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AG MAGNETISMUS
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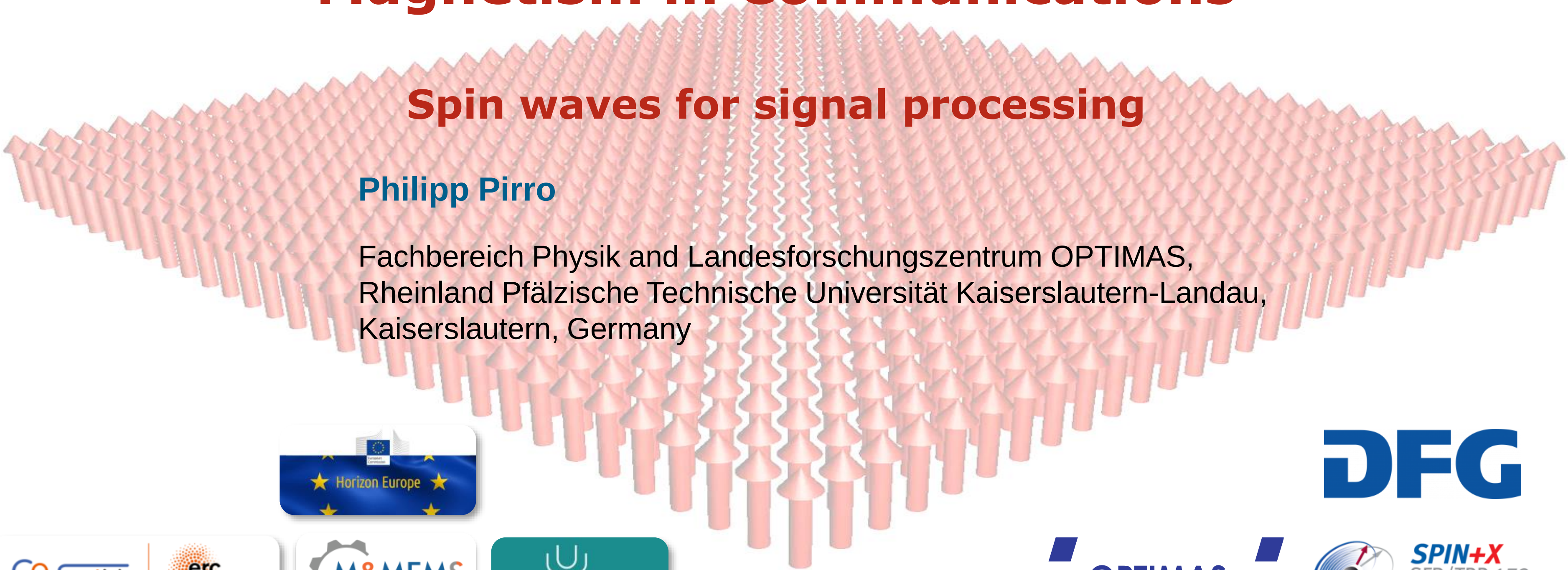

Magnetism in Communications

Spin waves for signal processing

Philipp Pirro

Fachbereich Physik and Landesforschungszentrum OPTIMAS,
Rheinland Pfälzische Technische Universität Kaiserslautern-Landau,
Kaiserslautern, Germany

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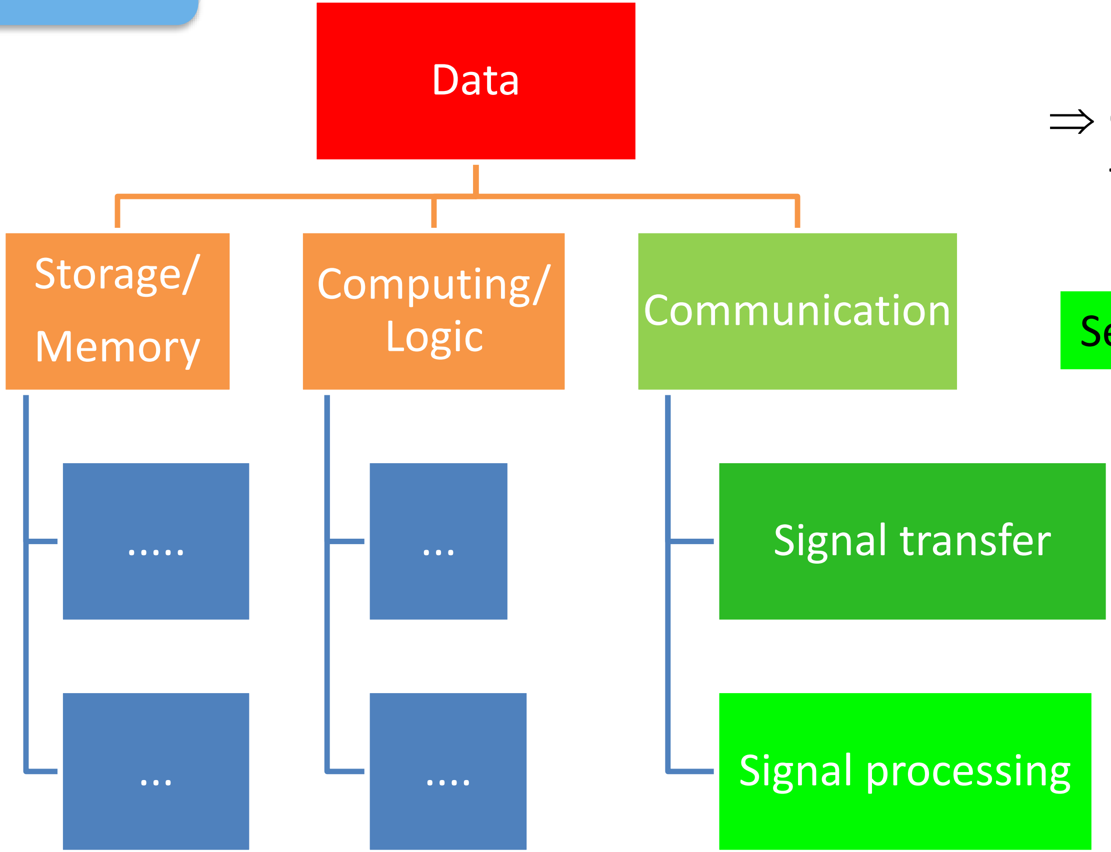
Outline

- **Introduction: Data, Communication, Waves …**
- **Spin waves for communication**
  - **Linear devices**
    - Filters, phase- and time delay units
  - **Nonlinear devices**
    - Limiter, signal-to-noise enhancement

Physical/technical side



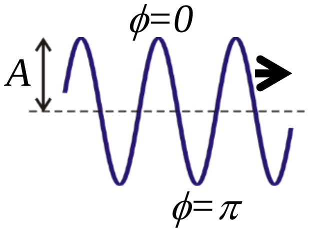
⇒ Communication: How to transfer data from A to B

⇒ 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 …)



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

Wave equation

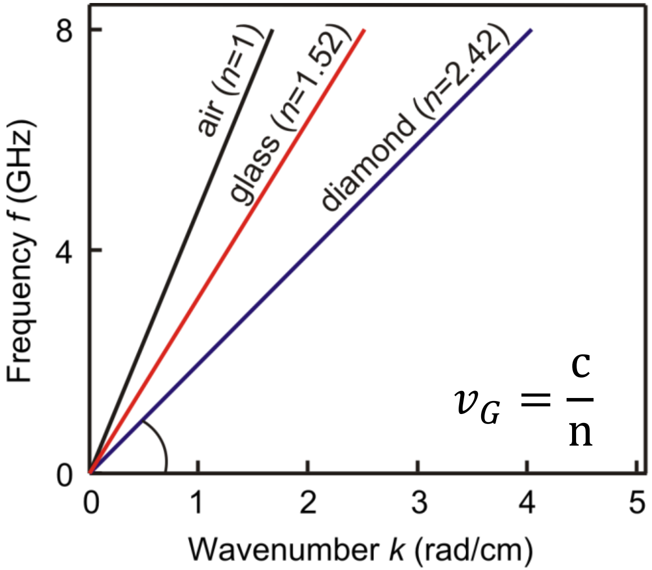
Interference phenomena

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



$$v_G = \frac{c}{n}$$

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 $\boldsymbol{t}$** of the signal is given by the group velocity $\boldsymbol{v_G}$ of the wave.
2. **Data transfer rate $\boldsymbol{R}$** of the communication is given by the **instantaneous bandwidth Δf** of the signal and the signal processing devices:

$$\boldsymbol{R \propto \Delta \mathrm{f}}$$

=> high bandwidth Δf needed for high speed data

Electro-magnetic waves as signal carrier

Visible light in optical fibers

λ_{em} = 1064 nm ($f \approx 280\ \mathrm{THz}$)

- High bandwidth
- Low attenuation

MAGNETISM?

(also still used: MHz-GHz electromagnetic waves in cables)

Radio-frequencies /Microwaves

f=30 MHz- 300 GHz / λ_{em} =10 km- 1mm

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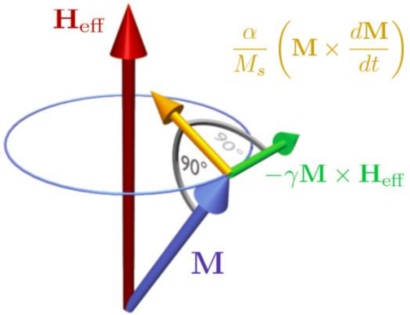
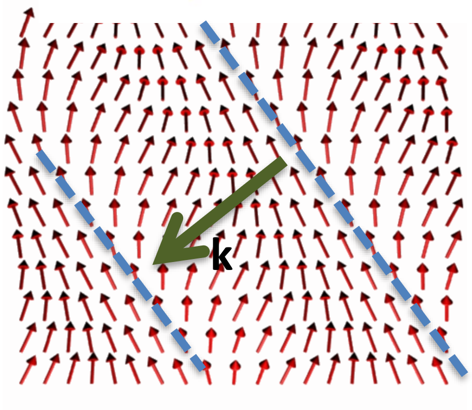
- Free-space propagation
  => wireless & mobile communications

Magnetization dynamics



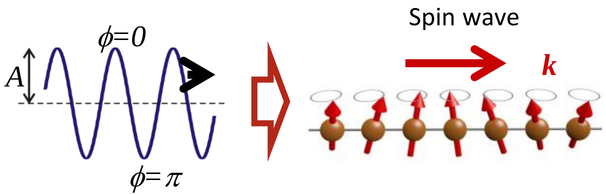
- Coherent coupled oscillations of magnetic moments
- Described by the Landau-Lifshitz-Gilbert equation



$\Rightarrow$ Fundamentals: See the two lectures of B. Hillebrands last Wednesday

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

Wave-based data processing



- Coherent propagation
- Interference effects and logic
- Intrinsic nonlinearity
- Scalability: down to nanometer wavelength
- Frequency multiplexing
- **Typical frequencies: GHz**

Ferromagnetic resonance of in-plane magnetized film:

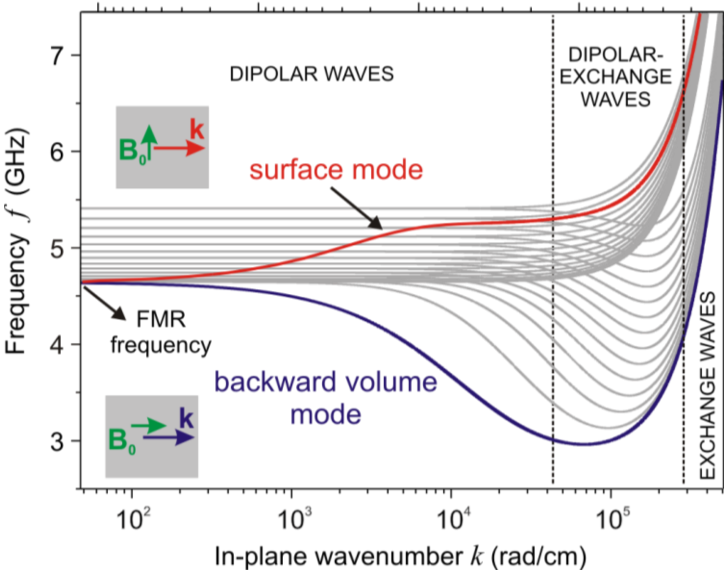
$$f_{FMR} = \gamma \sqrt{\mu_0 H \, (\mu_0 H + \mu_0 M_s)}$$

(effective) magnetic field saturation magnetisation

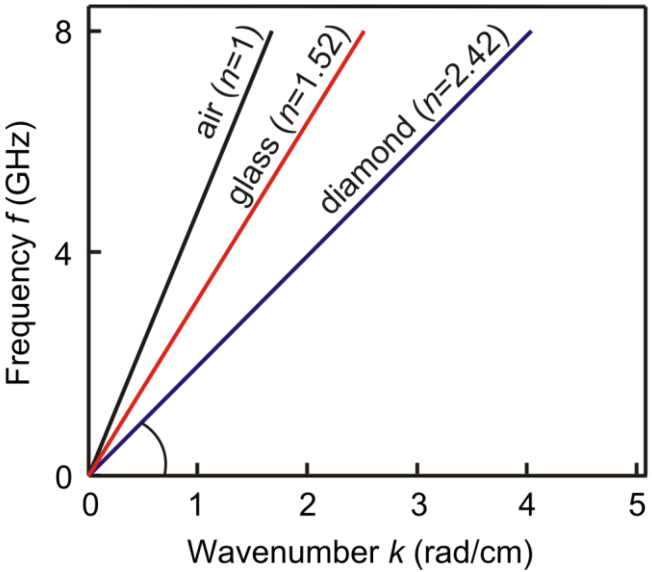
$$\gamma \approx 28 \frac{\text{GHz}}{\text{T}}, \mu_0 H = 0 - 1\ \text{T}, \mu_0 M_s = 0.175\ \text{T (YIG)} - 2.2\ \text{T (Fe)}$$

Magnon versus photon dispersion relations

Magnons in a YIG film



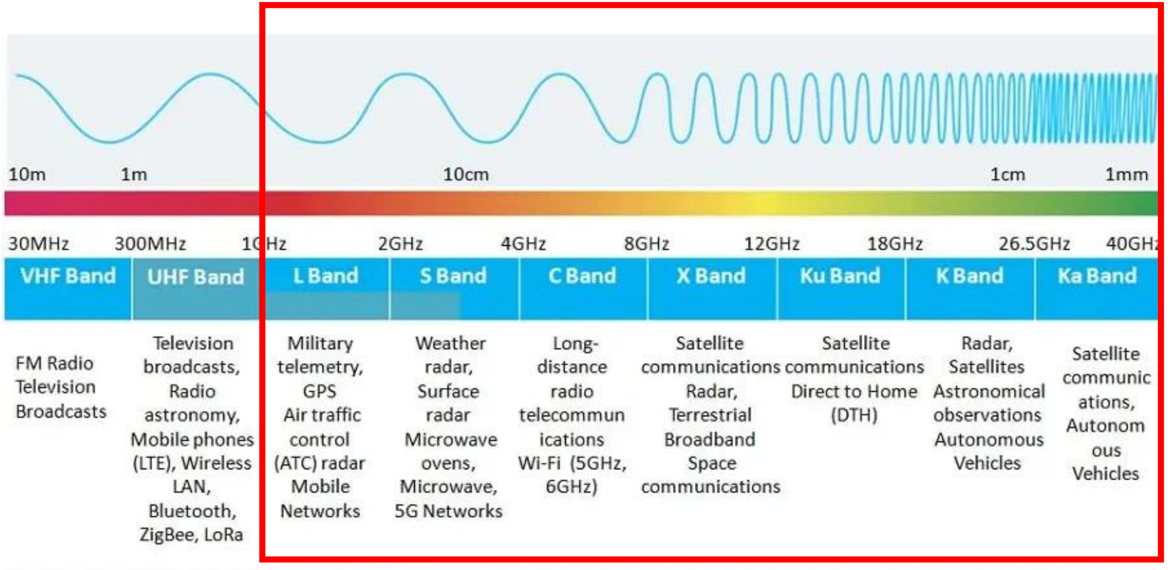
Photons in different media



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

- **Miniaturization** is facilitated: RF devices based on magnons are much smaller
- Magnons travel much **slower** than photons: **RF time** and **phase delay** possible in microstructures

RF applications in different frequency bands



VHF Band	UHF Band	L Band	S Band	C Band	X Band	Ku Band	K Band	Ka Band
FM Radio Television Broadcasts	Television broadcasts, Radio astronomy, Mobile phones (LTE), Wireless LAN, Bluetooth, ZigBee, LoRa	Military telemetry, GPS Air traffic control (ATC) radar Mobile Networks	Weather radar, Surface radar Microwave ovens, Microwave, 5G Networks	Long-distance radio telecommunications Wi-Fi (5GHz, 6GHz)	Satellite communications Radar, Terrestrial Broadband Space communications	Satellite communications Direct to Home (DTH)	Radar, Satellites Astronomical observations Autonomous Vehicles	Satellite communications, Autonomous Vehicles

Frequency range mainly targeted by magnonic applications:
1-60 GHz

Band	Name	Frequency	Wavelength	Applications
ELF	Extremely Low Frequency	3 KHz to 30 KHz	100 km to 10 km	Maritime radio, navigation
LF	Low Frequency	30 KHz to 300 KHz	10 km to 1 km	Maritime radio, navigation
MF	Medium Frequency	300 KHz to 3 MHz	1 km to 100 m	AM radio, Aviation radio, navigation
HF	High Frequency	3 MHz to 30 MHz	100 m to 10 m	Amateur radio, NFC, aviation, weather broadcast
VHF	Very High Frequency	30 MHz to 300 MHz	10 m to 1 m	FM radio, VHF television
UHF	Ultra High Frequency	300 MHz to 3 GHz	1 m to 100 mm	Mobile, Wi-Fi, GPS, 4G, UHF television
SHF	Super High Frequency	3 GHz to 30 GHz	100 mm to 10 mm	Satellite, 5G, Wi-Fi, Radio astronomy
EHF	Extremely High Frequency	30 GHz to 300 GHz	10 mm to 1 mm	

Magnonic systems for signal processing and computing

Linear systems

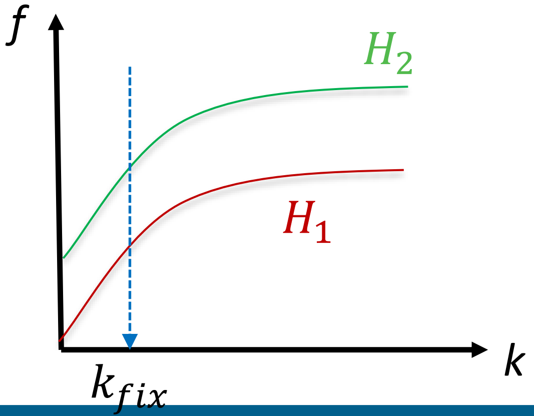
Linear SW propagation
- RF phase shifter
- RF delay lines
- RF filters, isolators

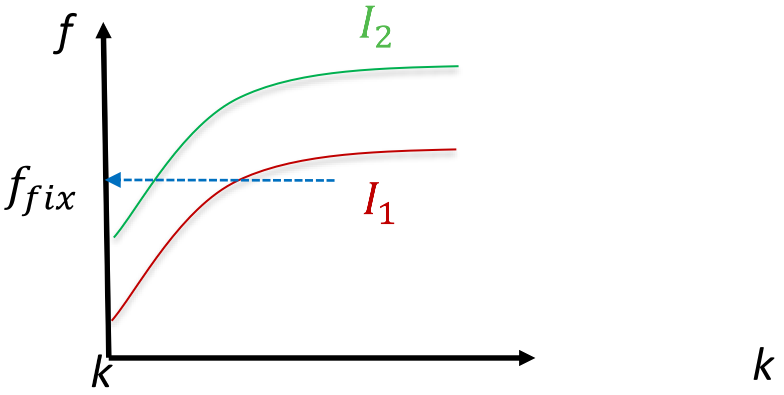
tunable via the applied magnetic fields (H_1, H_2)

Nonlinear magnon systems

Nonlinear SW propagation
- Half-adder (AND gate)
- Ring resonators
- Magnon Transistor

tunable via the magnon intensity (I_1 ,I_2)





Linear (Magnonic) devices for radio-frequency applications

Linear systems

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

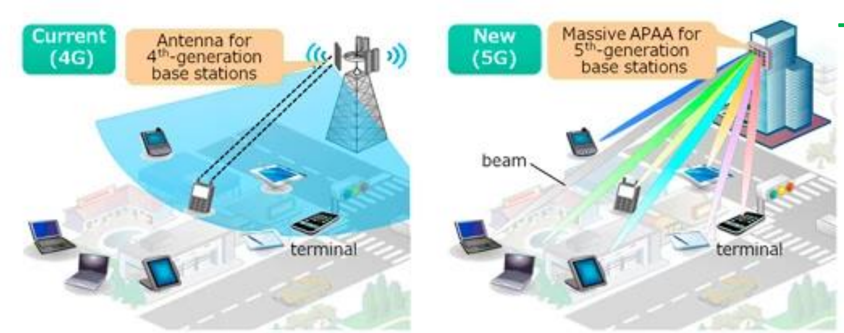
- **Phase delay unit**
  shifts (only) the phase ϕ of the signal by a shift $\Delta\phi$ (which should be constant over the bandwidth Δf)

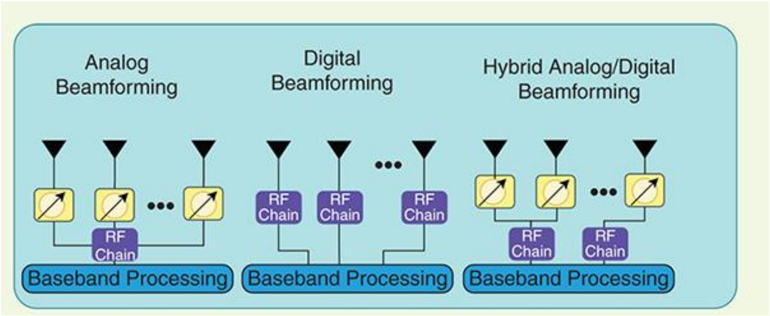
- **Time delay unit**
  delays a signal by a time delay Δt (all frequency components in the bandwidth should have the same delay to avoid signal distortion)

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

Applications of RF delay units

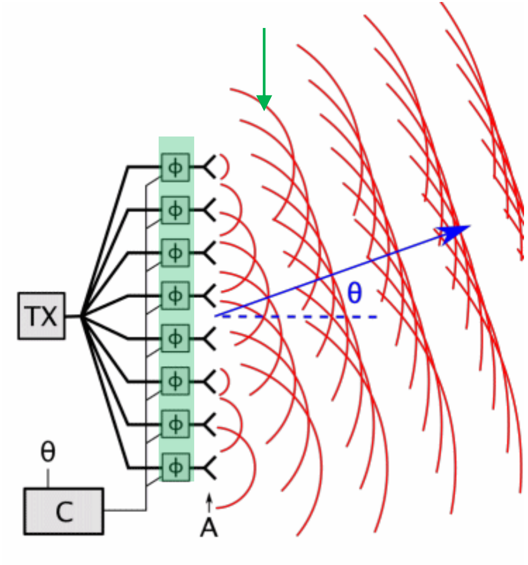
Tunable Directional antennas, e.g. for massive MIMO (“Multiple Input Multiple Output”)



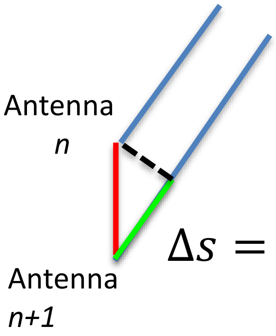


IEEE signal processing

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



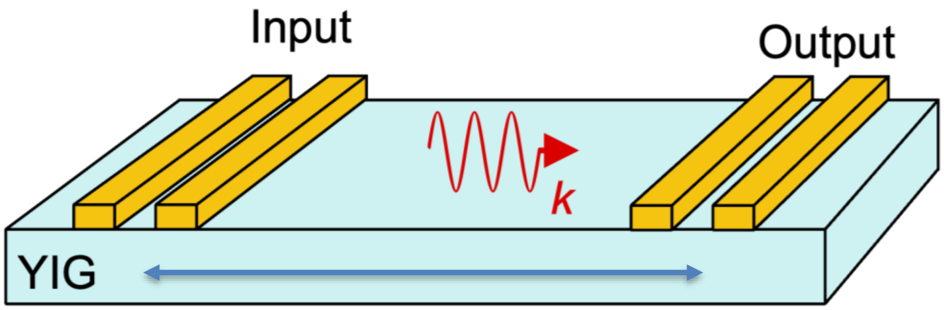
Many RF antennas with different time delays



$$\Delta s = v_g \cdot \Delta t$$

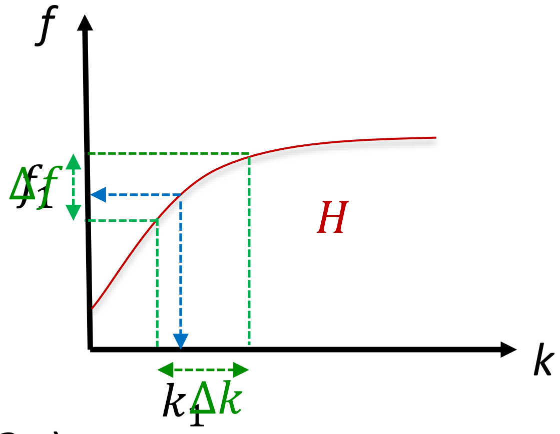
1. “Stationary” magnonic devices

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.



Propagation distance d

Dispersion relation (schematic)



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)

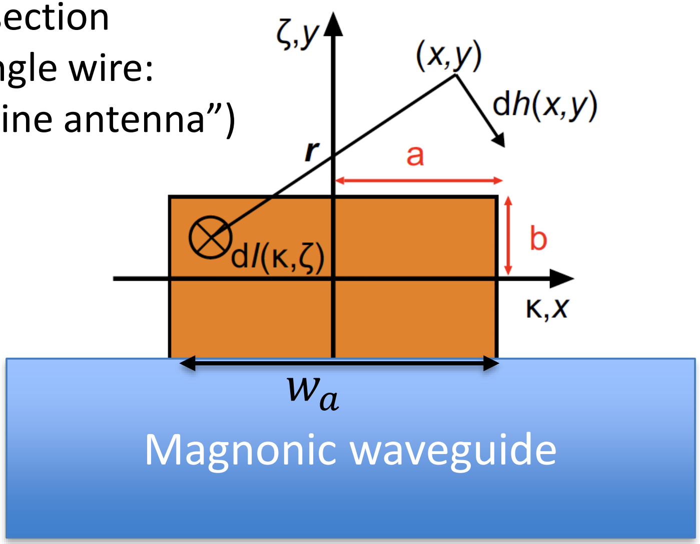
Filter function? BandwidthΔf ? Efficiency of energy transduction?

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")

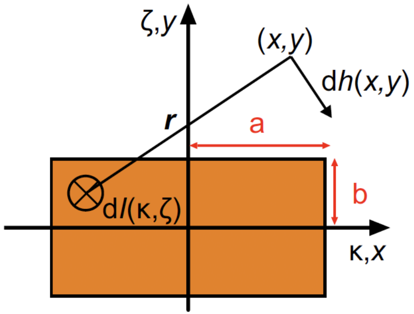


In z direction, the wire is usually considered as infinitely extended

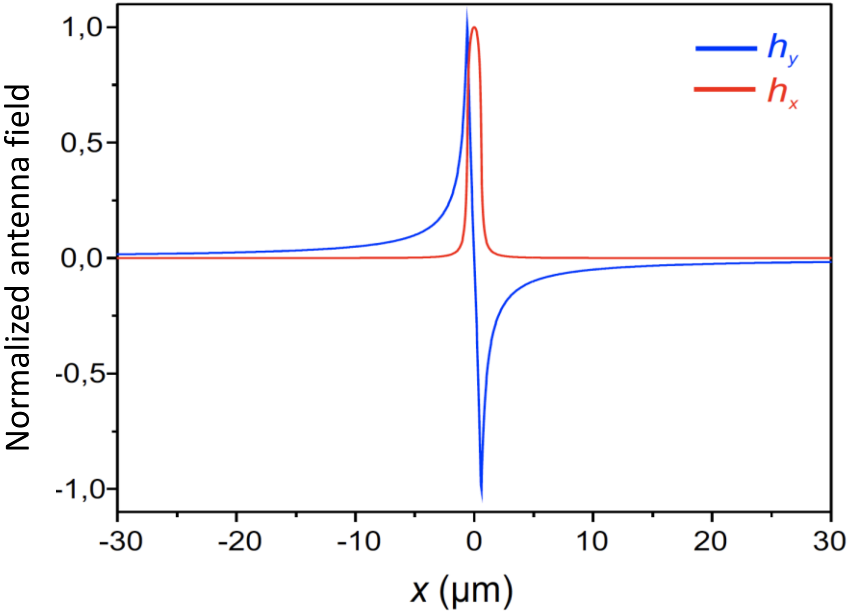
Conductor (orange): Au, Cu, Al, superconductor…

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:

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

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

width: $2a = 1.15\ \mu m$,

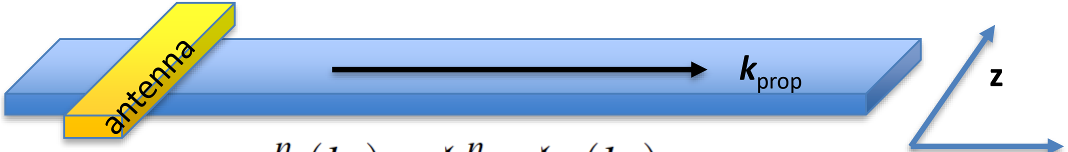
thickness: $2b = 0.22\ \mu\mathrm{m}$

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)



$$m_{\pm}^{n}(k_x) \propto \mathfrak{h}_{z,y}^{n} \cdot \mathfrak{h}_y(k_x).$$

Waveguide mode dependent factor

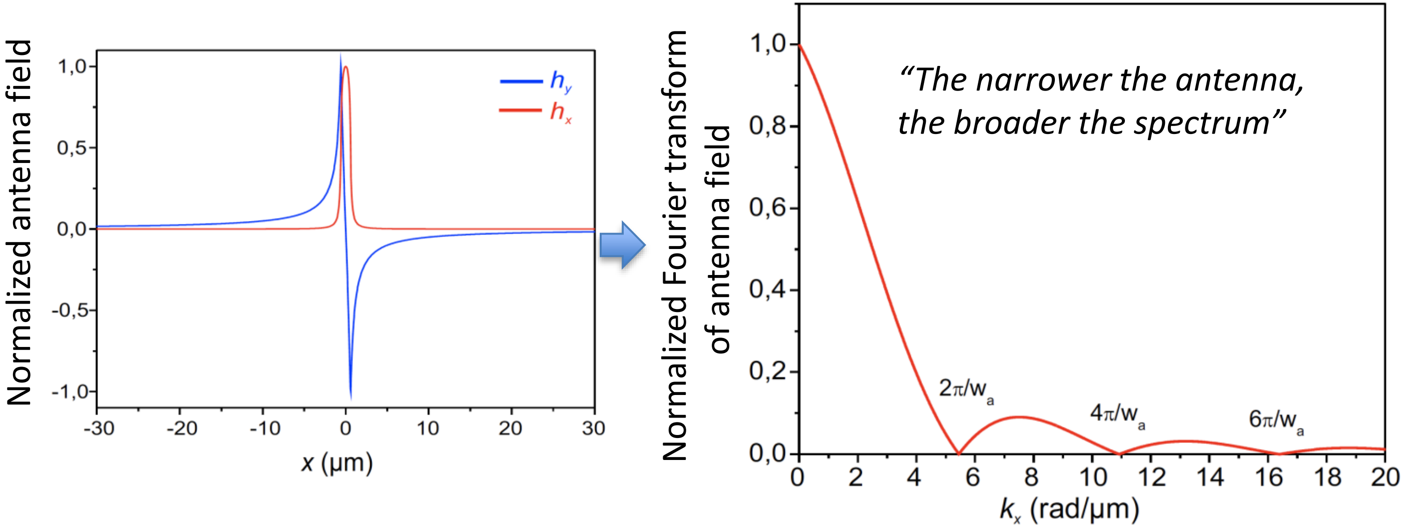
Fourier transform of the excitation field

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

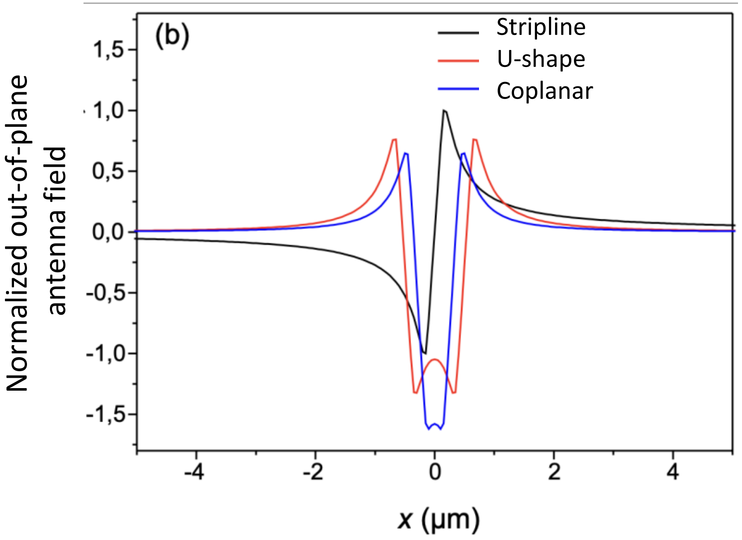
- Spatial extend of the antenna field defines the “effective linear momentum” which can be provided by the antenna to create linear momentum ($p = \hbar k$) of spin waves
- The **wave-vector-dependent excitation efficiency** is mainly given by the **Fourier transform of the antenna fields**

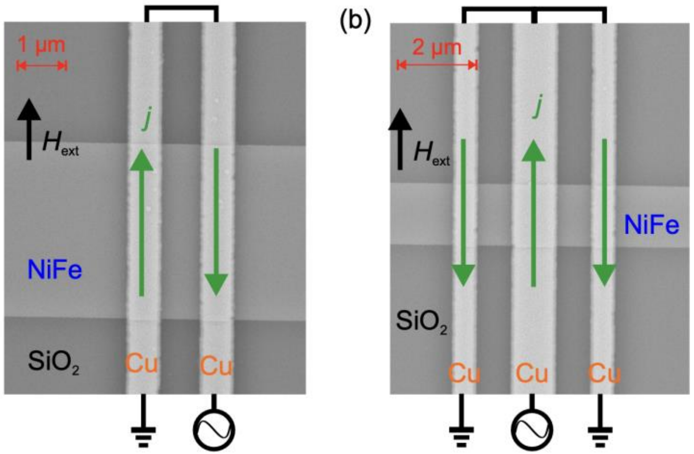


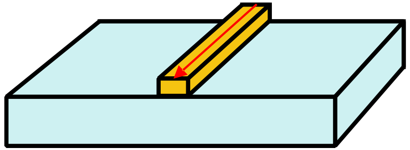
“The narrower the antenna, the broader the spectrum”

Fourier transform of both field components is the same!

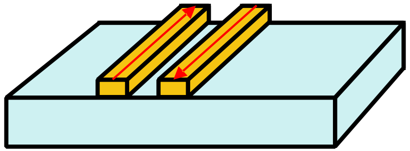
Antenna type examples



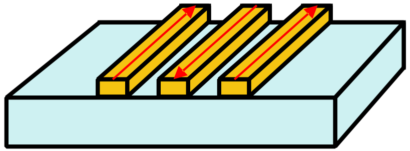




Stripline



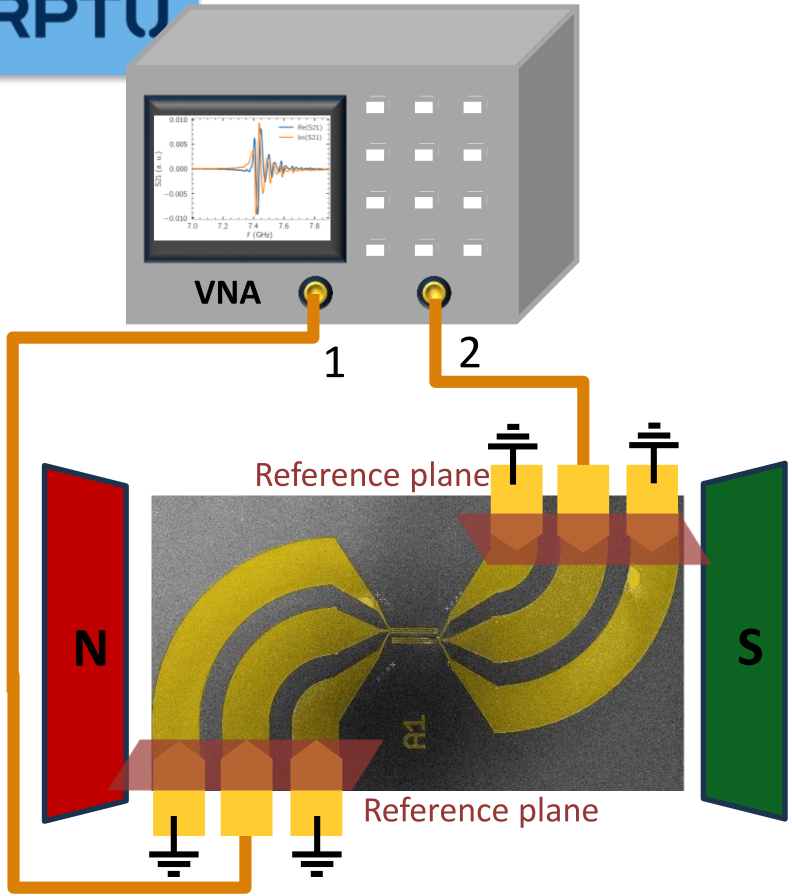
U-shape

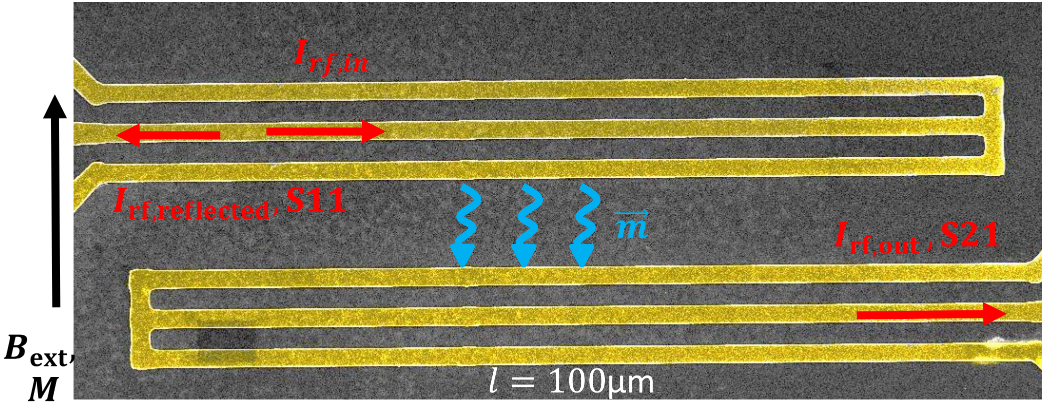


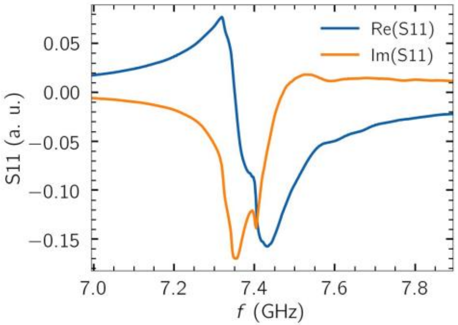
Coplanar waveguide (CPW)

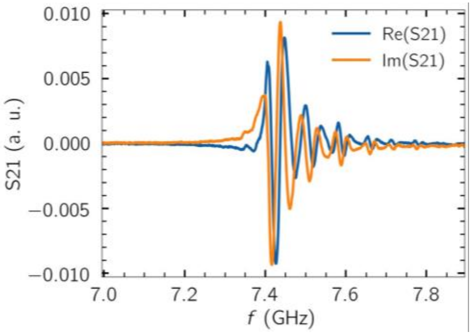
Due to the alternating current directions, the out-of-plane field of U-shape and CPW is much better confined

Coplanar waveguide (CPW)



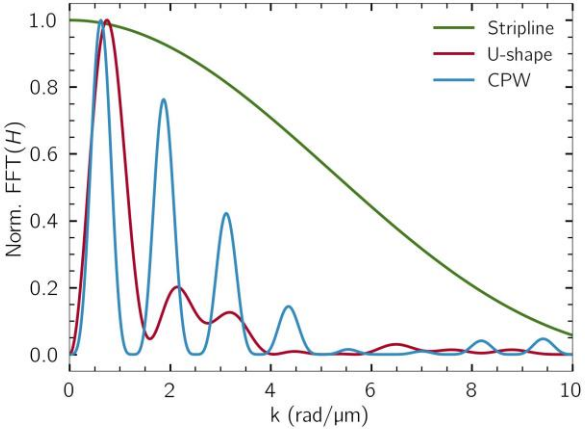




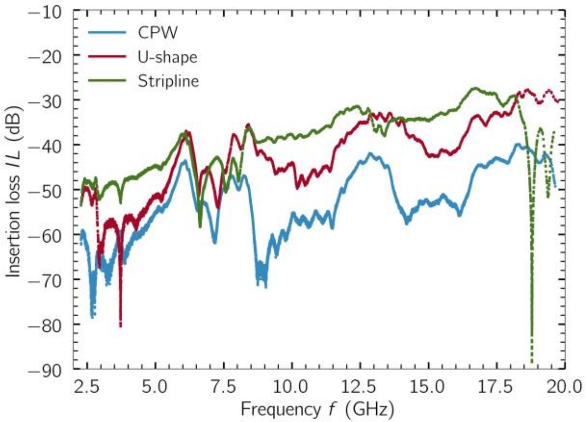


Antenna types

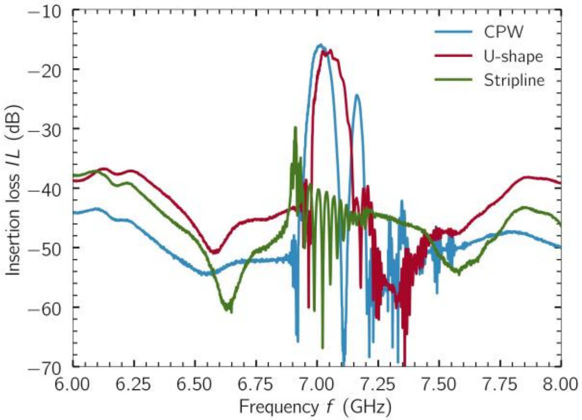
Wave-vector spectrum

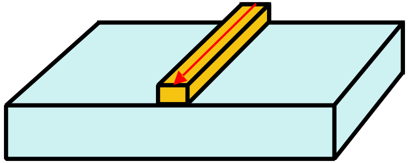


Unwanted electo-magnetic crossstalk

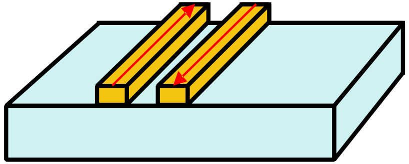


Signal Transmission

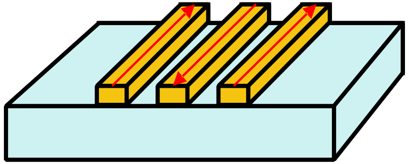




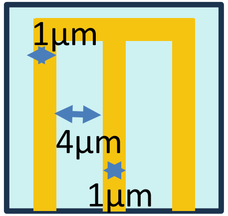
Stripline



U-shape



Coplanar waveguide
(CPW)

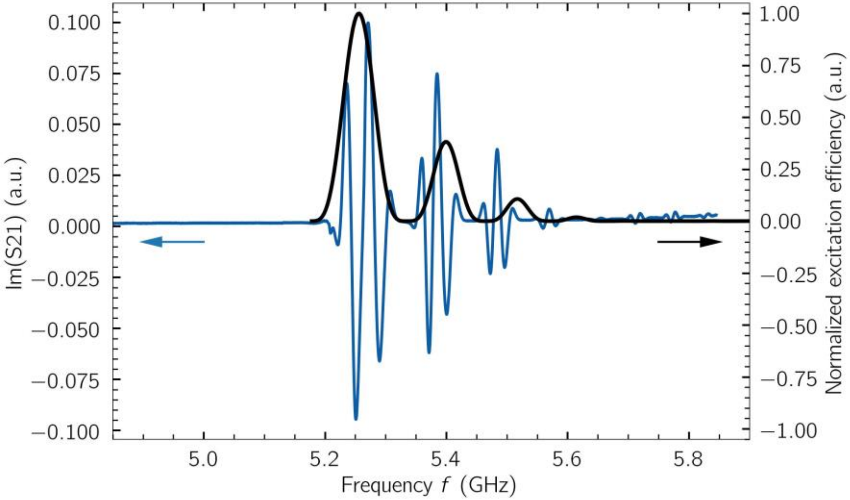


- ➢ **CPW offers lowest e.m.crosstalk (in this example also the best transmission)**

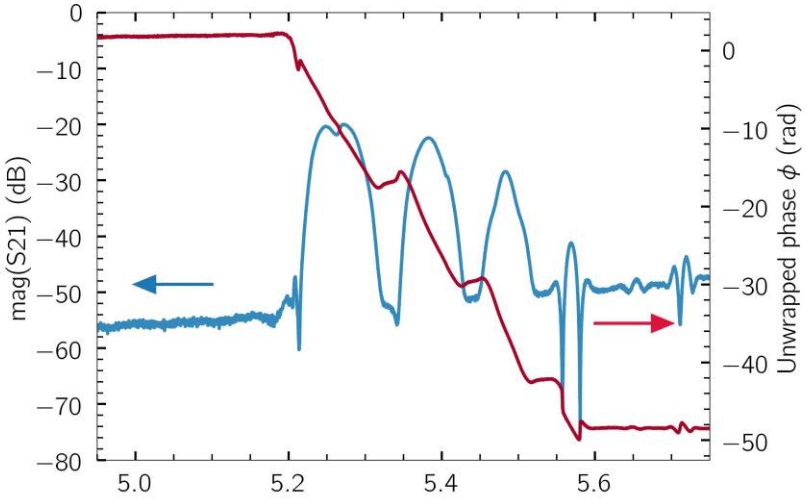
Spin-wave transmission

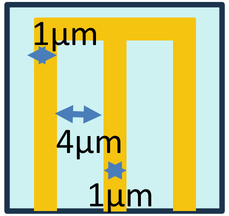
100nn YIG
$P = -20\text{dBm}$

Transmission spectrum



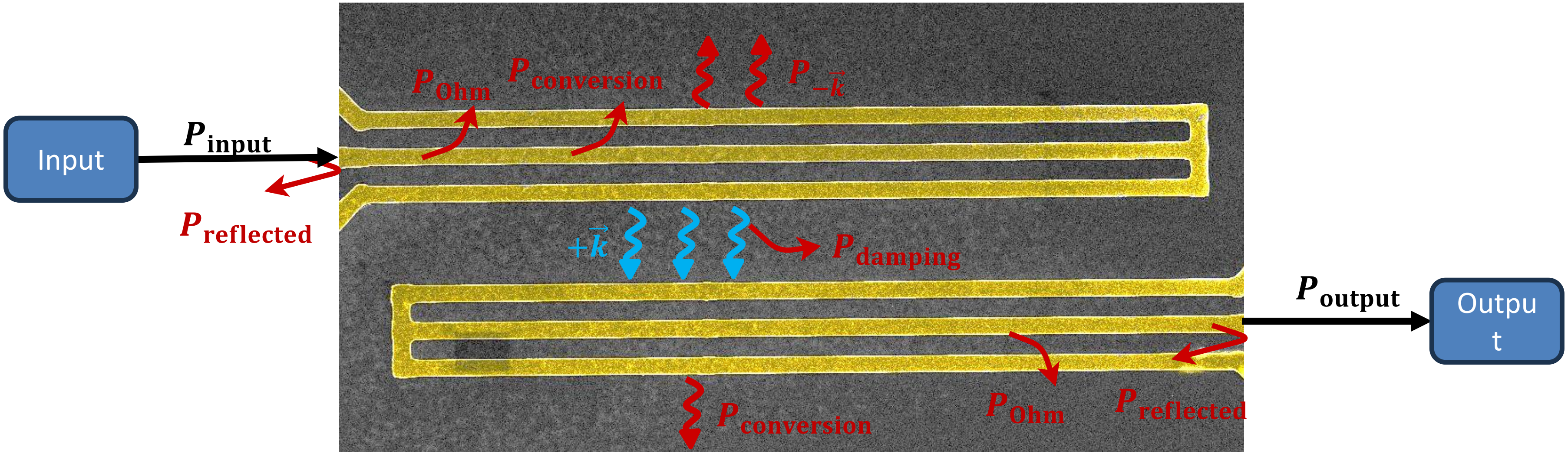
Magnitude and phase





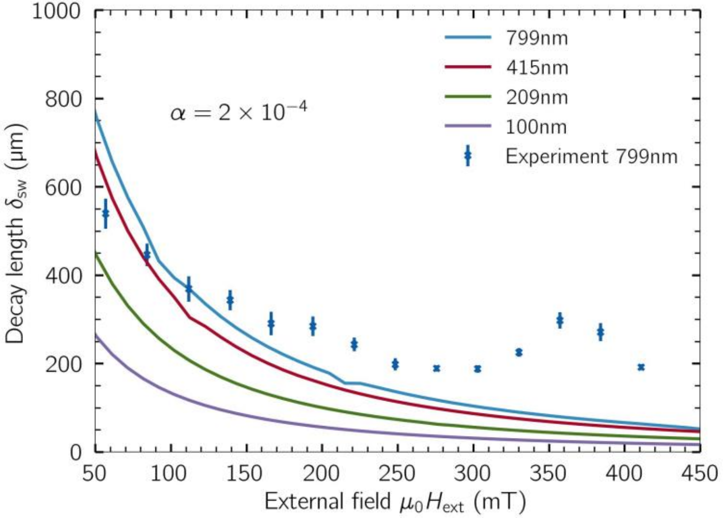
- ➢ **Transmission spectrum defined by antenna=> use antenna shape to build RF filters**
- ➢ **Strong phase accumulation by spin-waves:**

Potential loss channels



- **How much can these losses be reduced?**

Propagation losses

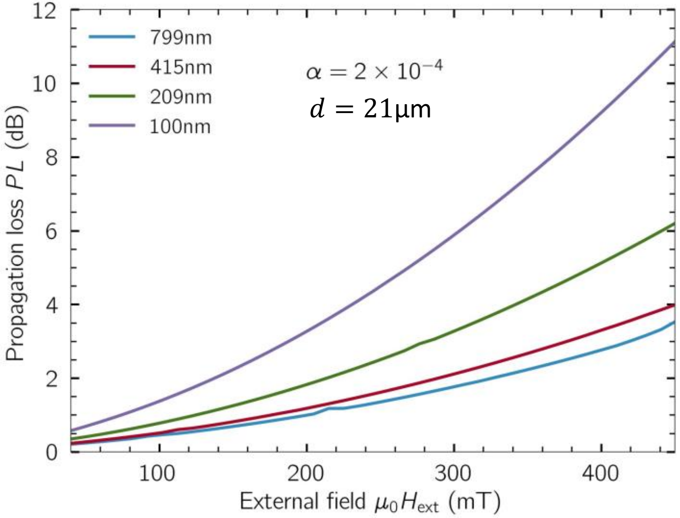


- (Gilbert) damping leads to propagation loss of SW
- $PL = -20\log_{10}(\exp(-\frac{d}{\delta_{sw}}))$
- $\delta_{SW} = \tau_{SW} \cdot v_g$

SW lifetime

$$\tau_{SW} \propto \frac{1}{(\alpha \cdot \omega)}$$

theory

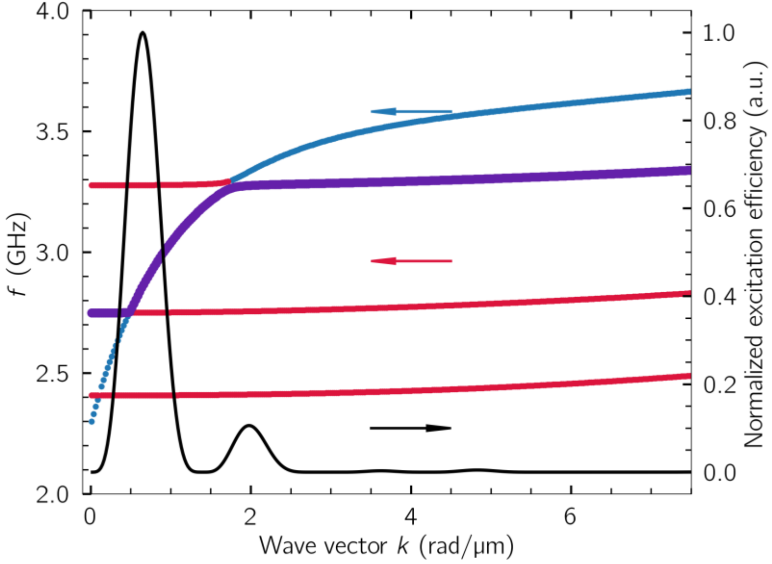


➢ **Reduction of propagation losses for thicker films**

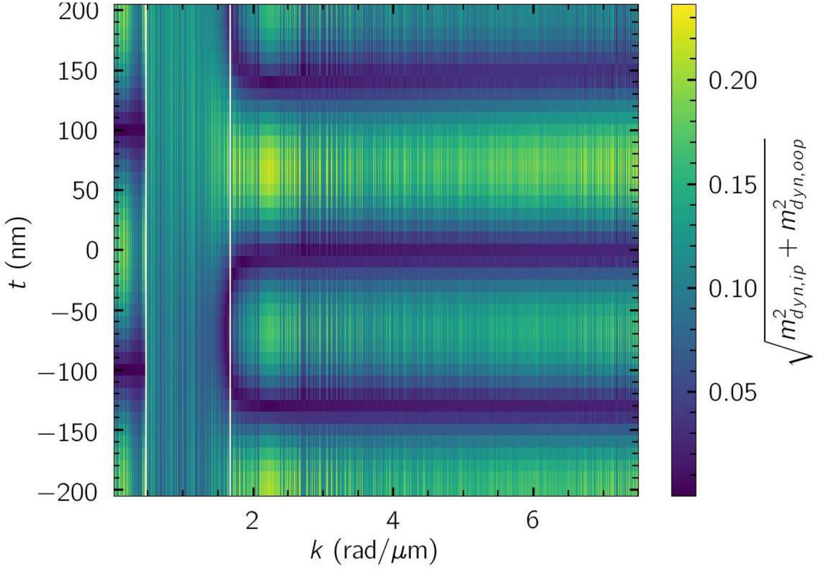
Spin-wave dispersion relations in thick YIG films

YIG film, 400 nm thickness, 30 mT external field, surface wave geometry

Dispersion relations



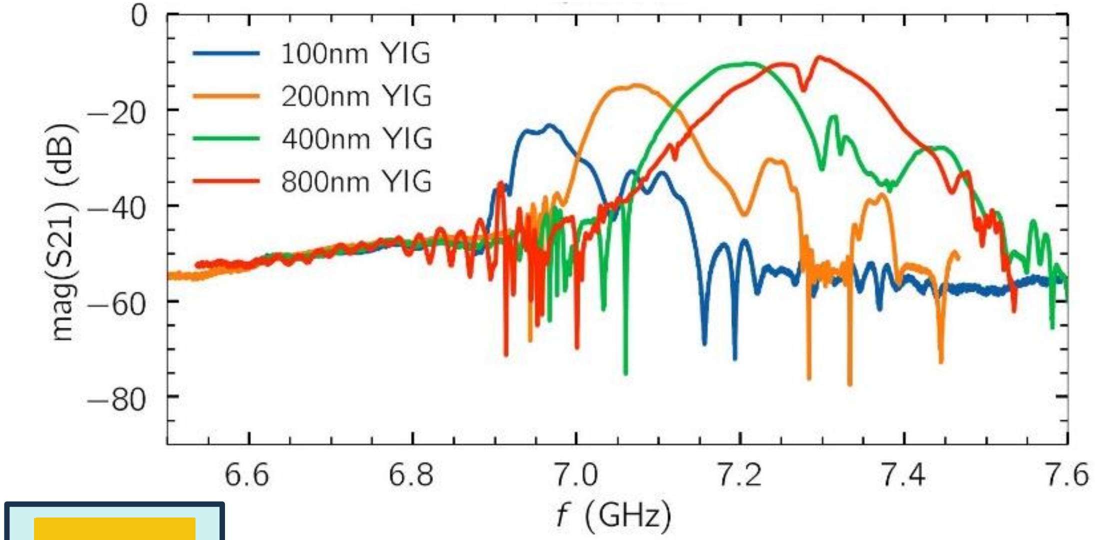
Mode profiles over the film thickness

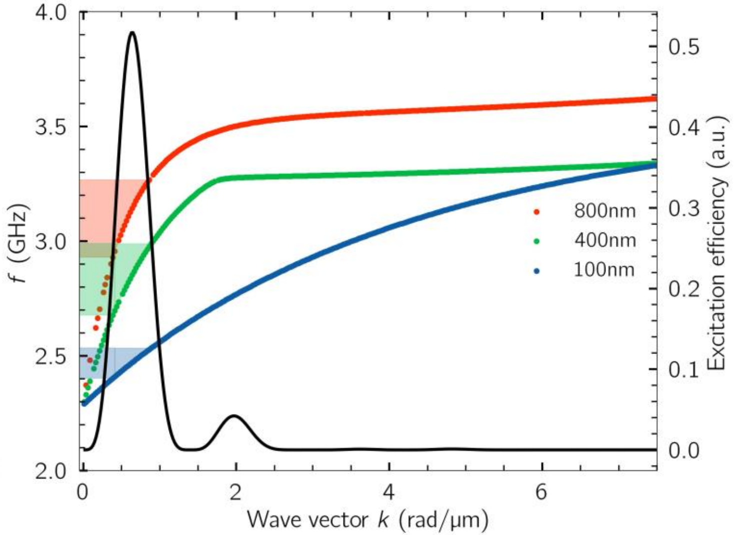


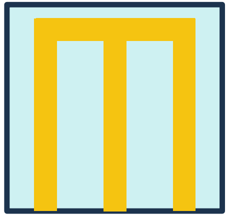
Surface mode hybridizes with modes quantized over the film thickness
(Perpendicular standing spin wave modes, PSSW) => “hybridization gaps” in the spectrum

Bandwidth

$P = -20\text{dBm}$
$B_{\text{ext}} = 166\text{mT}$



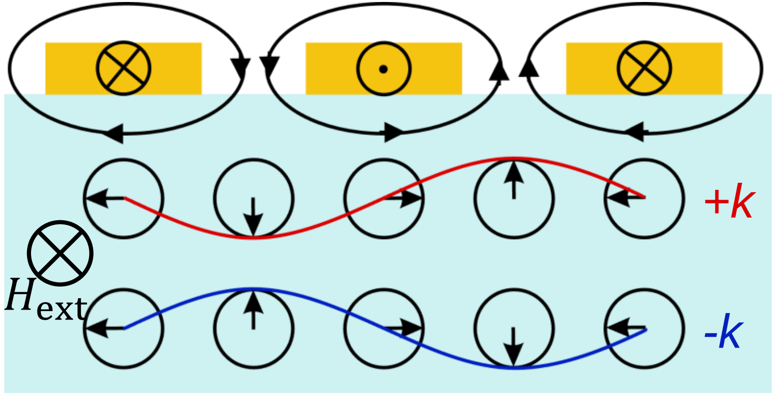


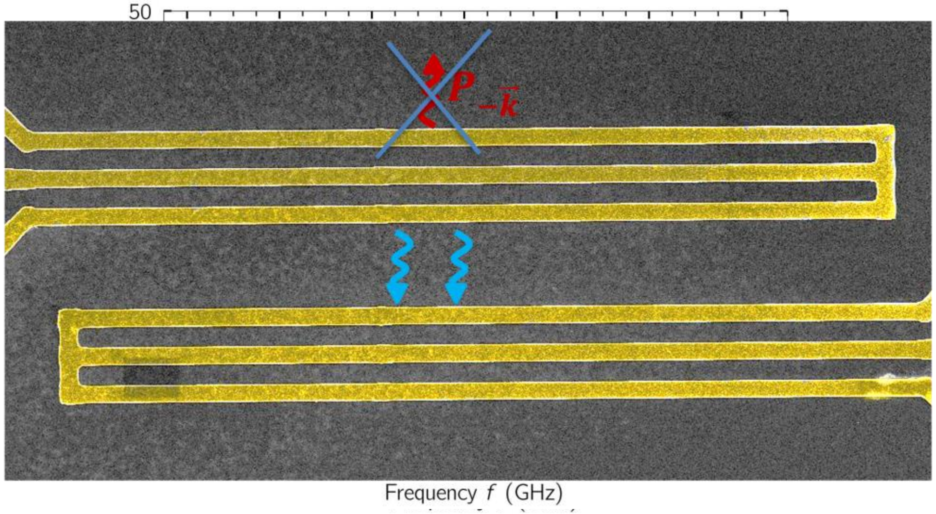


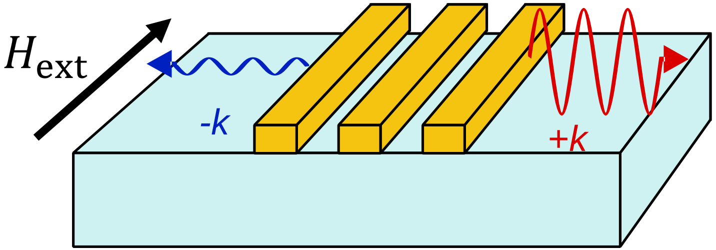
- ➢ **Steeper dispersion relation increases bandwidth for same antenna**

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

$P = -20\text{dBm}$







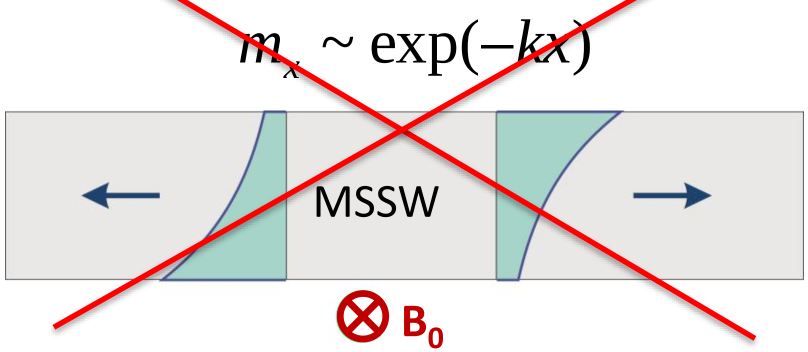
- ➢ **Directed flow of energy: lower losses**
- ➢ **Magnonic delay line is also a RF isolator**

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)

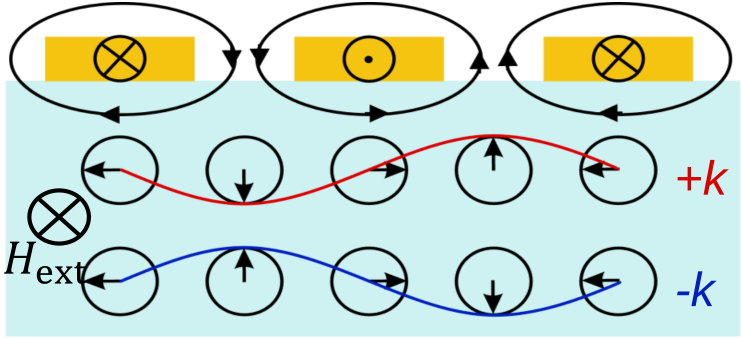
Most antennas excite only the Surface Wave using both components, that’s why the other modes (Backward Volume or Forward Volume) are (usually) excited reciprocally.

~~Non-reciprocal dynamic mode profile~~



$$m_x \sim \exp(-kx)$$

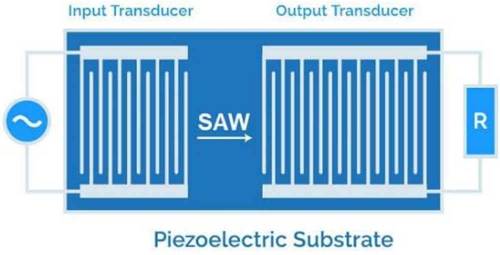
“Helicity” of magnetization precession



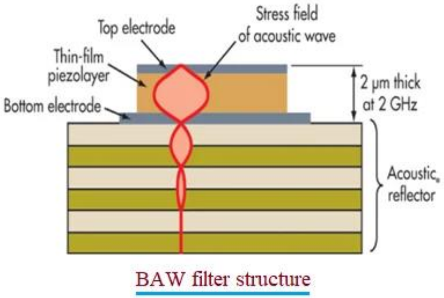
Frequencies of competing phonon-based technologies

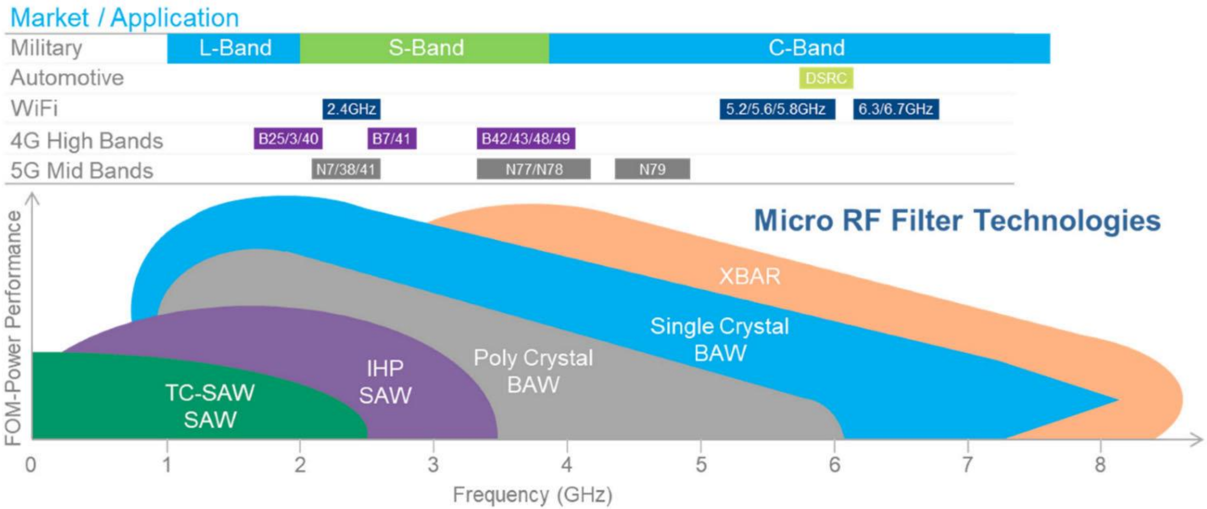
Miniaturized filters/phase shifters/time delay units in today's RF applications: **Surface and Bulk Acoustic Wave** systems

SAW



BAW





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

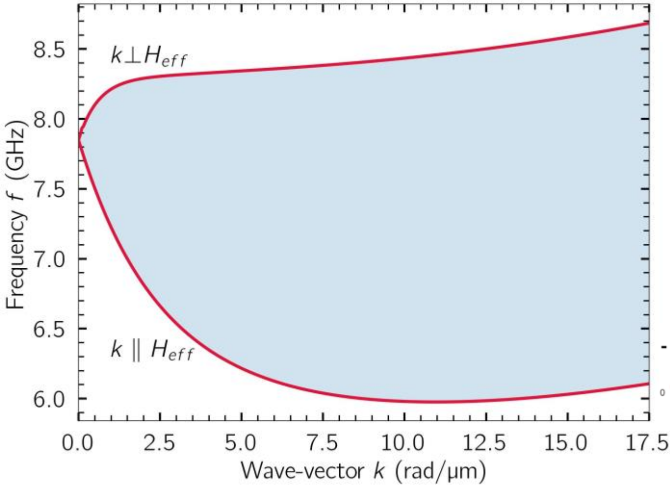
SAW /BAW:

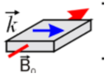
- **No tunability**
- No solutions above 10 GHz

2. Tuning magnonic devices

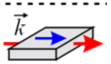
Example: Dispersion relations of dipolar-exchange spin-waves in an 800 nm thick film of Yttrium Iron Garnet (YIG) with in-plane magnetisation:

$\mu_0 H = 200\ mT$





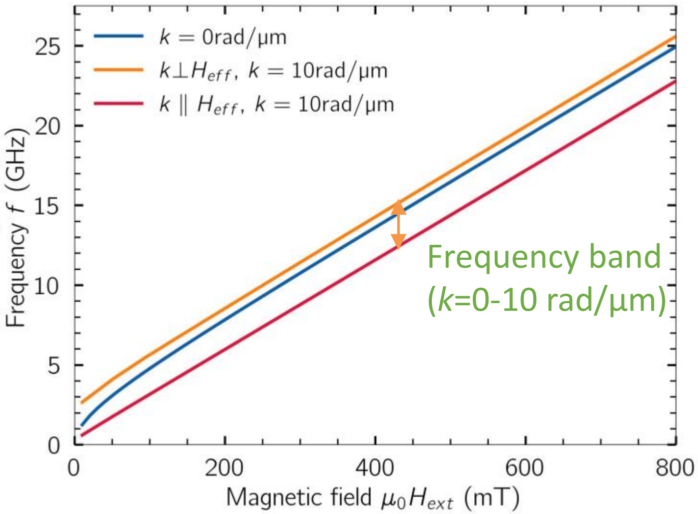
Damon-Eshbach surface mode



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

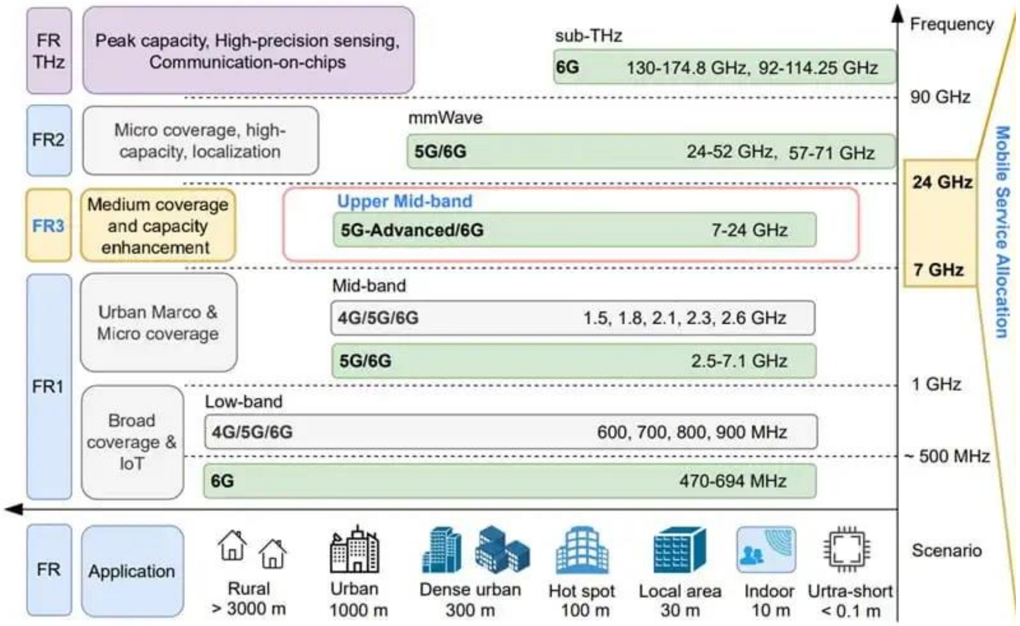
saturation magnetisation

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

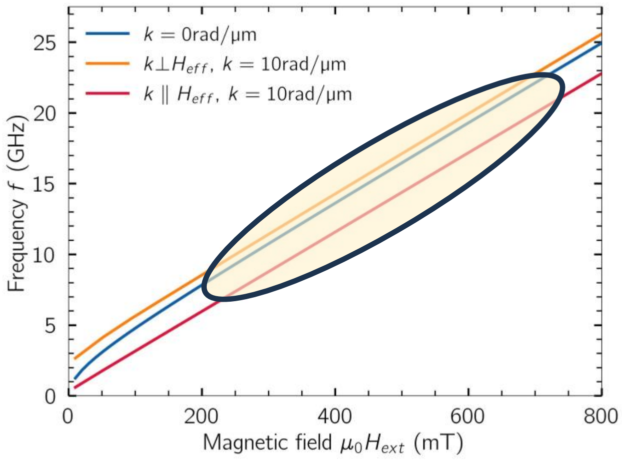
Previous lectures:
Dispersion relation of magnons depends on propagation direction, saturation magnetization, film thickness, magnetic field…..

Frequency bands available for magnonics

Important for cost-efficient 6G



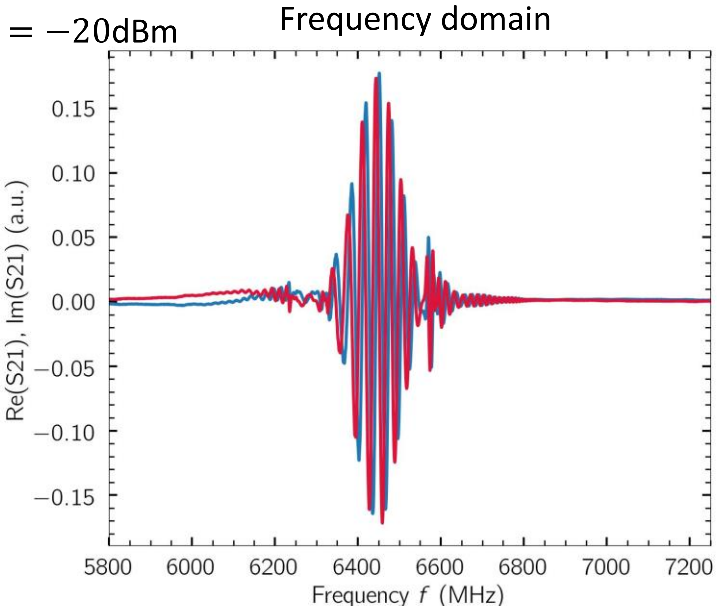
YIG



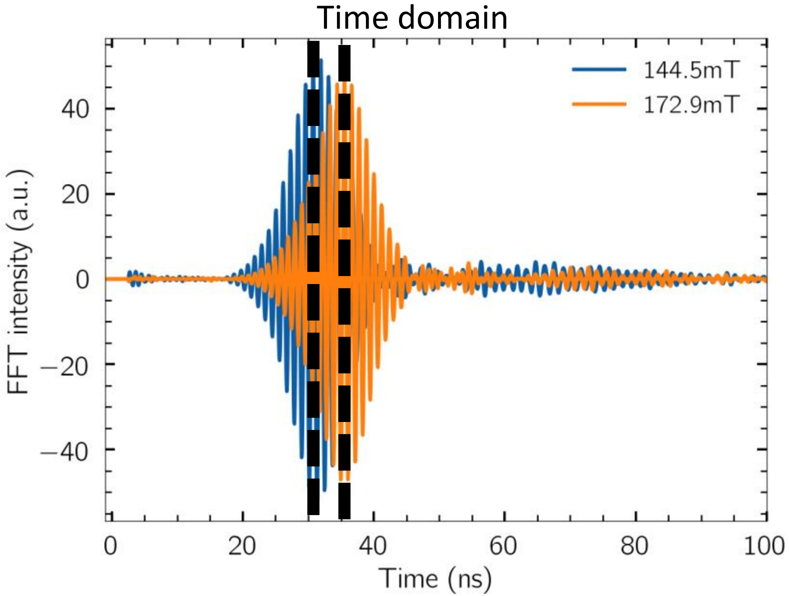
=> magnonic applications based on YIG are well suited for FR3 (7-24 GHz), no miniaturized solutions on the market

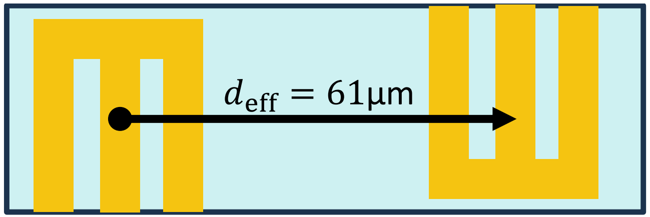
Tunable signal transmission in time domain

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



FFT

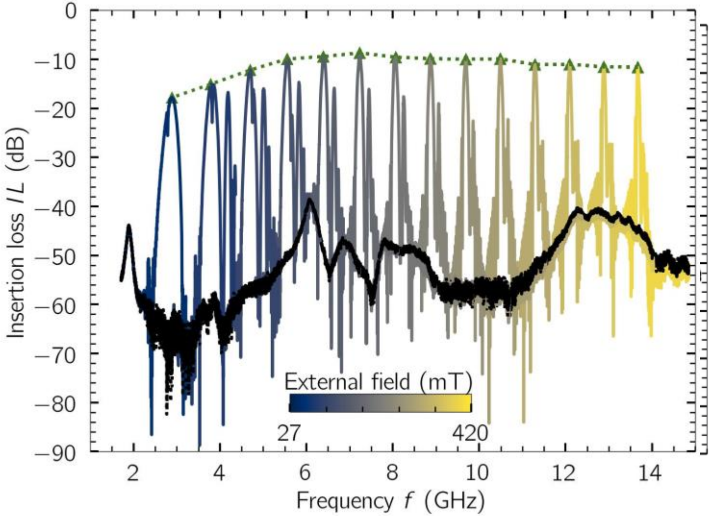




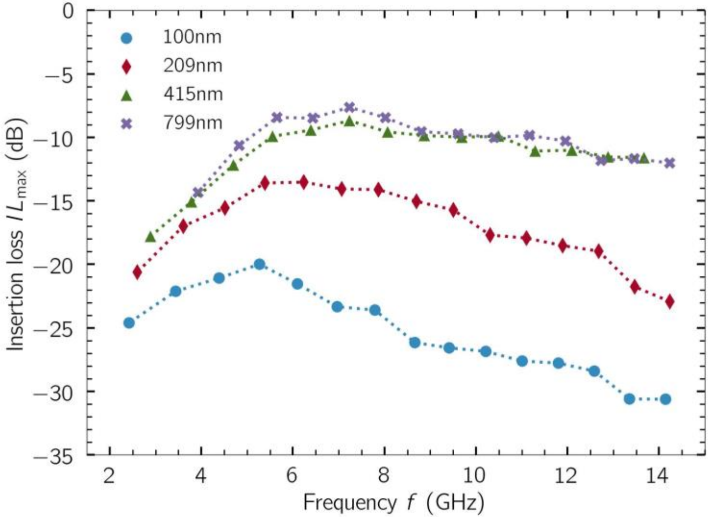
- **Induced time delay by changing external field**

Frequency dependence

Field dependence



Thickness dependence



- ➢ **Signal over 30dB larger than background**
- ➢ **No background removal needed**

- ➢ **Insertion losses <10dB achieved**
- ➢ **Lower losses with optimization possible**
- ➢ **Tunable operation over large frequency range**

Commerical magnonic components

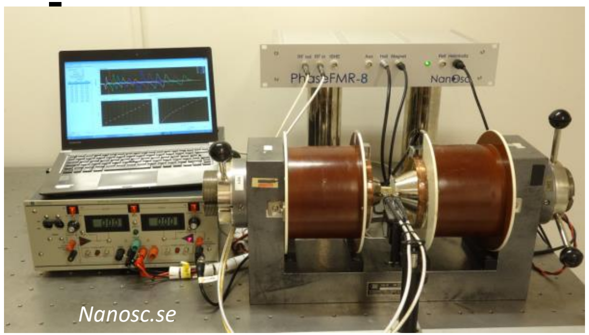
Yttrium-Iron-Garnet tuned **RF oscillators** (YTO) produced by Rohde & Schwarz.

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

“Field generation problem”

Strengths of Magnonics

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



Nanosc.se

Electromagnet

Standard experimental approach:

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

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

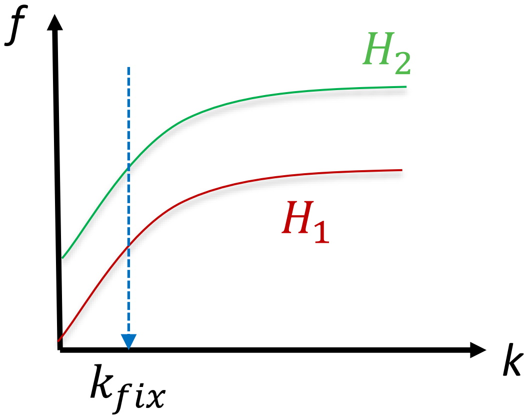
Challenge to create **energy-efficent** devices:
How to **provide magnetic fields (static and dynamic)** in an energy efficient, compact and scalable manner?

Magnonic systems for signal processing

Linear systems

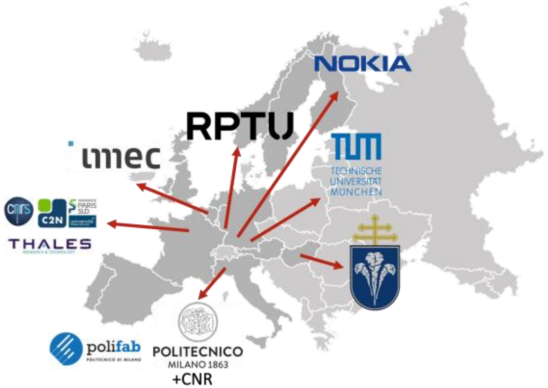
Linear SW propagation
- RF time-delay units
- RF filters, isolators

tunable via the applied magnetic fields (H_1, H_2)

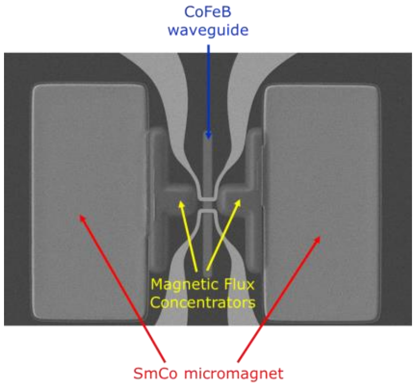


Funded by the European Union

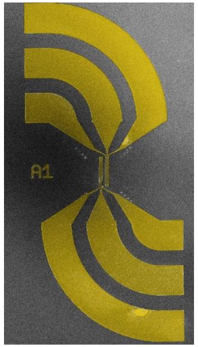
www.mandmems.eu



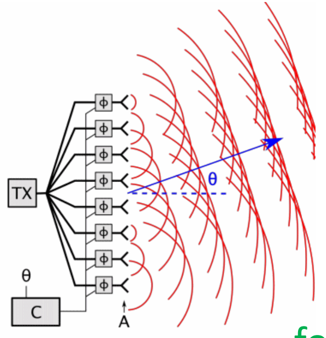
Standalone magnonic device



High frequency SW delay lines



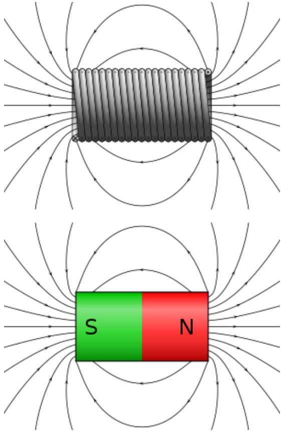
Tunable miniaturized time delay units



for 5G, 6G

M&MEMS approach to generate magnetic fields

Replace electric currents as sources for magnetic fields to maximize energy efficiency and scalability while maintaining tunablity of the devices.



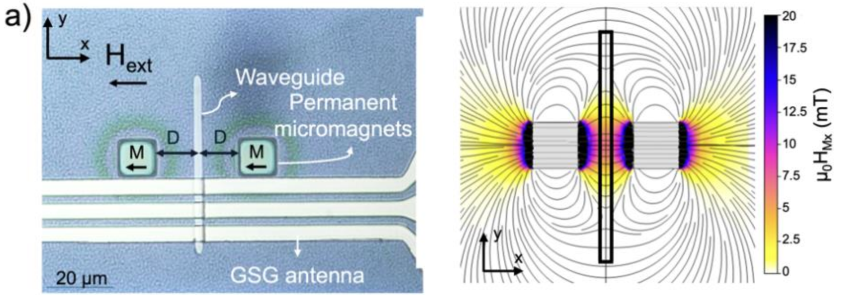
Two magnetic field sources are used in M&MEMS:

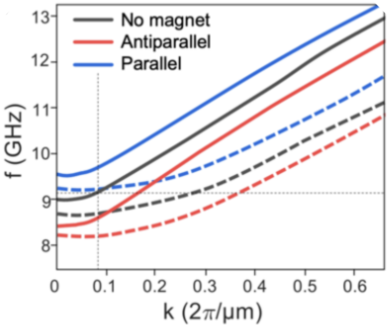
- **Permanent magnets**
  => Tunablity is provided by MEMS
- **Magneto-elastic fields**
  => Strain is provided by surface acoustic waves (SAW)

Both approaches allow for a **voltage-based** control and tuning of the magnonic devices with low energy consumption.

On-chip integrated permanent magnets

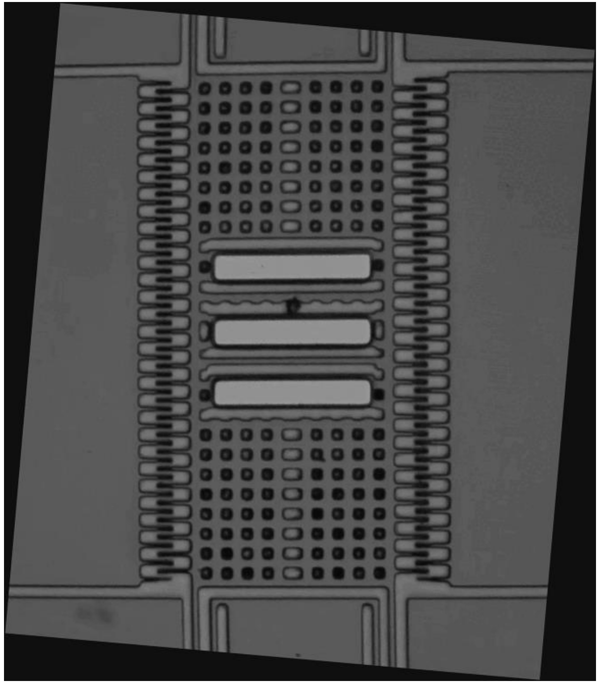
SmCo permanent magnets





Consiglio Nazionale delle Ricerche

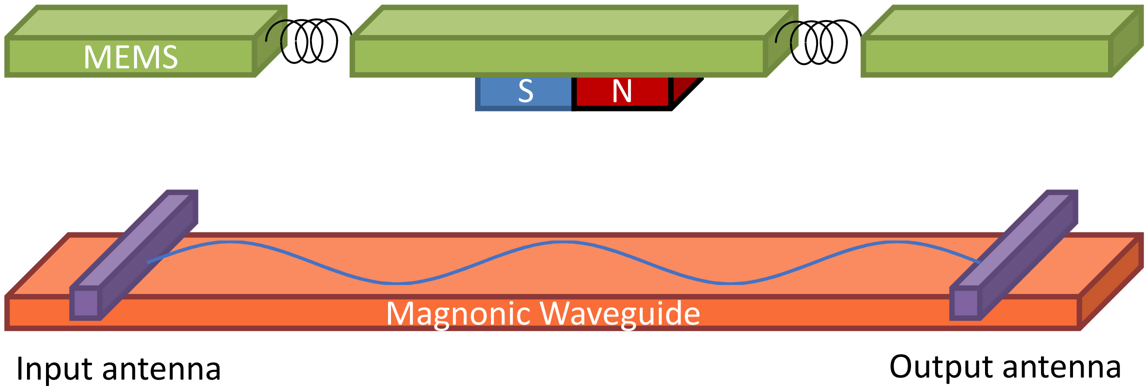
POLITECNICO MILANO 1863

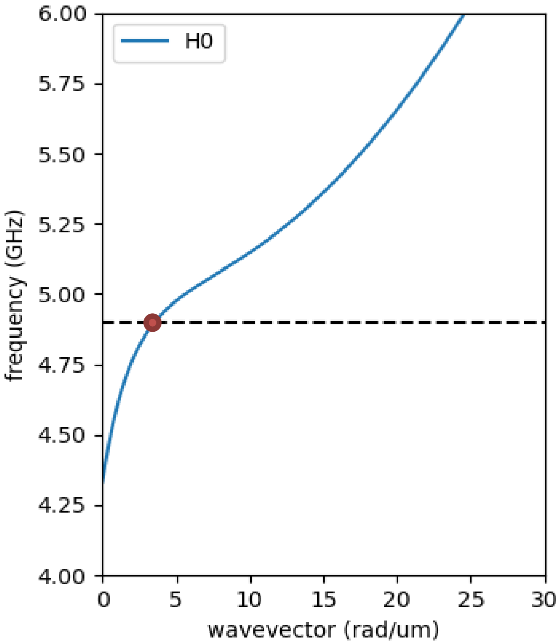


Permanent magnets on a laterally moving MEMS
(Micro electronic mechanical system)

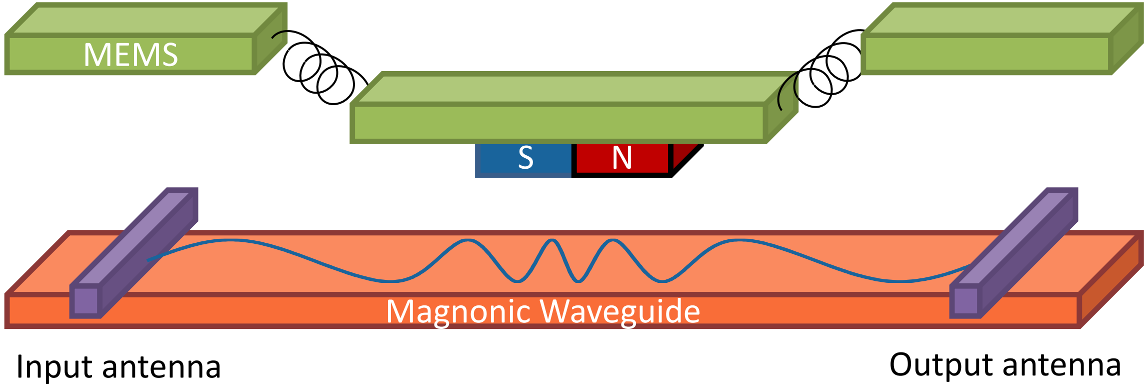
M. Cocconcelli et al., *Tuning Magnonic Devices with On-Chip Permanent Micromagnets*, arXiv 2406.03206 (2024).

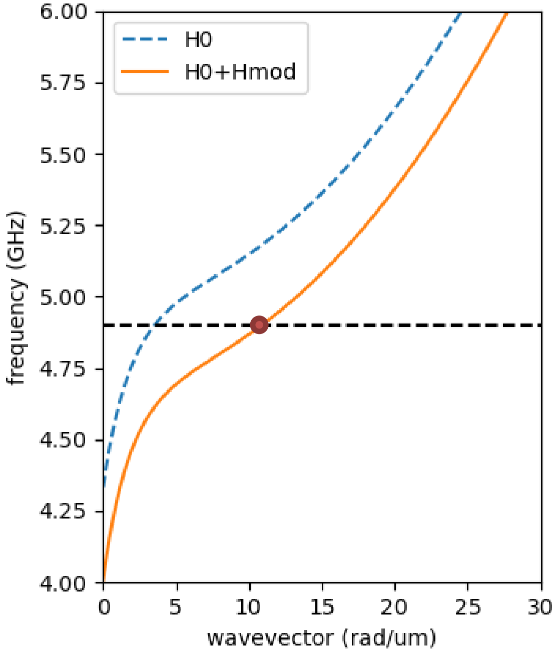
Device concept: Phase / time delay unit





Device concept: Phase / time delay unit

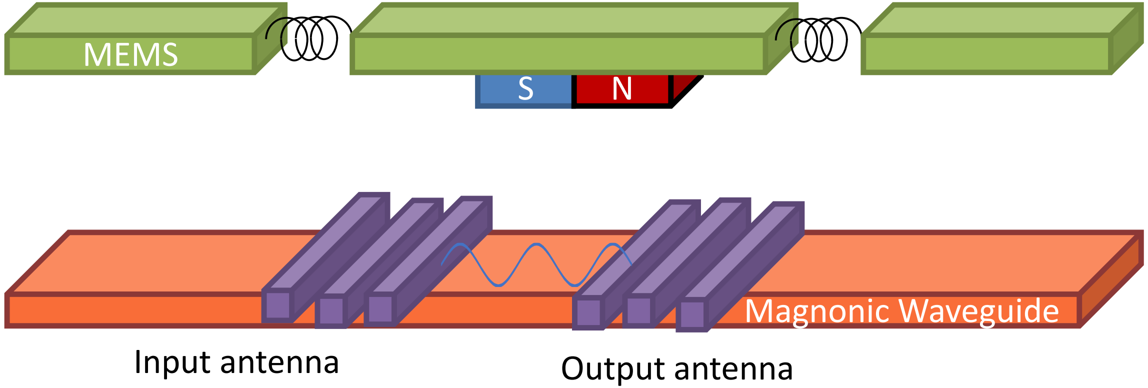


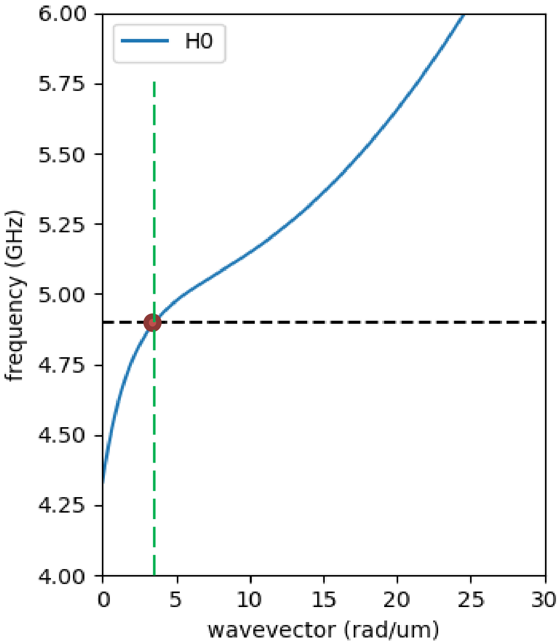


- Modulation of spin-wave wavelength between the antennas => phase and time delay are tuned

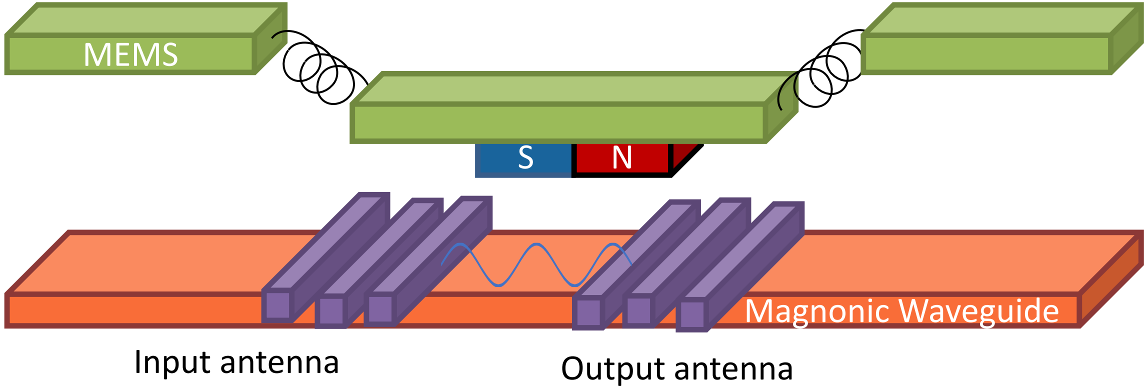
- **No influence on the input/output antenna** => constant amplitude

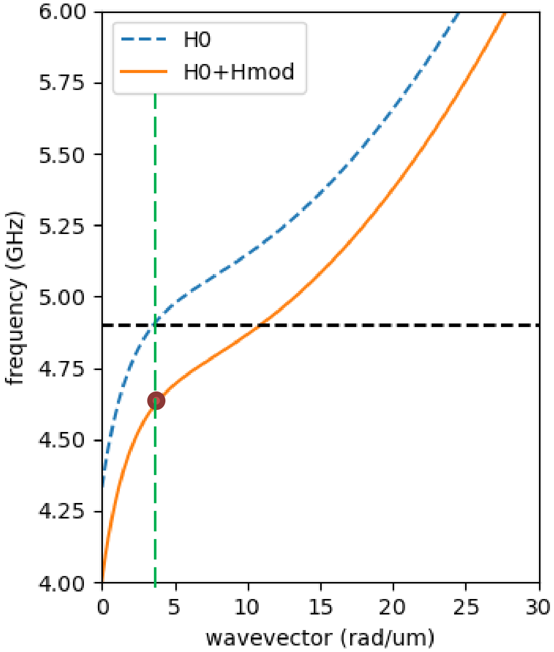
Device concept: Filter





Device concept: Filter

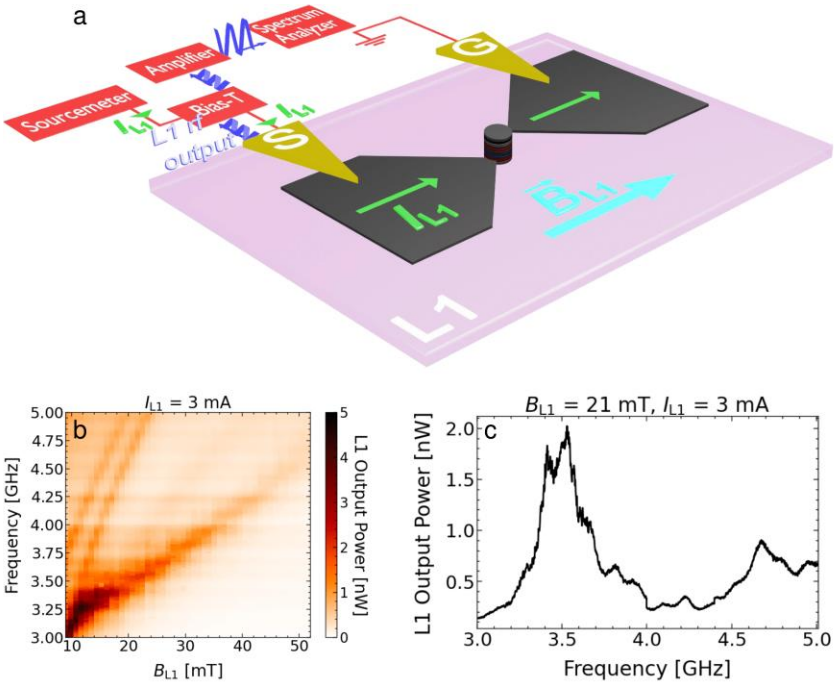




- Modulation of spin-wave resonance frequency **at the antennas** =>transmission frequency is shifted

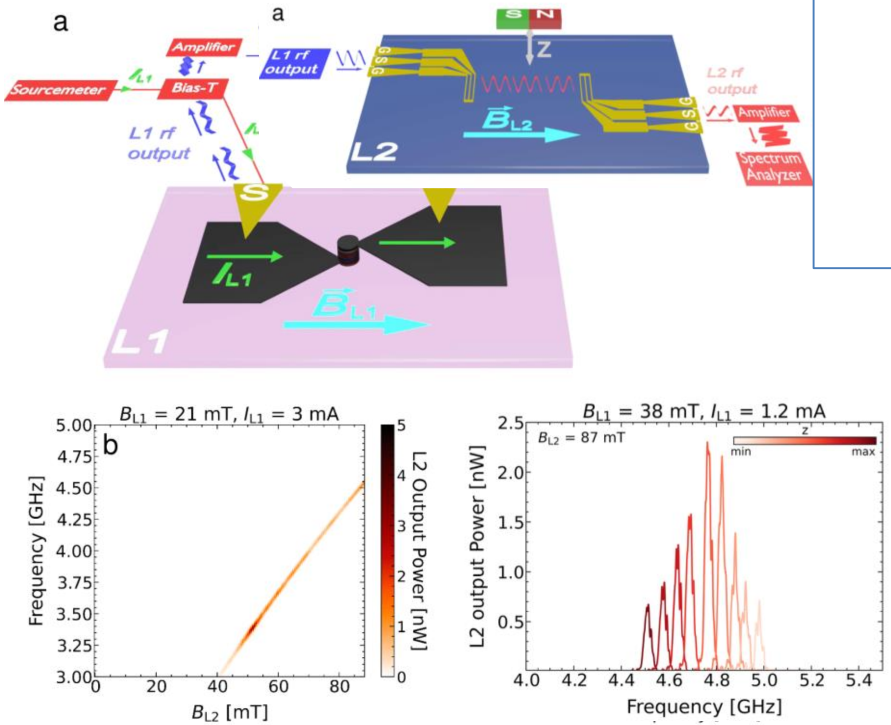
Example: Filter the signal from an STNO

Only STNO



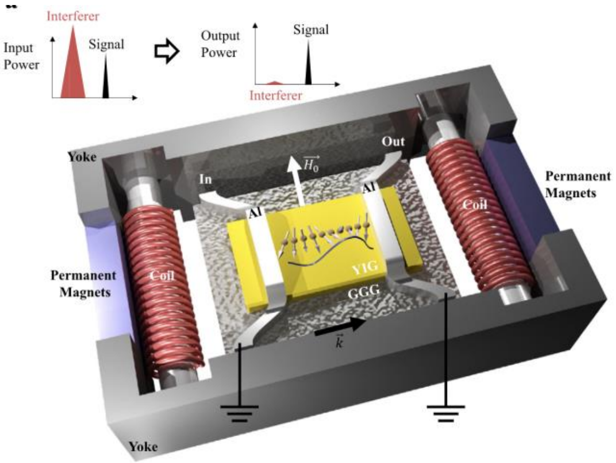
STNO from U. Ebels

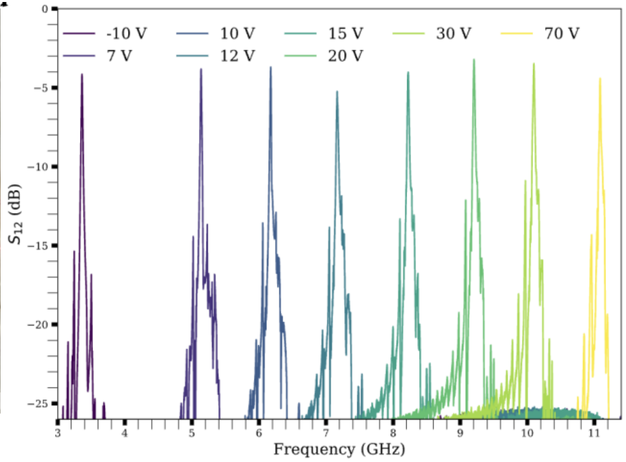
STNO filtered by magnonic filter



Filtered spectrum of STNO
as function of magnet position

Zero-power reconfigurable magnonic RF filter





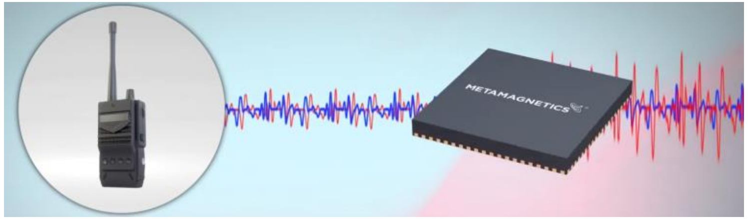
Short current pulses magnetize the AlNiCo (=> see lecture of P. Tozman) magnets partially
=> depending on the pulse voltage, different bias fields/resonance frequencies are reached

X. Du, et al., *Frequency Tunable Magnetostatic Wave Filters with Zero Static Power Magnetic Biasing Circuitry*, Nat. Commun. **15**, 3582 (2024).

Nonlinear magnonic devices

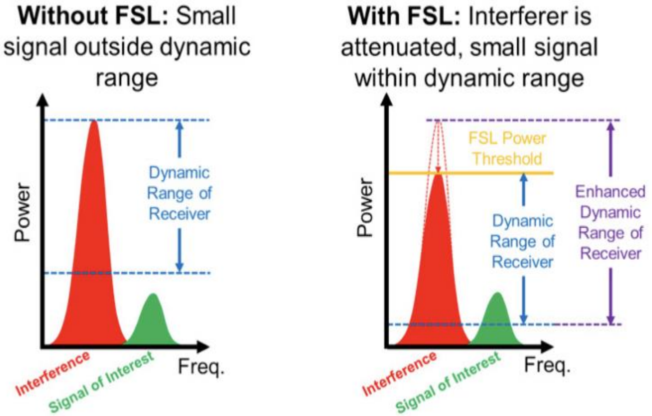
You can buy it:

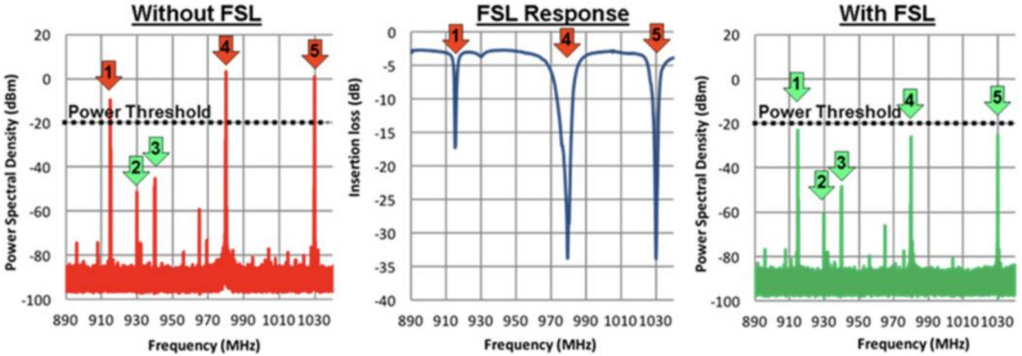
AtF
AUTO-TUNE FILTER



Auto-tune filters to mitigate electro-magnetic interference (Metamagnetics Inc.)

⇒Highly specialized, nonlinear spin-waves to lin
signal power in every frequency channel
("Frequency selective limiters", FSL)

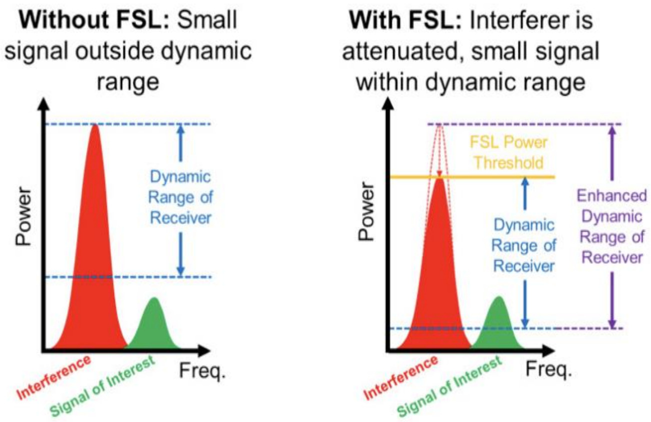




S. M. Gillette, et al. 2018 IEEE MTT-S Int. Microw. Work. Ser. Adv. Mater. Process. RF THz Appl. (IMWS-AMP) **00**, 1 (2018).

Nonlinear magnonic devices

How does this nonlinear limiter work?
They don't tell you ;-)



My guess:

1) If the RF frequency component gets too strong (the "attacking/jamming" signal), a **magnon instability** is triggered because the threshold for this process is triggered. The energy is flowing then from the initial mode to modes at other frequencies, which dissipate in several channels.
2) For large spin-wave powers, the **magnon impedance** is changed due to the nonlinearity. This leads to an **increase of RF reflection**, decreasing the transmitted signal.

Nonlinear devices based on the nonlinear magnon shift

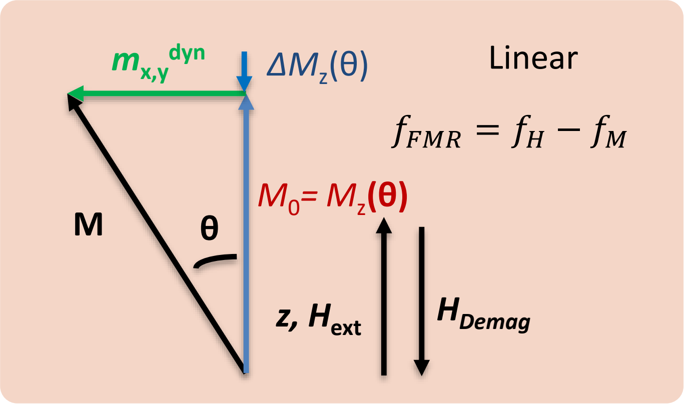
Nonlinear shift:

SW amplitude

$$f(k) = f_0(k) + T_k|c_k|^2$$

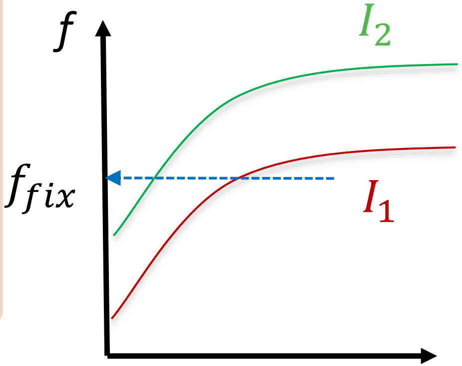
linear nonlinear

Out-of-plane magnetized film



Linear

$$f_{FMR} = f_H - f_M$$



$I_2 \gg I_1$

Including anisotropies: $T_k \propto M_{eff}$

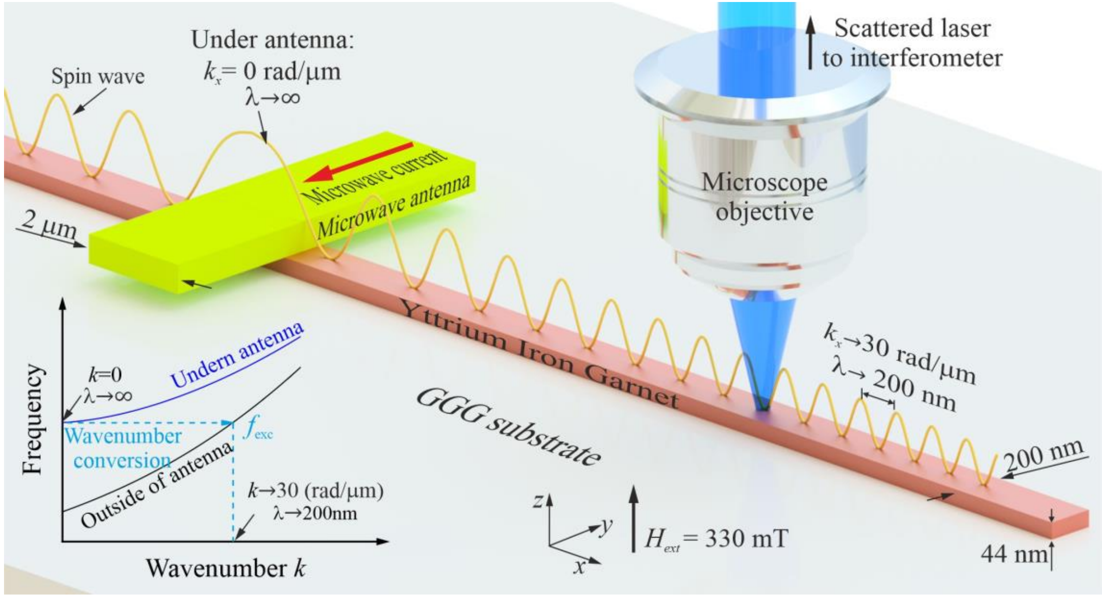
YIG: $M_{eff} \approx M_s$

„$T_k > 0$ if the system is saturated in a hard axis"

$M_{\mathrm{eff}} = M_{\mathrm{S}} - K_{\mathrm{u}}$, K_{u}: Uniaxial anisotropy out-of-plane

Bistability-based nonlinear magnon devices

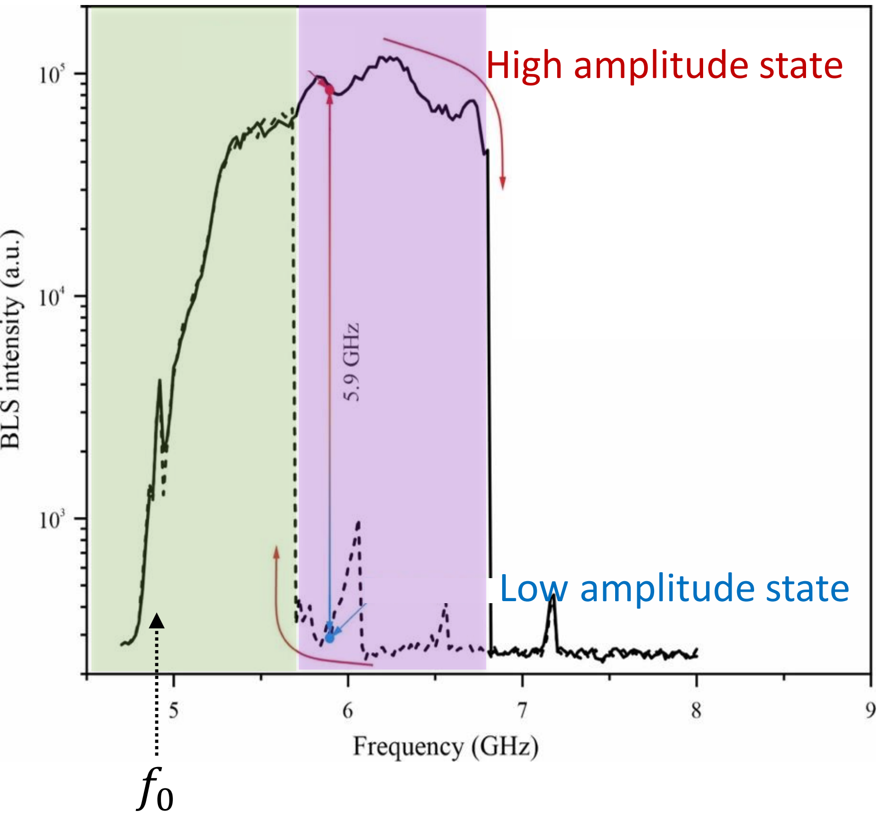
Nonlinear magnonic system A: YIG waveguide in ***Forward Volume Geometry***



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

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

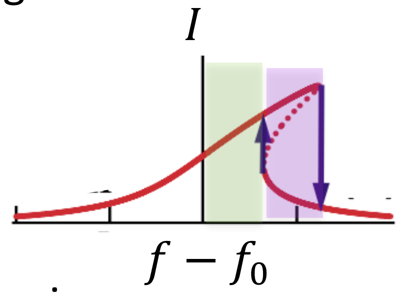
Nonlinear shift, foldover effect and bistability



- Very wide antenna: linear excitation only at $f(k \approx 0) = f_0$.
- Large MW-photon amplitude (high amplitude of dynamic magnetic fields)

Two nonlinear excitation regions:

- Single state foldover
- Bistable foldover

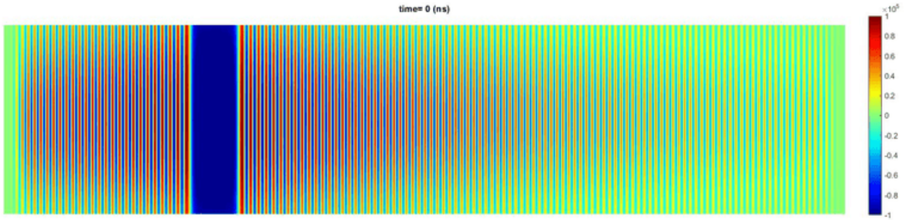


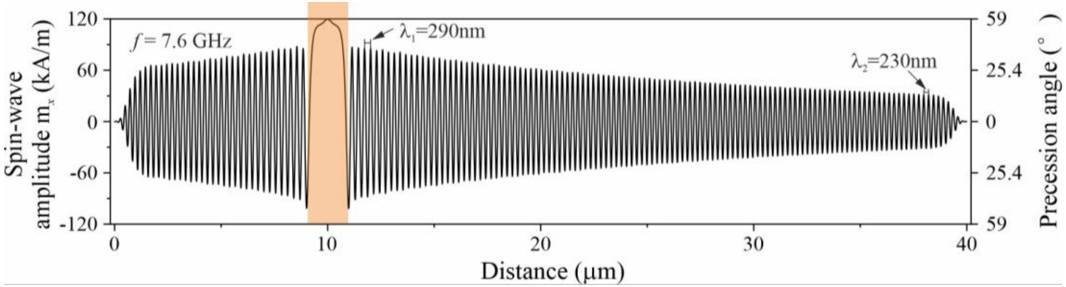
Relative size of the regions is strongly system and power dependent.

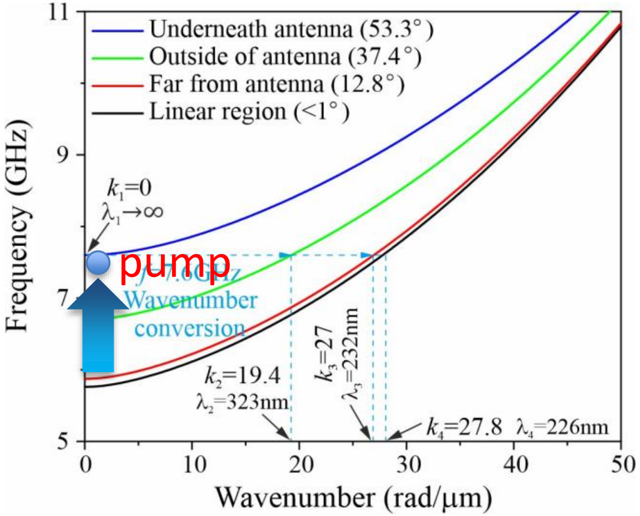
see: Q. Wang, PP, et al., Sci. Adv. **9**, eadg4609 (2023).

Spin-wave emission from high amplitude state

Micromagnetic simulations
(confirmed by time resolve µBLS)





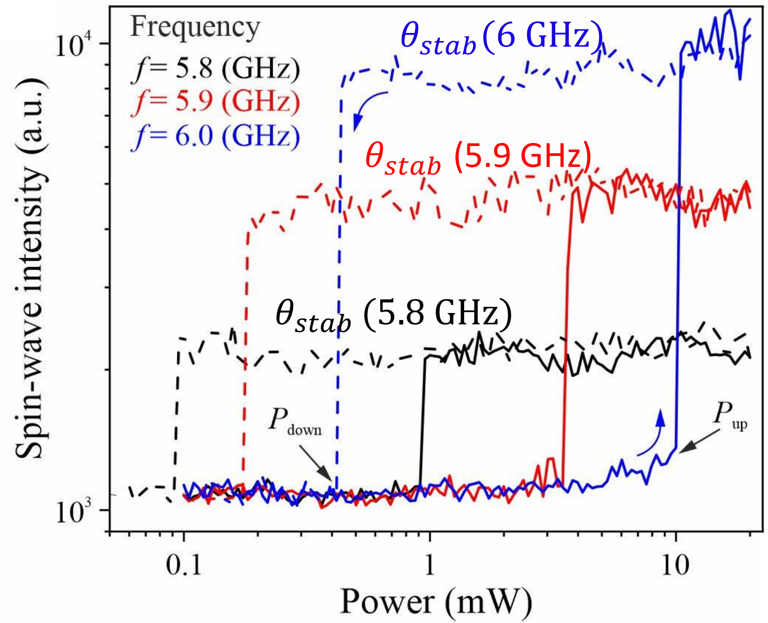


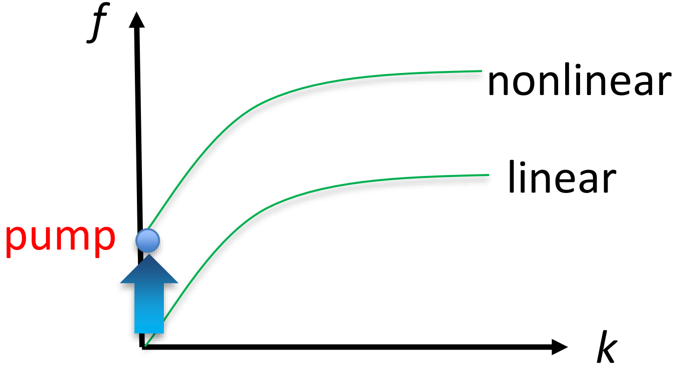
- Spin waves with **230 nm wavelength** (12 % of antenna width) are excited by the nonlinear transformation
- **Nonlinear emission** is about **260% more efficient** compared to a linear transformation in a simple field gradient gradient

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

Normalized spin-wave amplitudes from biastable systems

f_{RF}





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

Nonlinearly shifted resonance frequency:

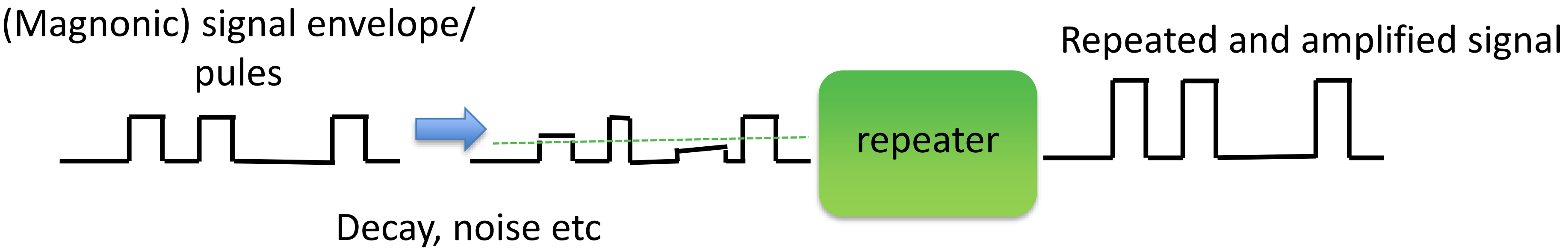
$$f\left(|c_k|^2\right) = f_{lin} + T_k \cdot |c_k|^2 \qquad |c_k|^2 = 1 - \cos^2(\theta)$$

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).

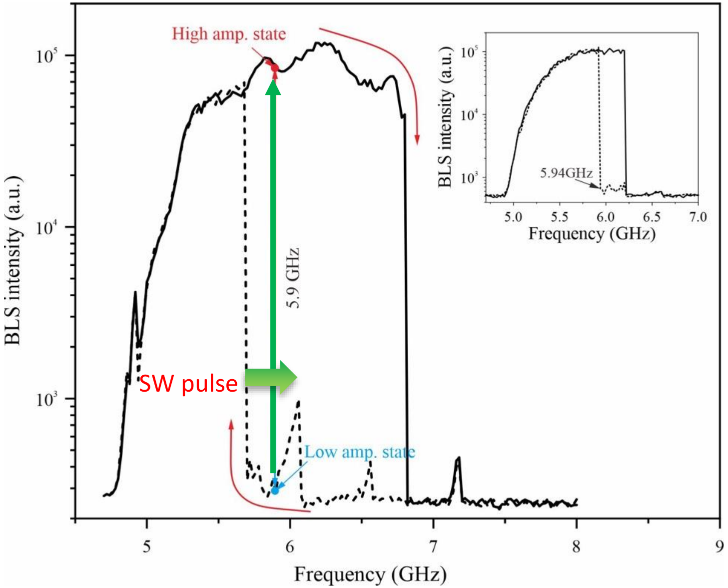
Signal repeater

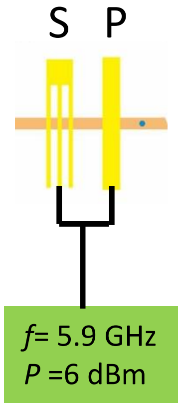


Q. Wang et al., *All-Magnonic Repeater Based on Bistability*, Nat. Commun. **15**, 7577 (2024).

Magnonic repeater based on bistability

YIG waveguide, 1 µm wide, Forward volume (330 mT)



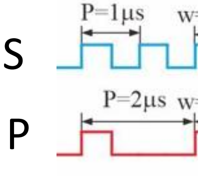


f= 5.9 GHz
P =6 dBm

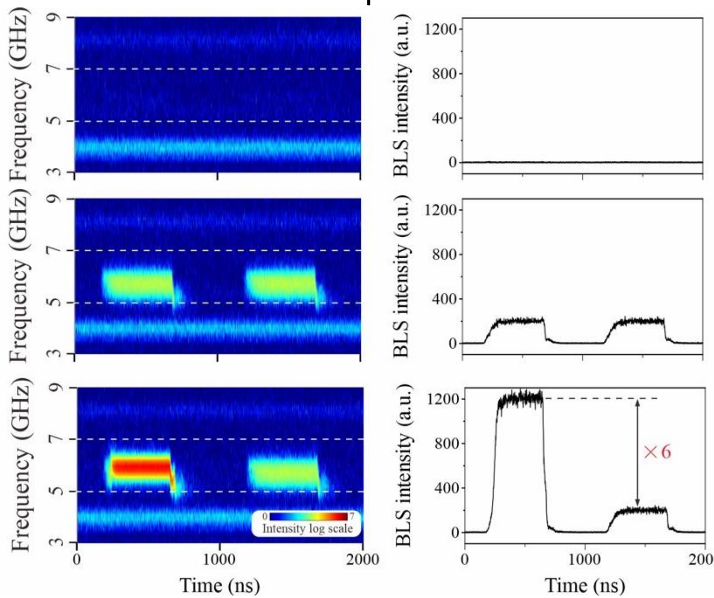
Only pump

Only source

With pump
vs without pump



µBLS



> “Trigger transition to high amplitude state using a SW packet.”

- Repeats spin-wave pulse with 6x intensity amplification

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

Conclusions

- Spin waves can be used to **delay** and **filter Radio-Frequency signals**
- Spin-wave devices are **tunable** by the magnetic field
  => replace several static devices by one flexible device
- Spin waves can act as **RF Isolators** due to their intrinsic non-reciprocities
- Due to **intrinsic nonlinearities**, SWs can play an important role for **advanced nonlinear RF processing** like signal-to-noise enhancement and frequency selective limiters.