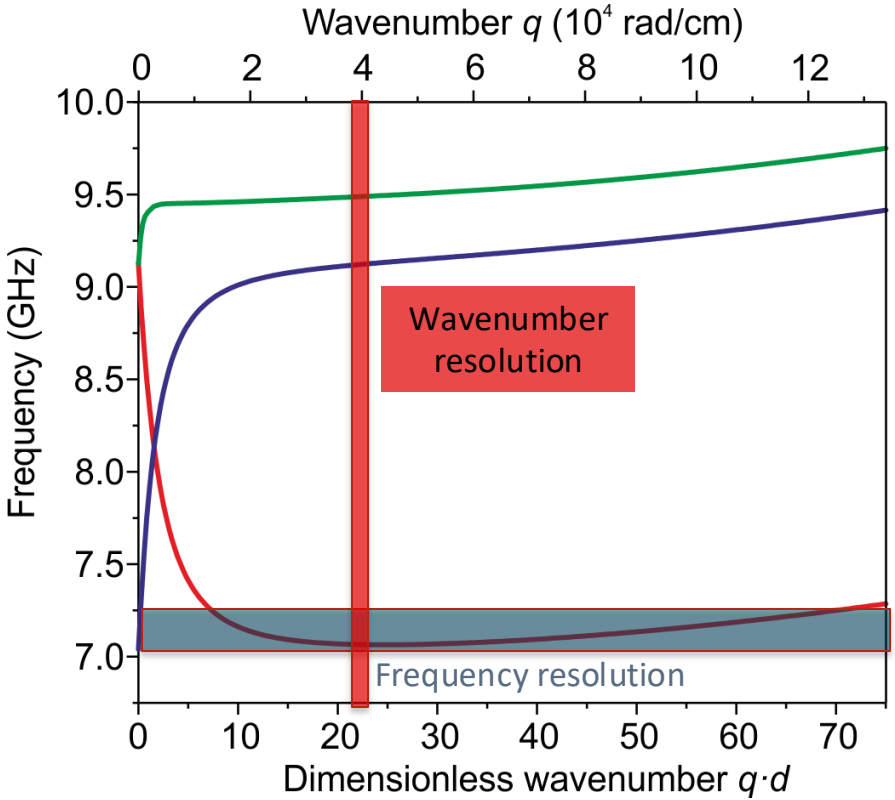
(Scattering mediated by same magneto-optic effects like MOKE)

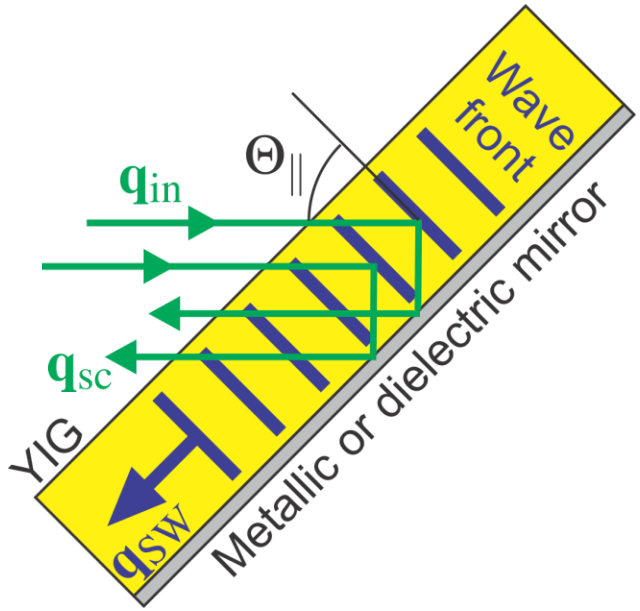




BLS intensity is proportional to the spin-wave intensity

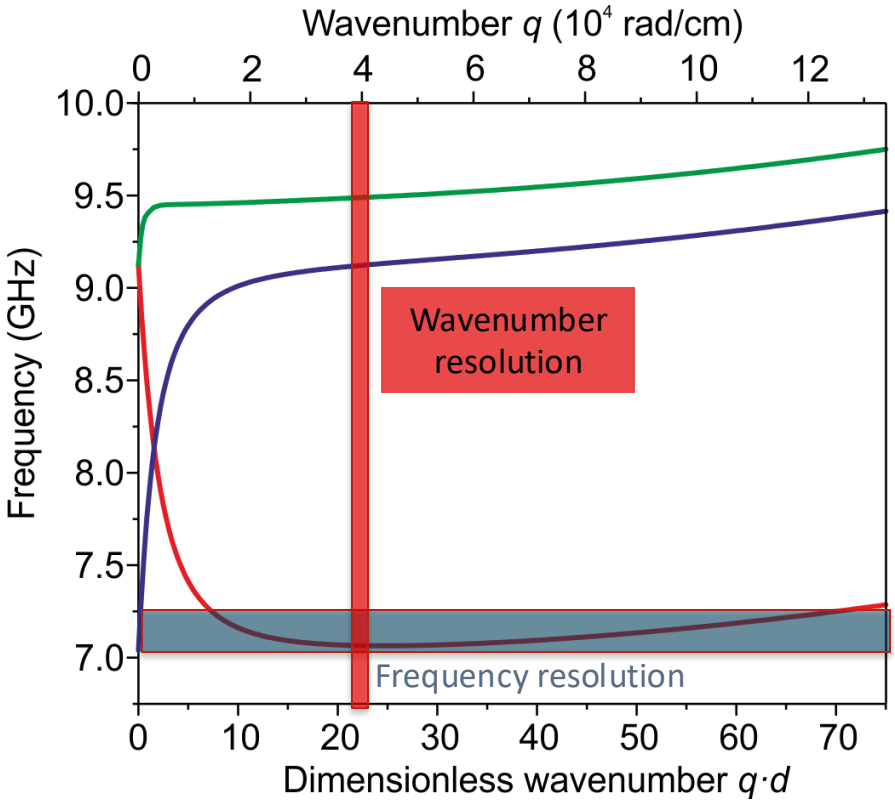
Wavenumber resolved BLS

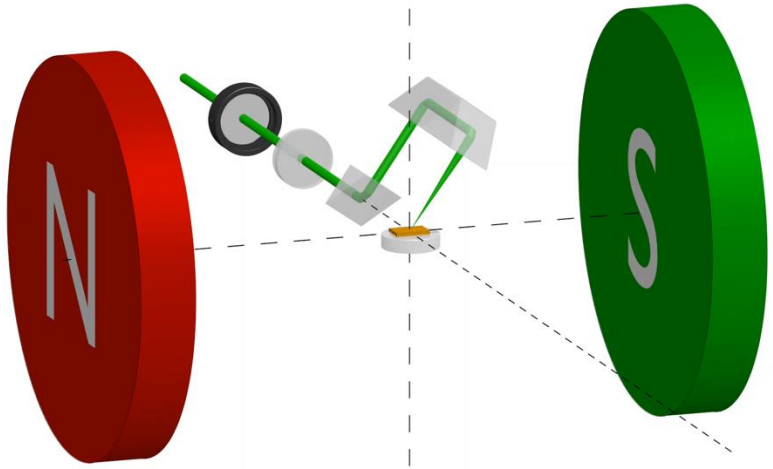




$$q_{\text{Spin wave}} = 2q_{\text{Laser}} \sin(\Theta_{\parallel})$$

Wavenumber resolution experiment

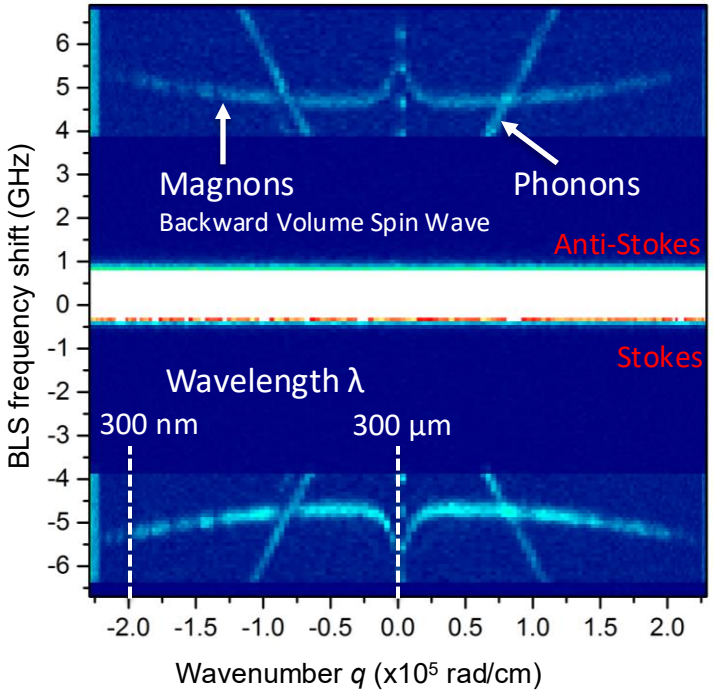




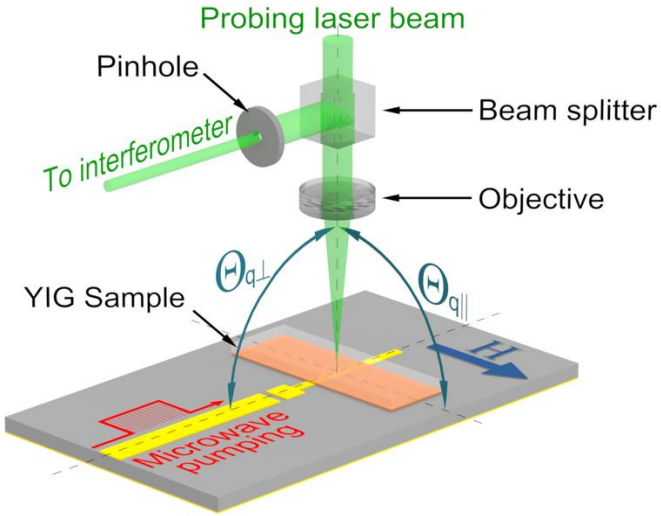
Max wavenumber	2.36×10^5 rad/cm
Wavenumber resolution	2×10^3 rad/cm

Wavevector-resolved BLS spectroscopy

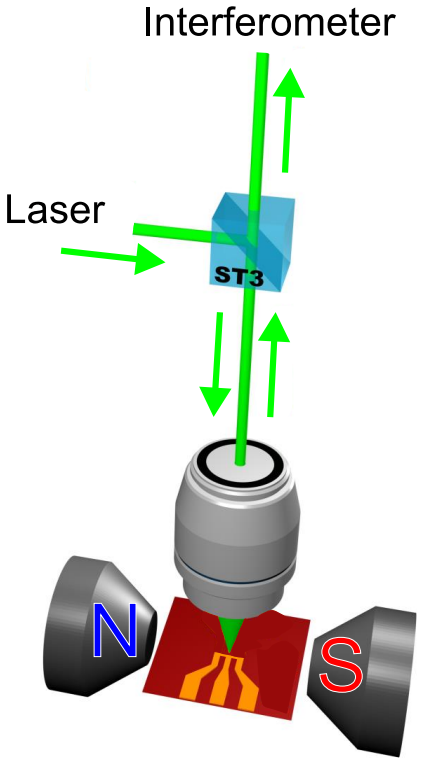
Thermal spectrum of 6 µm thick YIG film



$$q_{SW} = 2q_L \cos\left(\Theta_q\right)$$



Brillouin light scattering microscopy (µBLS)



Investigation of magnetic micro- and nano-structures

Spatial resolution better than 400nm

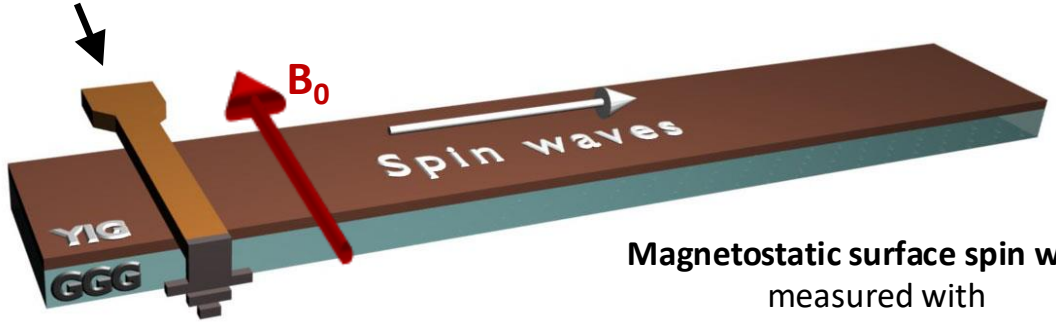
⇒ Loss of wave vector resolution

Spin wave detection up to $k \approx 20$ rad/µm
(can be enhanced by optical resonances)

T. Sebastian *et al.*,"*Micro-focused Brillouin light scattering: imaging spin waves at the nanoscale*"
Front. Phys. 3:35 (2015)

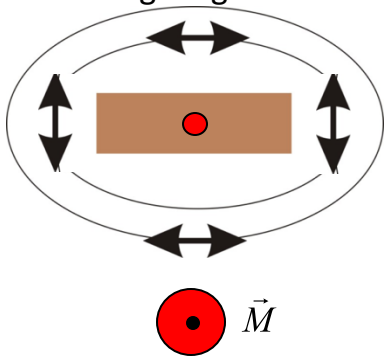
Excitation of dipolar spin waves

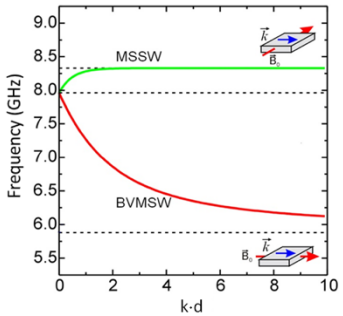
Input microwave signal



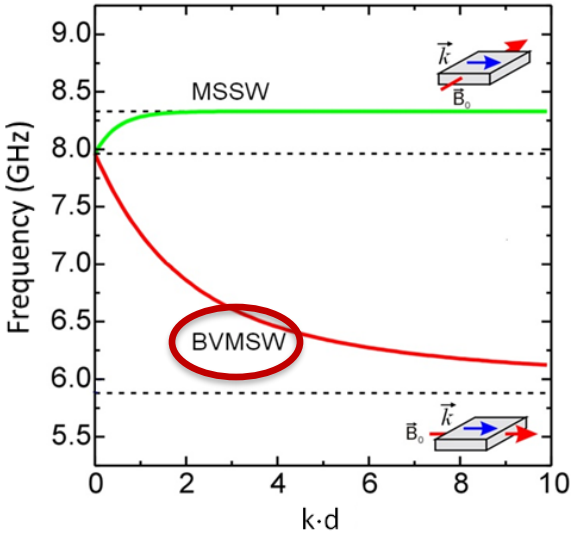
Magnetostatic surface spin waves
measured with
Brillouin light scattering spectroscopy

Alternating magnetic field

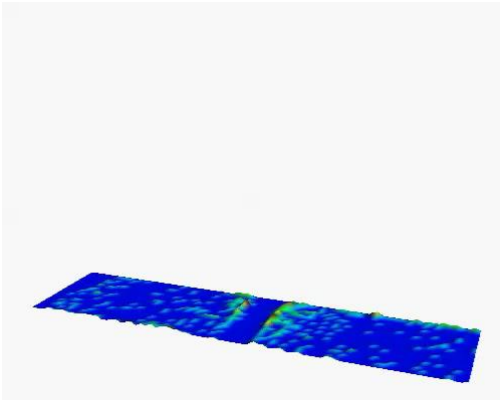




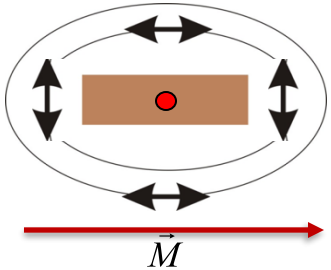
Backward volume magnetostatic spin waves (BVMSW)



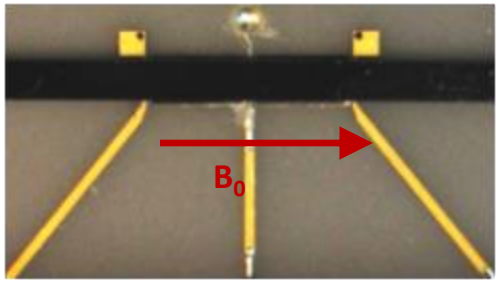
Excitation of BVMSW
measured with
Brillouin light scattering microscopy



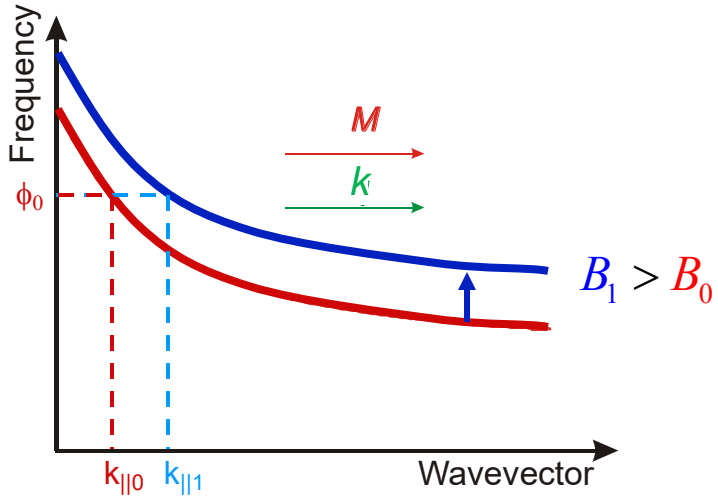
Alternating magnetic field



T. Schneider et al.,
Phys Rev B 77, 214411 (2008).



Control of spin wave propagation

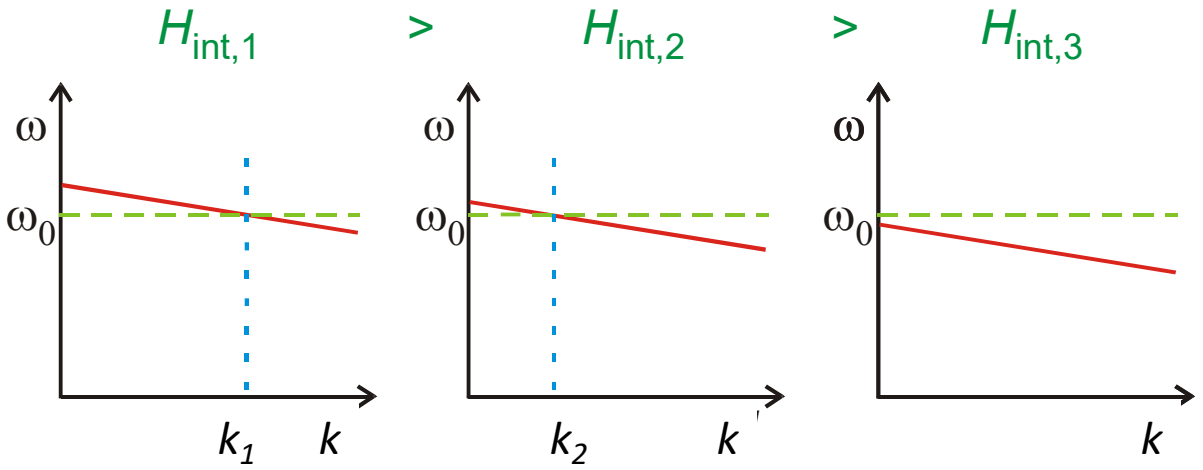


Wavevector **k**:

$k_{parallel}$ defined by input frequency and dispersion

Dispersion shifted vertically by change in magnetic field

Motion of a spin wave packet in varying field

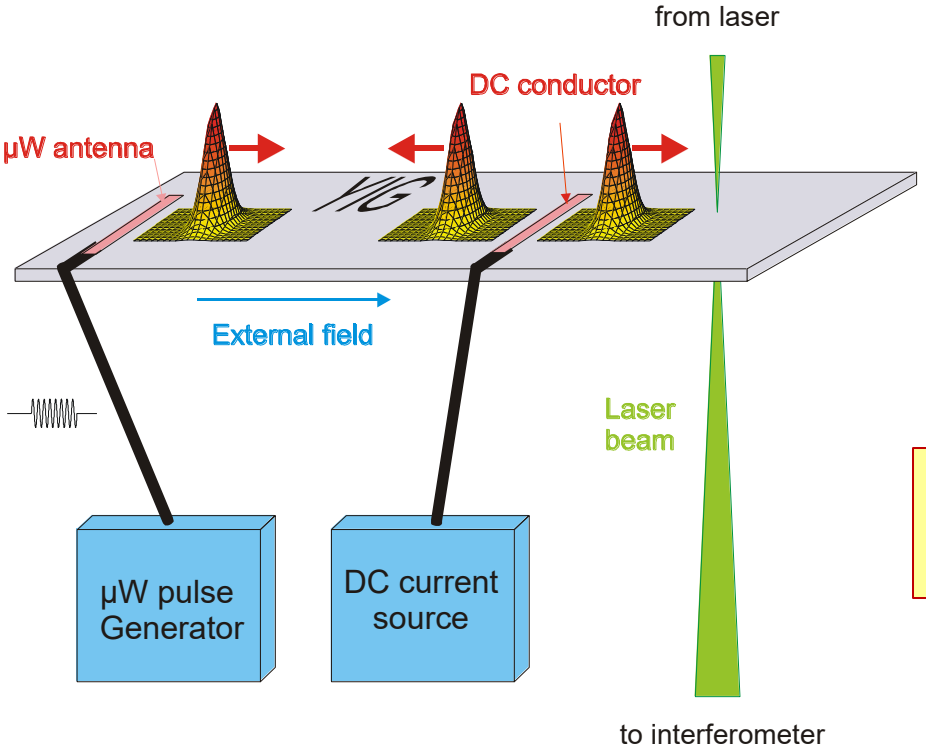


propagation
reflection

propagation ($q_2<q_1$)

Change of the wave vector depending on the local field

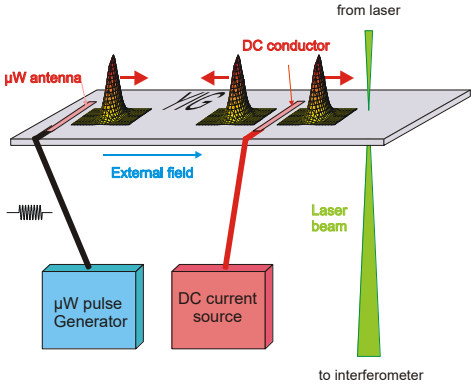
Real-time observation of spin wave propagation



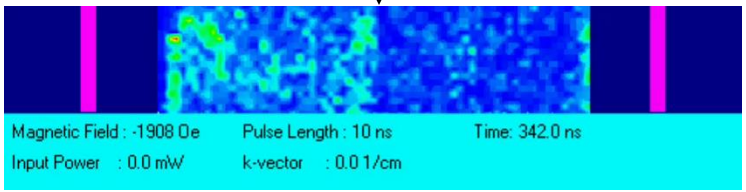
SW-pulses created by microwaves and detected by light scattering with time and space resolution

DC conductor provides a local field inhomogeneity

Spin wave pulse propagation

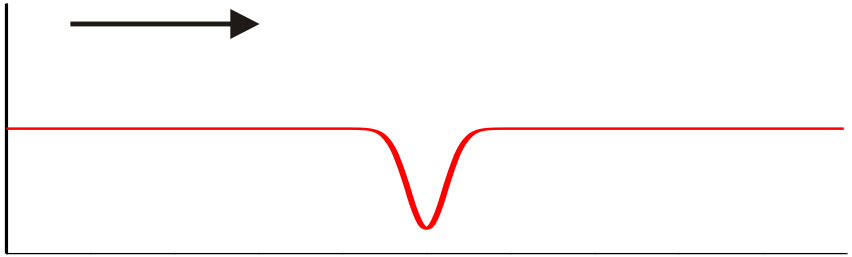


position of the dc conductor



Time resolved BLS intensity

positive current



magnetic material: YIG

dip in field acts like potential barrier

Potential barrier: reflection and tunneling

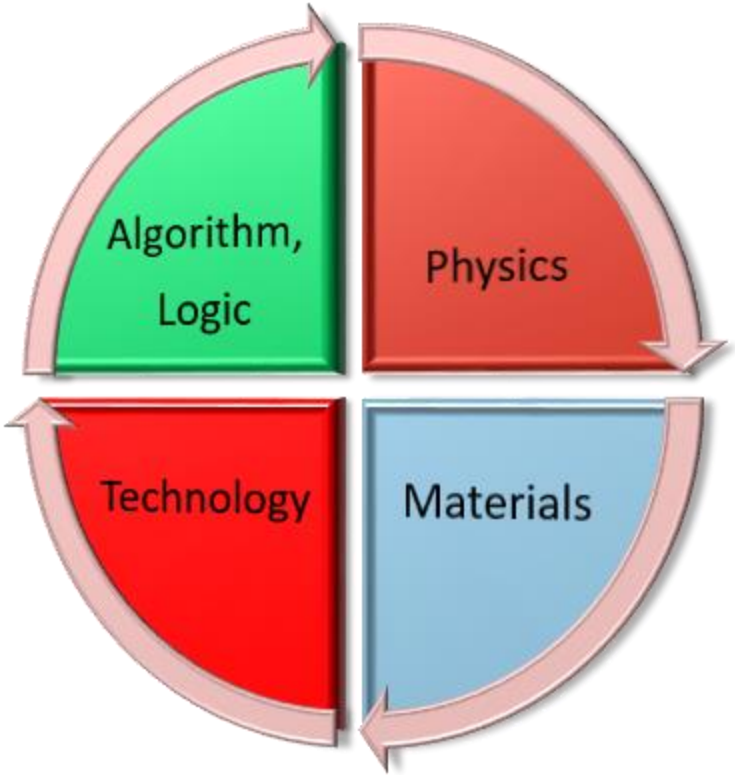
S.O. Demokritov et al., Phys. Rev. Lett. **93**, 047201 (2004)

Outline

- **Basics of spin waves**
  - Classical spin wave theory (micromagnetic model)
  - Spin-wave detection, manipulation and generation
- **Magnon signal processing and computing**
  - **Linear** magnonics for
    - Signal processing
    - Logic devices: interference-based approaches
  - **Nonlinear** magnonic elements

Magnonic data processing

- Information coding
- Computing concept
- Circuit design
- ……



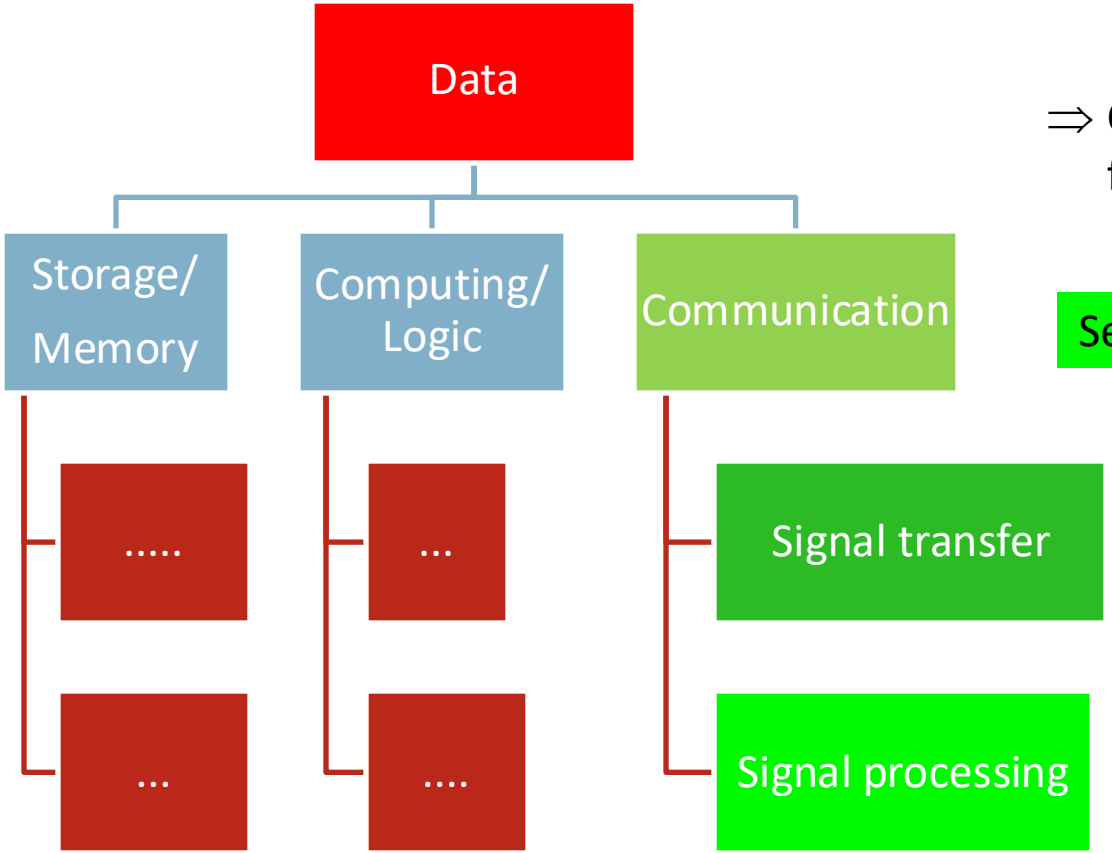
Current focus in magnonics

- Interference effects
- Nonlinearity
- Wave guiding
- …..

- Total energy consumption
- Integration
- Scalability
- Production
- ……

- Low damping
- High frequencies
- Easy fabrication
- ……

=> Magnon Computing is by nature very multidisciplinary



Physical/technical side

⇒ Communication: How to transfer data from A to B

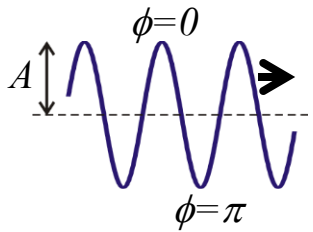
Sender → Propagation → Receiver

⇒ Mainly *electromagnetic*: high speed + low attenuation of photons

⇒ Different *solid state* solutions

Waves as signal carriers

Communication requires **spatially moving dynamics => waves** (sound, light, spin …)



$$\vec{A} = \vec{A}_0 \exp(\vec{k} \cdot \vec{x} - \omega t)$$

Wave equation

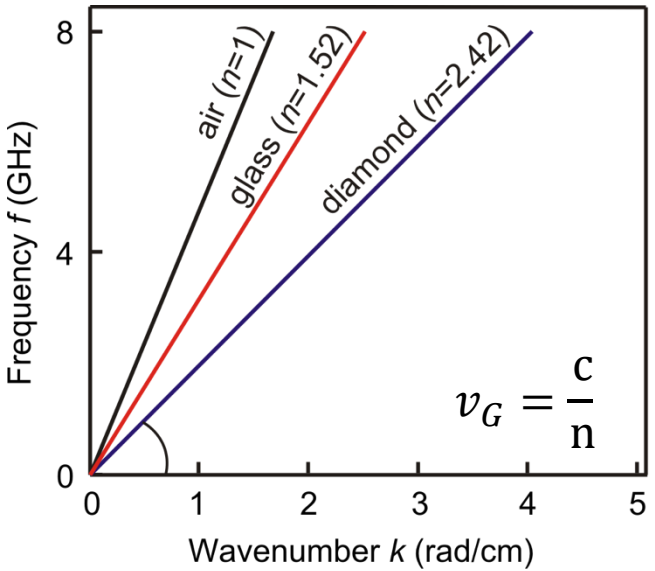
Interference phenomena

Speed of the wave packet:

$$v_G = \frac{\partial \omega}{\partial t} = 2\pi \frac{\partial f}{\partial t}$$

Group velocity defines speed of energy/information propagation.

Example: Dispersion relation of light waves in different media



Linear dispersion relation => Group velocity

- is equal to phase velocity
- is independent of frequency/wave vector

Communication speed

How “fast” is my communication?

1. **Delay time t** of the signal is given by the group velocity v_G of the wave.

2. **Data transfer rate R** of the communication is given by the **instantaneous bandwidth Δf_B** of the signal and the signal processing devices:

$$R \propto \Delta f_B$$

=> high **bandwidth Δf_B** needed for high-speed data

Magnonic systems for signal processing and computing

Linear systems

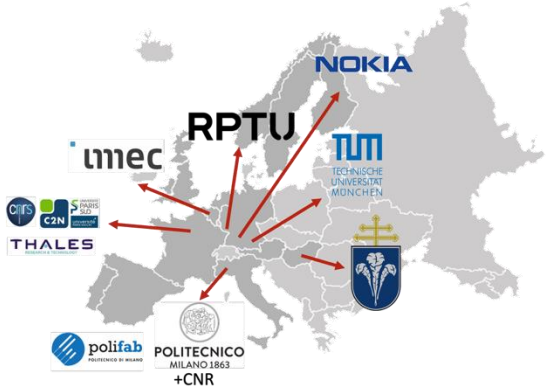
Linear SW propagation
- RF time-delay units
- RF filters, isolators

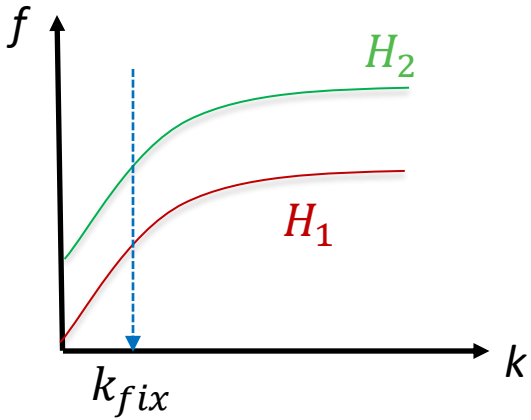
tunable via the applied magnetic fields (H_1, H_2)

M&MEMS

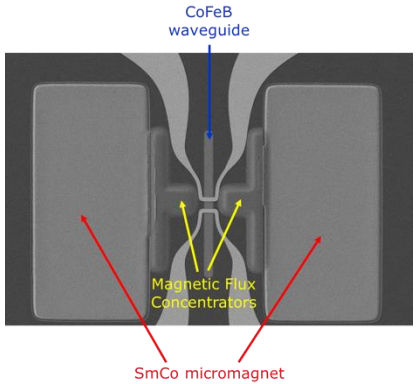
Funded by the European Union

www.mandmems.eu

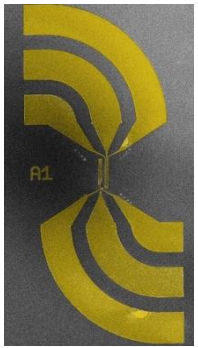




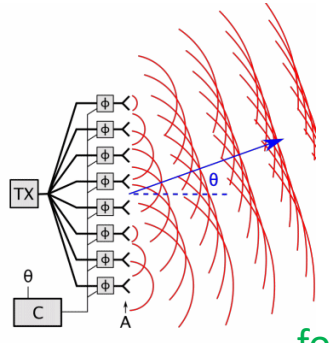
Standalone magnonic device



High frequency SW delay lines



Tunable miniaturized time delay units



for 5G, 6G

Linear (Magnonic) devices for radio-frequency applications

Linear systems
(Input-output relation independent of RF power/magnon intensity)

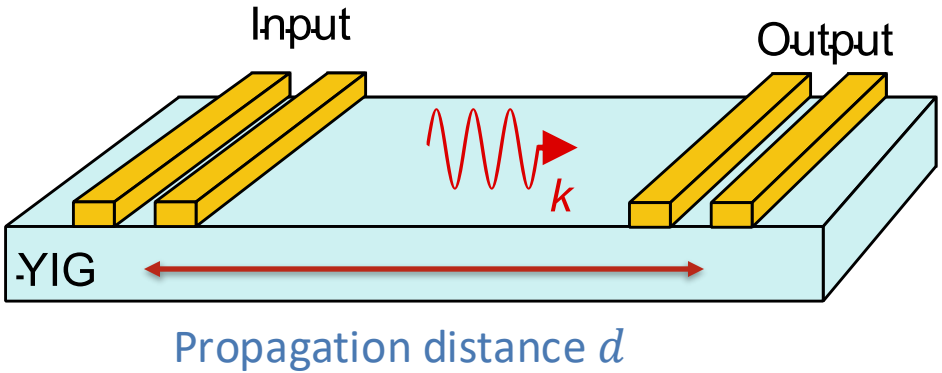
- **Phase delay unit**
  shifts (only) the phase ϕ of the signal by a shift $\Delta\phi$ (which should be constant over the bandwidth Δf)

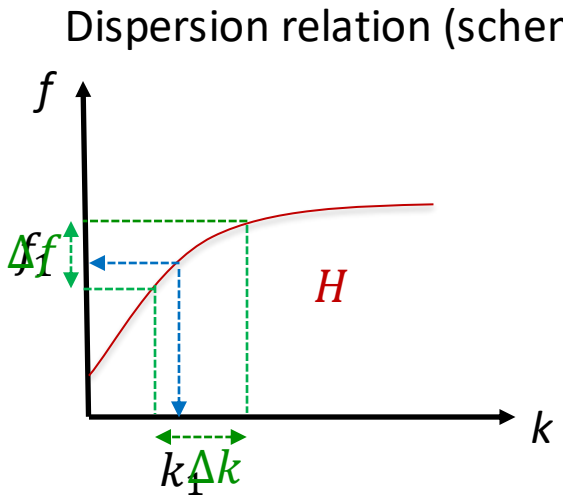
- **Time delay unit**
  delays a signal by a time delay Δt (all frequency components in the bandwidth should have the same delay to avoid signal distortion)

- **Filter**
  removes a selected frequency range from the spectrum

1. “Stationary” magnonic devices

One big advantage of magnonic devices is their reconfigurability using different external fields.
For simplicity, let us first understand how a magnonic devices works at a fixed external field.





Phase delay: $\Delta\phi(f_1) = k_1 \cdot d$ ($\Delta\phi$ can be >> 2π)

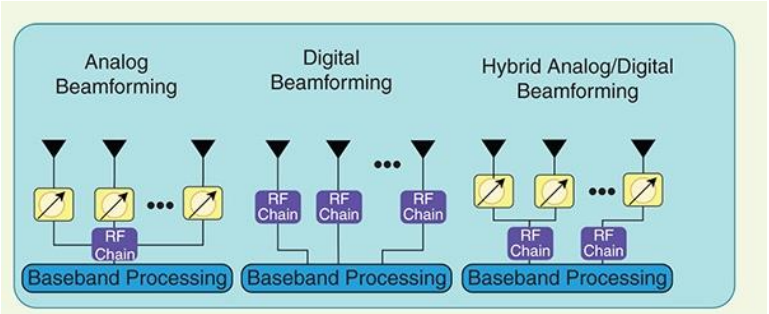
Time delay: $\Delta\tau(f_1) = \frac{d}{v_G(k_1)} = \frac{d}{\partial f/\partial k(k_1)}$ ($\Delta\phi$ can be >> 2π)

Filter function? Bandwidth Δf_B ? Efficiency of energy transduction?

Applications of RF delay units

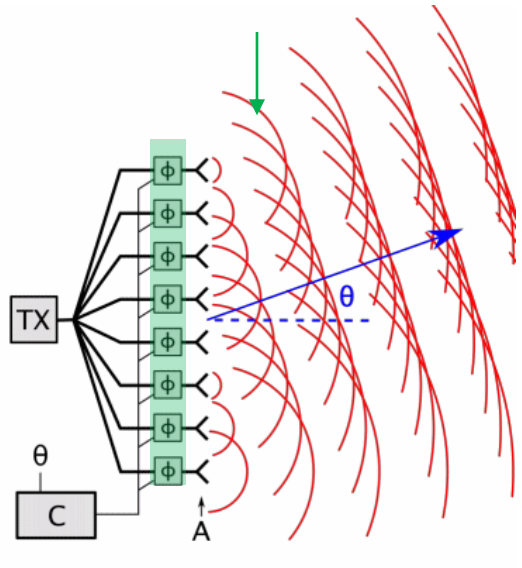
Tunable Directional antennas, e.g. for massive MIMO (“Multiple Input Multiple Output”)

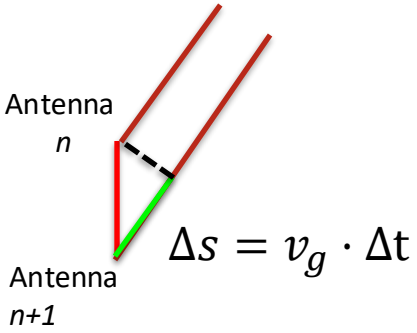




IEEE signal processing

Tunable miniaturized phase delay units (better: time delay units)





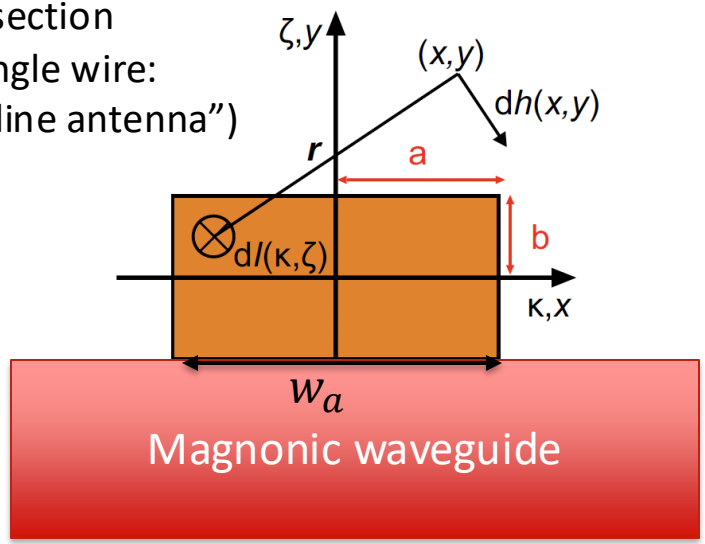
Many RF antennas with different time delays

Excitation of spin waves using microwave antennas

General idea:

- A microwave of frequency *f* propagating in a wire-like conductor is creating **AC electron currents** of the same frequency
- According **to Biot-Savart's law the AC currents create AC magnetic fields** which can excite the spin waves if their direction has a perpendicular to the static magnetization

Cross section of a single wire: ("stripline antenna")

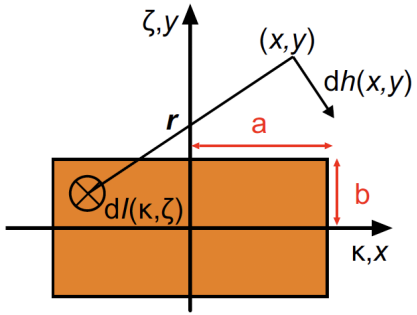


In z direction, the wire is usually considered as infinitely extended

Conductor (orange): Au, Cu, Al, superconductor…

Calculation of antenna fields

In the magneto-static approximation, Biot-Savart's law can be used to calculate the dynamic fields of the microwave currents:

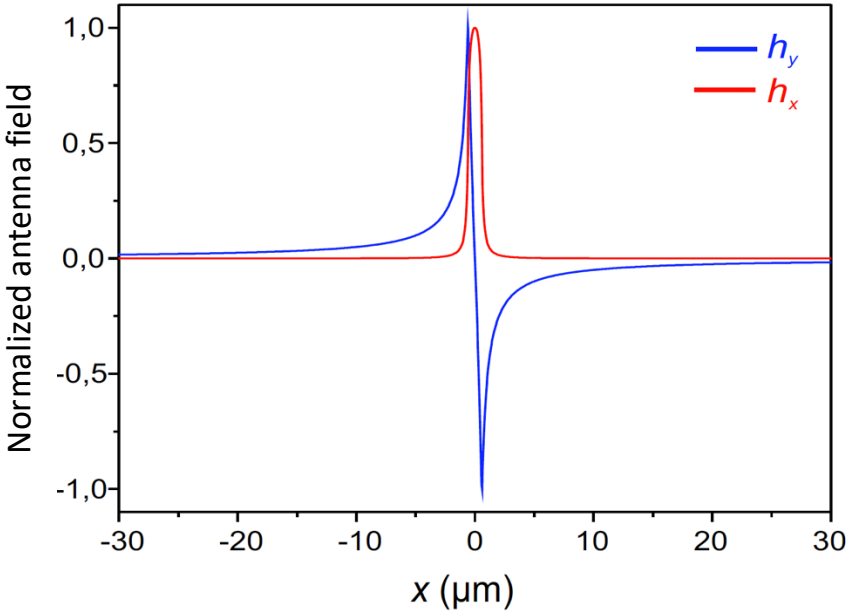


$$\mathrm{d}h(x,y) = \frac{j}{2\pi r}\mathrm{d}\kappa\mathrm{d}\zeta$$

Integration for a rectangular antenna cross section with width 2a and thickness 2b:

$$\begin{aligned} h_x(x,y) = & -\frac{I}{8\pi ab}\left[(a-x)\left[\frac{1}{2}\ln\left(\frac{(b-y)^2+(a-x)^2}{(-b-y)^2+(a-x)^2}\right)+\frac{b-y}{a-x}\operatorname{atan}\left(\frac{a-x}{b-y}\right)\right.\right. \\ & \left.-\frac{-b-y}{a-x}\operatorname{atan}\left(\frac{a-x}{-b-y}\right)\right]-(-a-x)\left[\frac{1}{2}\ln\left(\frac{(b-y)^2+(-a-x)^2}{(-a-x)^2+(-b-y)^2}\right)\right. \\ & \left.\left.+\frac{b-y}{-a-x}\operatorname{atan}\left(\frac{-a-x}{b-y}\right)-\frac{-b-y}{-a-x}\operatorname{atan}\left(\frac{-a-x}{-b-y}\right)\right]\right], \end{aligned}$$

- Here, *I* is the total current running in the antenna
- Similar expression for the field in y direction



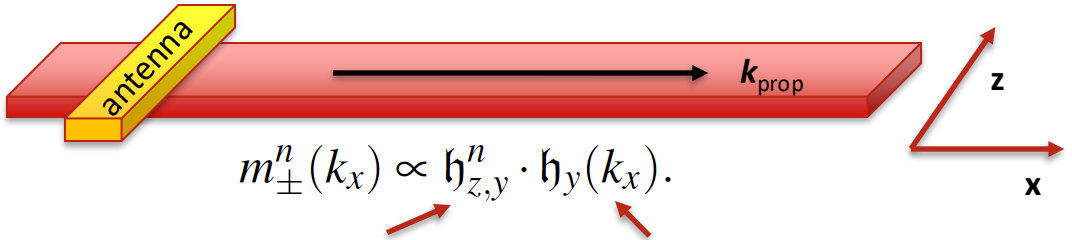
width: $2a = 1.15\ \mu m$,
thickness: $2b = 0.22\ \mu m$

Excitation efficiency of microwave antennas

The excitation efficiency of spin waves is calculated based on the general connection of the dynamic magnetization with the dynamic microwave field (external field) and the dynamic dipolar field of the spin wave via the susceptibility tensor:

$$\mathbf{m}^{\mathrm{dyn}} = \hat{\chi}(\mathbf{h}^{\mathrm{MW}} + \mathbf{h}^{\mathrm{d}})$$

- Results depend on the geometry (Surface waves, Backward Volume, Forward Volume…)
- **Efficiency of excitation** is **always proportional** to the **Fourier transform** of the **microwave field along the propagation direction** (and also on the mode profile across the waveguide)



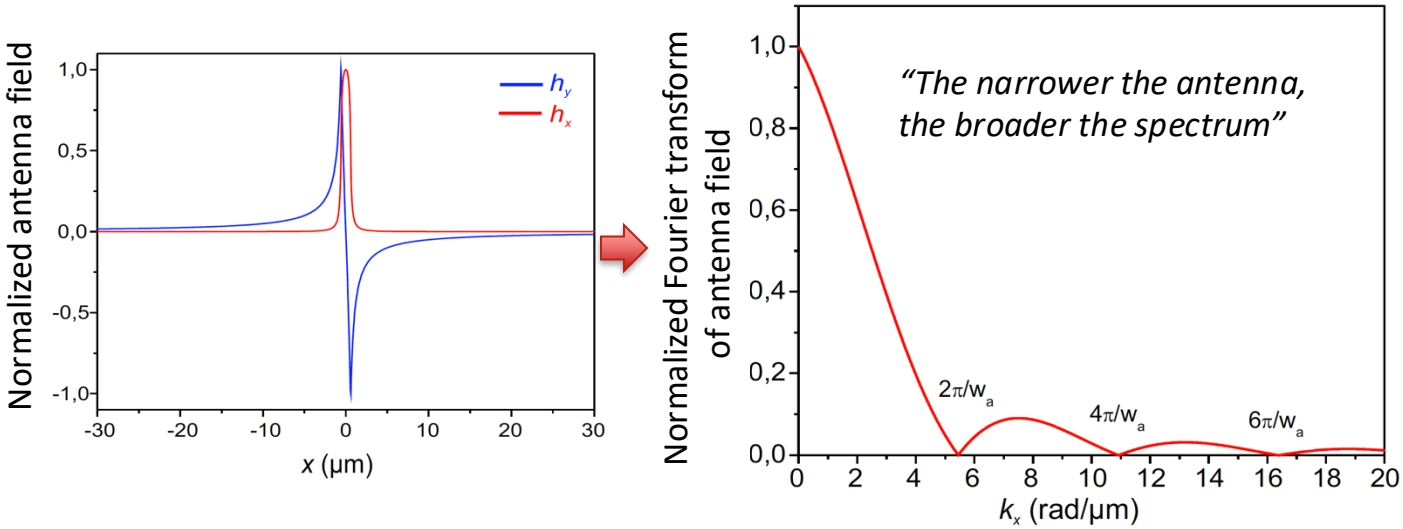
T. Schneider, A. A. Serga, T. Neumann, B. Hillebrands, M. P. Kostylev, Phase reciprocity of spin-wave excitation by a microstrip antenna, PRB **77**, 214411 (2008).

V. F. Dmitriev, B. A. Kalinikos, Excitation of propagating magnetization waves by microstrip antennas, Sov. Phys. J. 31, 875 (1988).

Excitation efficiency: wave vector dependence

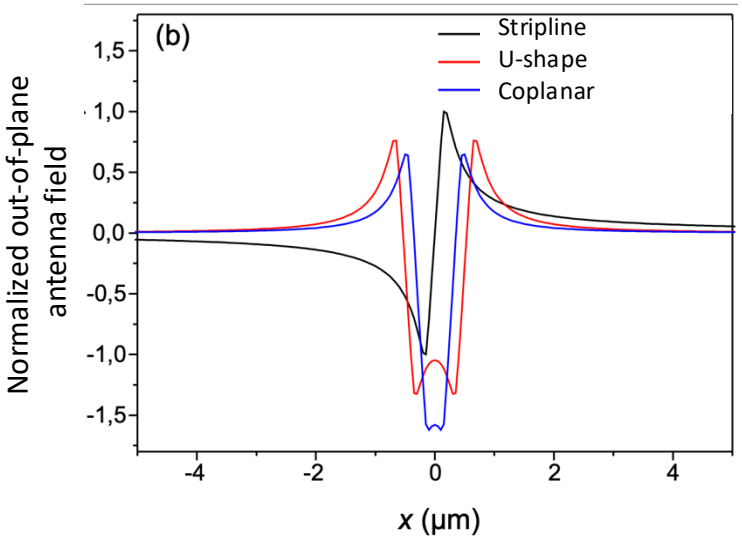
- Spatial extend of the antenna field defines the “effective linear momentum” which can be provided by the antenna to create linear momentum ($p = \hbar k$) of spin waves

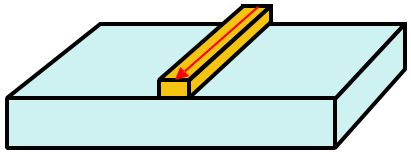
- The **wave-vector-dependent excitation efficiency** is mainly given by the **Fourier transform of the antenna fields**



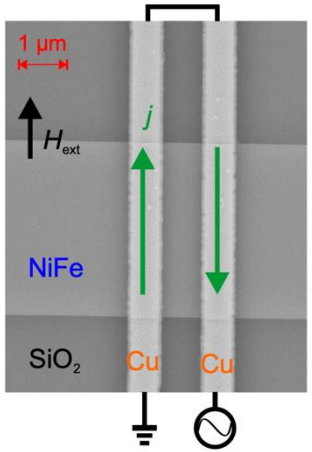
Fourier transform of both field components is the same!

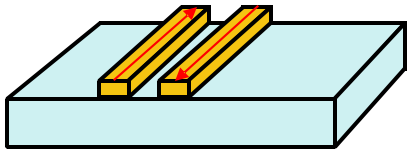
Antenna type examples



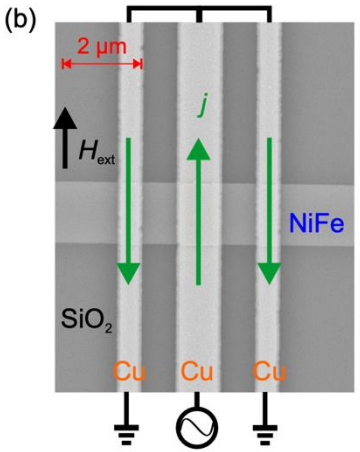


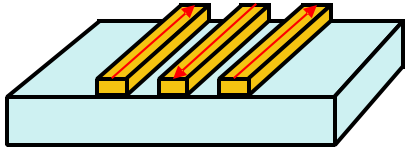
Stripline





U-shape

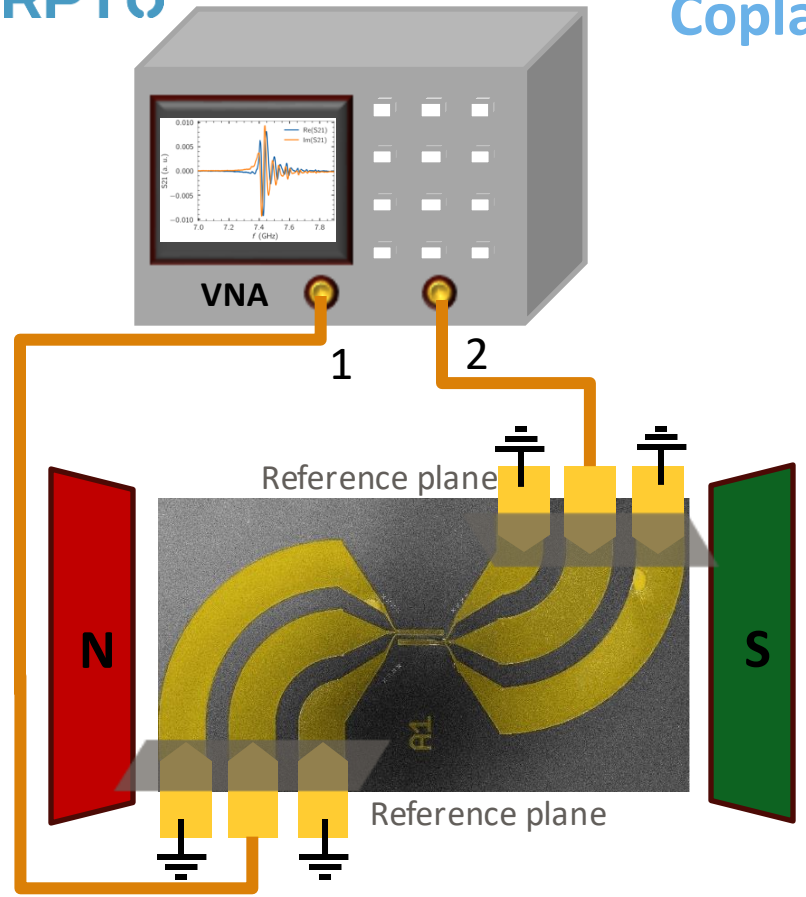


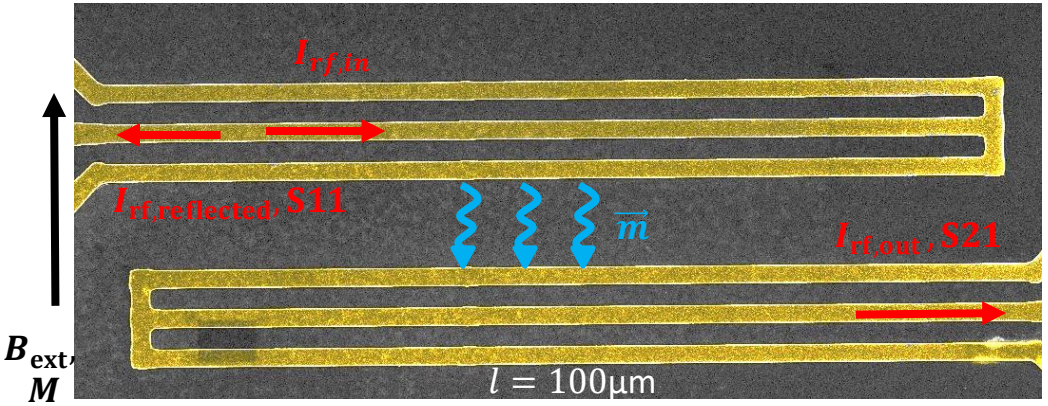


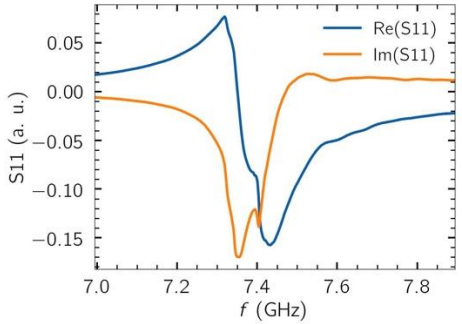
Coplanar waveguide (CPW)

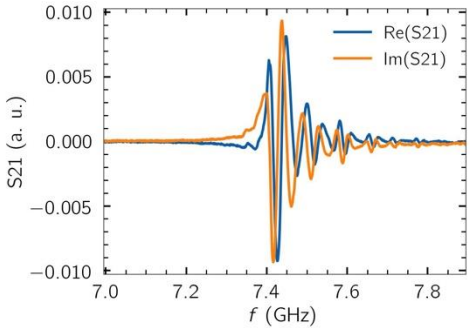
Due to the alternating current directions, the out-of-plane field of U-shape and CPW is much better confined

Coplanar waveguide (CPW)



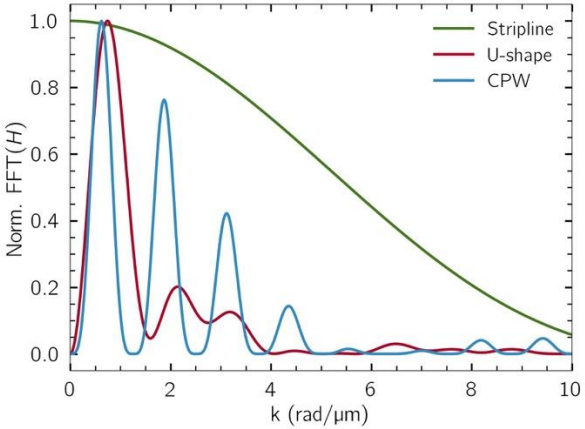




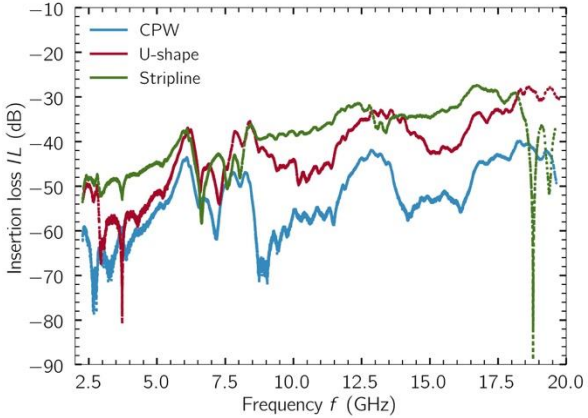


Antenna types

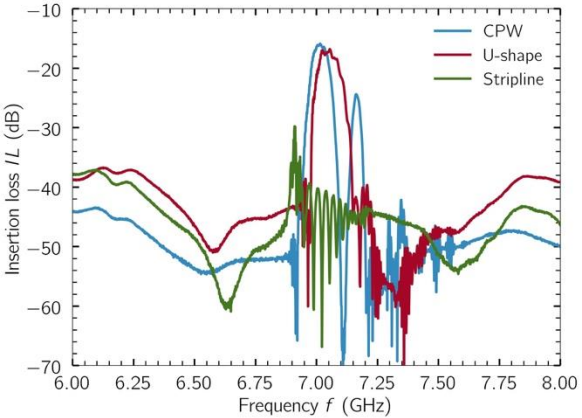
Wave-vector spectrum

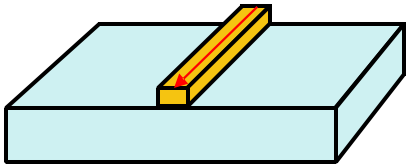


Unwanted electo-magnetic crossstalk

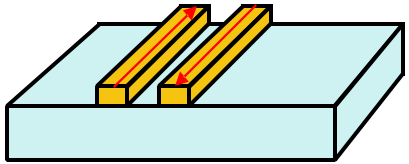


Signal Transmission

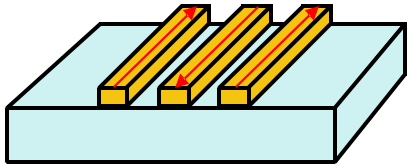




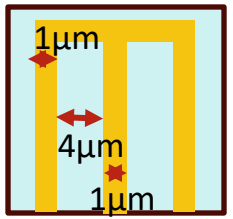
Stripline



U-shape



Coplanar waveguide (CPW)



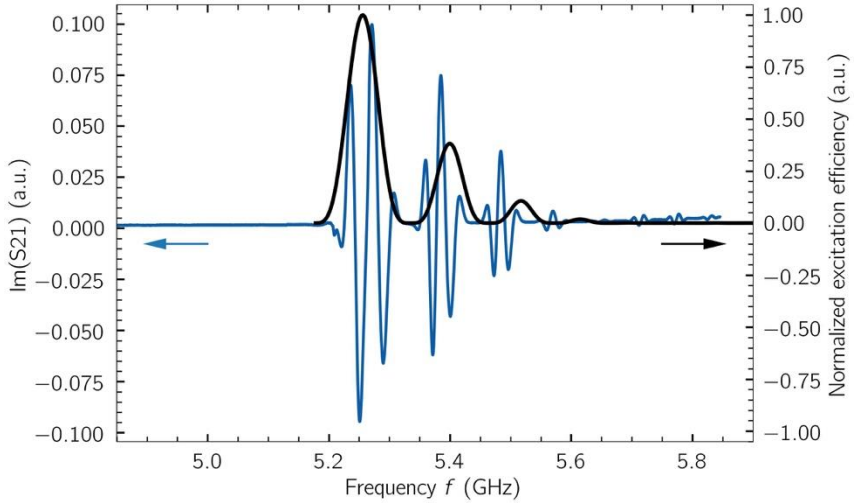
➢ **CPW offers lowest e.m. crosstalk (in this example also the best transmission)**

Spin-wave transmission

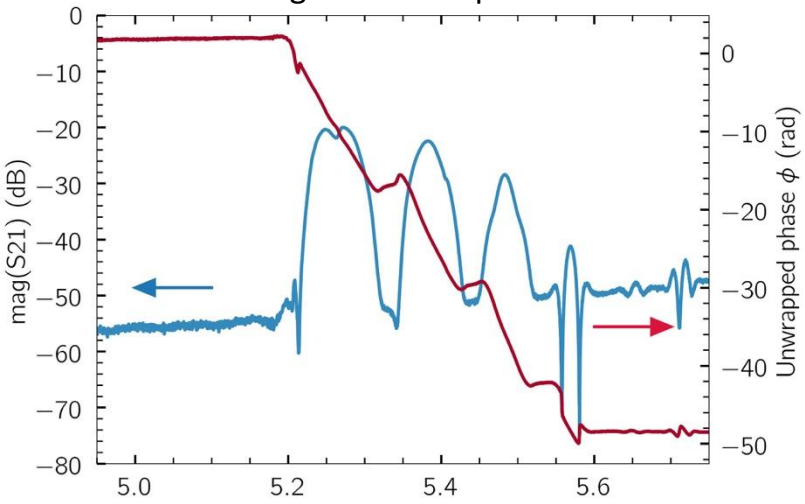
100nn YIG

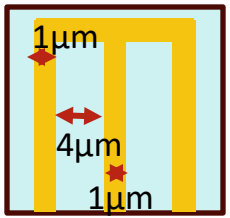
$P = -20\text{dBm}$

Transmission spectrum



Magnitude and phase



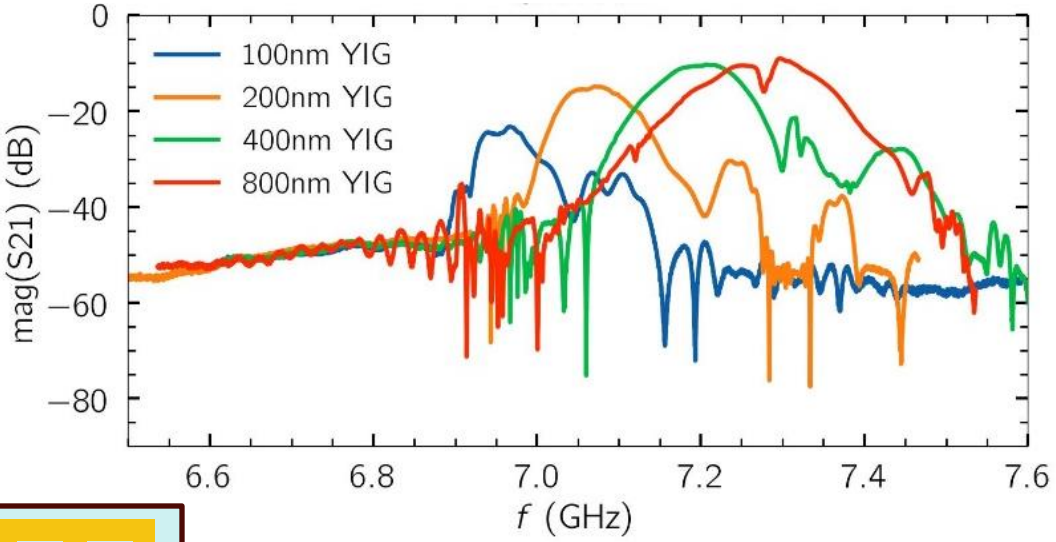


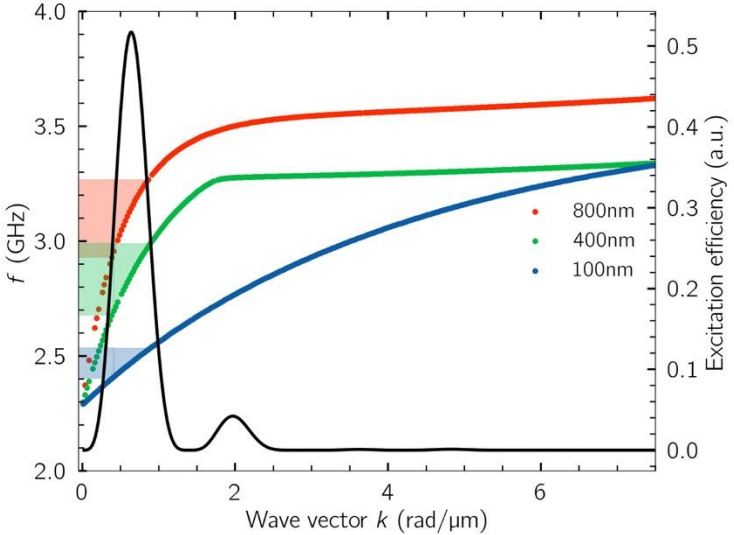
- **Transmission spectrum defined by antenna (and dispersion realtion)**

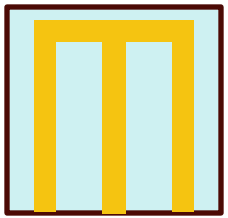
Instantaneous Bandwidth

$P = -20\text{dBm}$

$B_{\text{ext}} = 166\text{mT}$

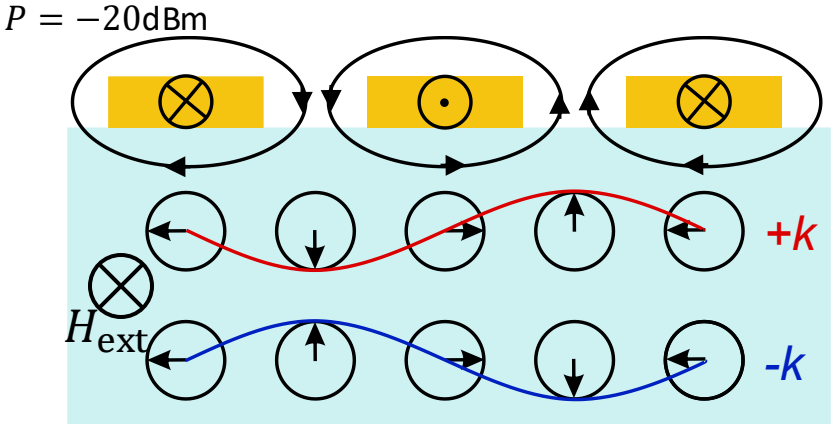


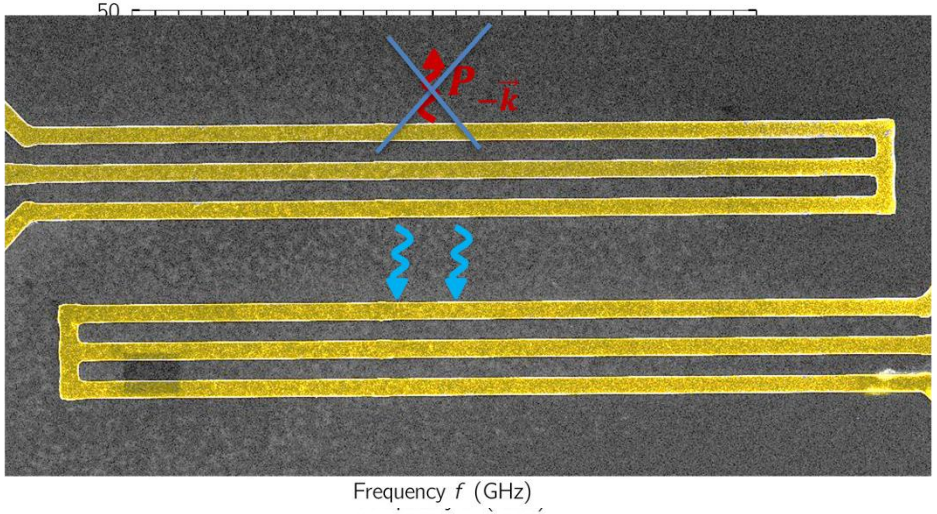


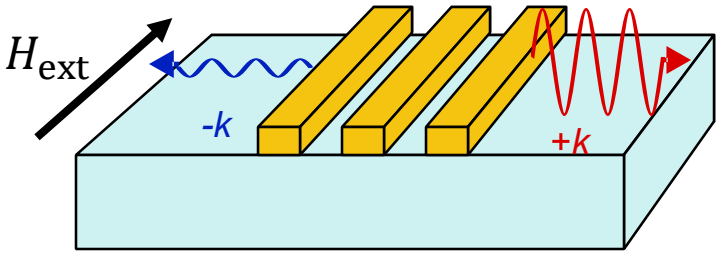


- **Steeper dispersion relation increases frequency bandwidth for same antenna (same k –spectrum)**

Isolation / Non-reciprocal excitation of the surface wave ($k \perp M$)







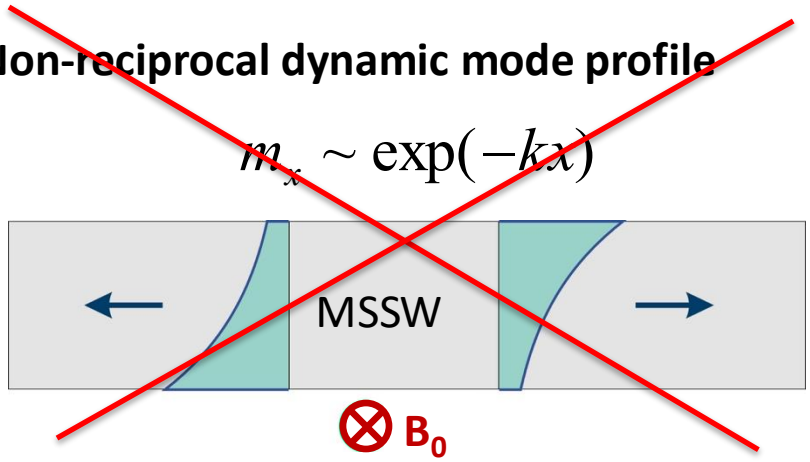
- **Directed flow of energy: lower losses**
- **Magnonic delay line is also a RF isolator**

Non-reciprocity doesn't always have the same reason

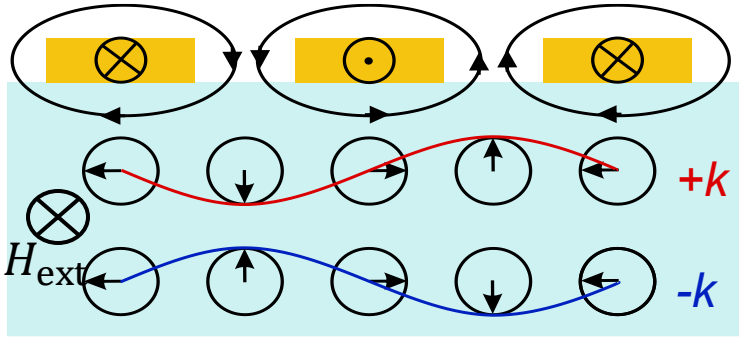
Non-reciprocal excitation caused by the ***break of time reversal symmetry*** + excitation by ***both antenna field components*** (in-plane and out-of-plane)
=> **NOT** connected to the spatial non-reciprocity of the Surface Wave (MSSW)

Most antennas excite only the Surface Wave using both components, that's why the other modes (Backward Volume or Forward Volume) are (usually) excited reciprocally.

Non-reciprocal dynamic mode profile

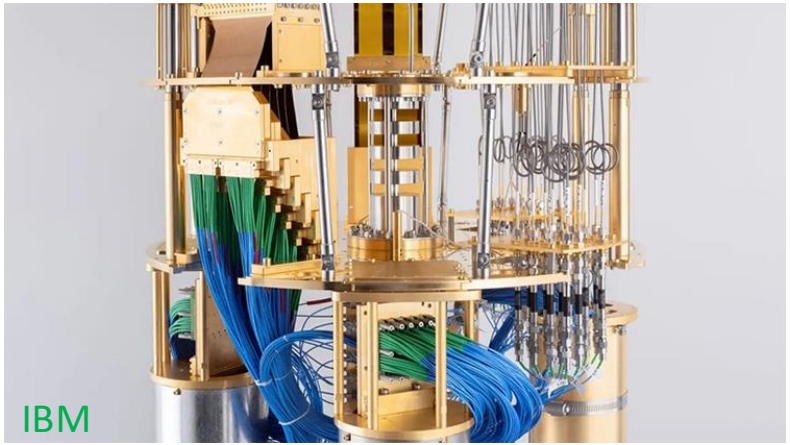


"Helicity" of magnetization precession

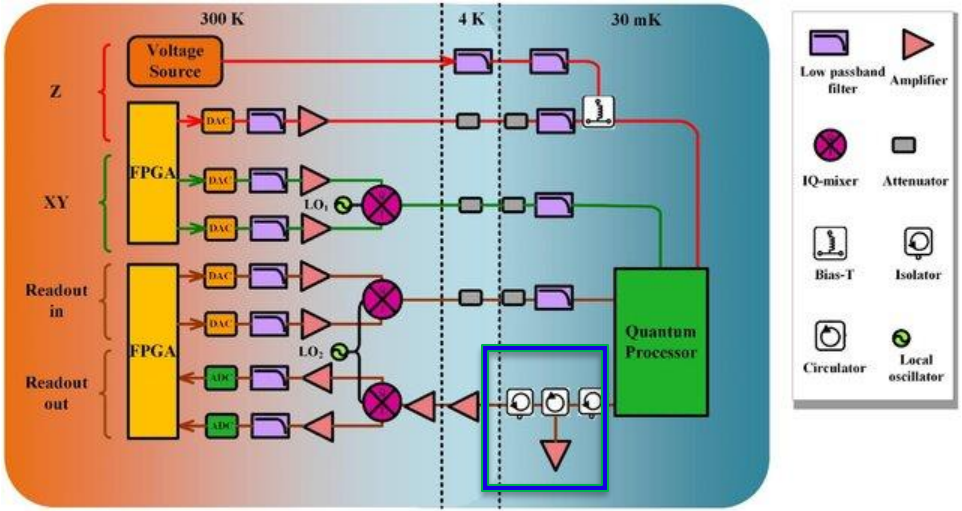


Magnonics as isolators for quantum applications

General idea: use **intrinsic magnonic non-reciprocity** to **isolate superconducting Qubits** on-chip against thermal noise.



Control RF electronics of superconducting quantum processor: RF **isolators** needed

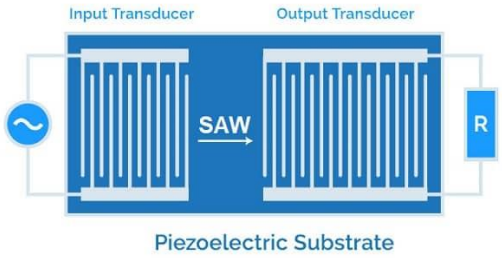


Y. He, J. Liu, C. Zhao, R. Huang, G. Dai, and W. Chen, Control System of Superconducting Quantum Computers, J. Supercond. Nov. Magn. **35**, 11 (2022).

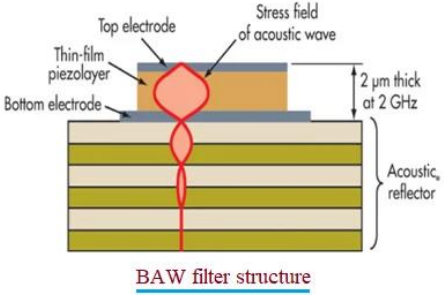
Frequencies of competing phonon-based technologies

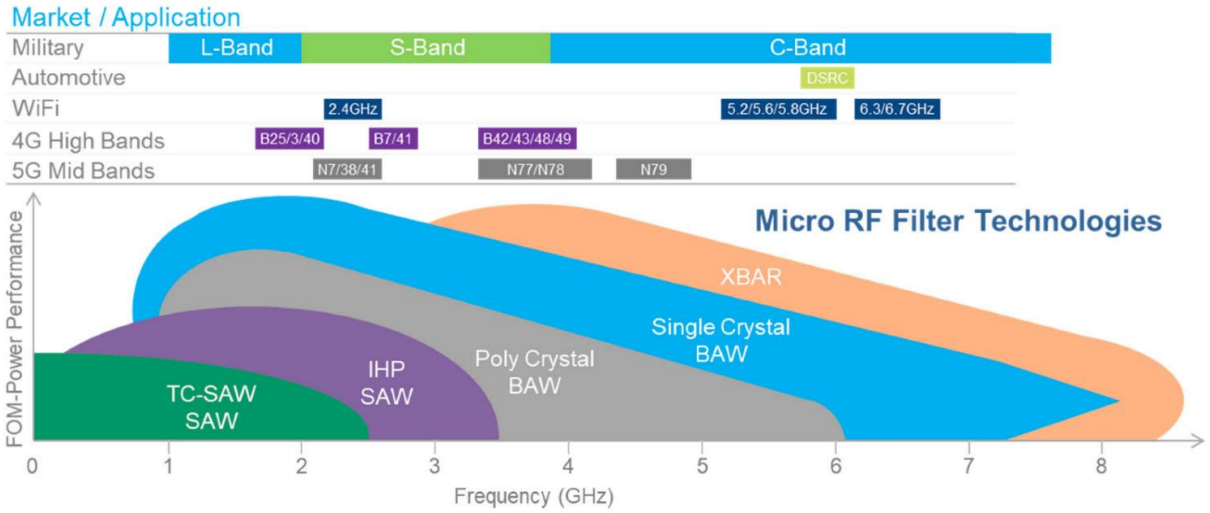
Miniaturized filters/phase shifters/time delay units in today's RF applications: **Surface and Bulk Acoustic Wave** systems

SAW



BAW





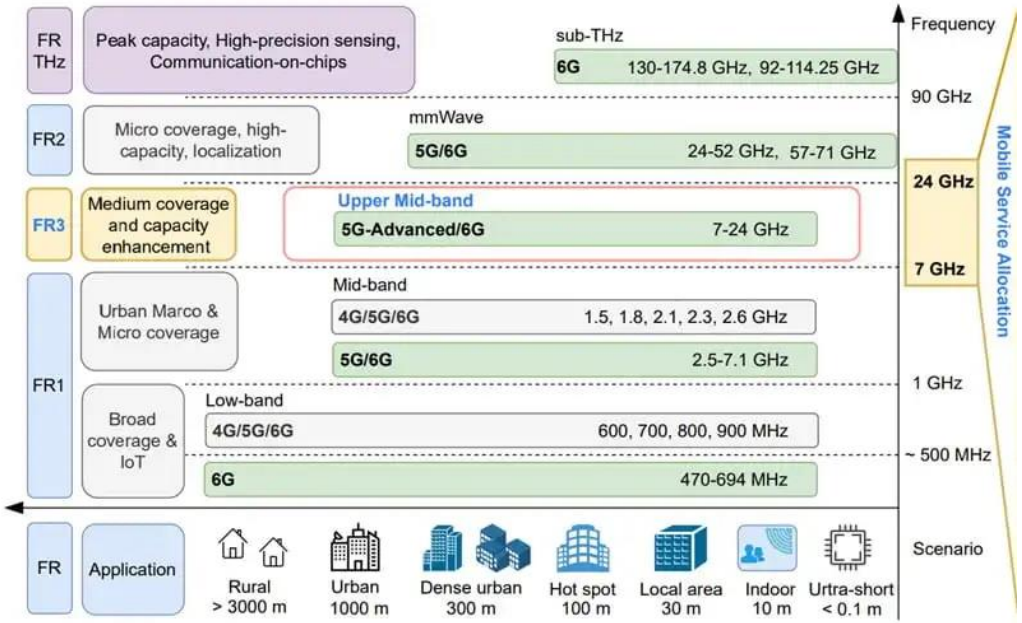
Chen, P.; Li, G.; Zhu, Z., Micromachines 2022, 13, 656, https://doi.org/10.3390/mi13050656

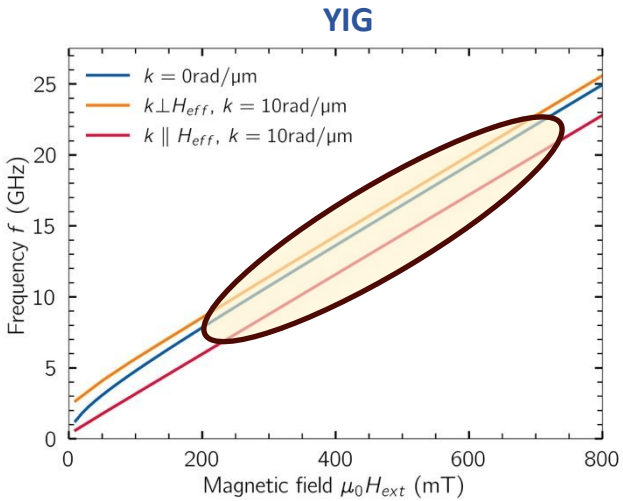
SAW /BAW:

- **No tunability**
- No solutions above 10 GHz

Frequency bands available for magnonics

Important for cost-efficient 6G



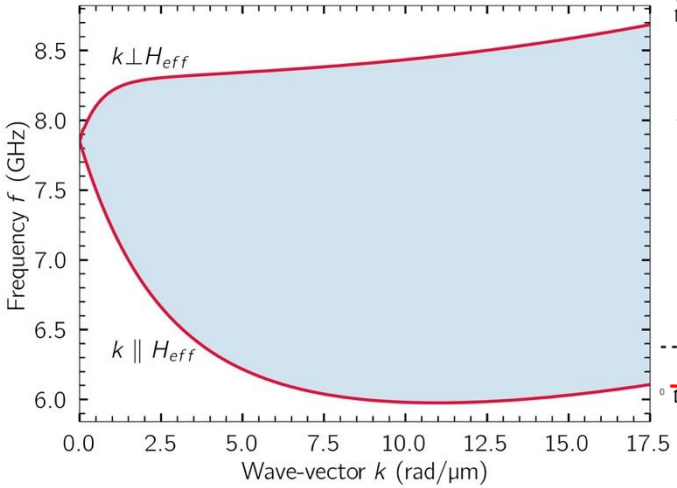


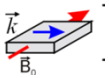
=> magnonic applications based on YIG are well suited for FR3 (7-24 GHz), no miniaturized solutions on the market

2. Tuning magnonic devices

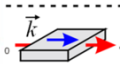
Example: Dispersion relations of dipolar-exchange spin-waves in an 800 nm thick film of Yttrium Iron Garnet (YIG) with in-plane magnetisation:

$$\mu_0 H = 200\ mT$$





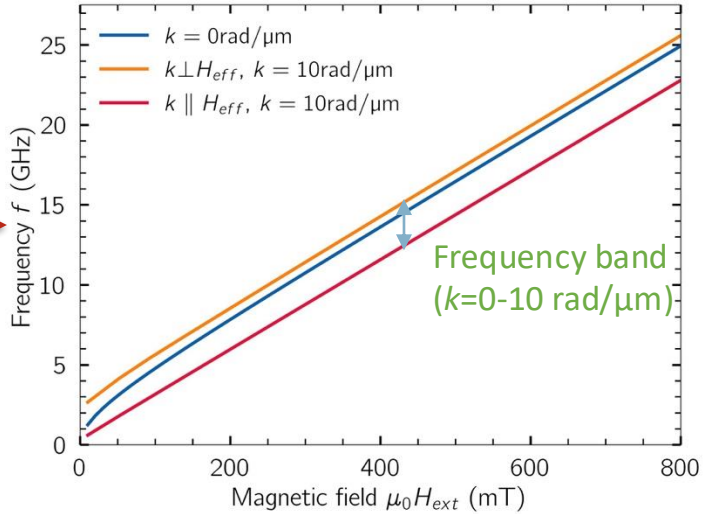
Damon-Eshbach surface mode



Backward-Volume mode

Change field

Magnetic field dependence of frequencies



$$f_{FMR} = \gamma \sqrt{\mu_0 H\ (\mu_0 H + \mu_0 M_s)}$$

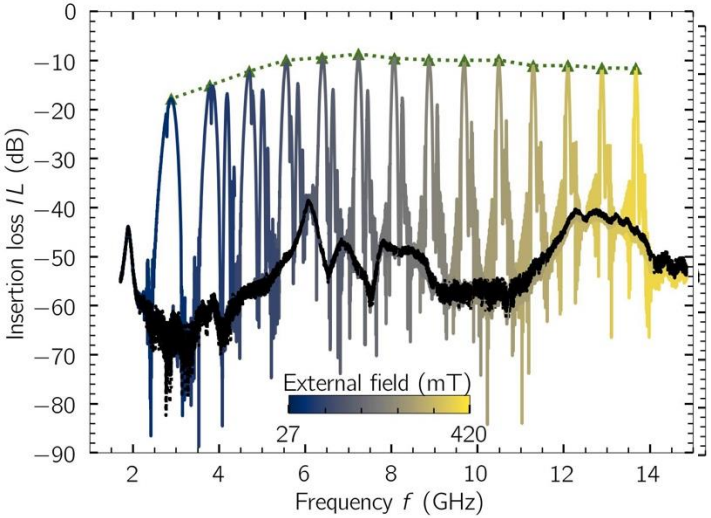
(effective) magnetic field — saturation magnetisation

Previous lectures:
Dispersion relation of magnons depends on propagation direction, saturation magnetization, film thickness, magnetic field…..

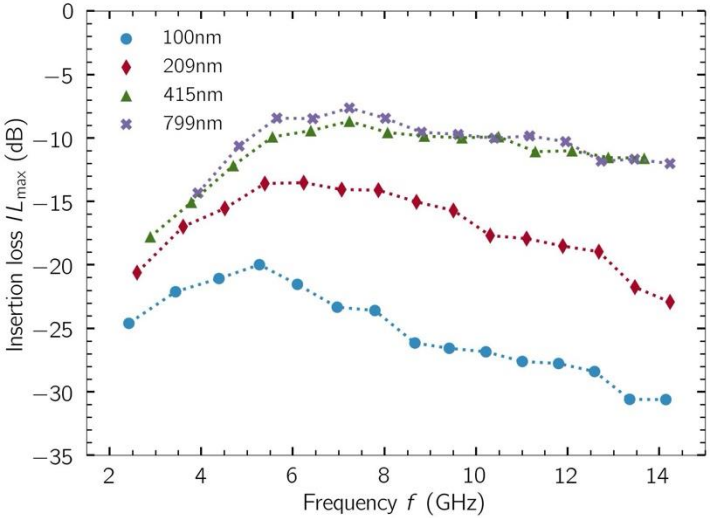
$$\gamma \approx 28 \frac{\mathrm{GHz}}{\mathrm{T}}, \mu_0 H = 0 - 1\ \mathrm{T}, \mu_0 M_s = 0.175\ \mathrm{T}\ (\mathrm{YIG})\ (2.2\ \mathrm{T}\ \text{for Fe})$$

Tuning transmission frequencies

Field dependence



Thickness dependence



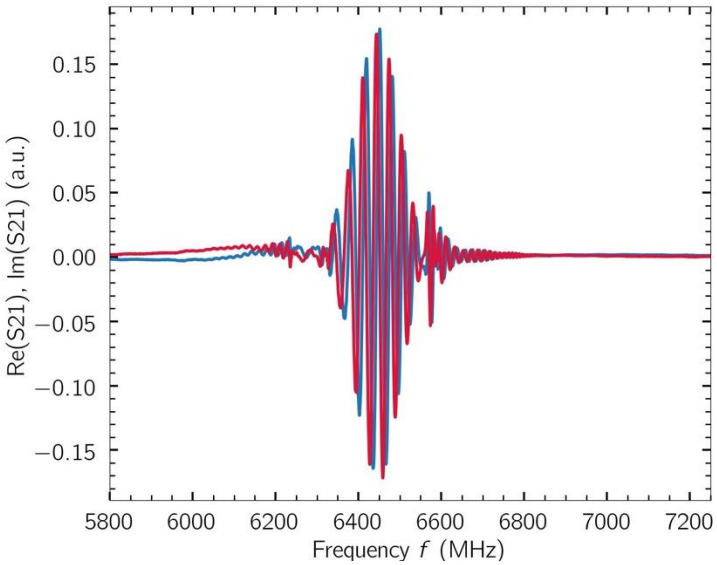
- **Signal tunable over broad frequency range**

- **Insertion losses <10dB achieved**

Example: Tunable signal transmission in time domain

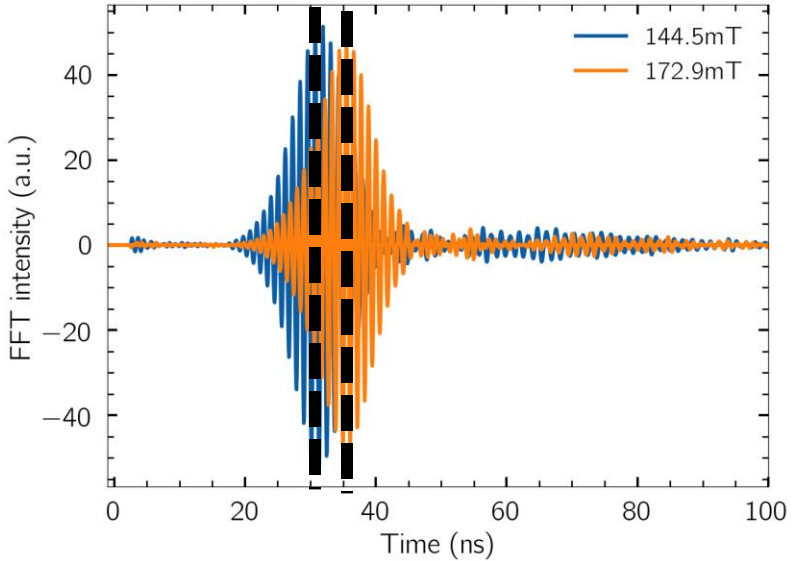
400nm YIG
$P = -20\text{dBm}$

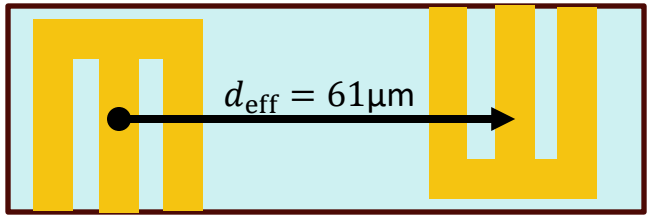
Frequency domain



FFT

Time domain

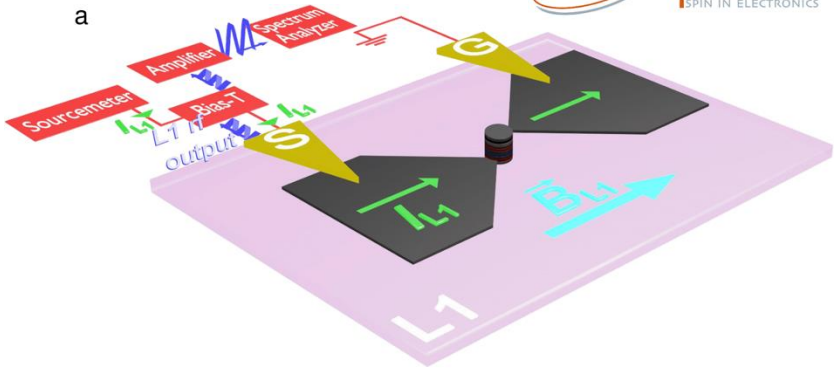




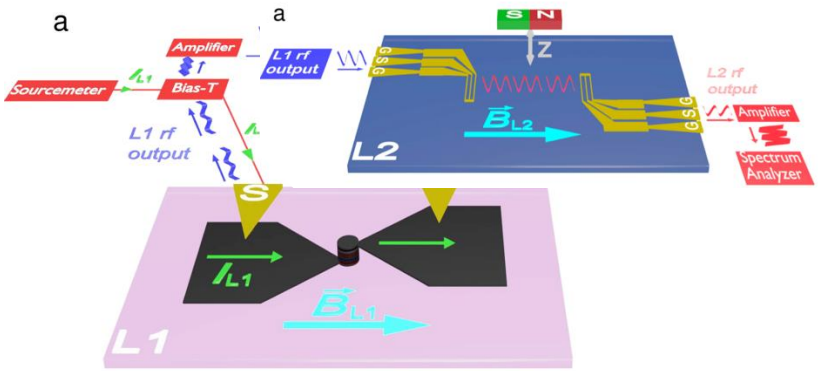
- **Induced time delay by changing external field**

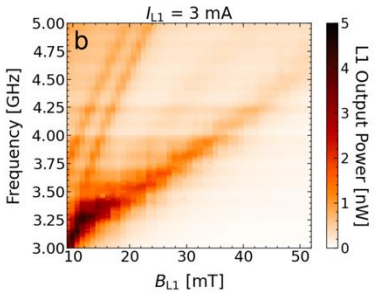
Example: Filter the signal from an STNO using spin waves

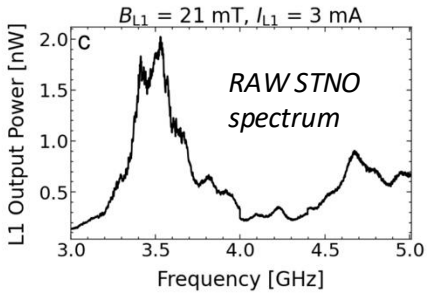
Only STNO

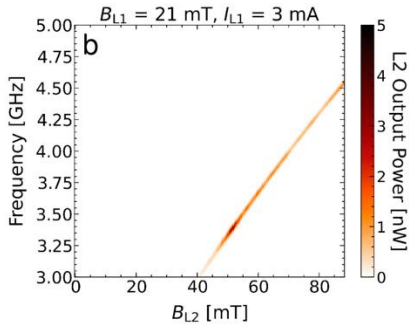


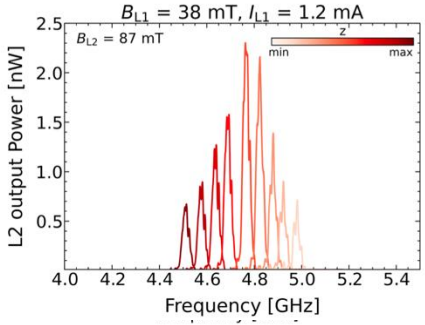
STNO filtered by magnonic filter







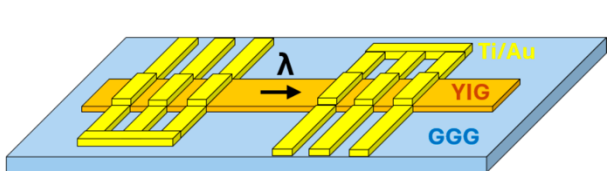


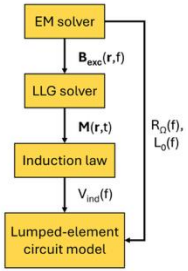


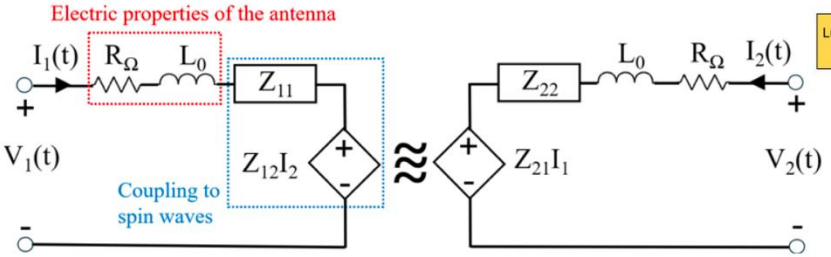
Filtered spectrum of STNO as function of magnet position

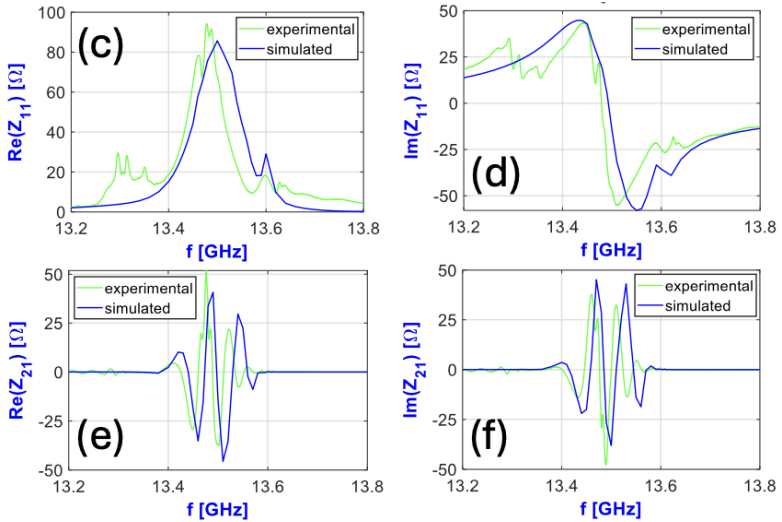
Hybrid magnonic spintronic system for tunable broadband signal filtering and microwave generation, A. Koujok, A. Hamadeh, L.Martins, F. Kohl, B. Heinz, U. Ebels, P. Pirro. Arxiv**2510.04976**

Lumped circuit model to predict impedance and performance









Prediction:
approx. 5dB loss with 1 µm thick YIG possible,
limited by *Gilbert damping* and *Ohmic resistance of CPW*

- Very good **quantitative agreement** between experimental and modeled **impedance without any fitting parameters**

Model by
Ádám Papp, Gyorgy Csaba,
Róbert Erdélyi (Budapest)

R. Erdélyi, et al. *„Design rules for low-insertion-loss magnonic transducers“*, Scientific Reports **15**, 9806 (2025)
compare: F. Bruckner, et al., *Micromag. Sim. And Optimization of SW Transducers*, arXiv:2501.16553 (2025)

Commercial magnonic components



Yttrium-Iron-Garnet tuned **RF oscillators** (YTO) produced by Rohde & Schwarz.

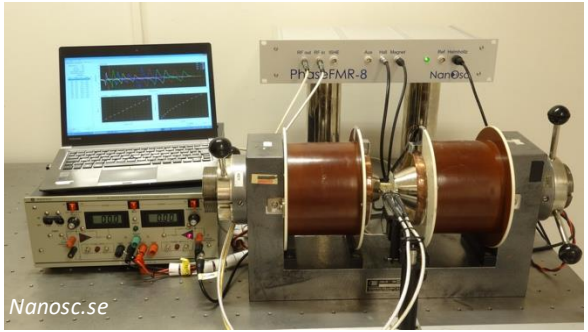
=> Bulky, power-hungry due charge current based magnetic fields

“Magnetic Field generation problem”

Strengths of Magnonics

- Tunablity via magnetic fields
- Low power loss inside the magnonic domain

.



Electromagnet

Standard experimental approach:

- Use an **electromagnet** to provide the bias field

=> Large energy consumption (Joule heating) outside the magnonic domain

M&MEMS

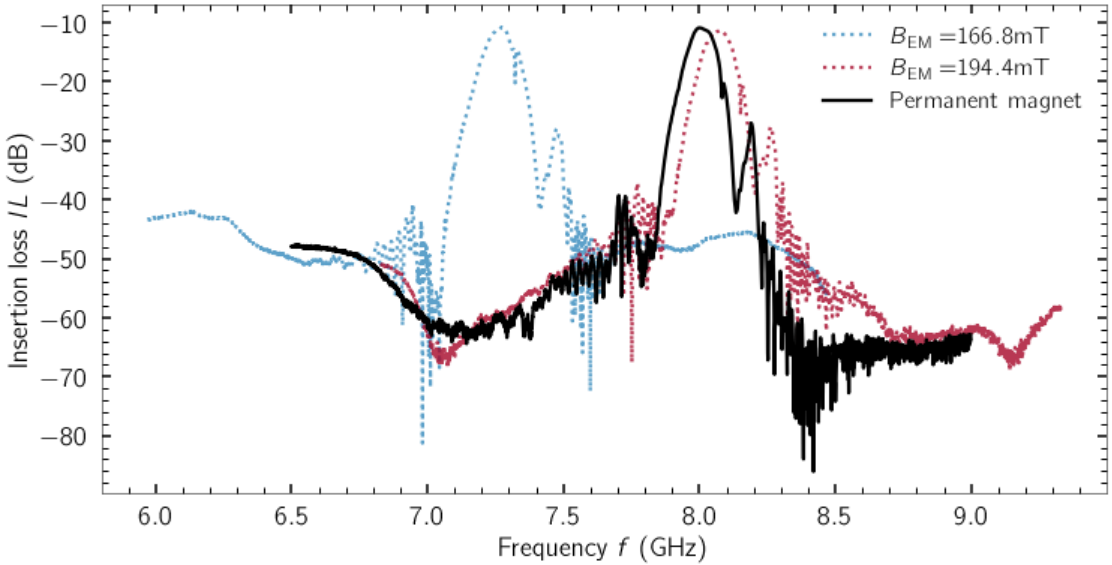
Funded by the European Union

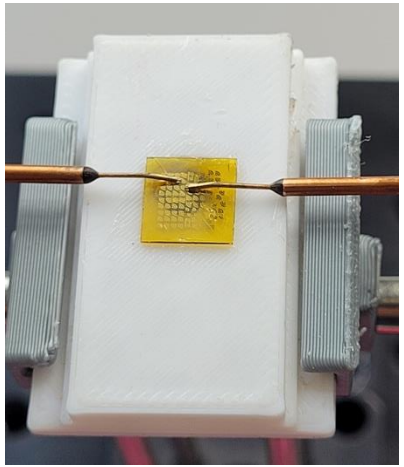
Challenge to create **energy-efficient** devices:
How to **provide magnetic fields** in an energy efficient, compact and scalable manner?

Permanent magnet biased device

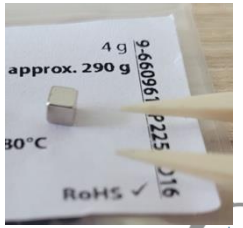
Type 4

$P = -25\text{dBm}$





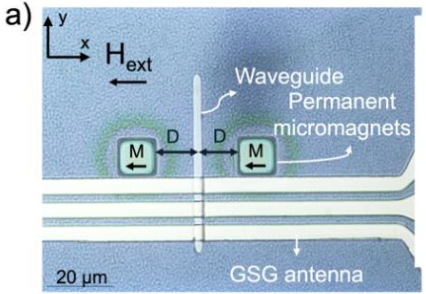
3mm NdFeB magnetic cube positioned below DUT

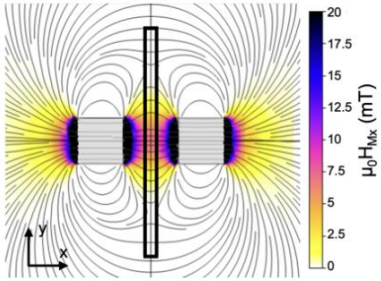


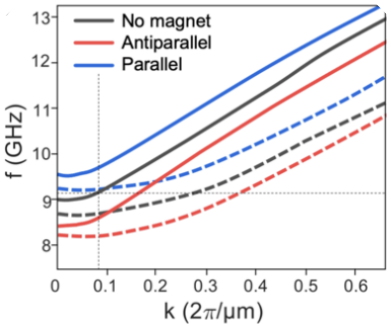
- Field homogeneity of NeFeB magnet is completely sufficient, no additional losses due to NdFeB excitation

(Moving) integrated permanent magnets

On-chip integrated SmCo permanent magnets

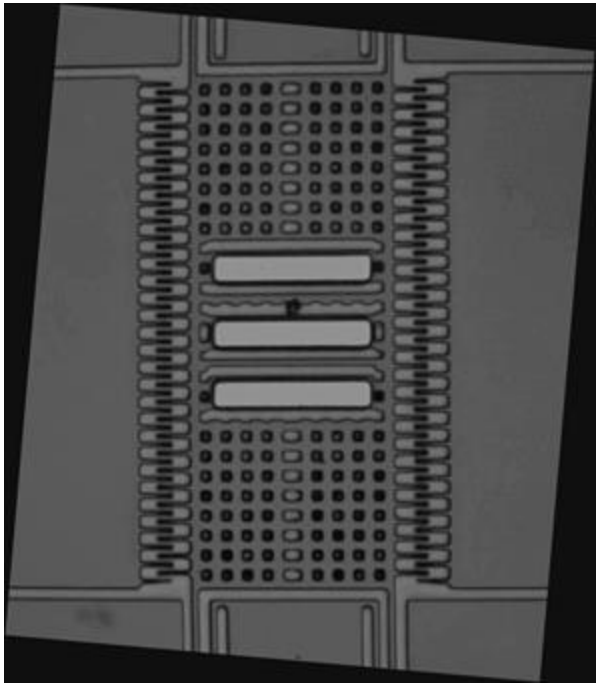






Consiglio Nazionale delle Ricerche

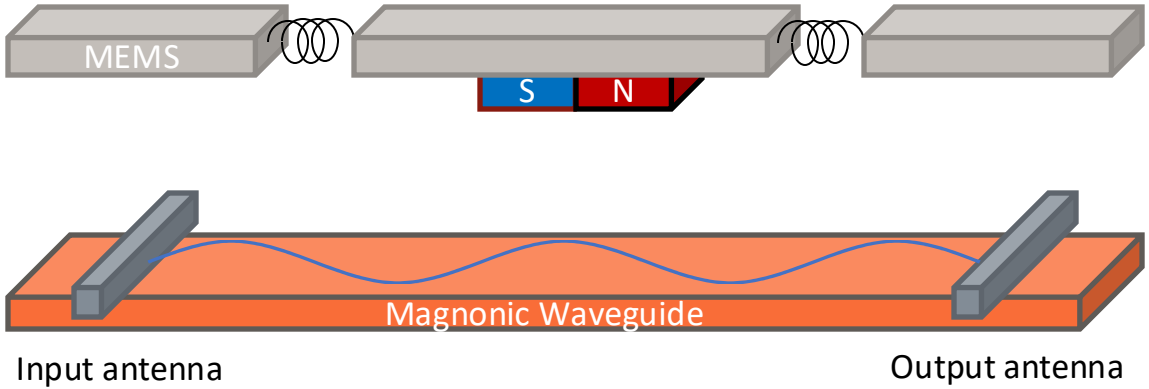
POLITECNICO MILANO 1863

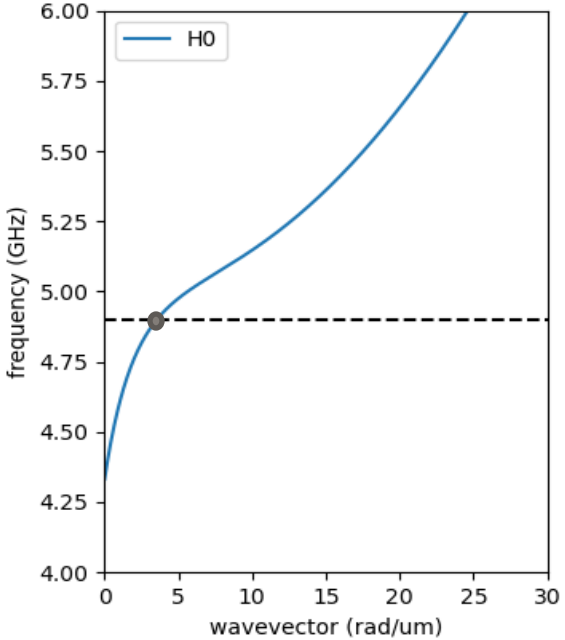


Permanent magnets on a laterally moving MEMS
(Micro electronic mechanical system)

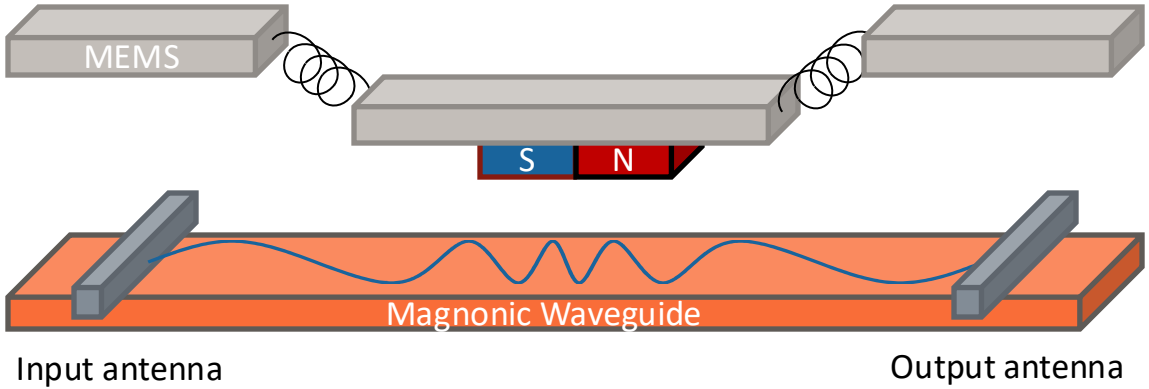
M. Cocconcelli et. al,., *Tuning magnonic devices with on-chip permanent micromagnets*, Phys. Rev. Appl. 22, 064063 (2024).
M. Cocconcelli et. Al., *Self Biased Integrated Magnonic Device*, arXiv.2502.03186

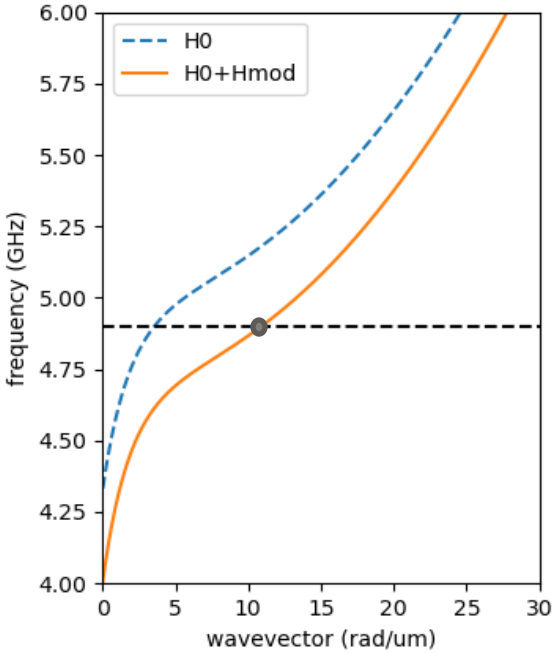
Oversimplified concept: Phase / time delay unit





Oversimplified concept : Phase / time delay unit



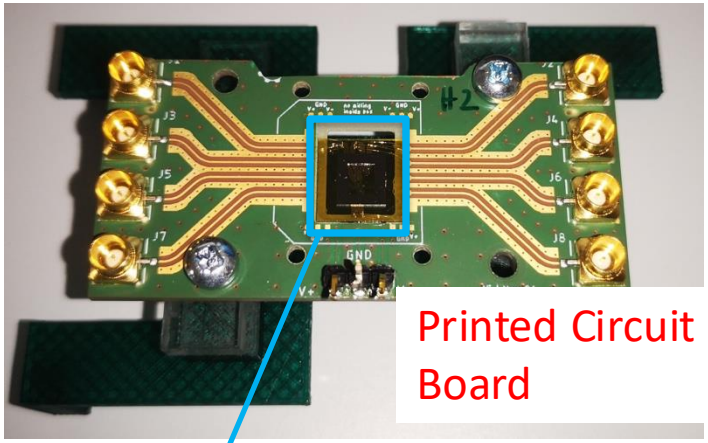


- Modulation of spin-wave wavelength between the antennas => **phase** and **time delay** are tuned
- **No influence on the input/output antenna** => constant amplitude

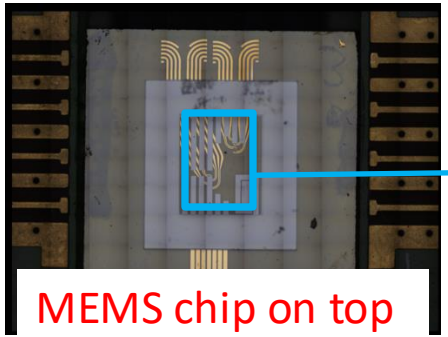
Situation is much more complicated than sketch..

... since $\nabla \times \vec{B}_{stray} = 0$

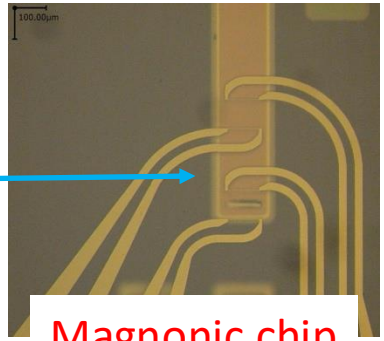
Fully integrated tunalbe magnonic-MEMES device on PCB



Printed Circuit Board

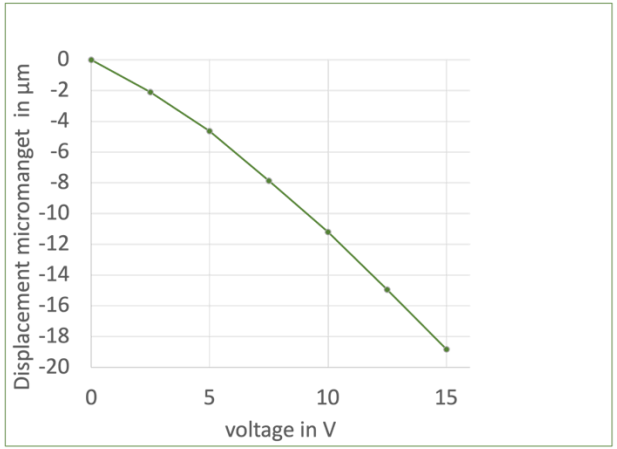


MEMS chip on top of magnonic chip



Magnonic chip

Micromagnet position

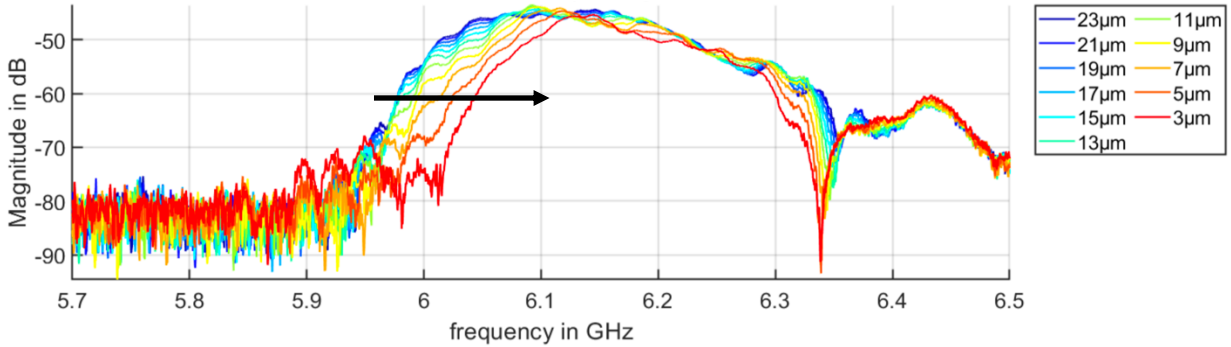


- Micromagnet on cantilever MEMS (piezo)

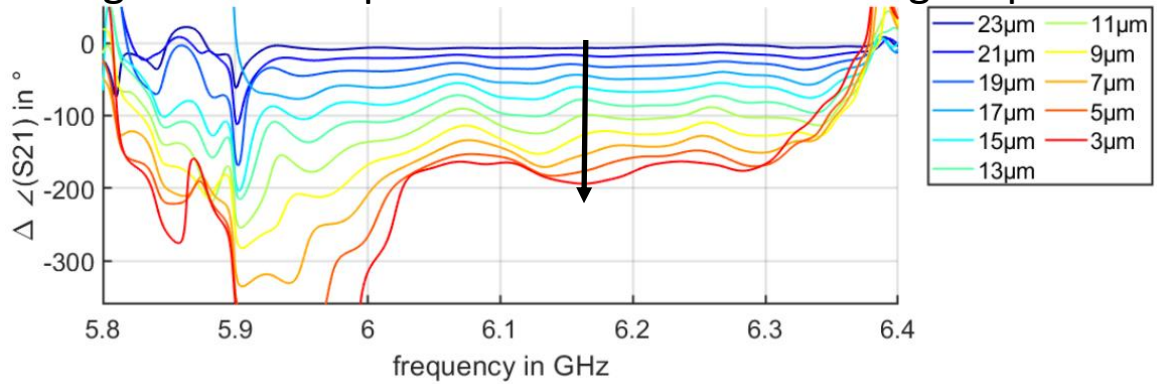
=> Tunable distance to magnonic chip by voltage, **no charge currents** needed

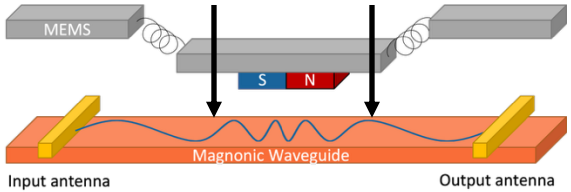
Reconfiguration via MEMS displacement of the biasing magnet

SW transmission for different micromagnet positions



Change of the SW phase for different micromagnet positions

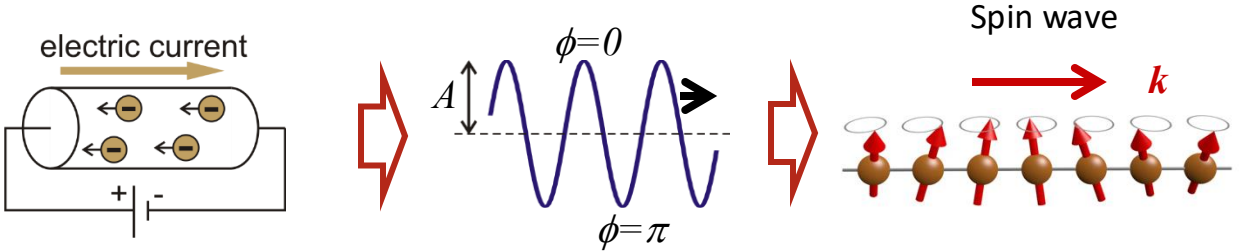




Outline

- **Basics of spin waves**
  - Classical spin wave theory (micromagnetic model)
  - Spin-wave detection, manipulation and generation
- **Magnon signal processing and computing**
  - **Linear** magnonics for
    - Signal processing
    - Logic devices: interference-based approaches
  - **Nonlinear** magnonic elements

Wave-based computing

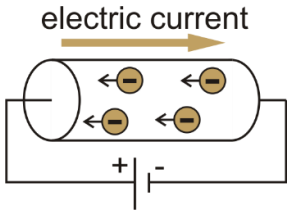


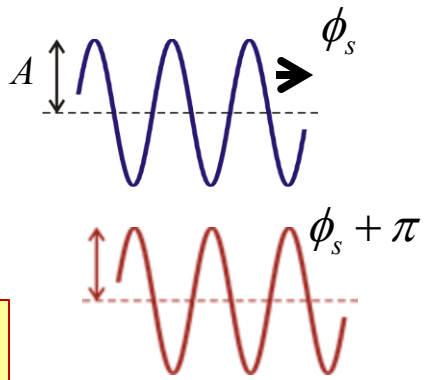
Variable	**Scalar**	**Vector**	(A, ϕ, f, $\boldsymbol{k}$)
Transport	Driven by **potential gradient**	Driven by **wave propagation**	Novel circuit design
Logic	Semiconductor based **transistors**	**Interference** phenomena	Simple realization of logic functionalities

Wave-based computing

Use wave packets instead of particles (electrons) for encoding of fata

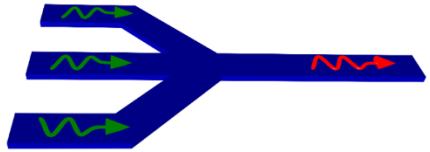
Scalar (binary), Boolean logic





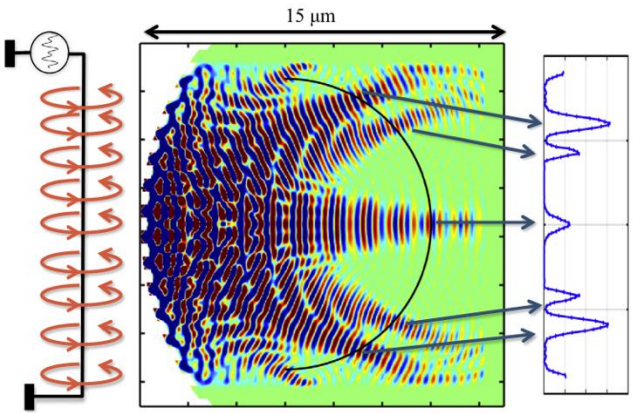
Advantages of wave-based computing:

- Possible use of both **phase** and **amplitude** (as **vector state variables**)
- Straightforward implementation of logic via **Interference** (majority gate, other logic gates…)
- **Low minimal energies** (quasiparticles)
- **Parallel computing** ($f_1, f_2, f_3, \ldots$)

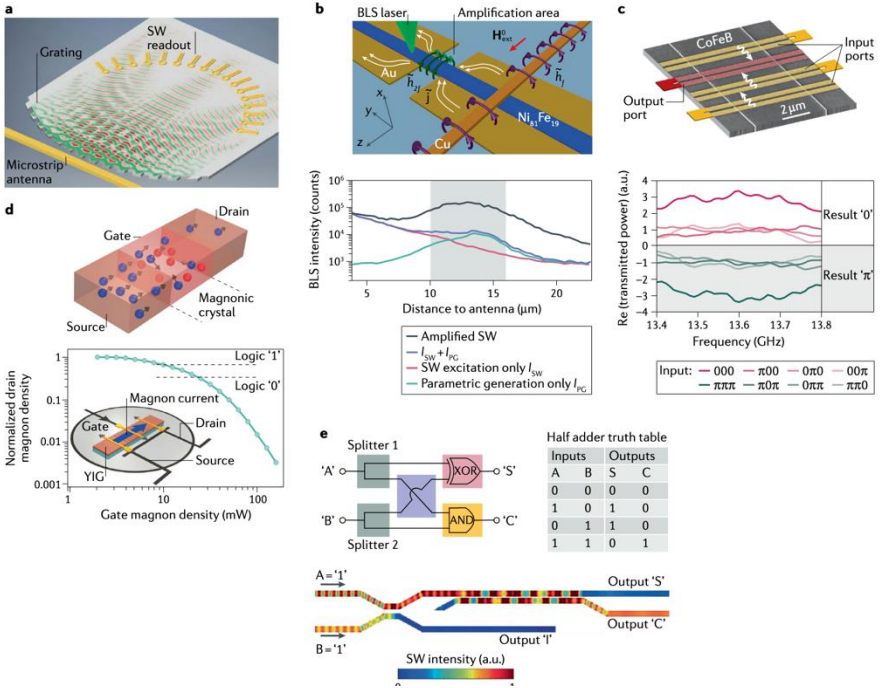


majority gate

Reviews about magnon computing



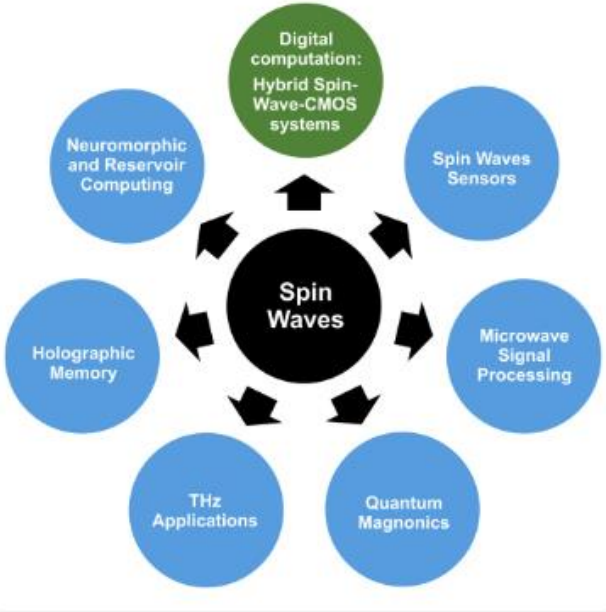
G. Csaba, Á. Papp, and W. Porod,
Perspectives of Using Spin Waves for Computing and Signal Processing,
Phys Lett A **381**, 1471 (2017).

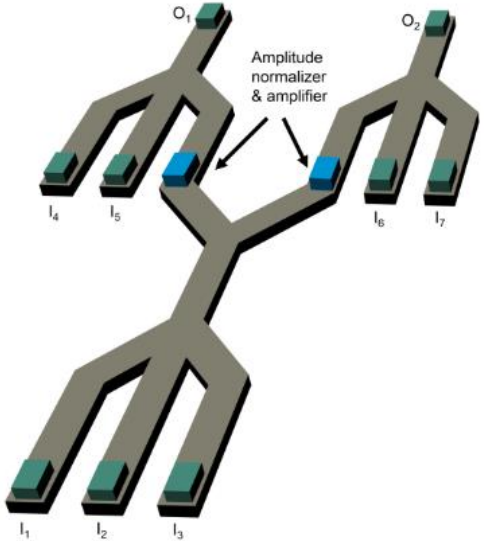


P. Pirro, V. I. Vasyuchka, A. A. Serga, and B. Hillebrands,
Advances in Coherent Magnonics,
Nat Rev Mater 6, 1114 (2021).

Reviews about magnon computing

Tutorial with focus on **Hybrid CMOS-SW** systems

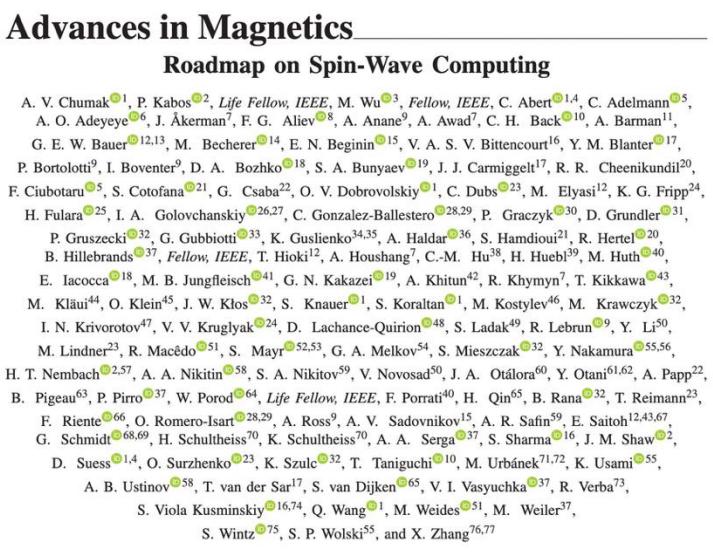




A. Mahmoud *et al.*
Introduction to Spin Wave Computing,
J Appl Phys **128**, 161101 (2020).

Review about magnon computing

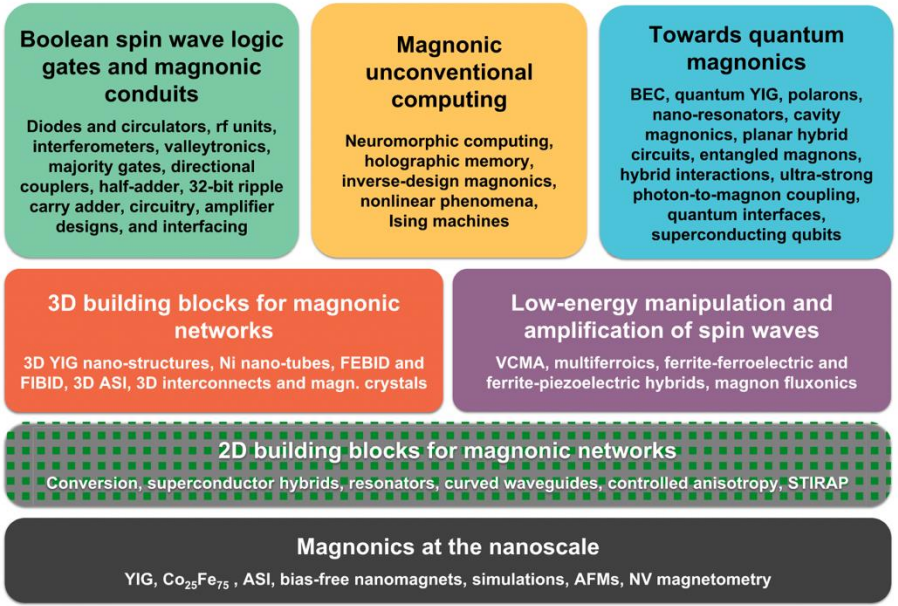
Comprehensive review about spin-wave computing



Advances in Magnetics

Roadmap on Spin-Wave Computing

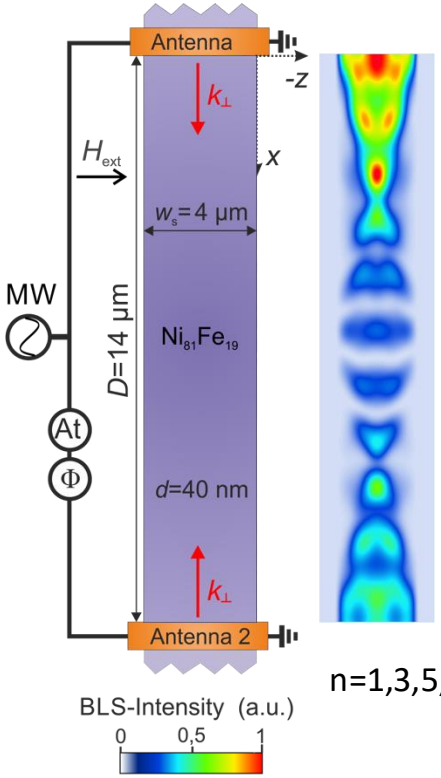
A. V. Chumak[1], P. Kabos[2], *Life Fellow, IEEE*, M. Wu[3], *Fellow, IEEE*, C. Abert[1,4], C. Adelmann[5], A. O. Adeyeye[6], J. Åkerman[7], F. G. Aliev[8], A. Anane[9], A. Awad[7], C. H. Back[10], A. Barman[11], G. E. W. Bauer[12,13], M. Becherer[14], E. N. Beginin[15], V. A. S. V. Bittencourt[16], Y. M. Blanter[17], P. Bortolotti[9], I. Boventer[9], D. A. Bozhko[18], S. A. Bunyaev[19], J. J. Carmiggelt[17], R. R. Cheenikundil[20], F. Ciubotaru[5], S. Cotofana[21], G. Csaba[22], O. V. Dobrovolskiy[1], C. Dubs[23], M. Elyasi[12], K. G. Fripp[24], H. Fulara[25], I. A. Golovchanskiy[26,27], C. Gonzalez-Ballestero[28,29], P. Graczyk[30], D. Grundler[31], P. Gruszecki[32], G. Gubbiotti[33], K. Guslienko[34,35], A. Haldar[36], S. Hamdioui[21], R. Hertel[20], B. Hillebrands[37], *Fellow, IEEE*, T. Hioki[12], A. Houshang[7], C.-M. Hu[38], H. Huebl[39], M. Huth[40], E. Iacocca[18], M. B. Jungfleisch[41], G. N. Kakazei[19], A. Khitun[42], R. Khymyn[7], T. Kikkawa[43], M. Kläui[44], O. Klein[45], J. W. Kłos[32], S. Knauer[1], S. Koraltan[1], M. Kostylev[46], M. Krawczyk[32], I. N. Krivorotov[47], V. V. Kruglyak[24], D. Lachance-Quirion[48], S. Ladak[49], R. Lebrun[9], Y. Li[50], M. Lindner[23], R. Macêdo[51], S. Mayr[52,53], G. A. Melkov[54], S. Mieszczak[32], Y. Nakamura[55,56], H. T. Nembach[2,57], A. A. Nikitin[58], S. A. Nikitov[59], V. Novosad[50], J. A. Otálora[60], Y. Otani[61,62], A. Papp[22], B. Pigeau[63], P. Pirro[37], W. Porod[64], *Life Fellow, IEEE*, F. Porrati[40], H. Qin[65], B. Rana[32], T. Reimann[23], F. Riente[66], O. Romero-Isart[28,29], A. Ross[9], A. V. Sadovnikov[15], A. R. Safin[59], E. Saitoh[12,43,67], G. Schmidt[68,69], H. Schultheiss[70], K. Schultheiss[70], A. A. Serga[37], S. Sharma[16], J. M. Shaw[2], D. Suess[1,4], O. Surzhenko[23], K. Szulc[32], T. Taniguchi[10], M. Urbánek[71,72], K. Usami[55], A. B. Ustinov[58], T. van der Sar[17], S. van Dijken[65], V. I. Vasyuchka[37], R. Verba[73], S. Viola Kusminskiy[16,74], Q. Wang[1], M. Weides[51], M. Weiler[37], S. Wintz[75], S. P. Wolski[55], and X. Zhang[76,77]



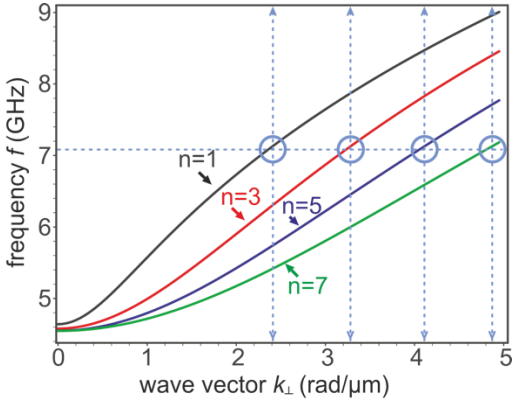
A.V. Chumak et al.,
Advances in Magnetics Roadmap on Spin-Wave Computing
IEEE Tran. on Magn. **58**, 0800172 (2022).

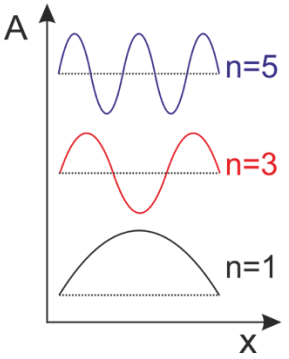
72 pages

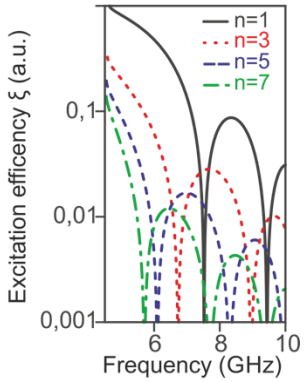
Interference: counter-propagating spin-waves in NiFe microstuctures



n=1,3,5,7







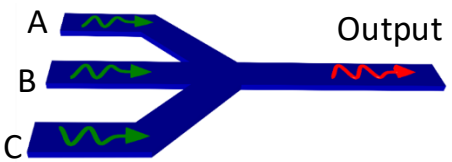
Coherence length of spin waves is sufficient even in metals to build wave based **microscaled** devices✓

P. Pirro, et al., PSSB, **248**, 2404 (2011)

Magnon majority gates: General idea

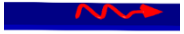
Data is coded into spin-wave **phase**

Majority gate



Inverter

λ/2 =>Δϕ=π



	Input A	Input B	Input C & Control	Output
AND	0	0	0	0
	1	0	0	0
	0	1	0	0
	1	1	0	1
OR	0	0	1	0
	1	0	1	1
	0	1	1	1
	1	1	1	1

0: ϕ=0 **1: ϕ=π**

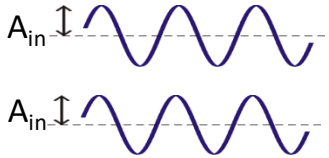
A. Khitun, et al., J. Phys. D. **43**, 264005 (2010)

- Simple realization (spin-wave combiner)
- Replaces about 26 transistors in CMOS
- Majority gate + inverter are building blocks for full logic functionality: direct access to AND, OR, NAND, NOR and Full Adder gates with reduced complexity

Side note: Interference of co-propagating waves

If the spin-waves are **coherently excited and propagate without any loss** (keep the amplitude) and dephasing (keep the phase), the **linear superposition** in a **single-mode** waveguide is:

Input:
Two waves of
equal amplitude
and phase



Assume:
Reflection-less superposition



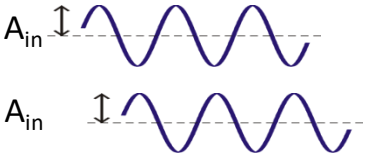
NOT plane waves…



$A_{out}=\sqrt{2}A_{in}$

Energy conservation

Two waves of
equal amplitude
in anti-phase



Assume:
single-mode waveguide



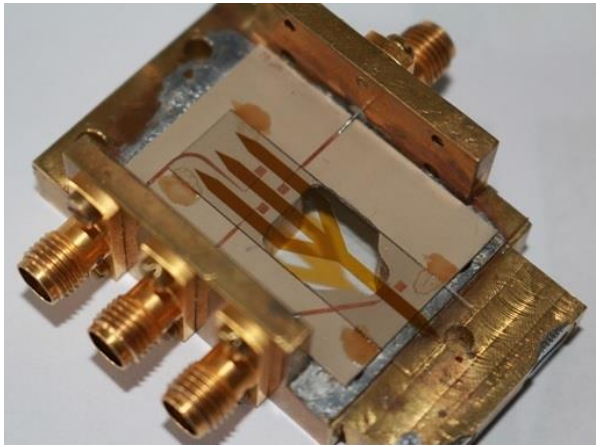


$A_{out}\approx 0$

Many magnonic systems are **not** single mode=> there is more than one spin wave mode at the working frequency
=> Increased complexity

Experimental realization

Macroscopic majority gate

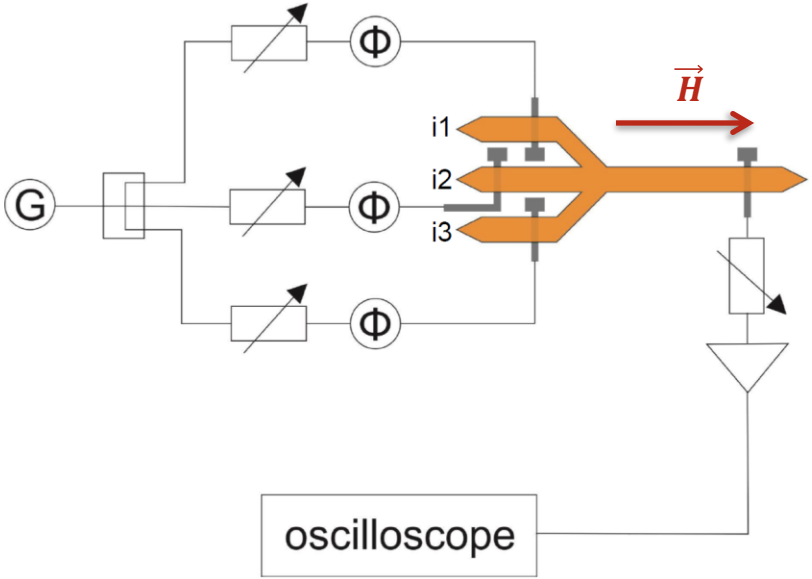


YIG sample:

- - thickness 5.4 µm
- - waveguide width 1.5 mm

Produced by Carat, Lviv, Ukraine

Experimental setup

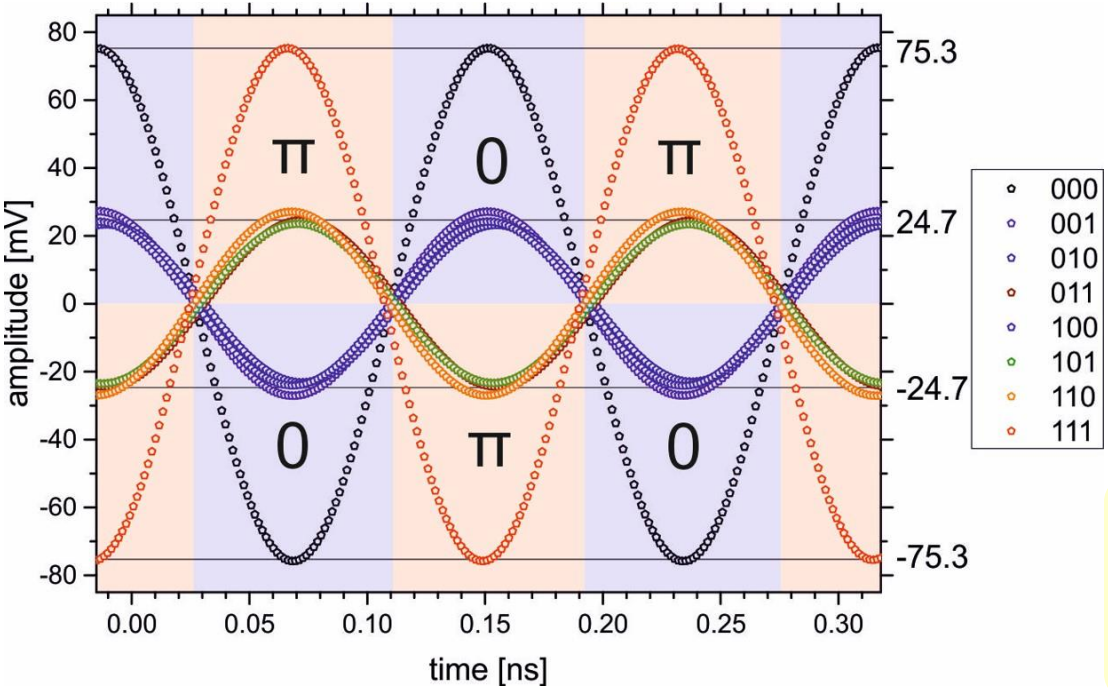


Geometry	BVMSW
Frequency	6.035 GHz
Magnetic field	142.9 mT

T. Fischer *et al.*, *APL* ***110***, *152401 (2017)*

Superposition of all channels

Real time observation of the resulting spin-wave interference via fast oscilloscope:



The phase of the output signal is defined by the majority of the input phases ✓

amplitude ratio: 75.3/24.7=**3.05,** expected: 3

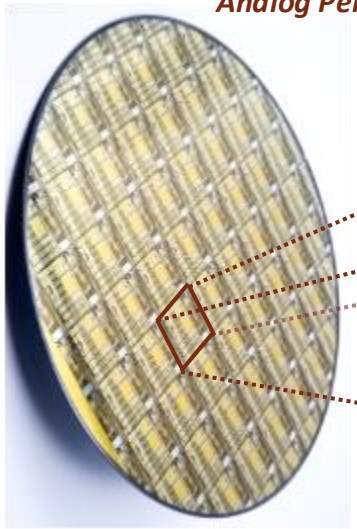
T. Fischer *et al., APL* ***110****, 152401 (2017)*

Hybrid CMOS-Magnon computer

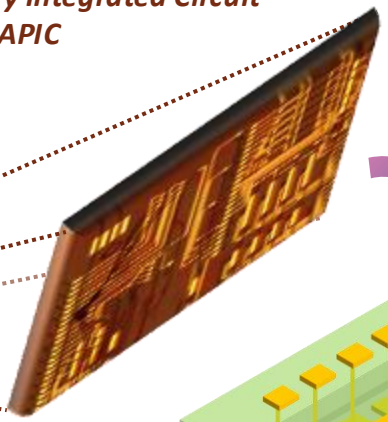
Funded by the European Union
GA No. 101070417
SPIDER

Challenge:
Reliable and **efficient** of CMOS-RF-Magnon transduction

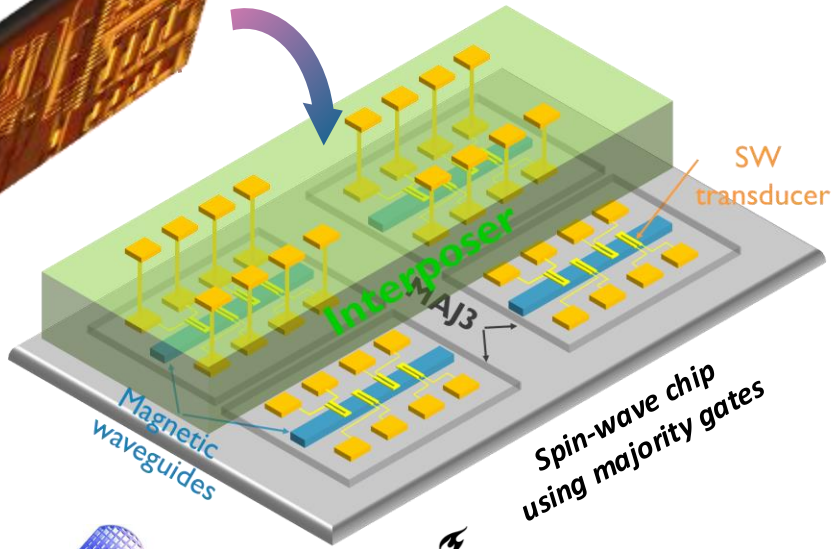
CMOS (TSMC):
Analog Periphery Integrated Circuit
APIC



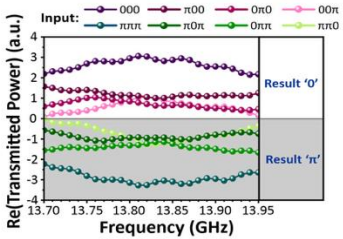
Multi Project Wafer prototype (WP4)

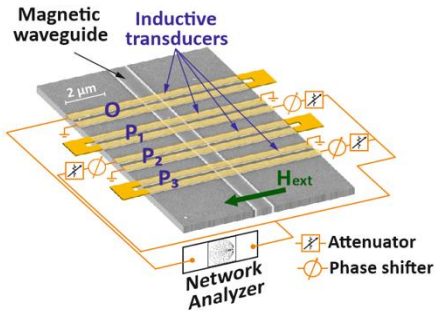


Integration via RF Interposer technology



Magnonic majority gates





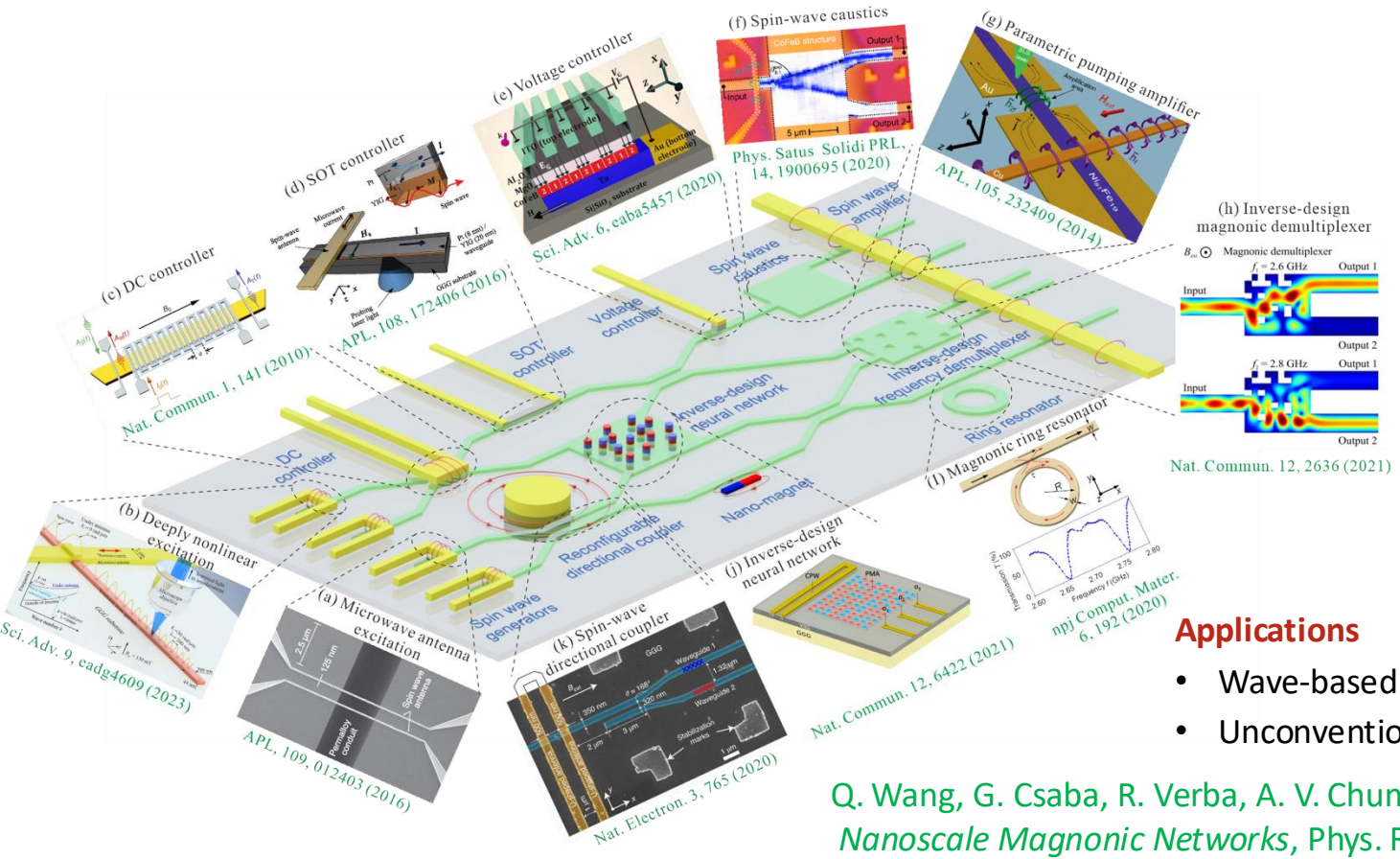
G. Talmelli, et al.,
Sci. Adv. **6** (2020) eabb4042.

imec Akronic RPTU Fraunhofer IZM TU Delft THALES

Outline

- **Basics of spin waves**
  - Classical spin wave theory (micromagnetic model)
  - Spin-wave detection, manipulation and generation
- **Magnon signal processing and computing**
  - **Linear** magnonics for
    - Signal processing
    - Logic devices: interference-based approaches
  - **Nonlinear** magnonic elements

Nanoscale magnonic networks

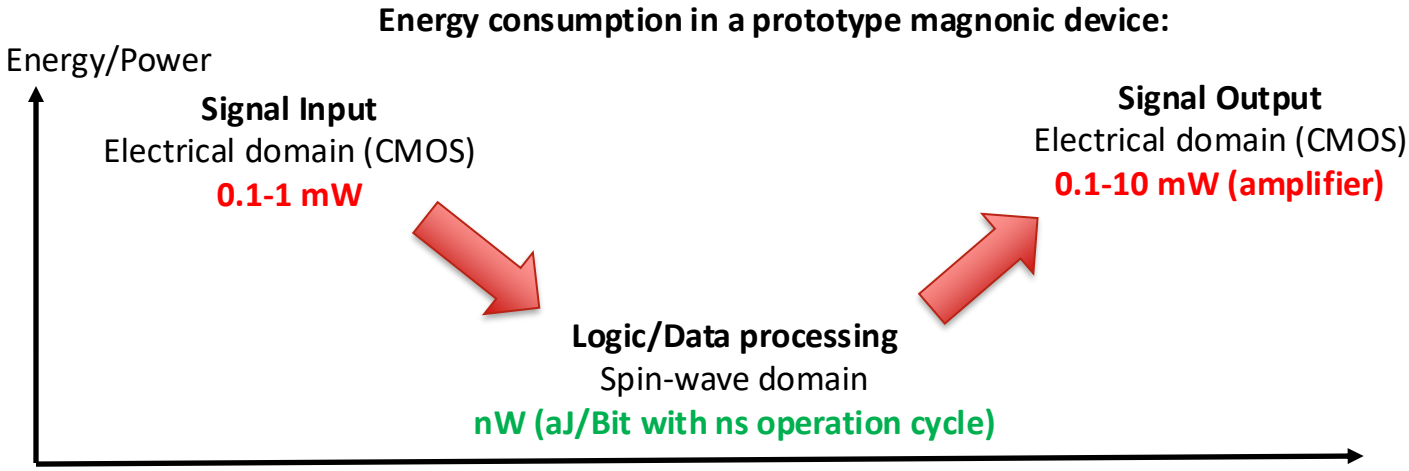


Applications

- Wave-based information processing
- Unconventional computing

Q. Wang, G. Csaba, R. Verba, A. V. Chumak, and P. Pirro,
Nanoscale Magnonic Networks, Phys. Rev. Appl. **21**, 040503 (2024).

Why integrated magnon circuits ?



- Most energy is consumed for moving the signal between the electrical and the spin-wave domain

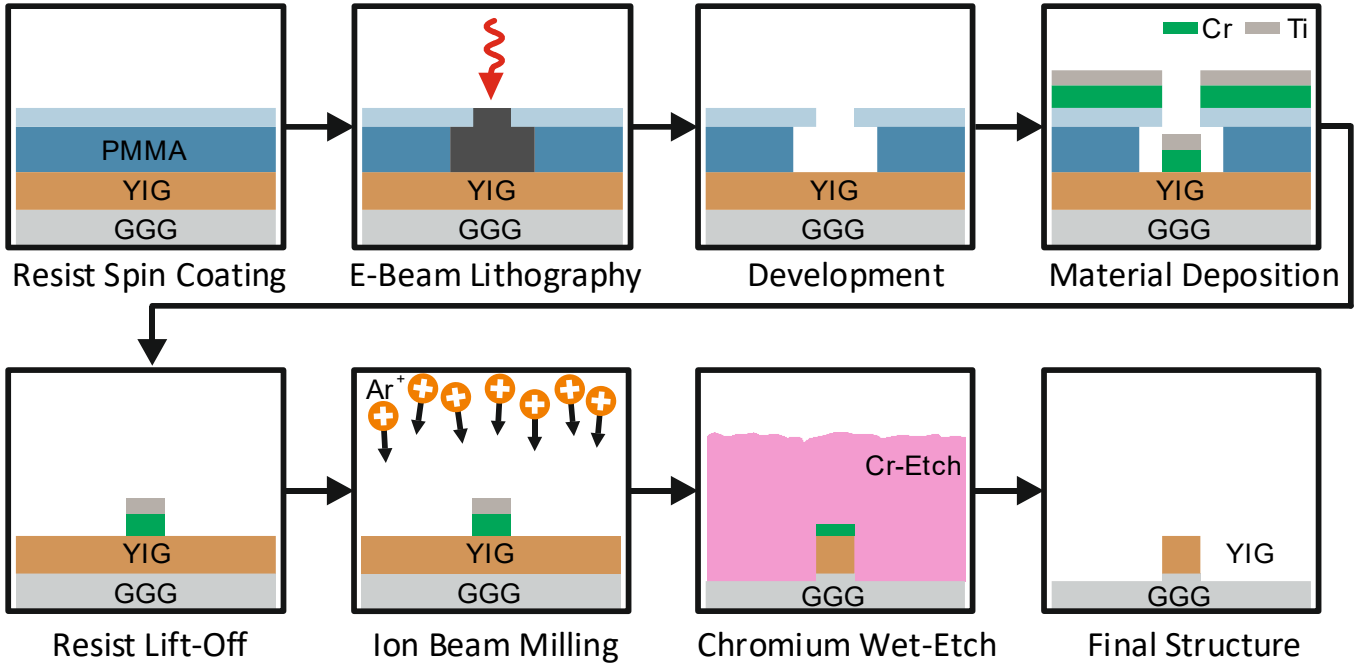
→ **"All-magnonic logic" reduces conversion losses** and gives access to low power computation

- Improve conversion efficiency in nanostructures (Spin-orbit torques, Voltage controlled anisotropy, magneto-electric and –acoustic coupling…)

Acknowledgements: IMEC team, Leuven and G. Csaba, Budapest

Structuring of magnonic nanostructures

Integrated magnonic circuits need low damping nanostructures with high magnon lifetime:

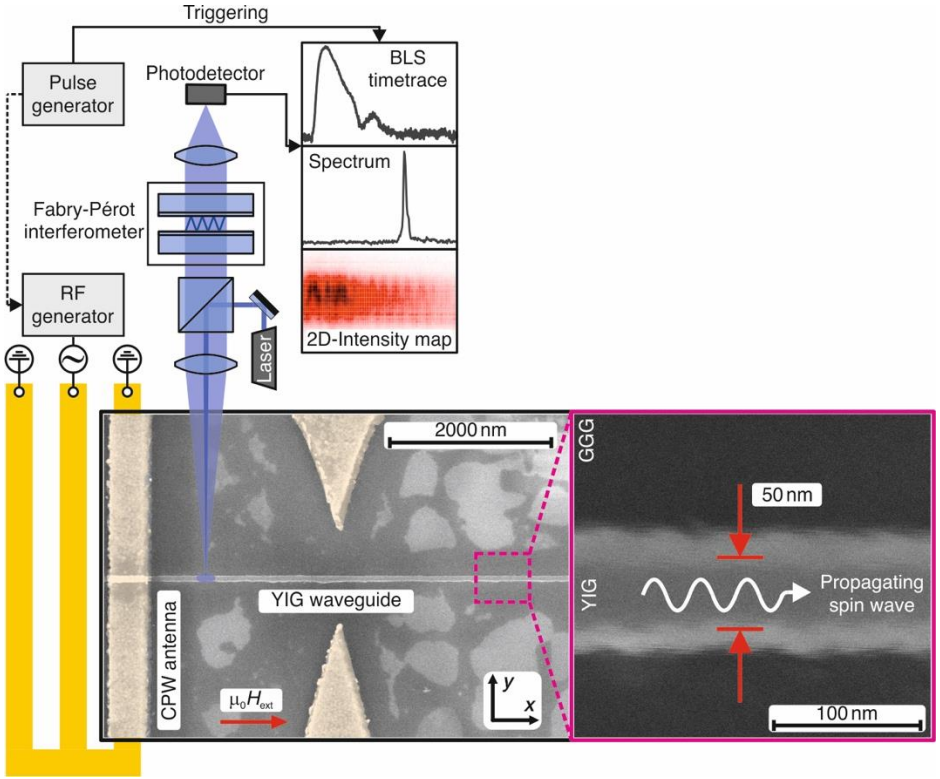


B. Heinz, PP *et al.*, Nano Letters, **20**, 4220 (2020).

✓ YIG nanoelements with feature sizes down to 50 nm

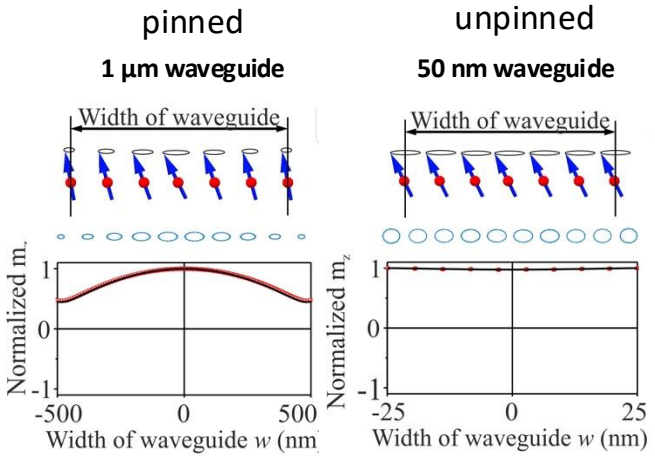
Other techniques: Si-ion irradiation: J. Bensmann et al., Nat. Mater. (2025) 10.1038/s41563-025-02282-y
Laser irradiation: V. Levati et al. arXiv.2409.17722

Micro-focused Brillouin Light scattering of YIG nanostructures



B. Heinz, PP *et al.*, Nano Letters, **20**, 4220 (2020).

Spin-wave unpinning on the nanoscale



Q. Wang, B. Heinz, PP, *et al.*,
Phys. Rev. Lett. ***122****, 247202 (2019).*

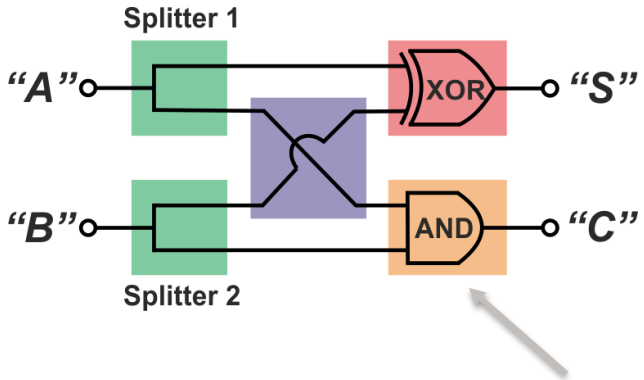
Prototype of integrated circuit: Half adder

Standard element of binary data processing

Input A	Input B	„S“	„C“
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

“Sum” “Carry”

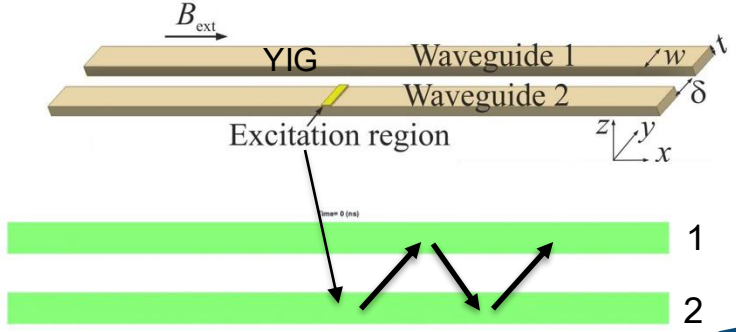
Standard realization:



AND gate: nonlinear system

Dipolar coupled waveguides

Micromagnetic simulation:

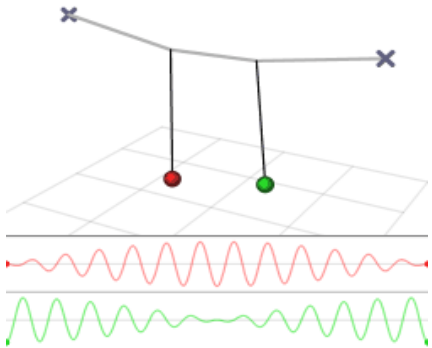


Yttrium Iron Garnet (YIG) :

M_s =1.4×10^5 A/m
A = 3.5 pJ
α= 2×10^{-4}

t = 50 nm
w = 100 nm
δ = 100 nm

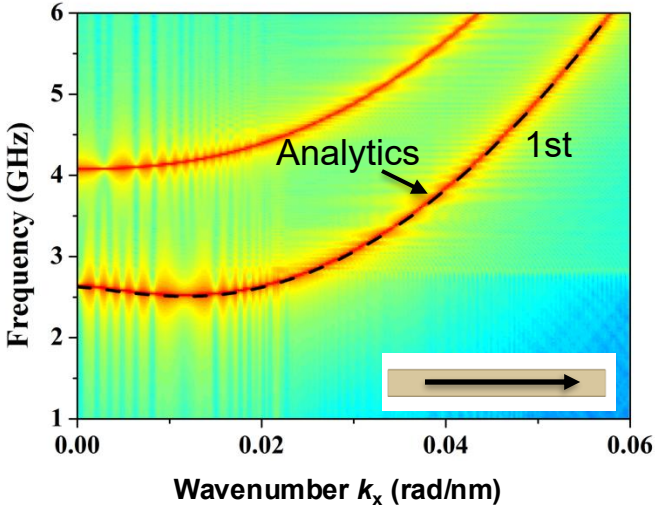
Coupled oscillators

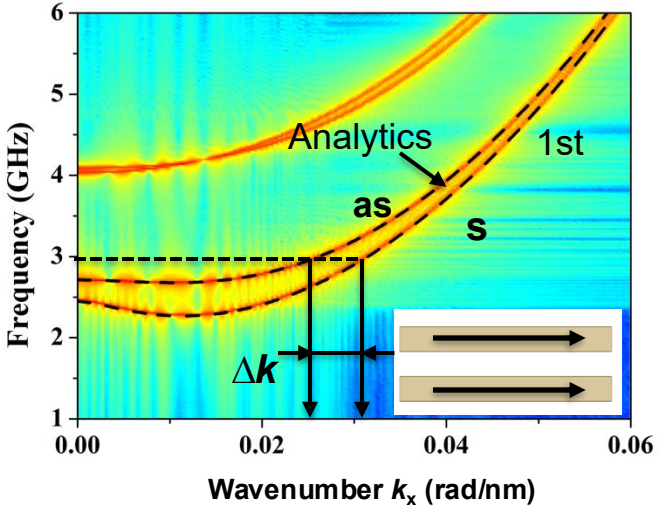


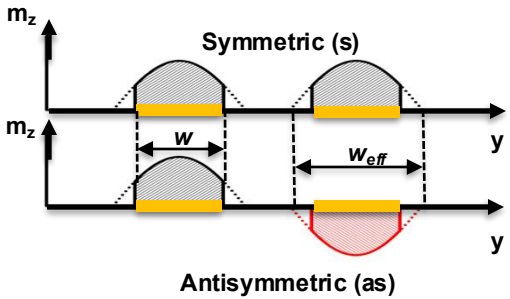
From: Wikipedia

Using Mumax3: A. Vansteenkiste, et al., *AIP Advance* **4**, 107113 (2014)

Spin-wave dispersions in coupled systems







Coupling length:

$$L = \frac{\pi}{\Delta k}$$

Analytics: R. Verba, A. Slavin

R. Verba et al., Phys. Rev. B **85**, 014427 (2012)

R. Verba, Ukrainian journal of physics **58**, 758 (2013)

AND-Gate

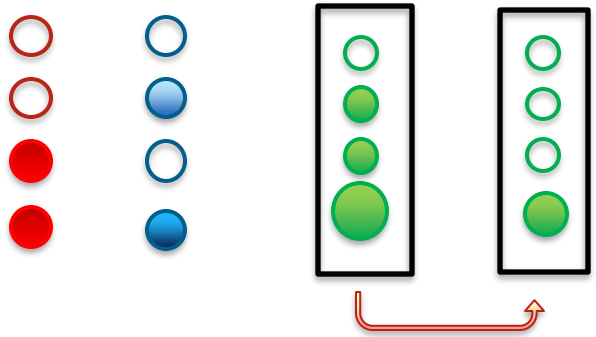
Encoding in amplitude:

Input 1	Input 2	Output
0	0	0
0	1	1
1	0	1
1	1	$\sqrt{2}$

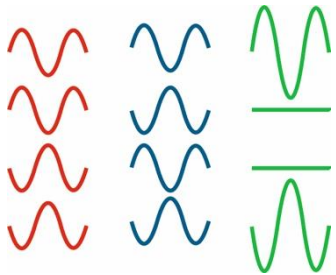
Encoding in phase:

Input 1	Input 2	Output
0	0	0
0	π	–
π	0	–
π	π	π

Linear superposition:



Nonlinear signal transformation by **nonlinear spin-wave transmission**



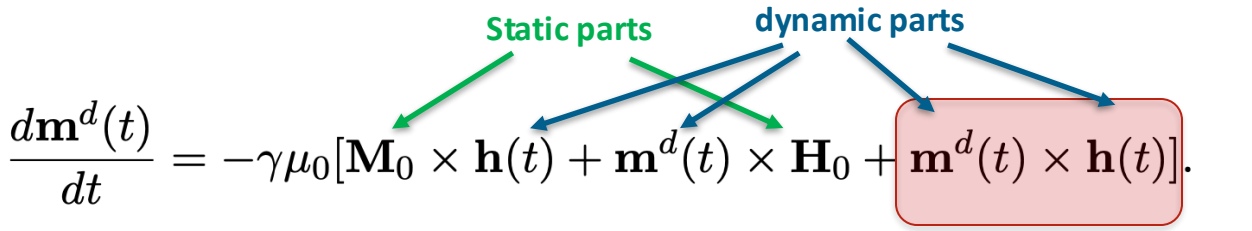
Truth table of AND gate:

Input 1	Input 2	Output
0	0	0
0	1	0
1	0	0
1	1	1

No simple **linear realization** of wave-based **AND gate** which can be easily **implemented in a magnonic network**

From linear to nonlinear magnonics

- **Landau-Lifshitz equation split in static and dynamic parts:**

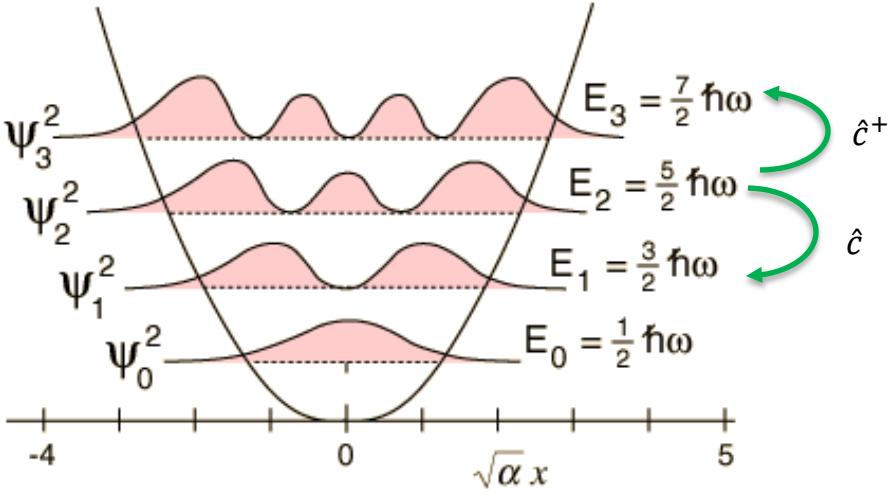


- Spin waves are the **eigenmodes** of the system **if** the product of the dynamic amplitudes can be neglected=> good approximation for low amplitudes

What do we do if this approximation is not valid anymore?

Theory for nonlinear magnonics

- The theory developed for nonlinear magnonics is a nice illustration for the **magnon quasiparticle picture**, since it uses the concepts of **"second quantization"**
- Magnon occupation is described by **magnon operators**, similar to the ladder operators from quantum mechanical theory of harmonic oscillators



QM Harmonic oscillator:

- Energy levels are spaced by the same energy difference $\Delta E = \hbar\omega$
- **Excitation** of a quasiparticle with the energy $\hbar\omega$ is associated with a transition from occupation state $|n>$ to state $|n+1>$ => described by ladder operator $\hat{b}^+$
- **Annihilation** of a quasiparticle is associated with a transition from occupation state $|n>$ to state $|n\pm>$
  $\Rightarrow$ described by ladder operator $\hat{b}$

Total magnon number $N = \hat{b}^+\hat{b}$
("Spin-wave intensity")

Magnon-magnon interactions

Number of magnons/waves involved

Eigenmodes (Harmonic oscillator)
(linear dispersion relation)

Four-magnon-
Interactions

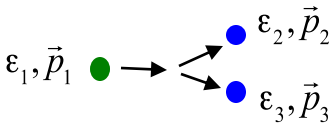
$$\mathcal{U}(b_k, \mathrm{b}_\mathrm{k}^*) = \sum_n \mathcal{U}^{(n)} = \mathcal{U}^{(0)} + \mathcal{U}^{(1)} + \mathcal{U}^{(2)} + \mathcal{U}^{(3)} + \mathcal{U}^{(4)} + \dots$$

Linear excitation
(e.g. via MW fields)

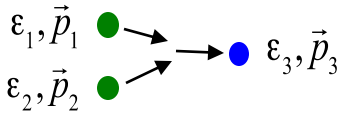
Three-magnon-
Interactions

"Nonlinear magnonics"

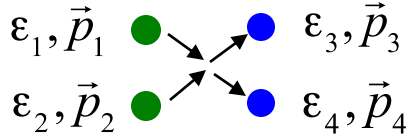
Three-magnon splitting



Three-magnon confluence



Four-magnon scattering



Energy and **momentum conservation** need to be fulfilled for all these processes

P. Krivosik, C. Patton, Phys. Rev. B **82**, 184428 (2010)

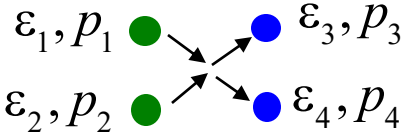
Nonlinear magnonic effects: examples

- **Nonlinear shifts**
  -Nonlinear frequency shift (for fixed wave vector)
  -Nonlinear wave vector shift (for fixed frequency)

"One mode is changed because of its high amplitude"

- **Magnon-magnon interactions**
  -Magnon scattering
  -Magnon instabilities

"Several modes interact because of high amplitudes"



"Four magnon scattering"

M. Mohseni, *et al*. Phys. Rev. Lett., **126**, 097202, (2021).

- **Parametric instabilities**
  -Parallel parametric amplification

"High dynamic external fields couples to the dynamic *m*-components"

T. Brächer, P. Pirro, B. Hillebrands. Physics Reports **699**, 1–34 (2017).

Nonlinear shift in the Hamiltonian formulation

Simplest form of magnon nonlinearity:
If only a single magnon mode b_k is significantly excited, an **increase of its amplitude changes the frequency or the wavevector** of the spin wave:

Nonlinear shift coefficient

Situation used to construct the nonlinear directional coupler

$$f(|b_k|^2) = f_{lin} + N_k \cdot |b_k|^2$$

(wave vector *k* is fixed in the experiment)

$$k(|b_k|^2) = k_{lin} + \frac{N_k}{v_g} \cdot |b_k|^2$$

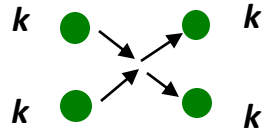
(frequency *f* is fixed in the experiment)

Group velocity

Similar to change of refractive index in nonlinear optics

Q. Wang et al., *Nature Electronics* **43**, 26400 (2020).

Nonlinear shift N_k of a spin-wave mode is given by the "nonlinear four-magnon self-interaction"



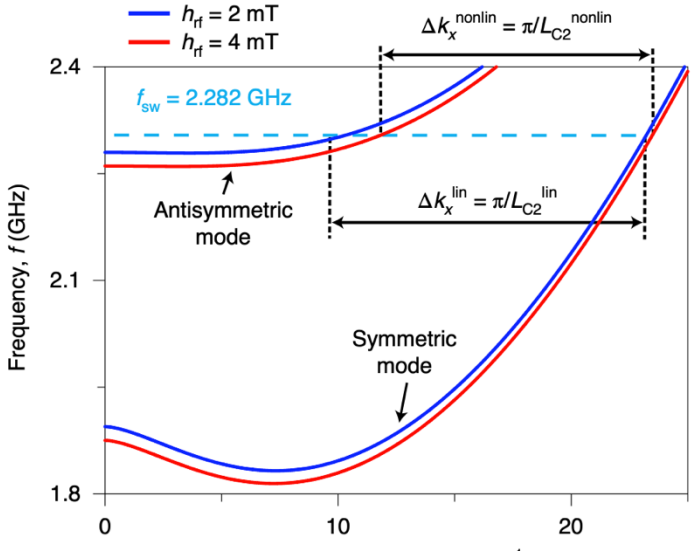
"Mode scatters with itself"

$$N_k = X_{kk,kk}$$

Nonlinear wave vector shift: nonlinear directional coupler

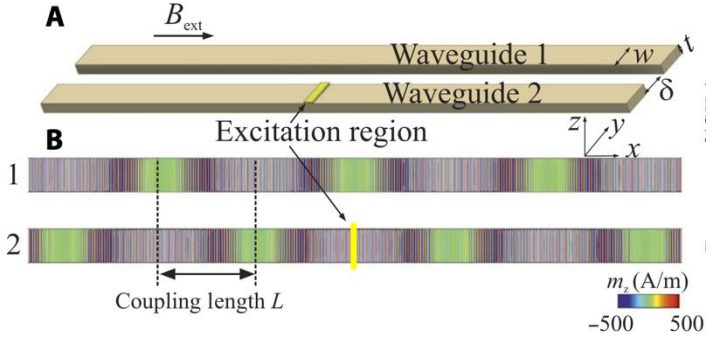
Nonlinear directional coupler: *fixed* SW *frequency* is used

$N_k = X_{kk,kk}$ is negative in this case
(in-plane magnetized, $M_{\text{eff}} > 0$)



$$f(|c_k|^2) = f_{lin} + N_k \cdot |c_k|^2$$

$$k(|b_k|^2) = k_{lin} + \frac{N_k}{v_g} \cdot |b_k|^2$$



Coupling length L_C changes due to nonlinearity:

$$L_c = \frac{\pi}{\Delta k(|b_k|^2)}$$

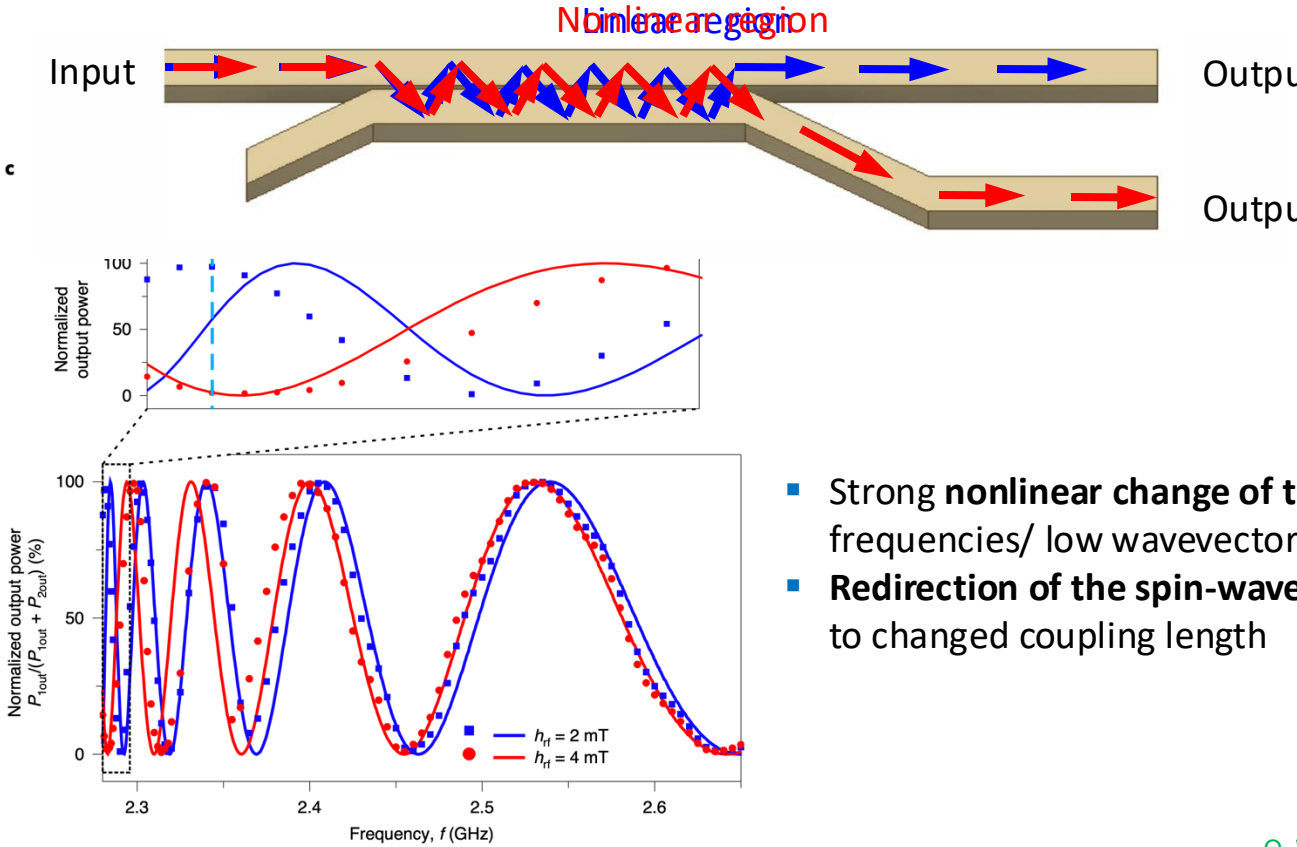
⇒ **High nonlinearity in wavevector** for **low group velociti**es

⇒ Trade-off between needed SW amplitudes and speed of nonlinear devices

Q. Wang, *et al*. Science Advances, **4**, e1701517, (2018).

Q. Wang,, *et al.*, *Nature Electronics* **3**, 765–774, (2020).

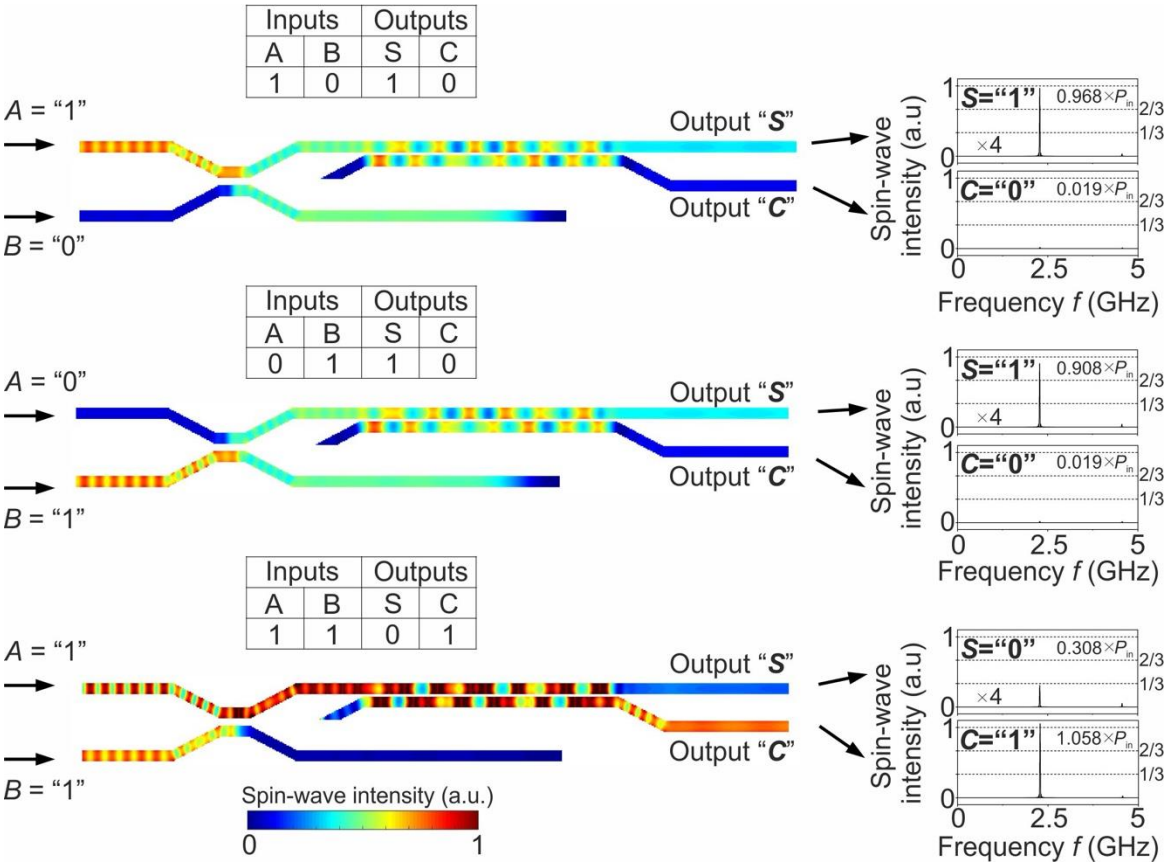
Nonlinear directional coupler



- Strong **nonlinear change of the coupling length** for low frequencies/ low wavevectors(low group velocities)
- **Redirection of the spin-wave signal** to other output due to changed coupling length

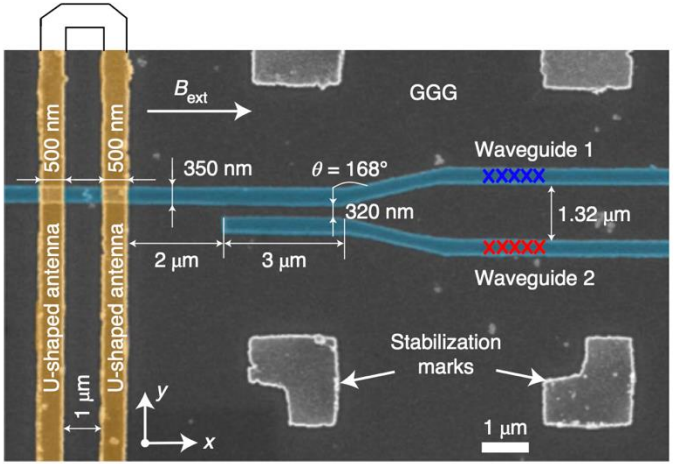
Q. Wang,, *et al.*, *Nature Electronics* **3**, 765–774, (2020).

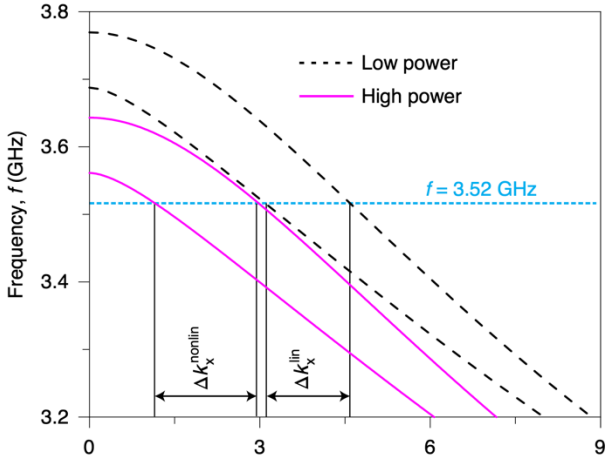
Working principle

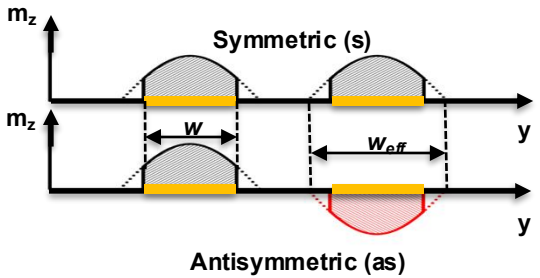


Nonlinear spin-wave directional coupler: experiment

Nanoscaled directional coupler (YIG)

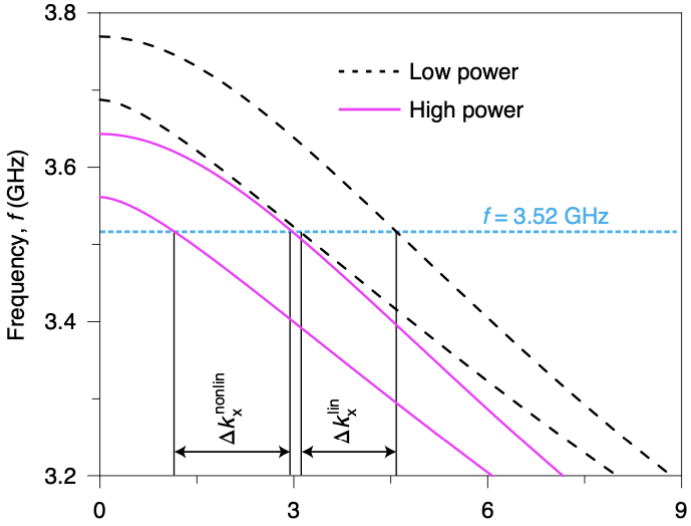






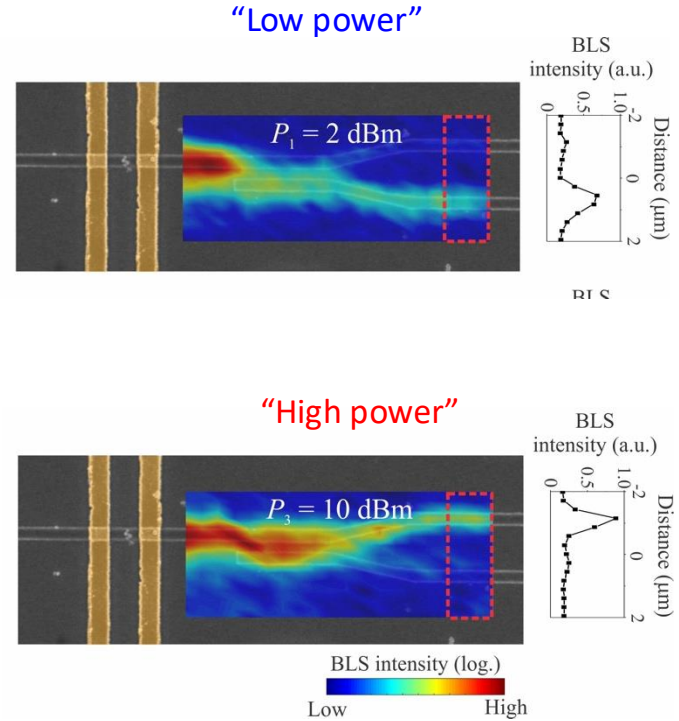
Q. Wang, PP, *et al., Nature Electronics* ***3****, 765–774, (2020).*

Nonlinear directional coupler: experiment



$$\Delta k^{nonlinear} > \Delta k^{linear}$$

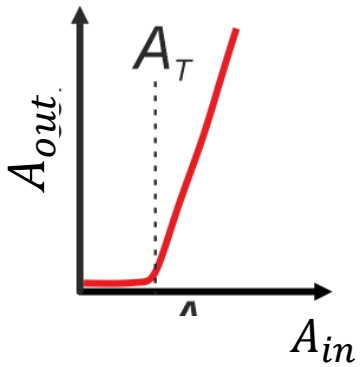
$$\Rightarrow L_c^{nonlinear} < L_C^{linear}$$



Microfocused Brillouin light scattering measurements

Q. Wang, *et al.*, *Nature Electronics* **3**, 765–774, (2020).

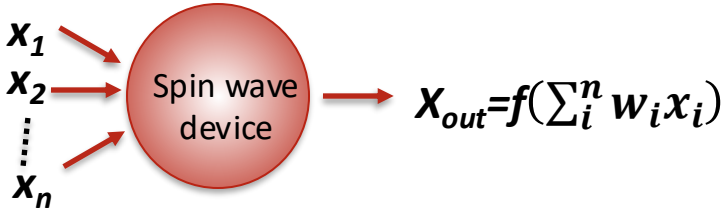
Neuromorphic computing: magnonics?



Activation function for neuron

How to shape **complex transfer/activation functions *f*** using only spin waves?

=>Spin-wave nonlinearity



Input spin waves

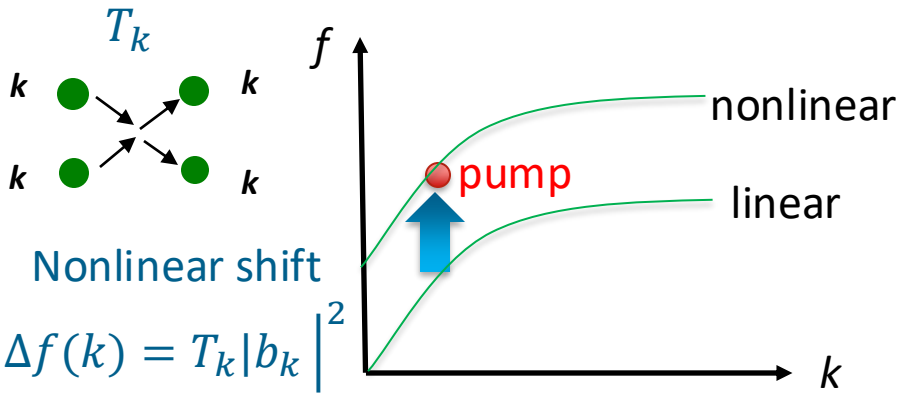
Output spin waves

Nonlinear magnon excitation

General idea: create a magnon **source/amplifier (active element)** which is very nonlinear in magnon output vs. magnon/RF input

General ingredients of nonlinear magnon excitation approach:

- **Coherent driving field "pump"** (RF, spin torque auto-oscillator) which is **off-resonant** for the **linear magnonic system**
- Magnonic system with **strong nonlinear shift** T_k based on magnon-magnon coupling



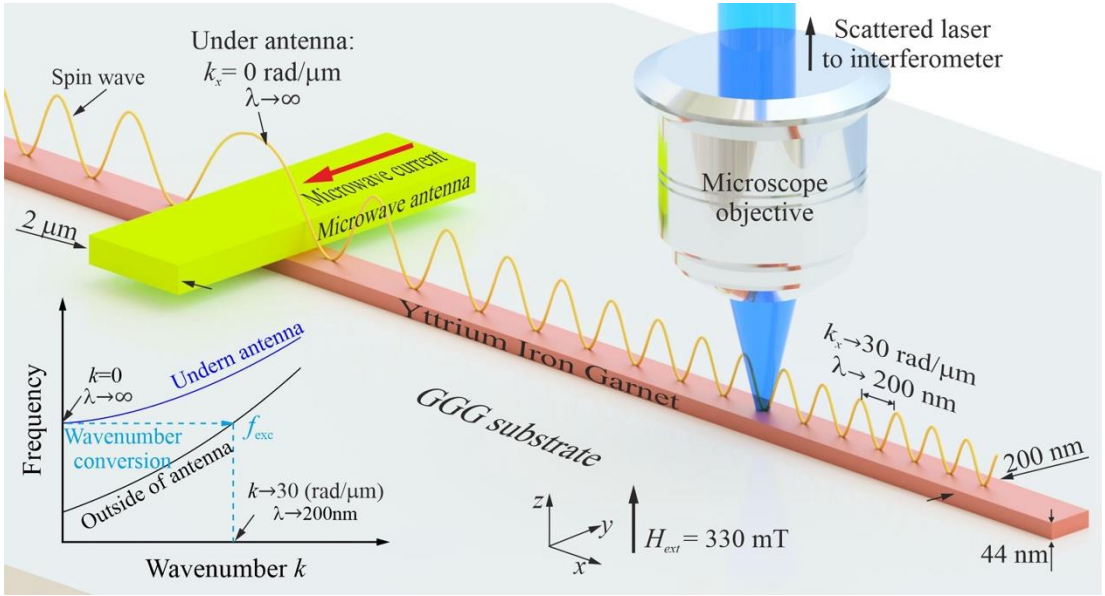
- Use **nonlinear shift** provided
  - by forced oscillations
  - incoming magnons

  to **make** the **pump** excitation **resonant**

=> Nonlinear photon-magnon coupling

Nonlinear magnon excitation

Nonlinear magnonic system A: YIG waveguide in Forward Volume Geometry

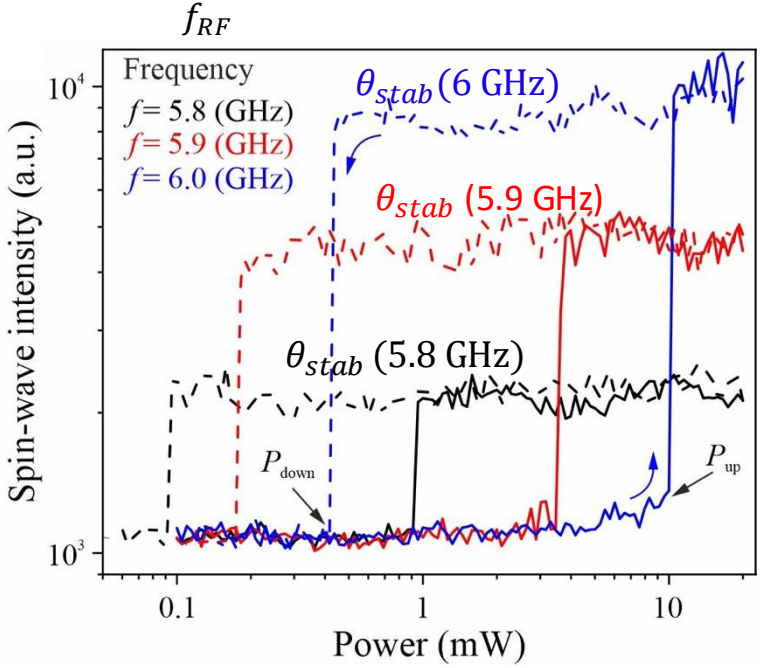


- Pure YIG (out-of-plane saturated): Positive nonlinear shift coefficient T_k ($M_{\text{eff}} > 0$)
- Large antenna that excites only $k \approx 0$ in the linear case

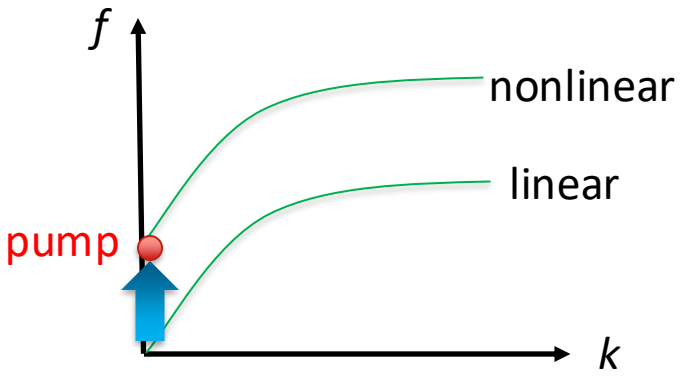
Q. Wang, PP, *et al.*, Sci. Adv. **9**, eadg4609 (2023).

Q. Wang, PP, et al., *All-Magnonic Repeater Based on Bistability*, Nat. Commun. **15**, 7577 (2024).

Nonlinear magnon excitation



Output spin-wave intensity is **independent** of the input power



Nonlinearly shifted resonance frequency:

$$f(|b_k|^2) = f_{lin} + T_k \cdot |b_k|^2 \qquad |b_k|^2 = 1 - \cos^2(\theta)$$

Condition of stable high amplitude state:

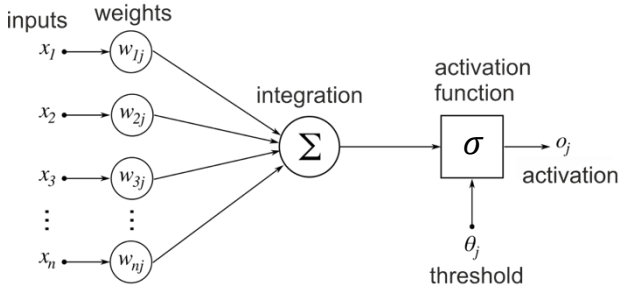
$$\Rightarrow \cos(\theta_{stab}) = 1 - (f_{RF} - f_0)/T_k$$

Q. Wang, PP, et al., Sci. Adv. **9**, eadg4609 (2023).

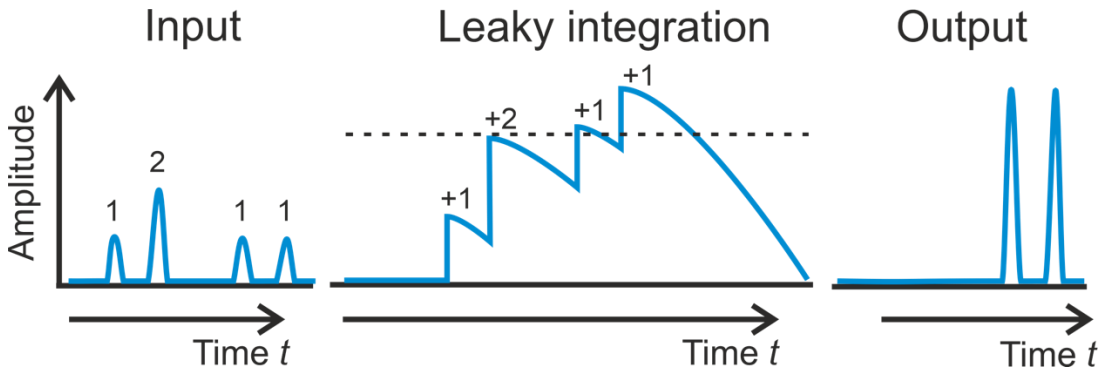
(Leaky) integrate-and-fire neurons

Excitability/ Neuron activation:

$$o_j = \sigma_j\left(\Sigma x_i w_{ij} + \theta_j\right)$$



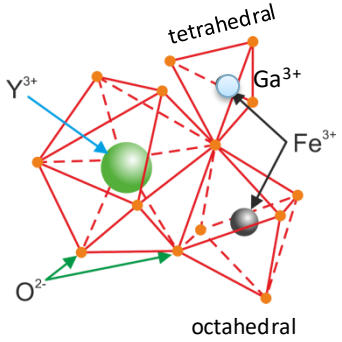
- Nonlinear activation function σ_j
- Variable neuron threshold θ_j
- Integration functionality $\Sigma x_i w_{ij}$
  - Over inputs x_i from different neurons
  - Over inputs $x_i(t)$ over time (spikes)
- Additional properties of neuron output
  - Leakyness: $o_j(t)$ decays over time
  - Cascadibility

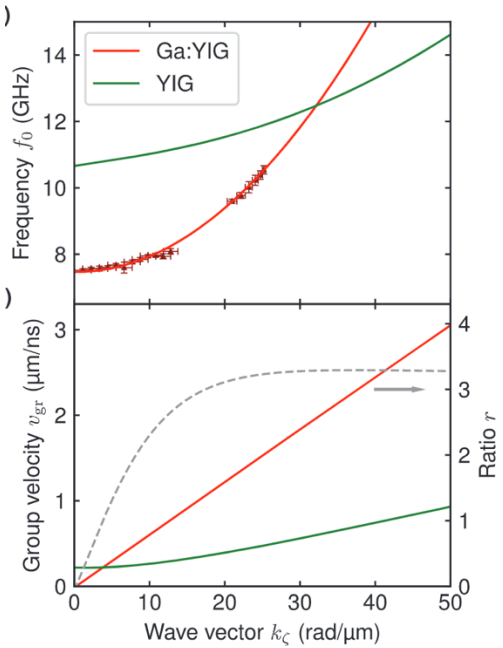


=> Integration over several pulses in time requires **pule-to-pulse interaction**

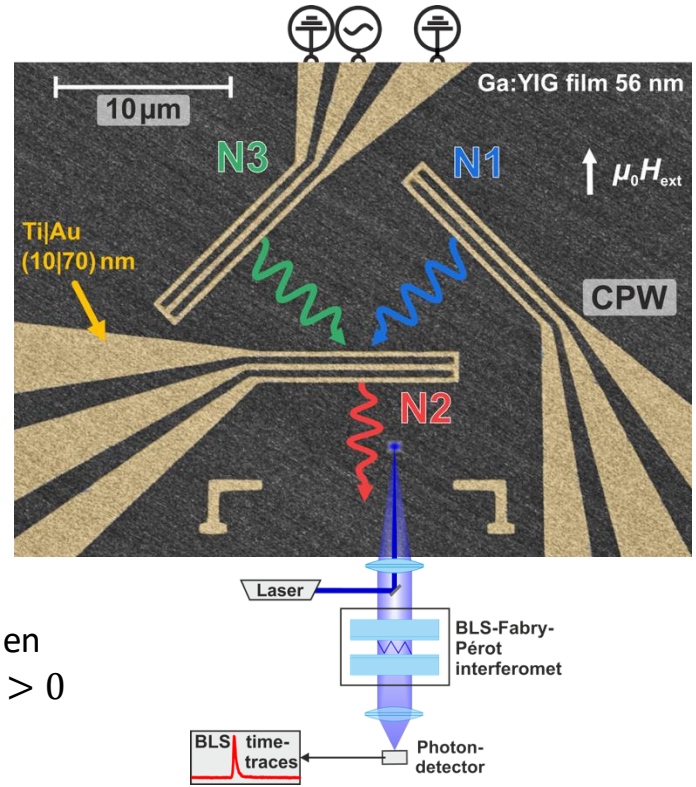
Multi neuron structure based on Ga:YIG

Ga substituted YIG





Multi neuron structure



- Uniaxial out-of-plane anisotropy $\mu_0 H_{u1} = 94.1\ \mathrm{mT}$
- Film thickness $t = 59\ \mathrm{nm}$

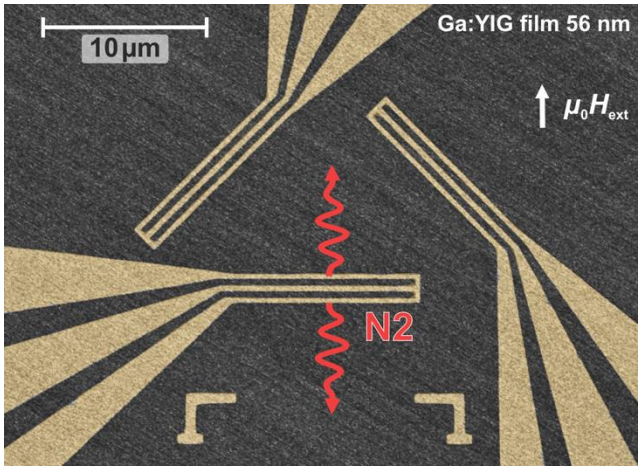
$$\mu_0 M_S \approx 20\ \mathrm{mT}$$
$$\mu_0 M_S^{eff} \approx -74\ \mathrm{mT}$$

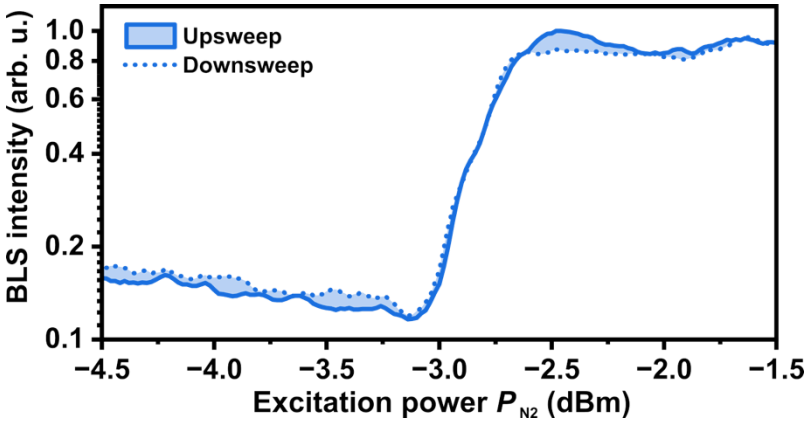
Ga:YIG shows positive nonlinear shift when saturated in the film plane: $T_k \propto -M_{eff} > 0$

See also T. Böttcher *et al.*, Appl. Phys. Lett. **120**, 102401 (2022)
D. Breitbach, *et al.*, Appl. Phys. Lett. **124**, 092405 (2024)

Nonlinear excitation function

Continuous excitation of **N2** at 1.69 GHz

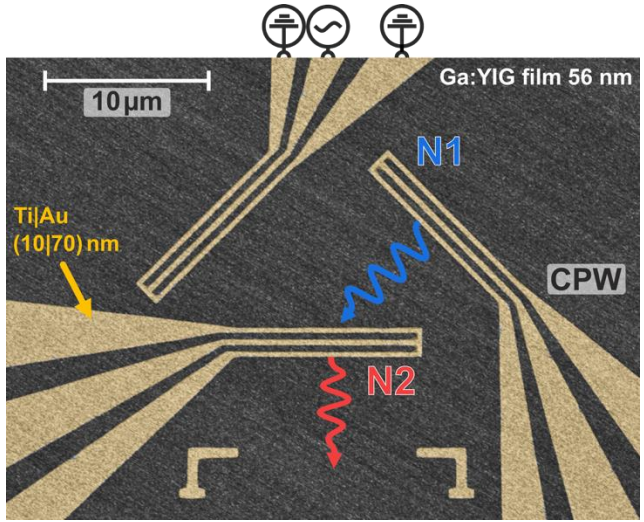


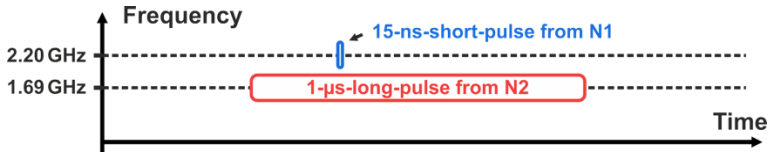


- Shift of the resonance towards excitation frequency leads to **nonlinear power-dependency** of the excited SW signal

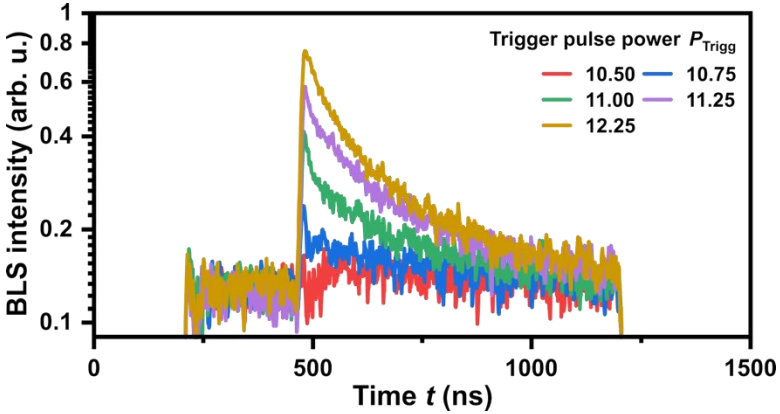
All-magnonic neurons for analog artificial neural networks
D. Breitbach, PP et al., Arxiv **2509.18321**

Nonlinear activation function σ_j

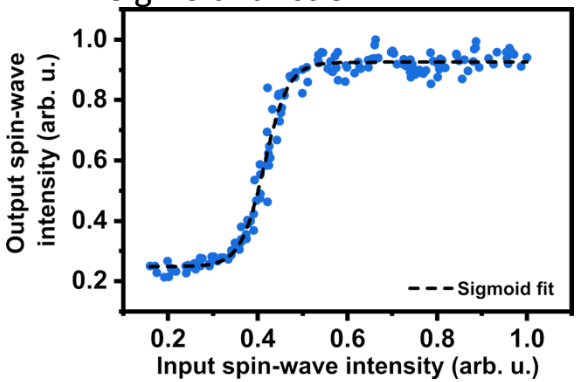




Sweeping intensity of **incoming** stimulus

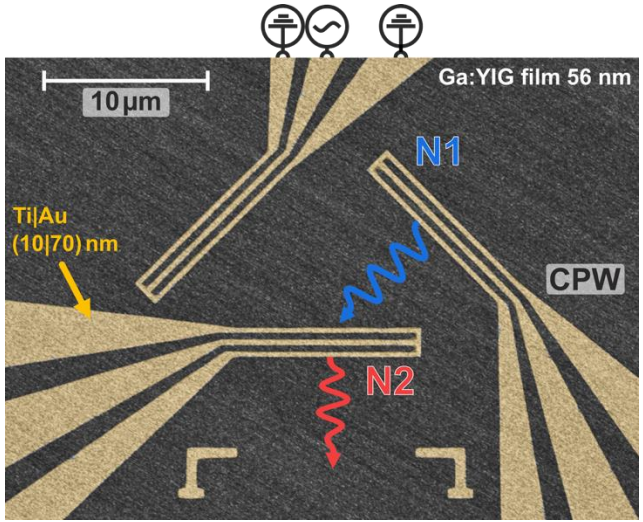


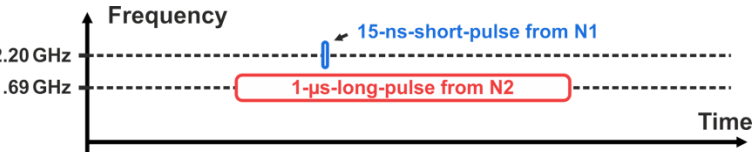
Sigmoid function

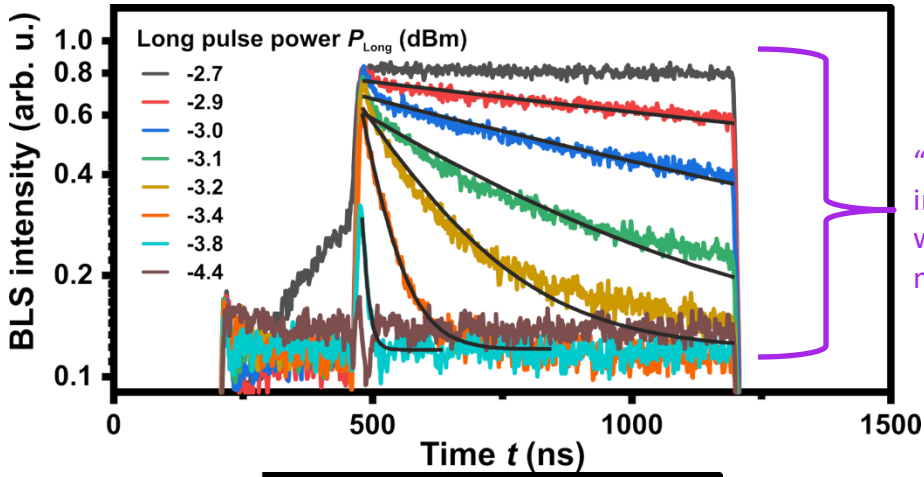


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D. Breitbach, PP et al., Arxiv **2509.18321**

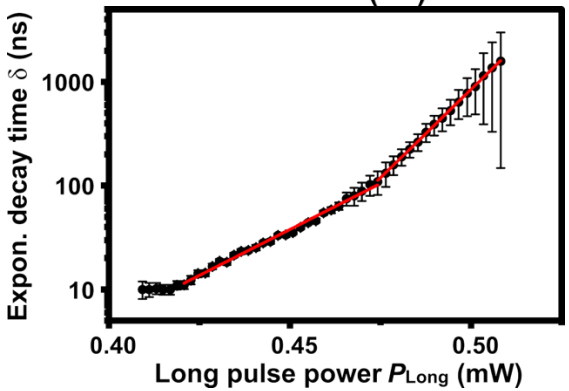
Neuron triggering







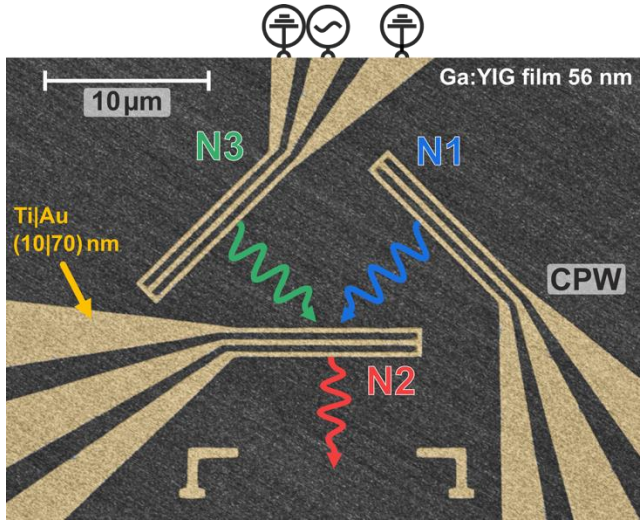
"Leaky integrator" with tunable memory time

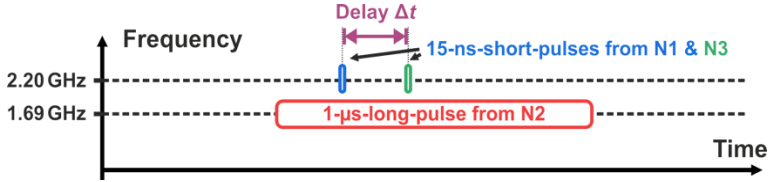


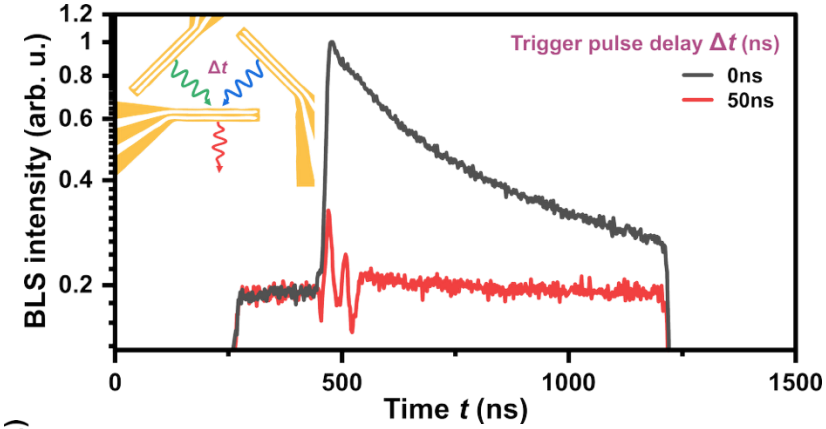
Memory time tunable by two orders of magnitude

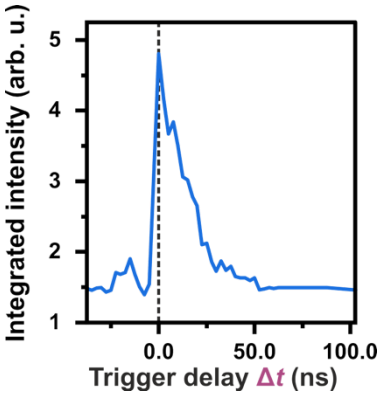
All-magnonic neurons for analog artificial neural networks
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Multi-Neuron Triggering $N_1 + N_3 \rightarrow N_2$









- Depending on the input delay **N1** & **N3**, a different output by **N2** is observed
- Neuron **activation only** when **input** signals are **correlated**

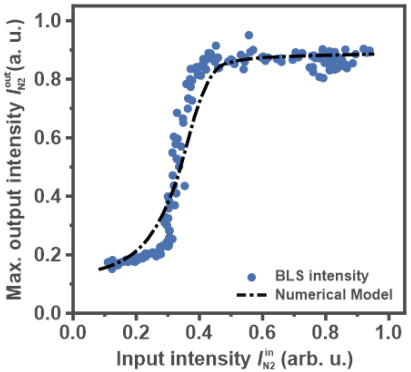
→ **AND Gate for "Correlation test", can be used for stochastic computing**

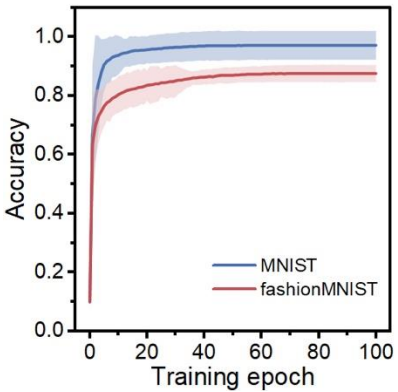
Magnonic neuron application in neural networks

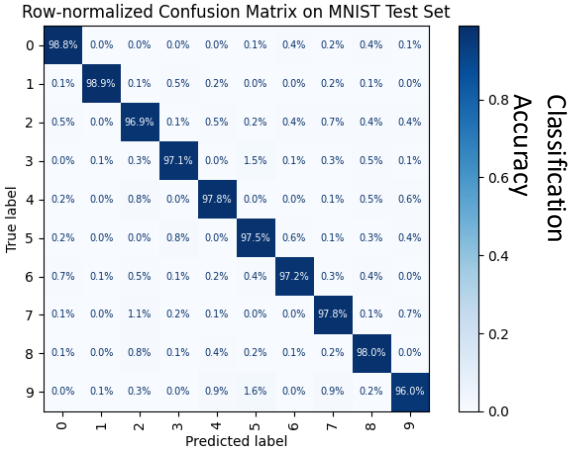
Hardware restrictions

- Custom activation function
- Max. **10x10** fully connected neurons → sparse
- Weighting by **linear SW interference**: $|w_{\max}| = 1$
- Interference is in amplitude, while neurons are triggered "by intensity"
  → Negative amplitudes also activate neurons

- A hardware feasible convolutional neural network adhering to these restrictions achieves:
- $(97.15 \pm 0.016)\%$ accuracy on MNIST
- $(87.60 \pm 0.01)\%$ accuracy on fashionMNIST

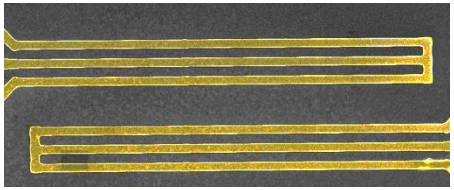




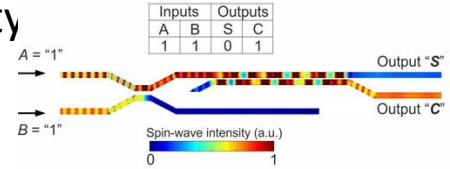


All-magnonic neurons for analog artificial neural networks
D. Breitbach, PP et al., Arxiv **2509.18321**

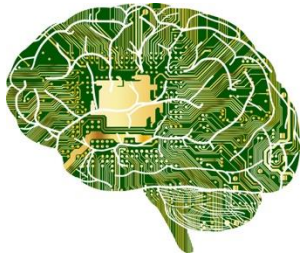
Conclusion

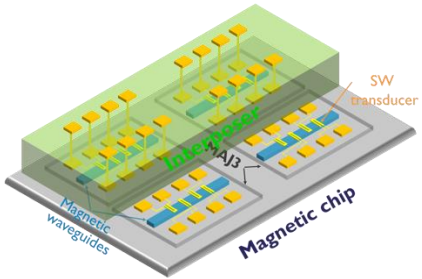


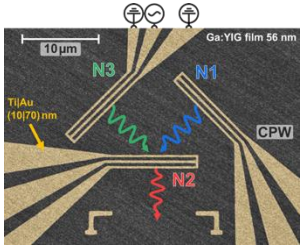
- Spin waves are interesting candidates for wave-based
  - signal processing in the GHz range
  - computing with low power, intrinsic nonlinearity, scalability



- Prototypes of micro- and nanoscaled spin-wave logic elements can be fabricated, full spin waves circuits with CMOS-integration are under investigation

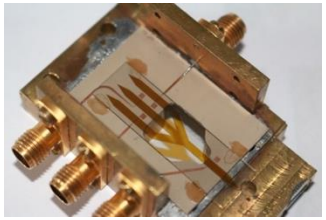






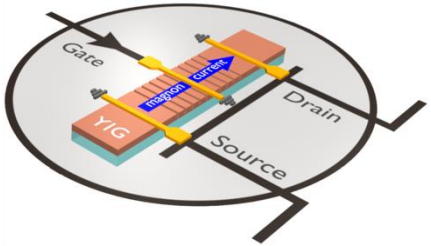
Examples of spin-wave device architectures

Majority Gate



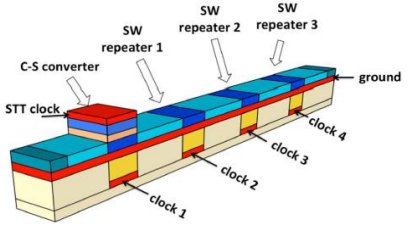
Fischer et al., APL 110, 152401 (2017)

Magnon Transistor



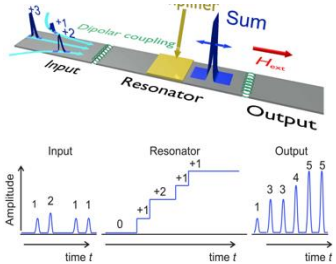
Chumak et al., Nat. Commun. 5, 4700 (2014)

Non-volatile clocked spin wave nanomagnet pipelines



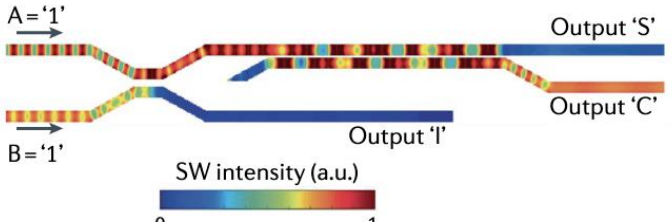
S. Dutta, A. Naeemi (Georgia Institute of Technology, USA)

Analog Magnon adder



T. Brächer, P. Pirro, J. Appl. Phys. **124**, 152119 (2018)

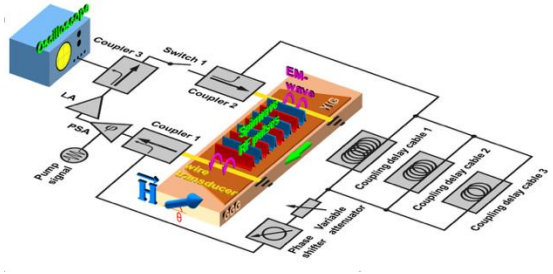
Magnonic half-adder



Q. Wang et al., Nat Electron **3**, 765 (2020).

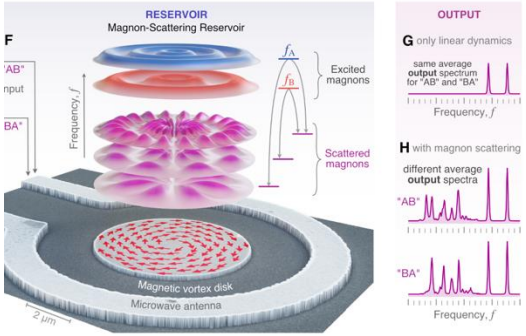
Examples of spin-wave device architectures

Spinwave Ising machine

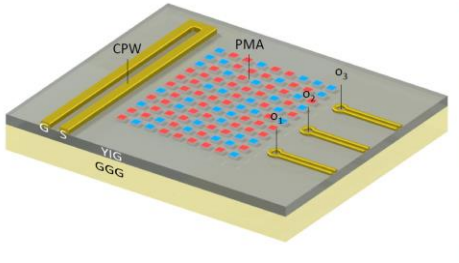


A. Litvinenko, et al. Comm. Phys. 6:227 (2023)

Pattern recognition

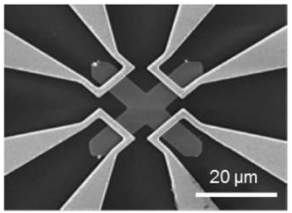


L. Körber, et al., Nat. Commun. **14**, 3954 (2023).



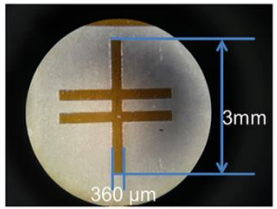
Á. Papp, W. Porod, G. Csaba, Nat. Commun. **12**, 6422 (2021)

Holographic Memory



F. Gertz et al., IEEE Magn. Lett. 7, 3200204 (2016)

Factorization Problem



Y. Khivintsev et a., JAP 120, 123901 (2016)

Neuromorphic networks

