TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

AG MAGNETISMUS TU KAISERSLAUTERN

Neuromorphic magnon-spintronic networks

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OPTIMAS light-spin-matter

SPIN+X SFB/TRR 173 Kaiserslautern • Mainz

DFG

Neuromorphic computing

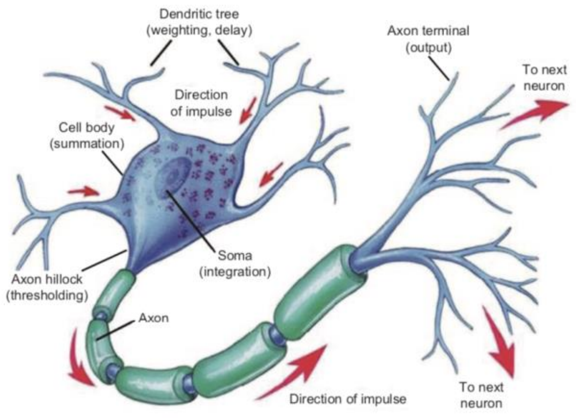
Use of novel ways to compute which are inspired by the astonishing **energy efficiency** of the human brain

Digital Computing
(CMOS power density)

Human Brain

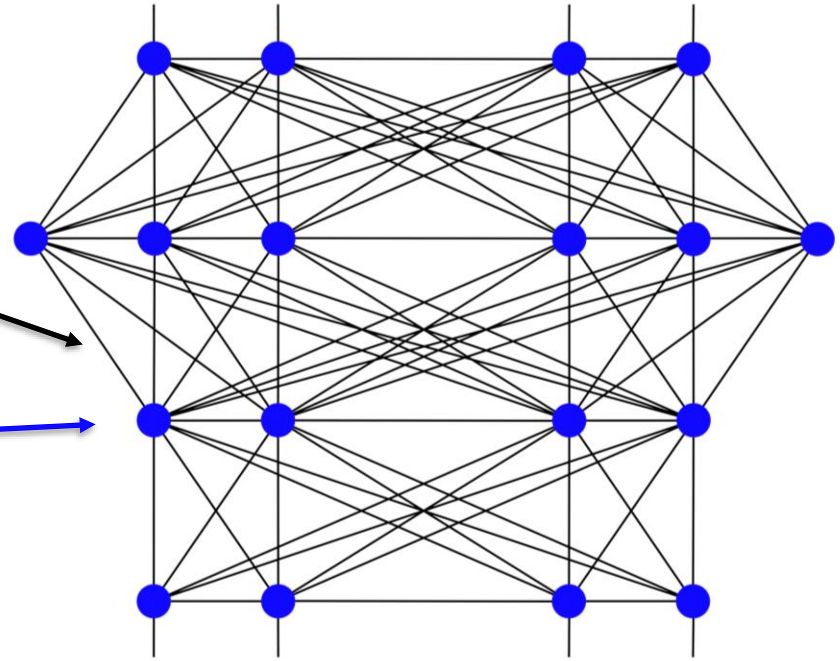
Only 20 W **total power consumption** …

Artifical Neural networks

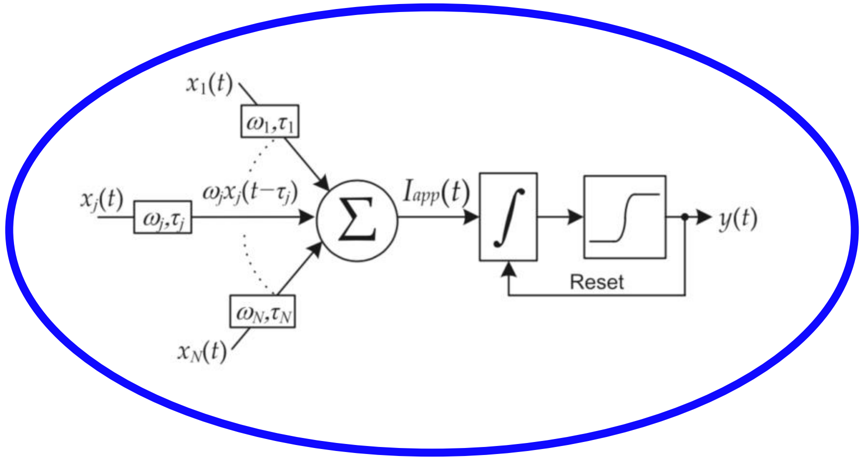


Biological Neuron

Artificial neural Network



Connections
„Artificial synapses“



Nonlinear Building block:
„**Artificial neuron**“

Computation using a highly connected networks
of nonlinear elements

P. Prucnal and B. Shastri, Neuromorphic photonics, CRC PRess (2017)

Neuromorphic networks

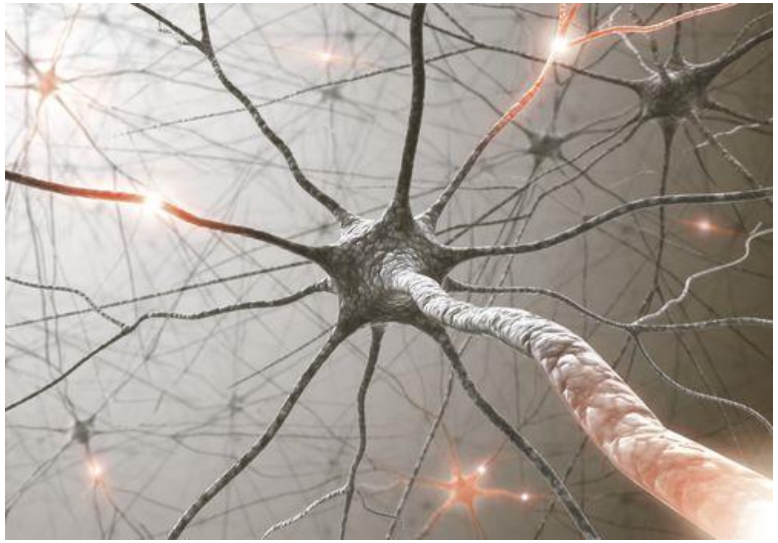
- Inherently **analog processing**
  → digital systems are rather inefficient, wave-based approaches have a natural advantage

- **Nonlinearity**: every neuron has a build-in nonlinear function

- **Highly interconnected systems**:
  the (energy) efficiency of the connections can be more important than the efficiency of the neurons

- **Reprogramming**: to learn, the strengths of the interconnections ("weights") between neurons need to be changed

Human brain:
- About 85 billion neurons connected by about **10^{14} synapses**
- **Every neuron has about 1.000-30.000 direct connections to other neurons**
- Total length of the connections: 5.6 million km

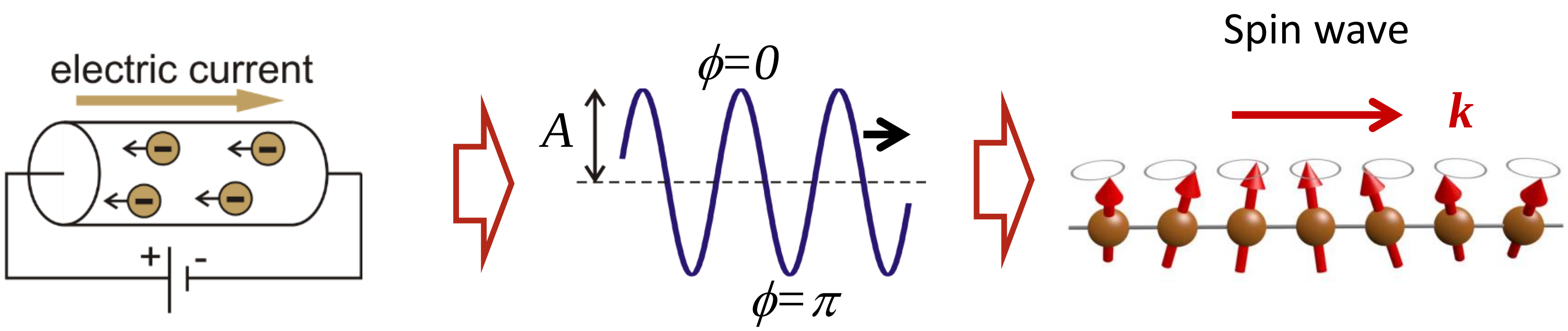


Outline

- General concept of an all-spintronic network using spintronic auto-oscillators and spin waves
- Neuromorphic computing using spintronic auto-oscillators
- Nano-magnonic building blocks
- Inverse design magnonics
- Coupling of spintronic auto-oscillators and nano-magnonic building blocks

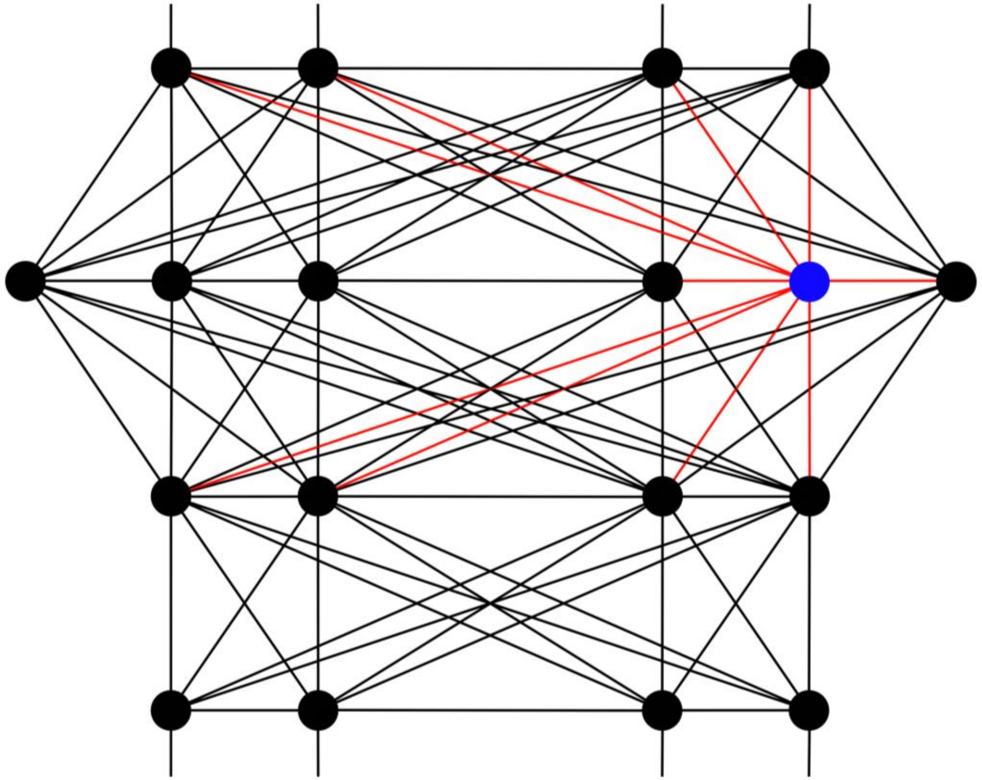
Magnonics

- Use of spin waves (quasi particle: magnon) to transport and process data



Variable	**Scalar**	**Vector**	(A, ϕ, f, $\mathbf{k}$)
Transport	Driven by **potential gradient**	Driven by **wave propagation**	• Coherent coupling • Interference effects and logic • Intrinsic nonlinearity • Scalability: Nanometer wavelength • Frequency multiplexing

Connectivity challenge



Direct physical realization?

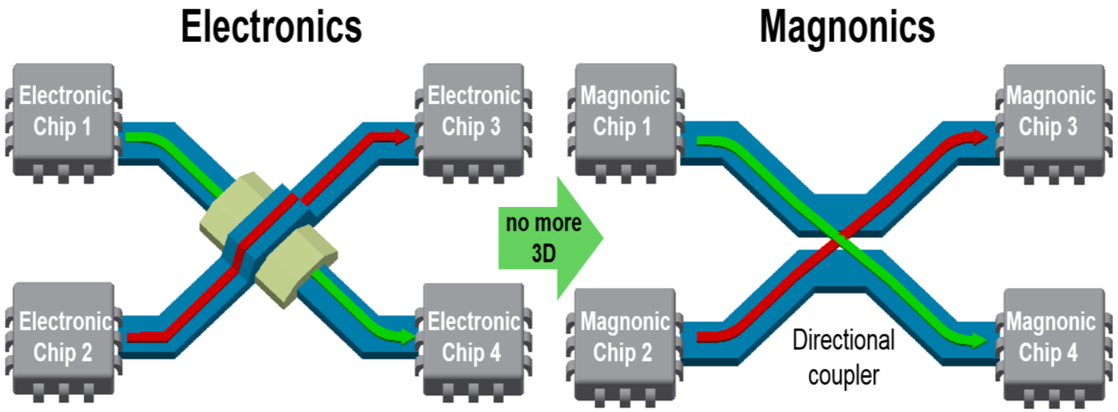
Electrical wiring scheme

A network with N neurons needs $\frac{N(N-1)}{2}$ physical connections to create *all-to-all connectivity*

“Hopfield network”:
J. J. Hopfield, Proc. Natl Acad. Sci. USA 79, 2554 (1982).

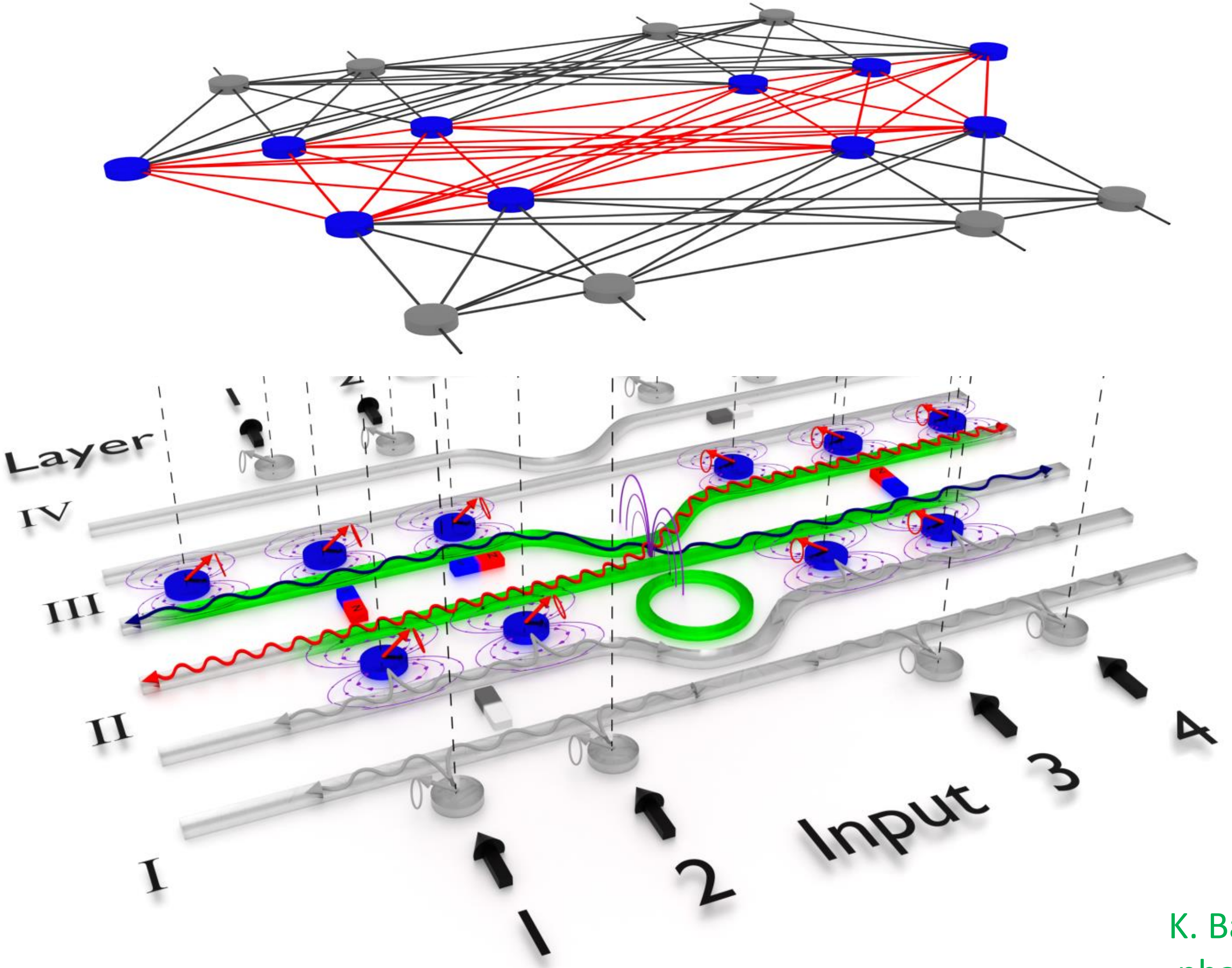
Connection by waves

Use of **coherent coupling effects** allows to use 2D systems



Additional reduction of physical interconnects by **frequency multiplexing**

Our concept: all-spintronic approach



Artificial Neurons: spintronic auto-oscillators (SAO)
Nanoscaled objects with high intrinsic nonlinearity

Interconnects: coherent spin waves

- Artificial synapses created by ultralow-damping magnonic nano-conduits
- Including coherent coupling effects, interference, spin-wave nonlinearity and frequency multiplexing

Programming: magnetic memory cells
Nanomagnets like those used in MRAM influencing the spin-wave propagation

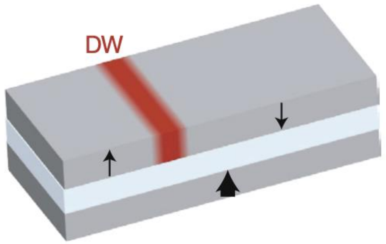
Not the focus of this talk, but several realizations exist

K. Baumgaertl and D. Grundler, “Bistable nanomagnet as programable phase inverter for spin waves,” Appl Phys Lett, **118**, 162402, (2021).

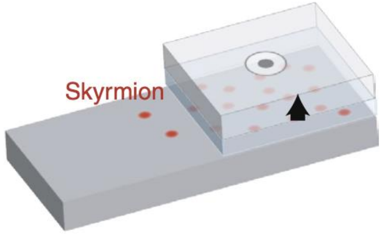
Further neuromorphic spintronic elements

Spintronic Memristors

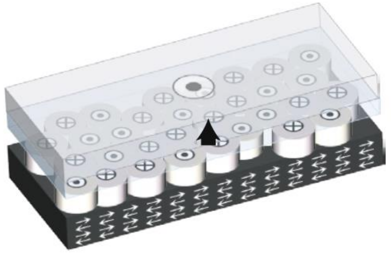
Domain walls



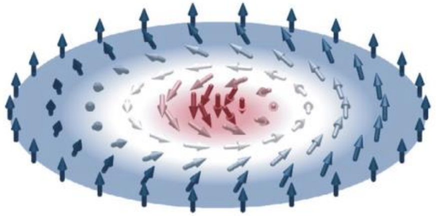
Skyrmions

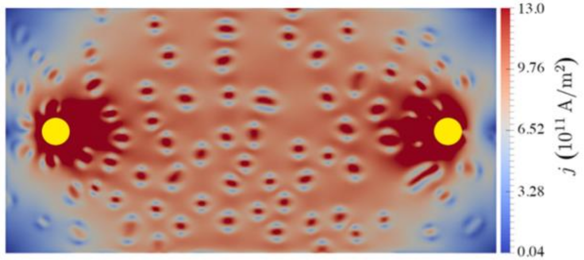


Magnetic tunnel junctions (MTJ)

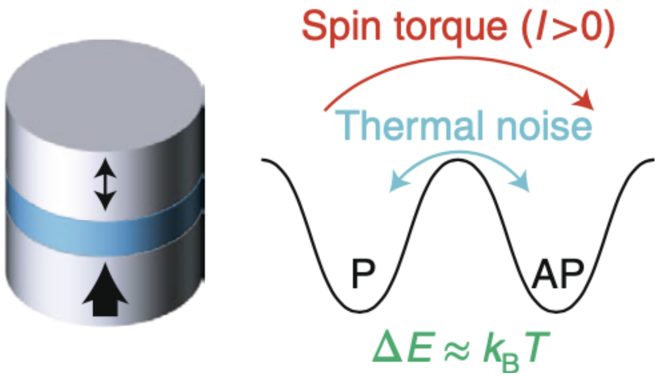


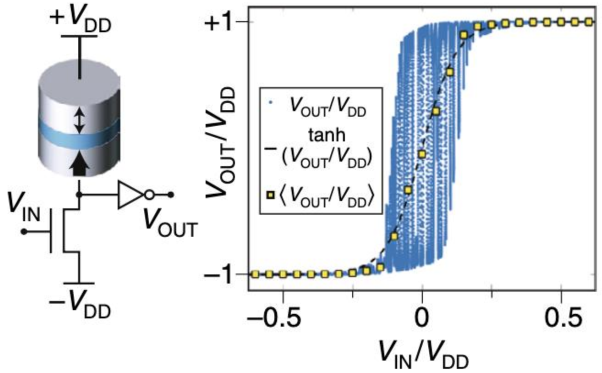
Skyrmion reservoirs





Stochastic MTJ for probabilistic computing





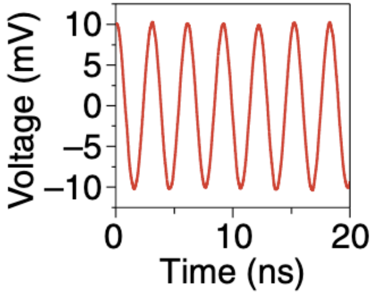
"Spintronic p-Bit"

J. Grollier, D. Querlioz, K. Y. Camsari, K. Everschor-Sitte, S. Fukami, and M. D. Stiles, "*Neuromorphic spintronics*," *Nature Electronics* **3**, 360–370 (2020).

Spintronic (auto)-oscillators

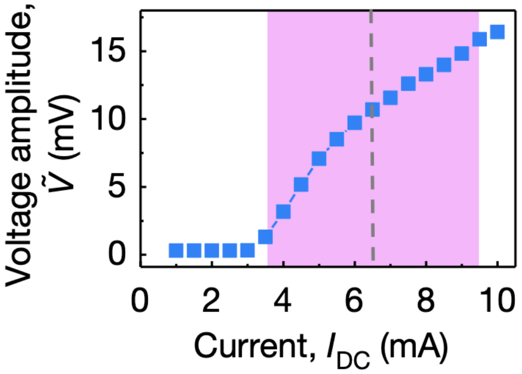
Example: **Spin torque nano-oscillator (STNO)**

MTJ

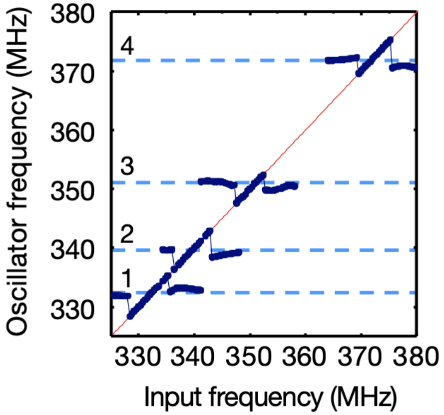


- Converts a DC electronic current in a sustained magnetic auto-oscillation
- Frequency ranges from 0.1 to several tens of GHz
- Both amplitude and frequency of the auto-oscillation depend nonlinearly on injected current, external signals

Oscillator amplitude



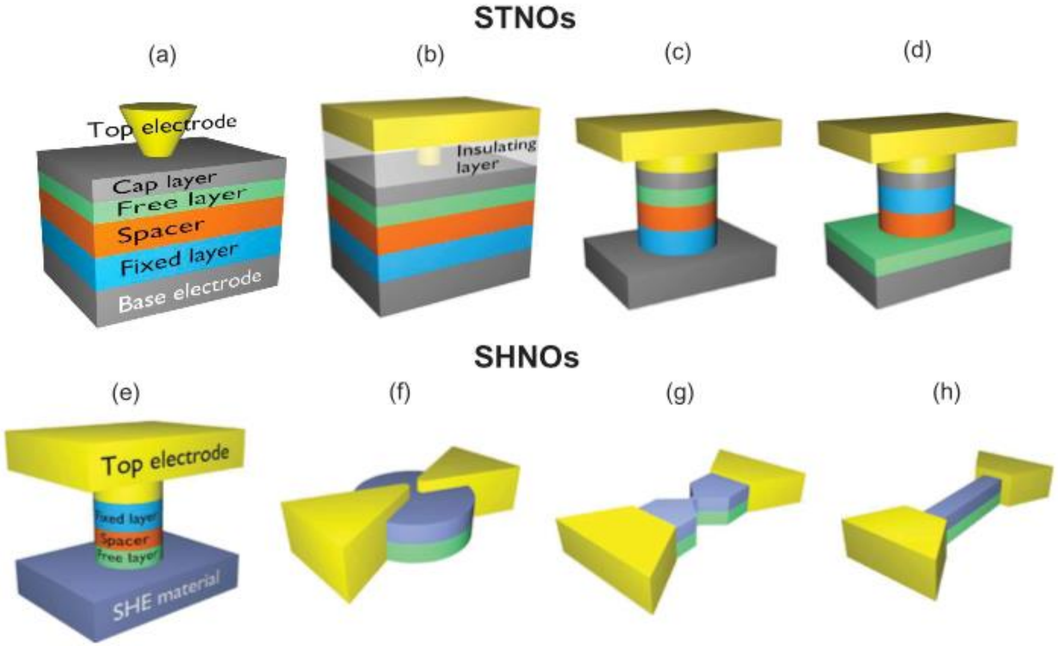
Oscillator frequency



M. Romera, *et al.*, *Nature* **563**, 230–234, (2018).
J. Torrejon, *et al.*, *Nature* **547** 428–431 (2017).

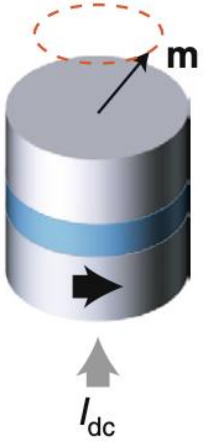
Different types of spintronic auto-oscillators (SAO)

Spin-torque nano oscillators (STNO) based on spin current injected from a fixed magnetic layer

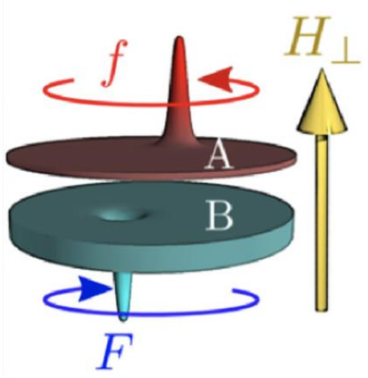


Spin Hall nano oscillators (SHNO) based on spin current injected via the Spin Hall effect in an adjacent heavy metal like Pt

T. Chen, *et al., Proc. IEEE*, **104**, 1919–1945 (2016).



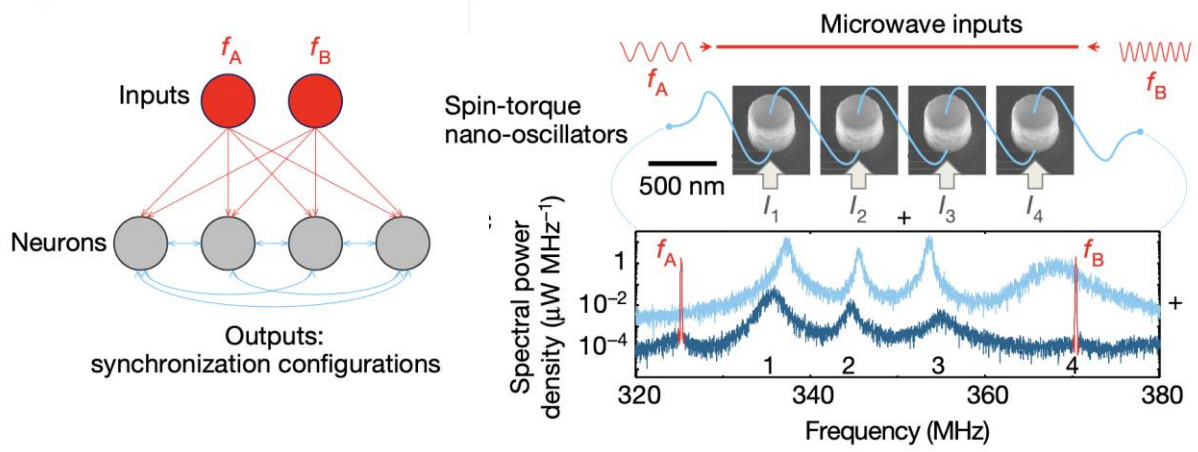
Uniformly magnetized oscillators

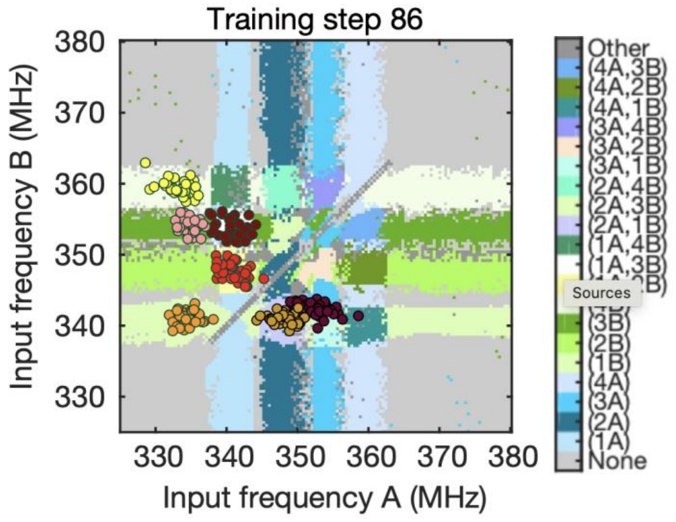


Vortex oscillators

J. Torrejon, *et al.* *Nature*, 547 428–431 (2017).
A. Hamadeh, *et al*. Phys. Rev. Lett., 112, 257201 (2014).

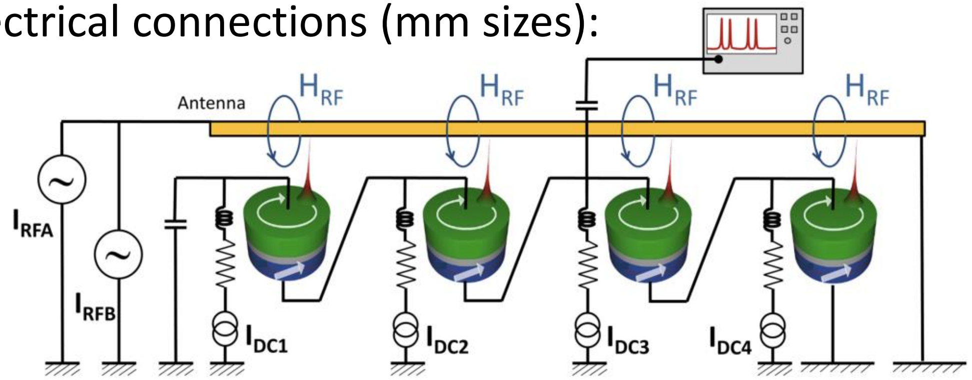
Spintronic auto-oscillators for neuromorphic computing





Each color represent a different synchronization state

Electrical connections (mm sizes):

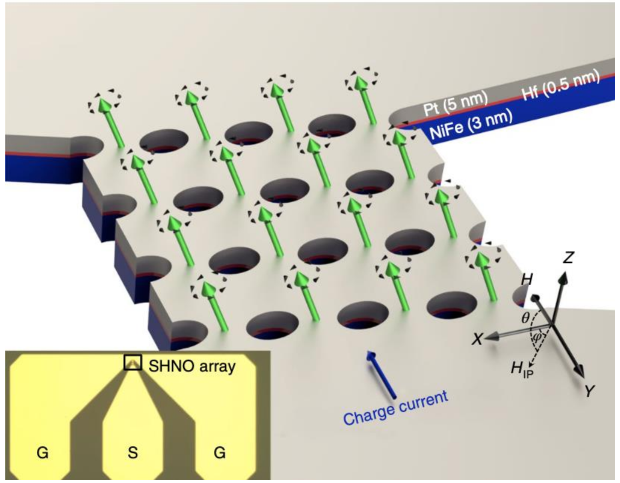


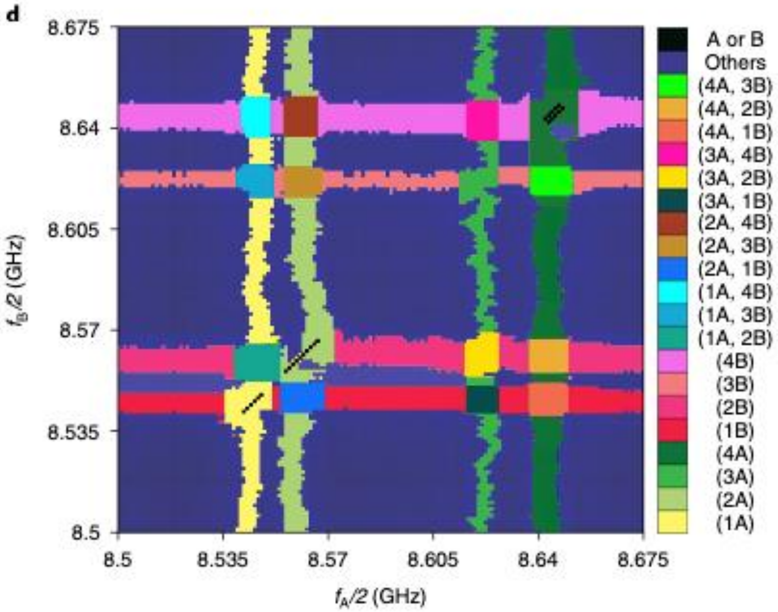
- Electrically coupled **SAOs synchronize to external microwave signals** representing the input data
- Training: Oscillator frequencies are tuned electrically by changing the DC current
- After training, vowel is recognized from the synchronization state: which oscillators synchronizes to which input frequency

M. Romera, *et al.*, “Vowel recognition with four coupled spin-torque nano-oscillators,” Nature **563**, 230–234, (2018).

Spintronic auto-oscillators for neuromorphic computing

Similar approach is possible using Spin Hall Nano Oscillators…





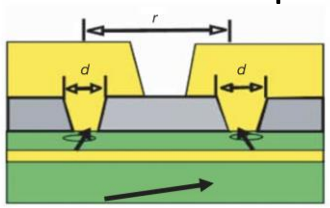
Synchronization map

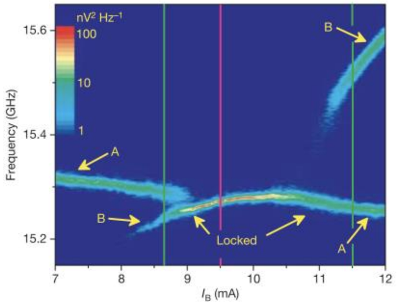
However, challenge to change the connection between oscillators and to adjust individual oscillators for training…

M. Zahedinejad, *et al.*, *Nature Nanotech*., **104**, 1–6, (2019).

Spin-wave based synchronization of SAOs

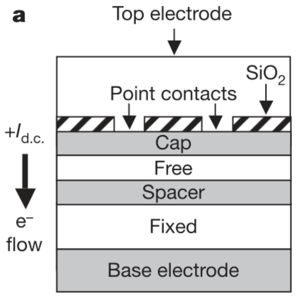
Synchronization for
max. 500 nm separation

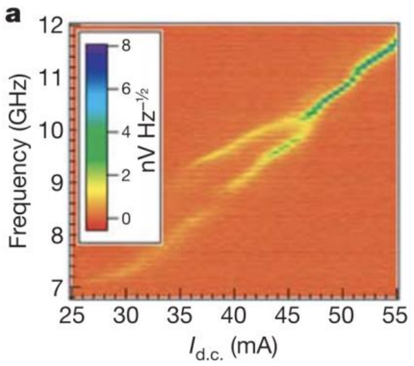




Spin-wave medium:
5 nm NiFe

S. Kaka, *et al.*,
Nature **437**, 389–392 (2005).

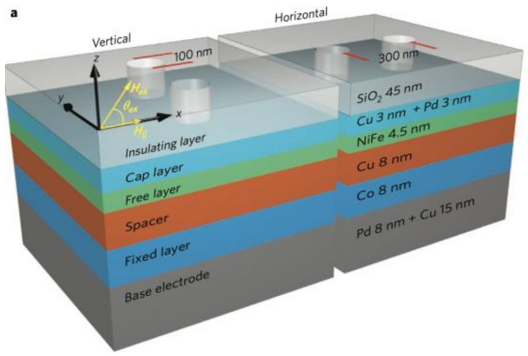




Spin-wave medium:
4.5 nm NiFe

F. B. Mancoff, *et al.*,
Nature **437** 393–395, (2005)

Synchronization for
max. 1000 nm separation



Spin-wave medium:
4.5 nm NiFe

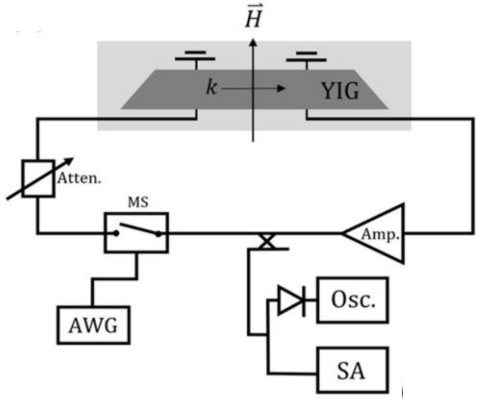
A. Houshang, *et al.*,
Nature Nanotech. **11**,280–286, (2016).

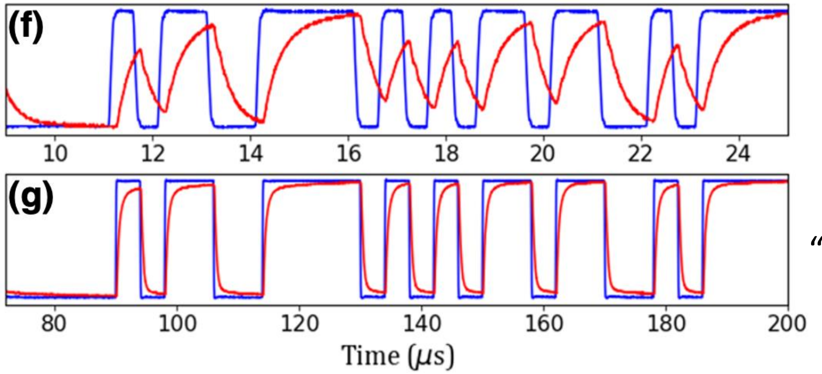
Systems are optimized for spin-toque effects, no emphasis on the magnonic aspects

- Very **small spin-wave decay length** (material, no dedicated waveguiding), **no interference effects** possible
- Only applicable for closely spaced SAOs with **next-neighbor coupling**, **no change of connections** possible

Pure magnonic neuromorphic approaches

Spin-wave delay-line active-ring resonator system





input pulse length

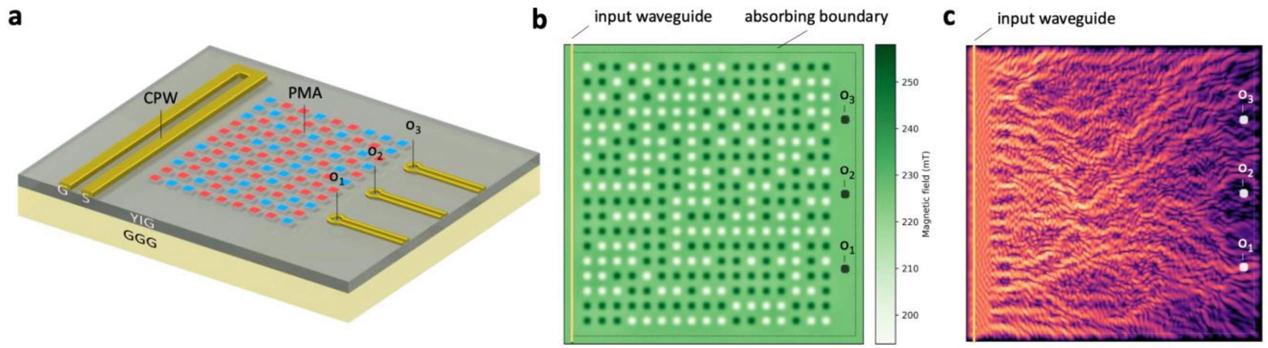
0.5 µs
“memory”

“ no memory”

S. Watt and M. P. Kostylev, Phys. Rev. Applied, 13, 034057 (2020).

- Uses strong **nonlinearity** of the spin-wave system
- Delayed response, fading memory for **reservoir computing**

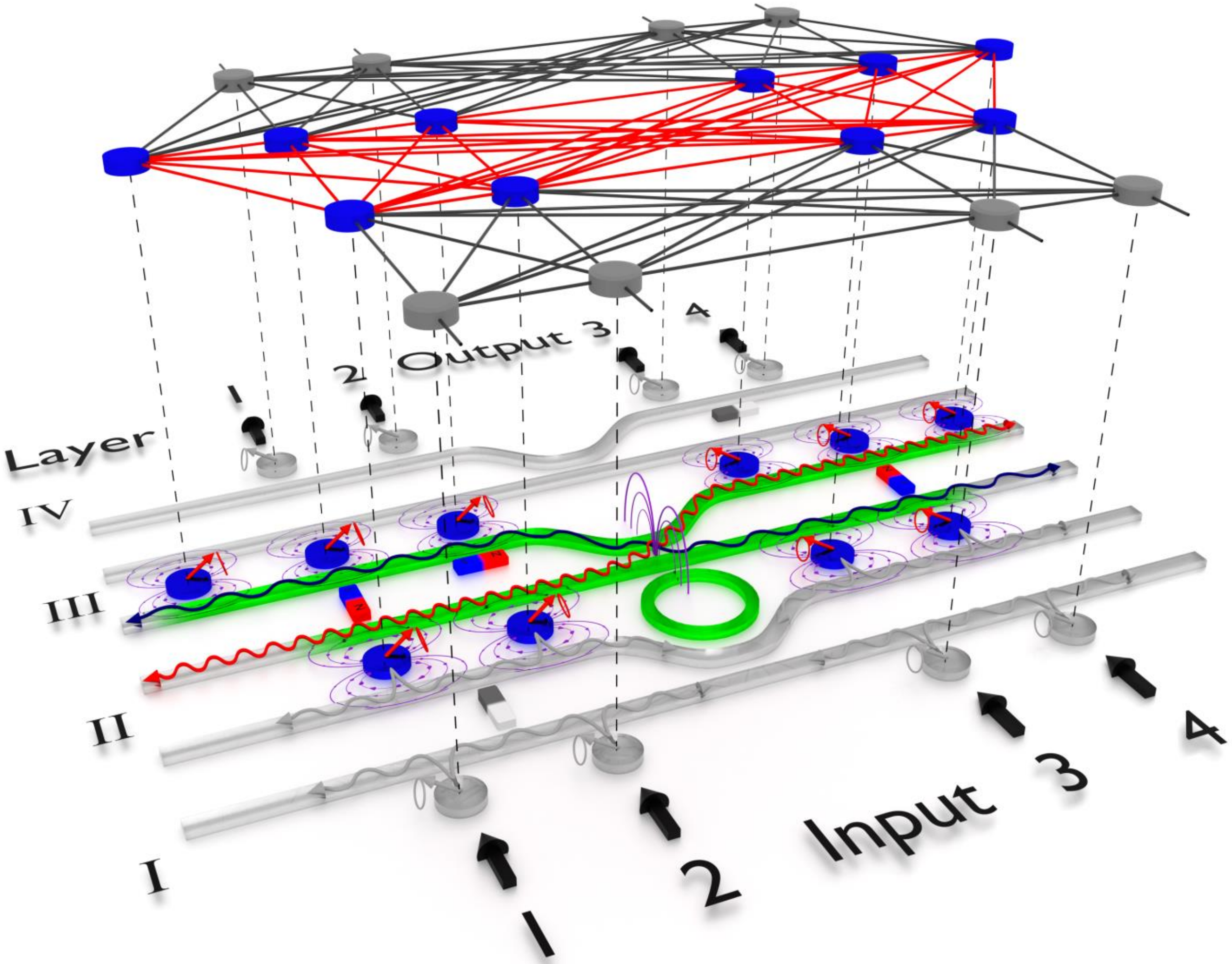
Trainable magnonic neural network



A. Papp, *et al*., arXiv: 2012.04594v1 (2020)

- Uses strong **nonlinearity** of the spin-wave system
- Small permanent magnets to train the system for **pattern recognition**

Our concept



Artificial Neurons: spintronic auto-oscillators (SAO)
Nanoscaled objects with high intrinsic nonlinearity

Interconnects: coherent spin waves

- Artificial synapses created by ultralow-damping magnonic nano-conduits
- Including coherent coupling effects, interference, spin-wave nonlinearity and frequency multiplexing

Theory for SAO coupled by spin waves

Extended Kuramoto model for the coupling of nonlinear oscillators by waves:

c_n: amplitude of oscillator *n* p_n : power of oscillator *n*

$\Omega_{n,m}$: **coupling strength** between two SAOs

$\beta_{n,m}$: **coupling phase** between two SAOs

$$\underbrace{\frac{dc_n}{dt} + \left[\mathrm{i}\,\omega_n(p_n) + \Gamma_{+,n}(p_n) - \Gamma_{-,n}(p_n)\right]c_n}_{\text{Dynamics of free running oscillator } n} = \underbrace{\sum_m \Omega_{n,m} \cdot e^{\mathrm{i}\beta_{n,m}}\, c_m}_{\text{Coupling of oscillator } n \text{ to other oscillators } m \text{ (via SW)}} + \underbrace{f(t)}_{\text{External force}}$$

Dynamics of free running oscillator *n*

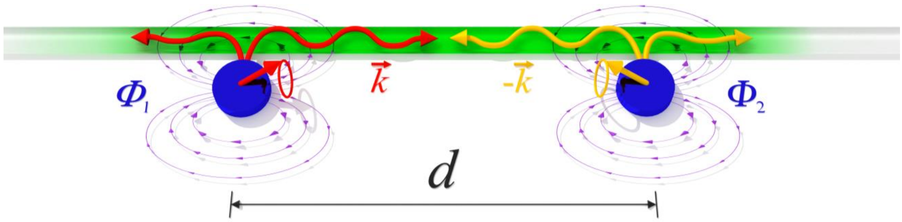
Coupling of oscillator *n* to other oscillators *m* (via SW)

External force

$\Omega_{n,m} \propto \frac{\mathbf{1}}{\boldsymbol{d}} e^{-d_{n,m}/\delta}$ for unguided spin-waves in an infinite thin film

$\Omega_{n,m} \propto e^{-d_{n,m}/\delta}$ for spin waves guided in a waveguide

$\beta_{n,m} = k \cdot d$ for spin-wave with wave vector k

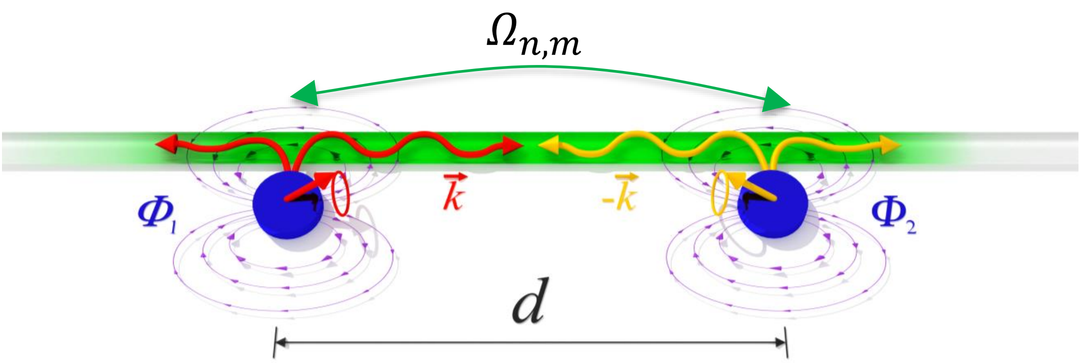


δ: exponential spin-wave decay length

*A. Slavin and V. Tiberkevich, "Nonlinear Auto-Oscillator Theory of Microwave Generation by Spin-Polarized Current," IEEE Trans. on Magn, **45**, 1875–1918 (2009).*

Increasing connectivity range

High coupling strength also for large distances:



$\Omega_{n,m} \propto \frac{\mathbf{1}}{\boldsymbol{d}} e^{-d_{n,m}/\delta}$ for **unguided** spin-waves in an infinite thin film

$\Omega_{n,m} \propto e^{-d_{n,m}/\delta}$ for spin waves guided **in a waveguide**

→ Switching to guided waves removes geometrical decay

Need to maximize the **spin-wave decay length** δ to increase the coupling:

$$\delta = \tau \cdot v_g$$

Spin-wave lifetime

Spin-wave group velocity

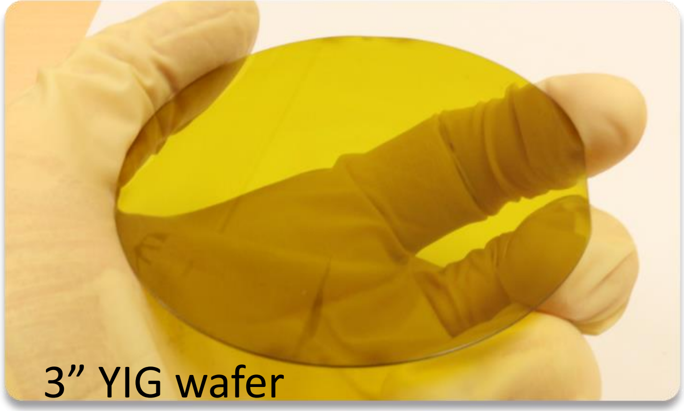
Depends on

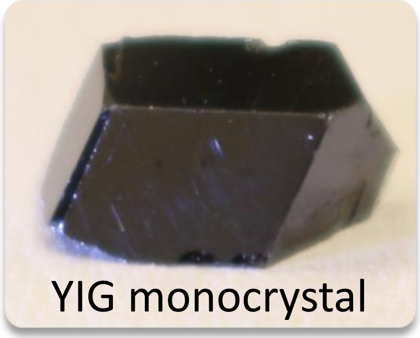
(Mainly) material

Dispersion relation (material, geometry, wave vector…)

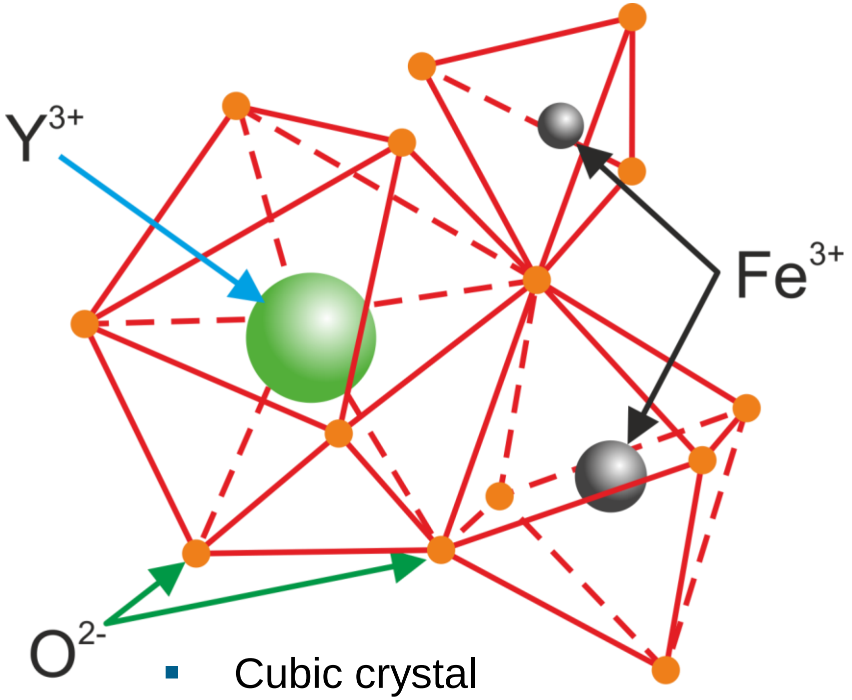
Yttrium Iron Garnet (YIG, $Y_3Fe_5O_{12}$)

- Room temperature ferrimagnet ($T_C = 560$ K)
- Low phonon damping
- Magnon lifetime up to 500 ns !





Scientific Research Company "Carat", Lviv, Ukraine



- Cubic crystal
- Lattice constant 12.376 Å
- Unit cell – 80 atoms

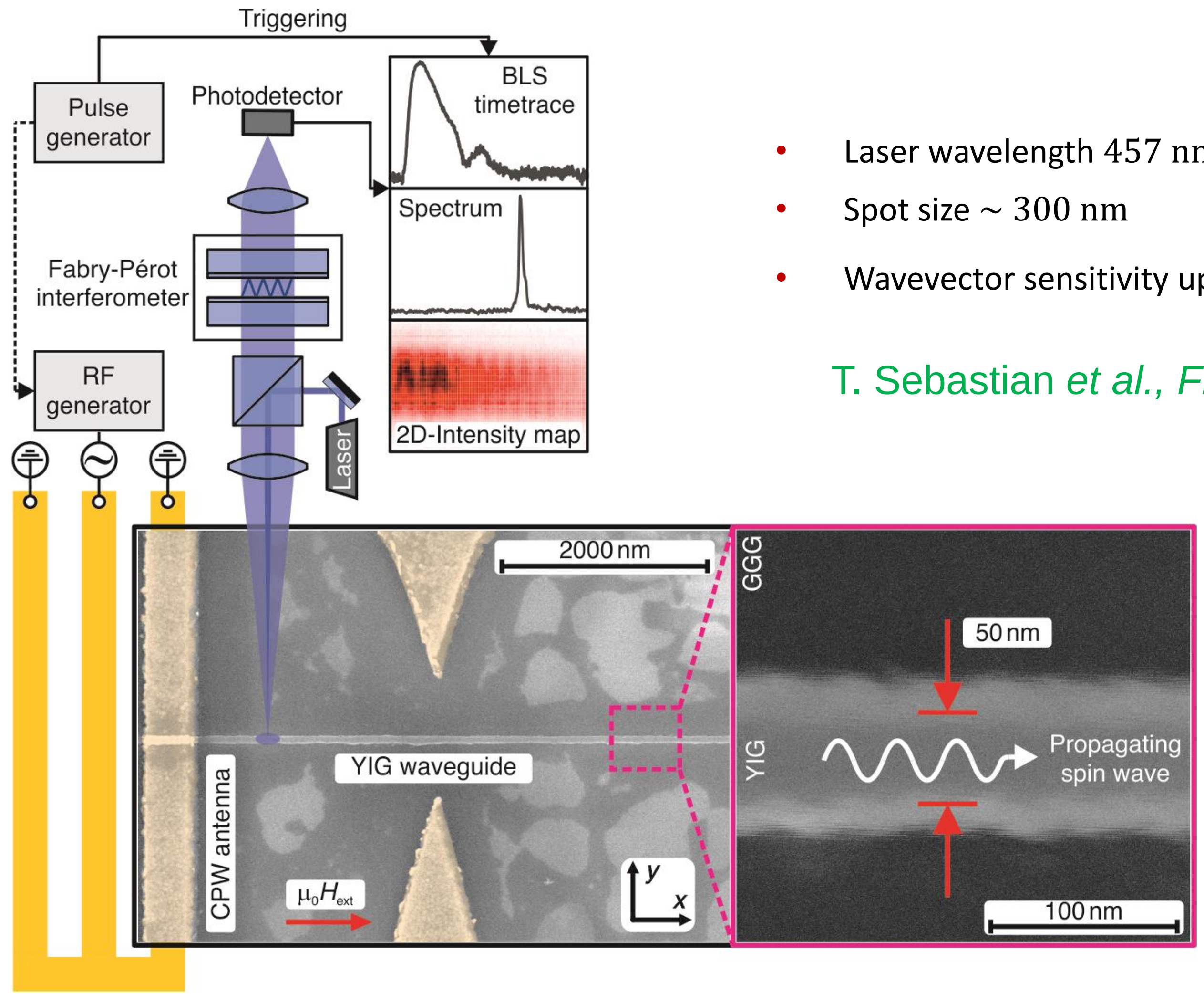
8 octahedral iron atoms (spin 5/2 up)
12 tetrahedral iron atoms (spin 5/2 down)

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

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

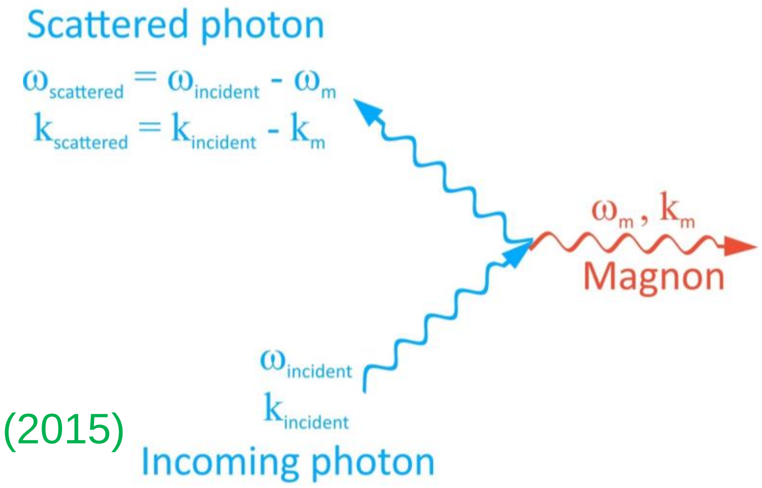
C. Dubs, *Phys. Rev. Materials*, 4, 024416, (2020).

Micro-focused Brillouin Light scattering



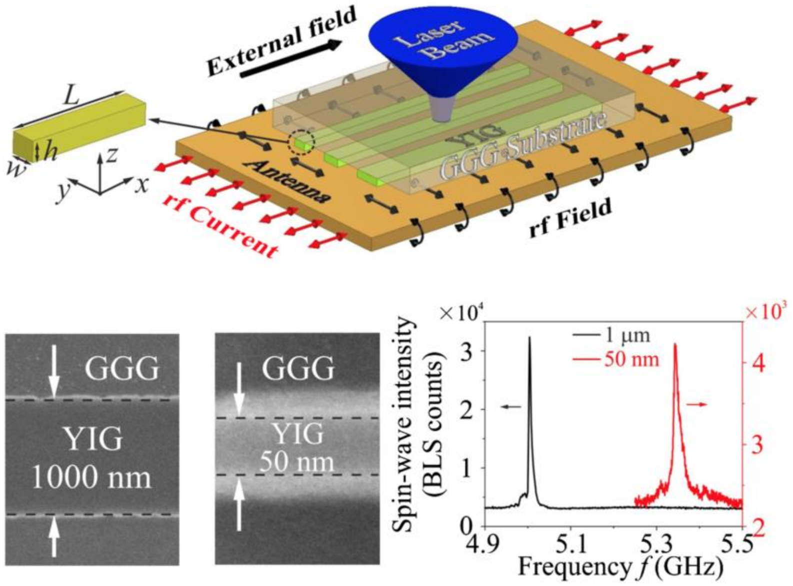
- Laser wavelength 457 nm
- Spot size ~ 300 nm
- Wavevector sensitivity up to $k_x = 24\ \frac{\mathrm{rad}}{\mu\mathrm{m}}$

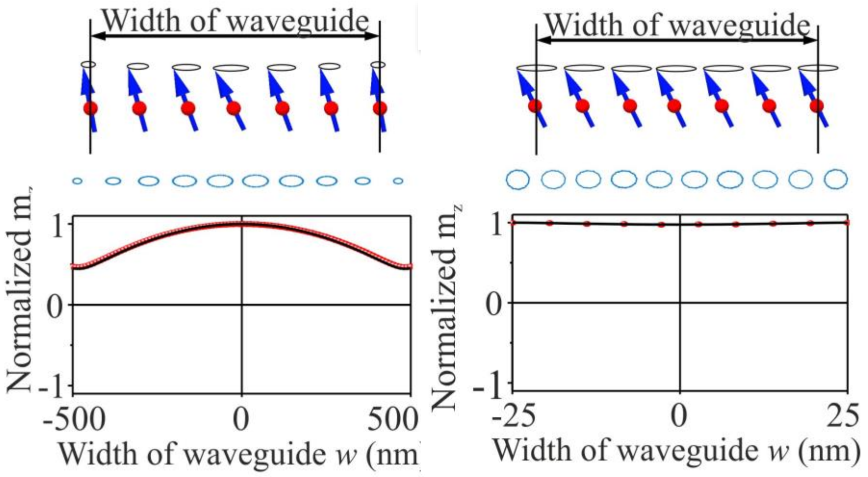
T. Sebastian *et al.*, *Front. Phys.* 3:35 (2015)



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

Spin-wave unpinning on the nanoscale





- Increase of the quantized **exchange** energy $\propto A_{ex}\left(\frac{\pi}{w_{\mathrm{eff}}}\right)^2$ leads to suppression of dipolar pinning of the modes: unpinning for waveguide widths below a critical value w_{crit}

- **Unpinning increases the dynamic dipolar coupling between nanostructures**
  → key factor for directional coupler, ring resonator, coupling to spintronic auto-oscillators…

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

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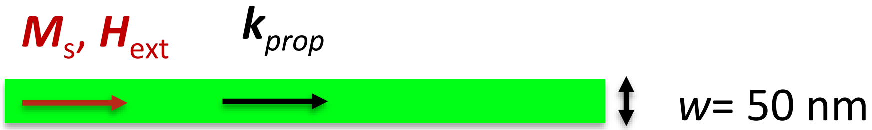
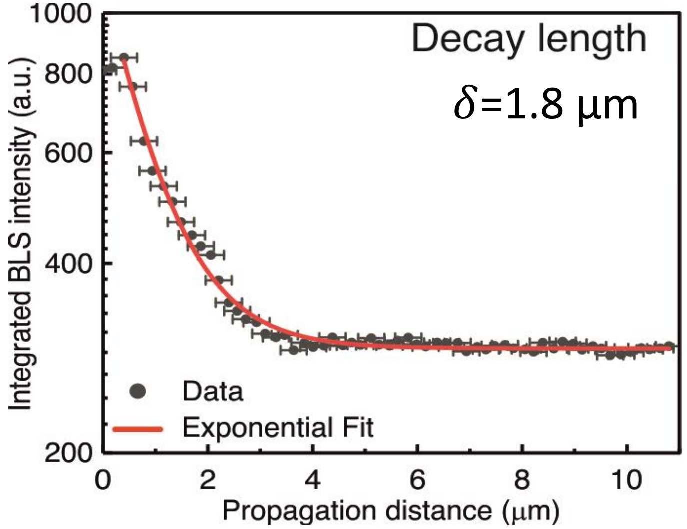
Decay length in 50nm wide YIG waveguides

“Backward Volume Geometry”

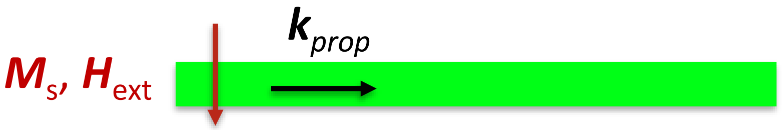


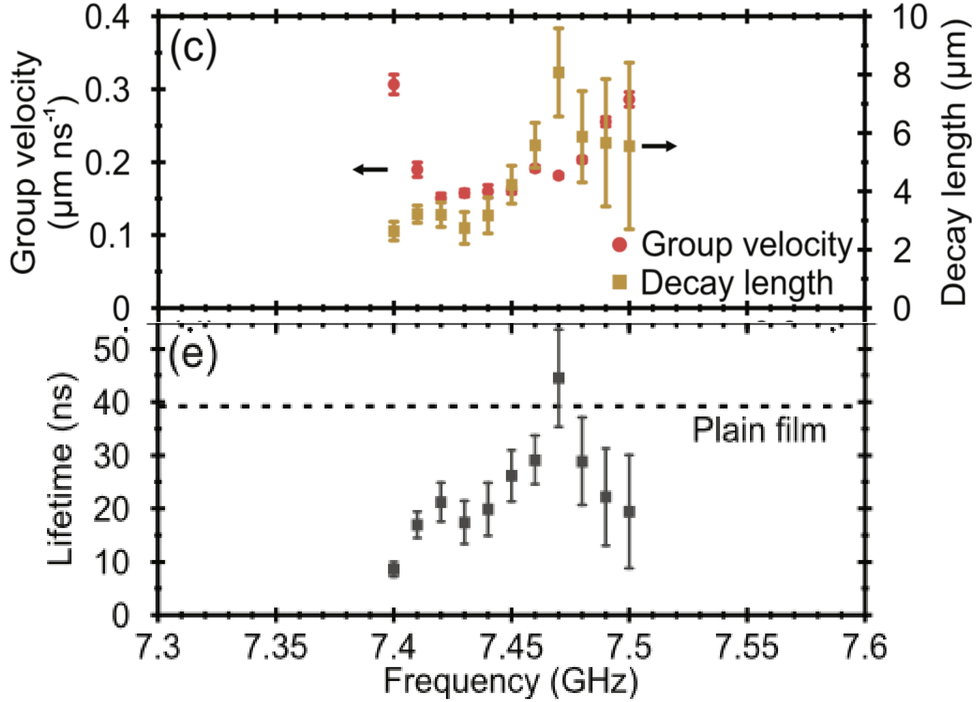


- Decrease of exponential decay length δ for small width due to drop in group velocity of dipolar spin waves

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

“Surface wave geometry”

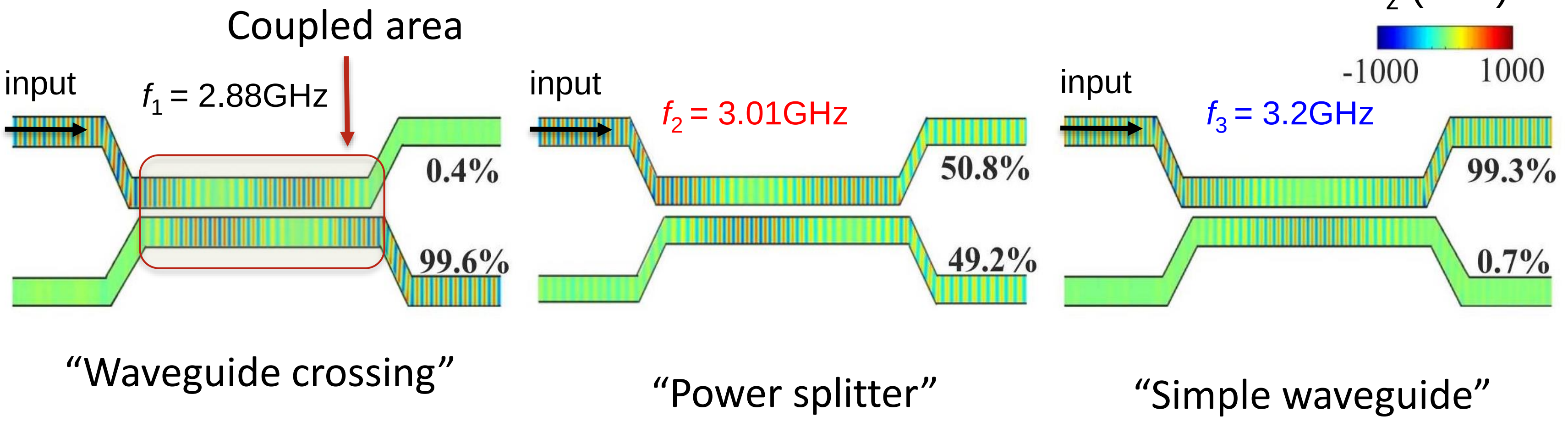


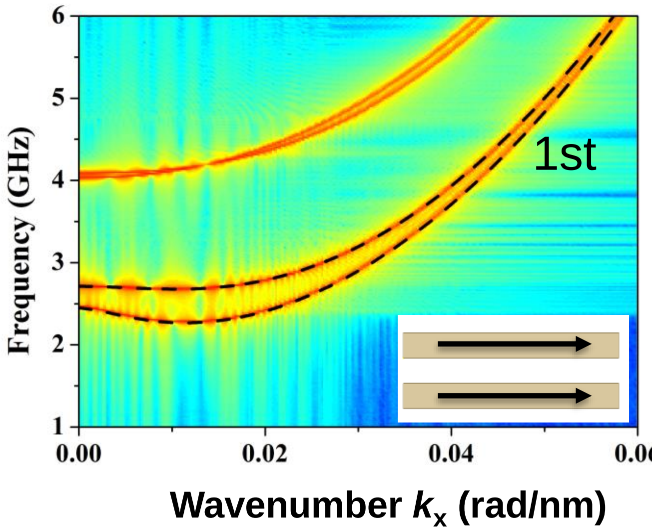


- **Long-range spin-wave propagation in transversely magnetized nano-scaled conduits**:
  exponential decay length **δ> 5µm**

B. Heinz, PP, et al., *APL* **118**, 132406, (2021).

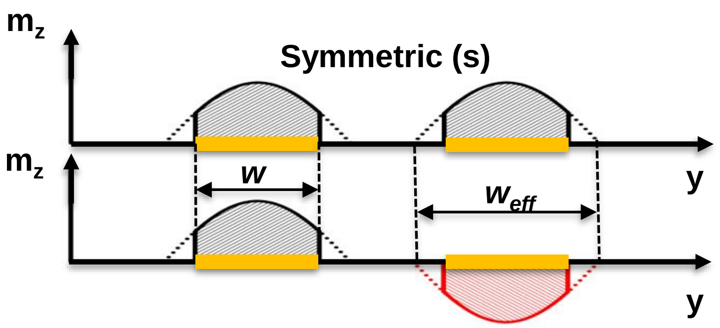
Spin-wave directional coupler





Coupling length depends on **wavelength/frequency** and **magnetic field**

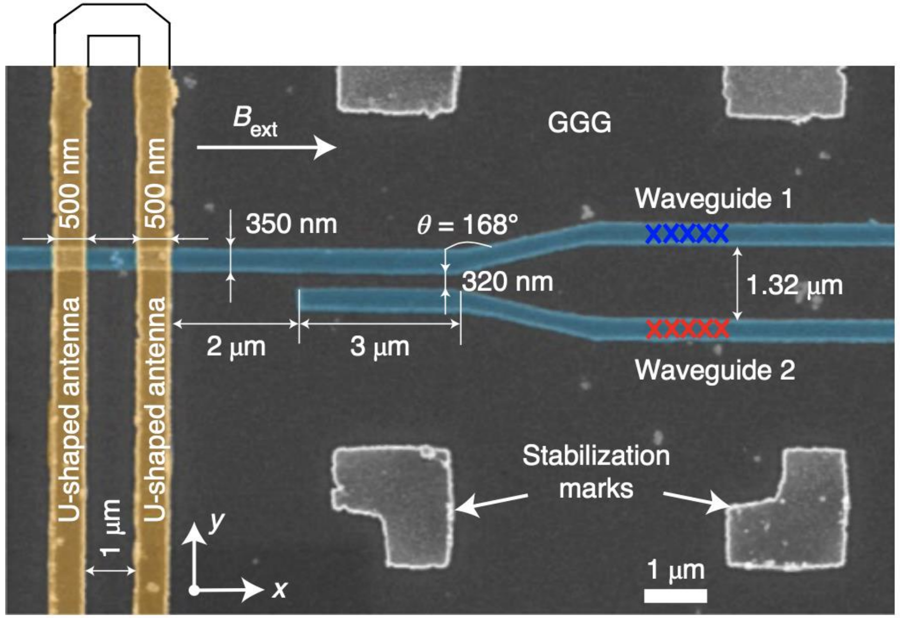
→ Switching of functionality with changing wavelength: crossing, power splitter, simple waveguide



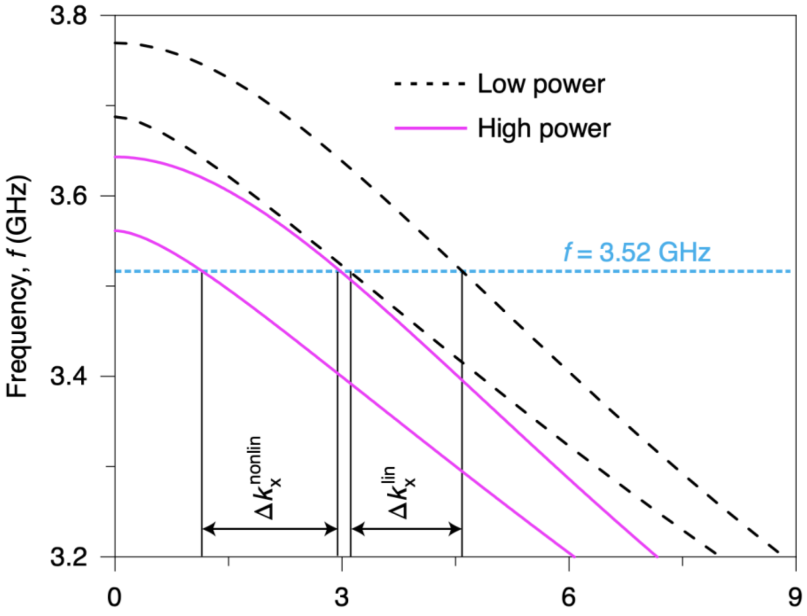
Q. Wang, PP, *et al.*, Science Advances **4**, e1701517 (2018)

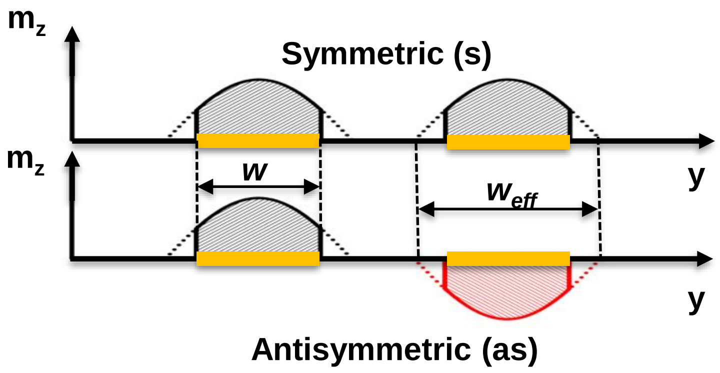
Nonlinear spin-wave directional coupler

In contrast to nonlinear SAO, nonlinear spin-wave devices usually work at **fixed frequency employ a nonlinear change of the wave vector *k*:**



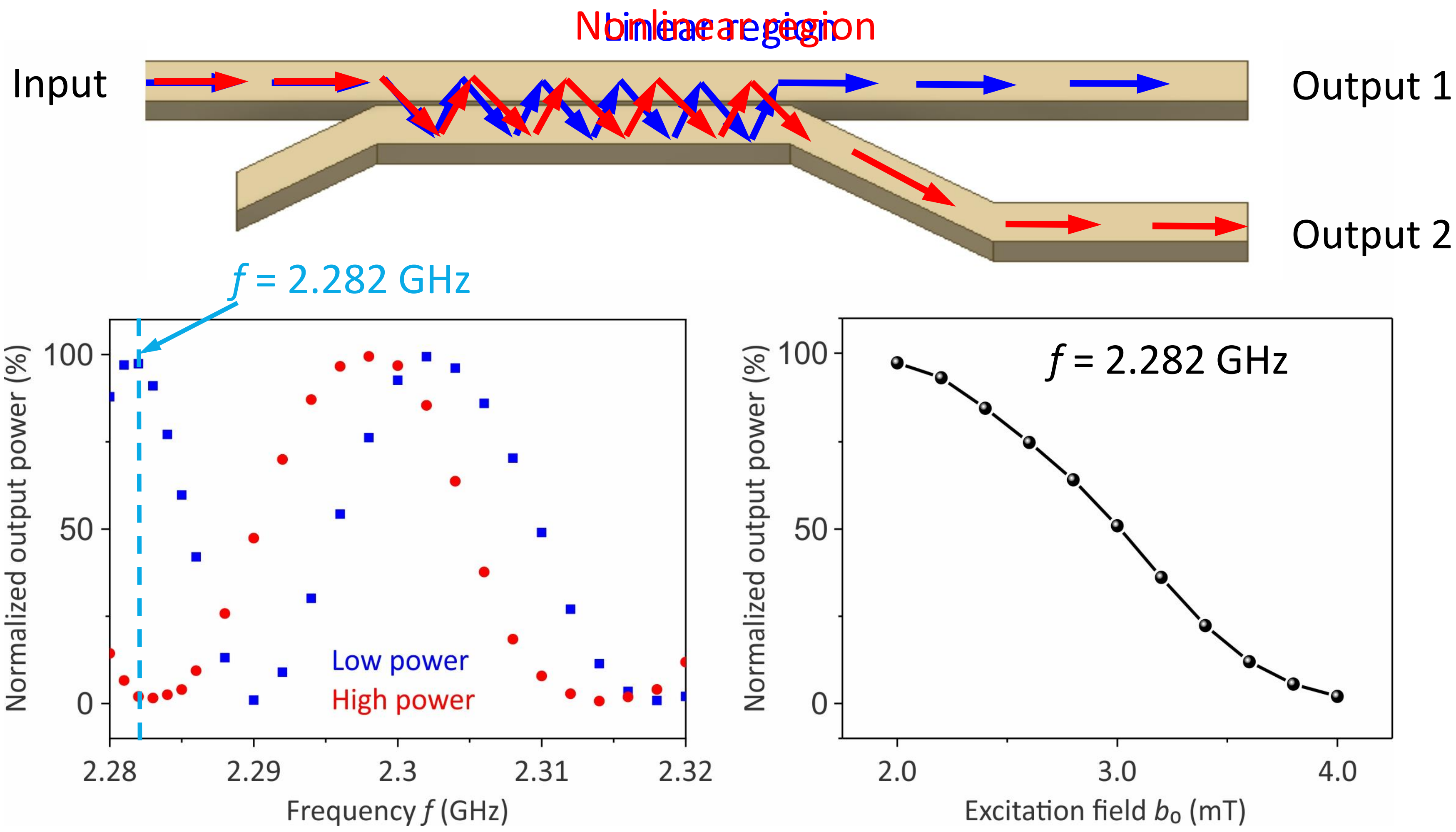
Nanoscaled directional coupler (YIG)





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

Nonlinear spin-wave coupler



Directional coupler changes the output depending on the input power

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

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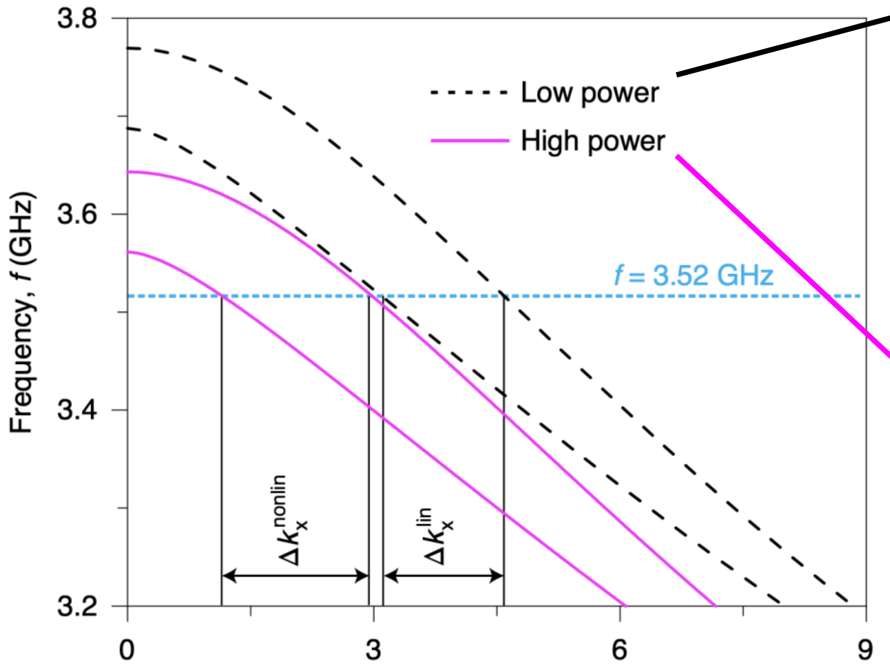
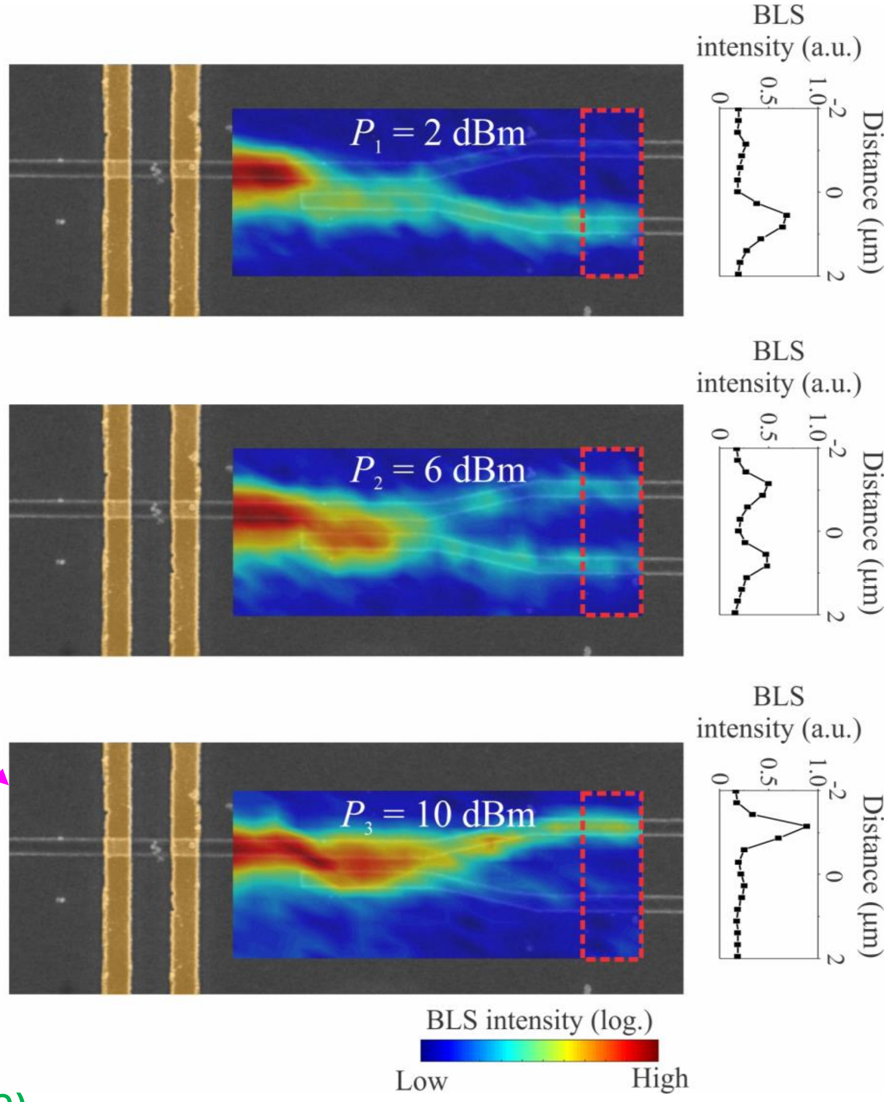
Nonlinear directional coupler: experimental validation

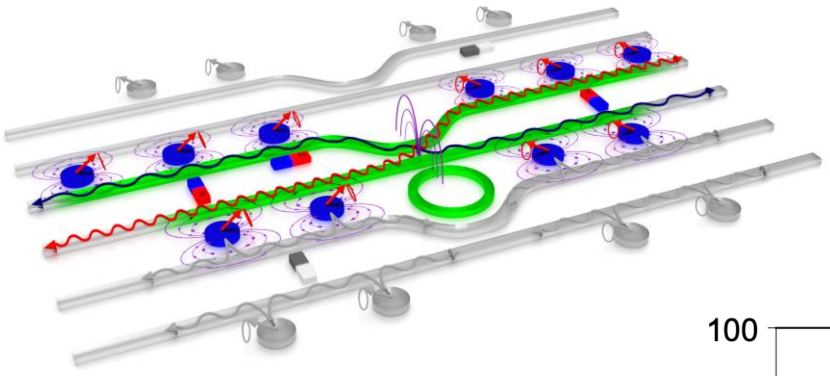




Nonlinear change of the dispersion relation leads to logic functionality

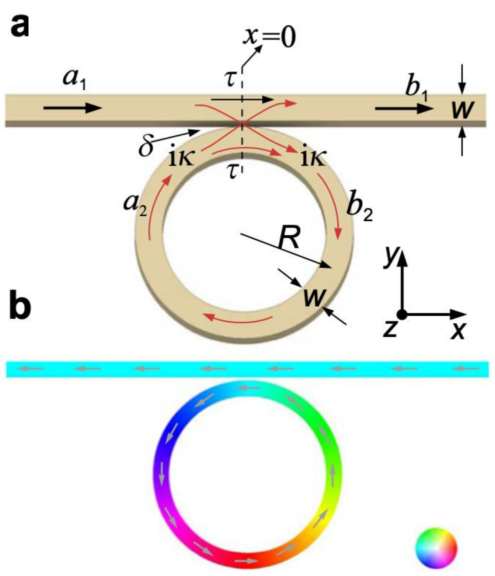
Q. Wang, PP, *et al.*, *Nature Electronics* ***3***, *765–774, (2020).*

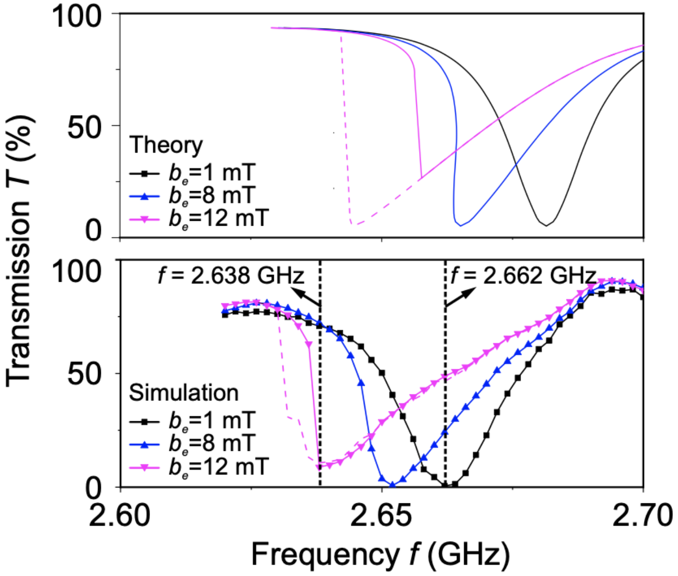
Nonlinear magnonic ring resonator

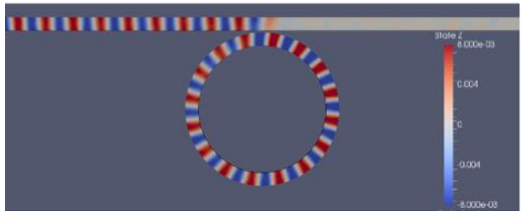


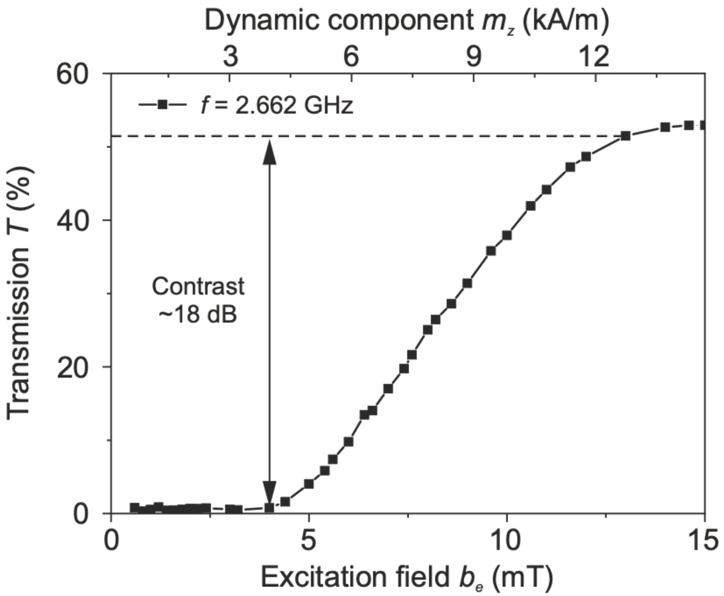
Ring resonator:

- Frequency-dependent resonance for wave multiplexing
- Intrinsic spin-wave nonlinearity to create activation function





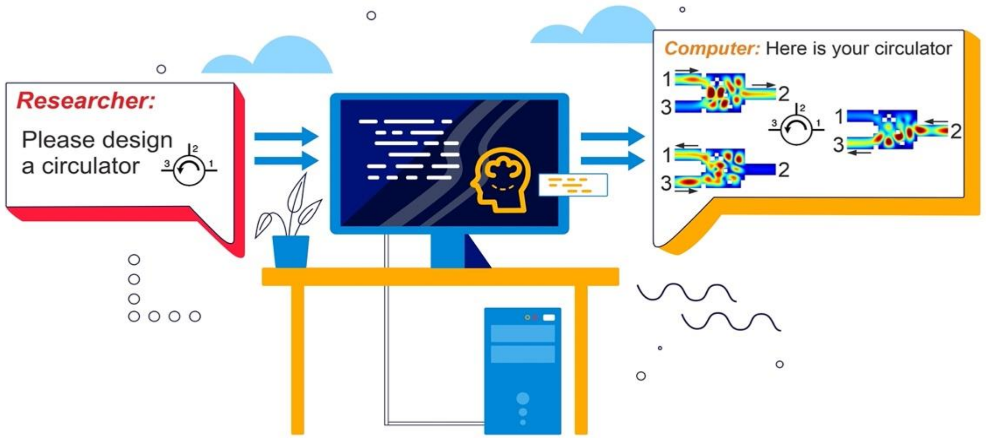




Magnonic activation function

Q. Wang, PP, *et. al.*, npj Comput Mater, 6, 453 (2020).

How to design devices faster?



Use automized optimization algorithms to run micromagnetic simulations

nature COMMUNICATIONS

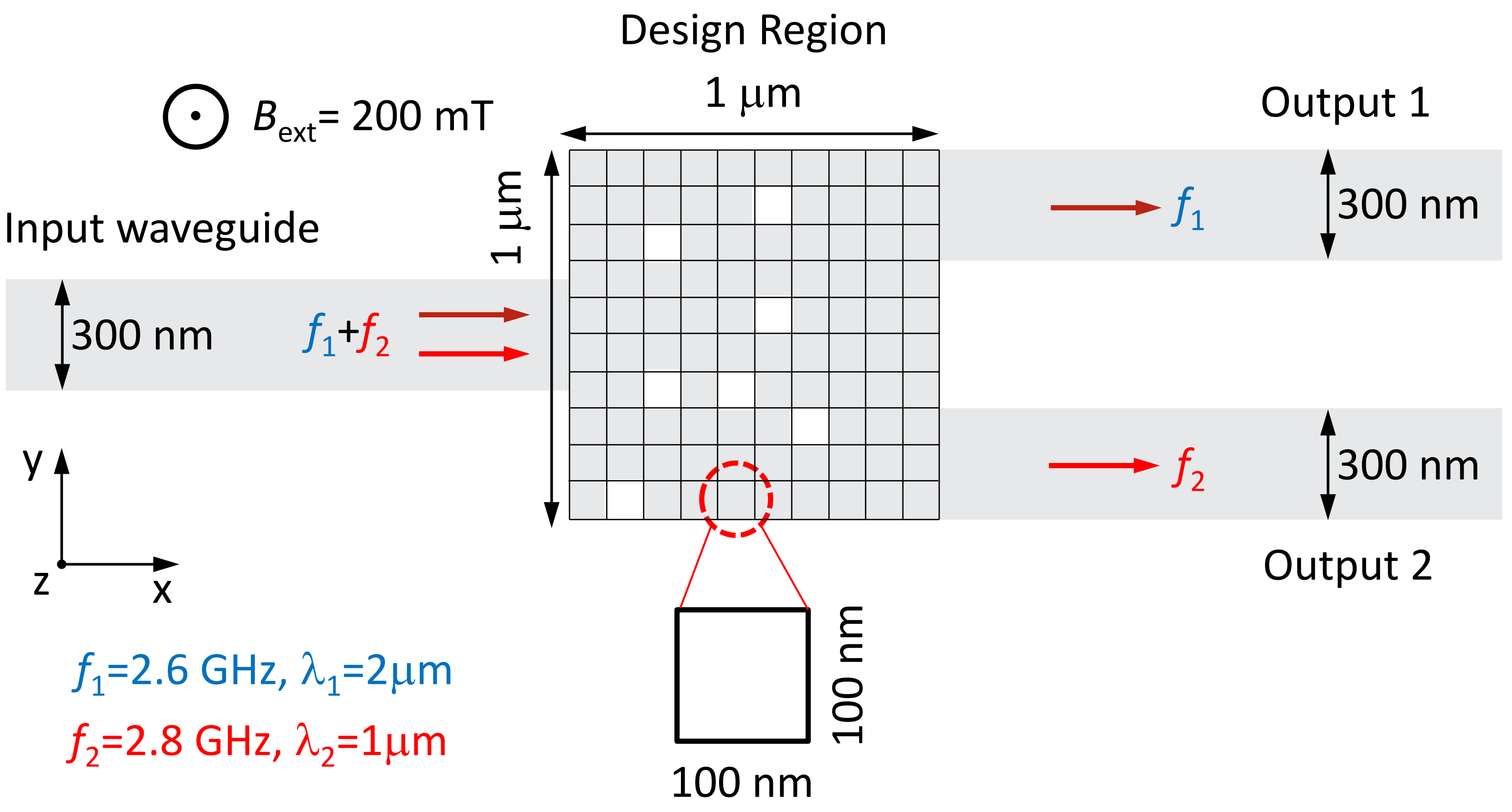
ARTICLE

https://doi.org/10.1038/s41467-021-22897-4 OPEN

Inverse-design magnonic devices

Qi Wang [1✉], Andrii V. Chumak [1] & Philipp Pirro [2]

Inverse design magnonics



f_1=2.6 GHz, λ_1=2µm

f_2=2.8 GHz, λ_2=1µm

Yttrium Iron Garnet (YIG):

$M_s = 1.4\times10^5$ A/m

A = 3.5 pJ/m

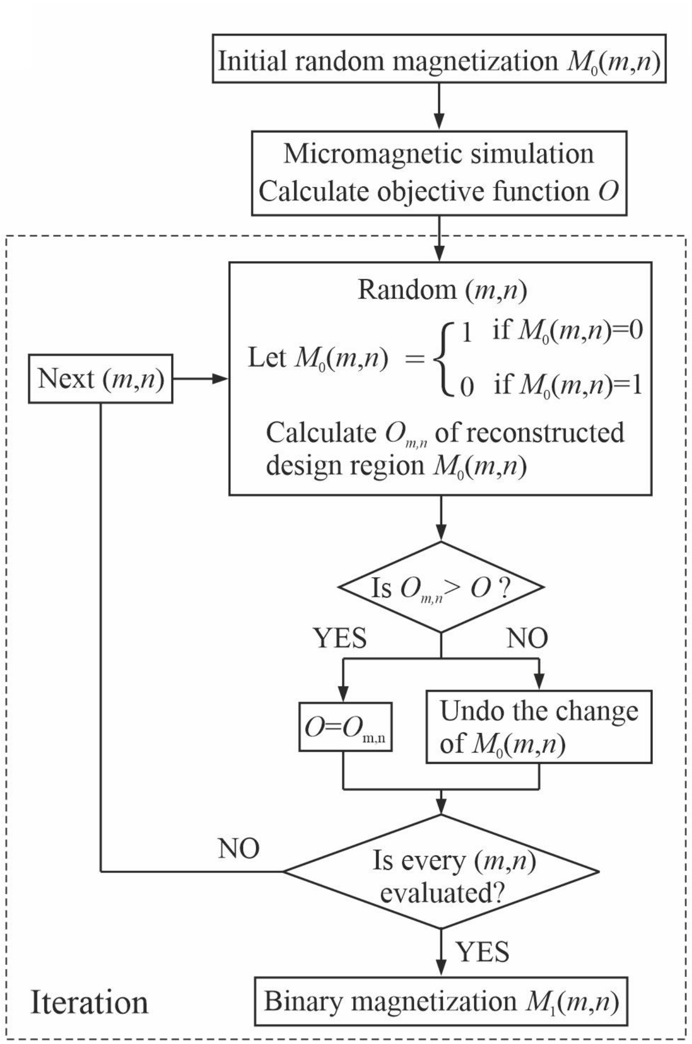
$\alpha = 2\times10^{-4}$

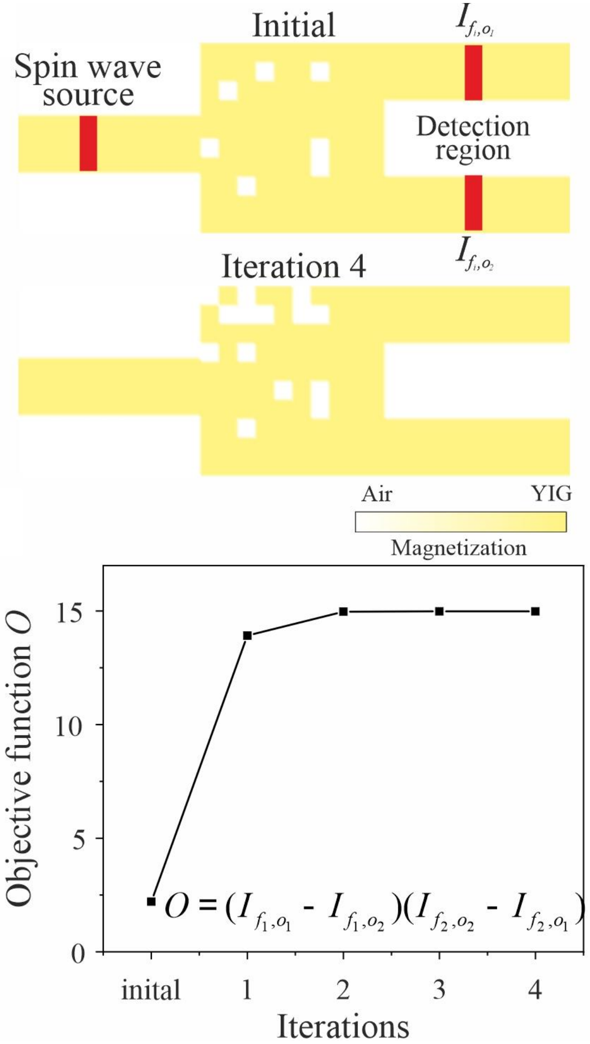
thickness = 100 nm

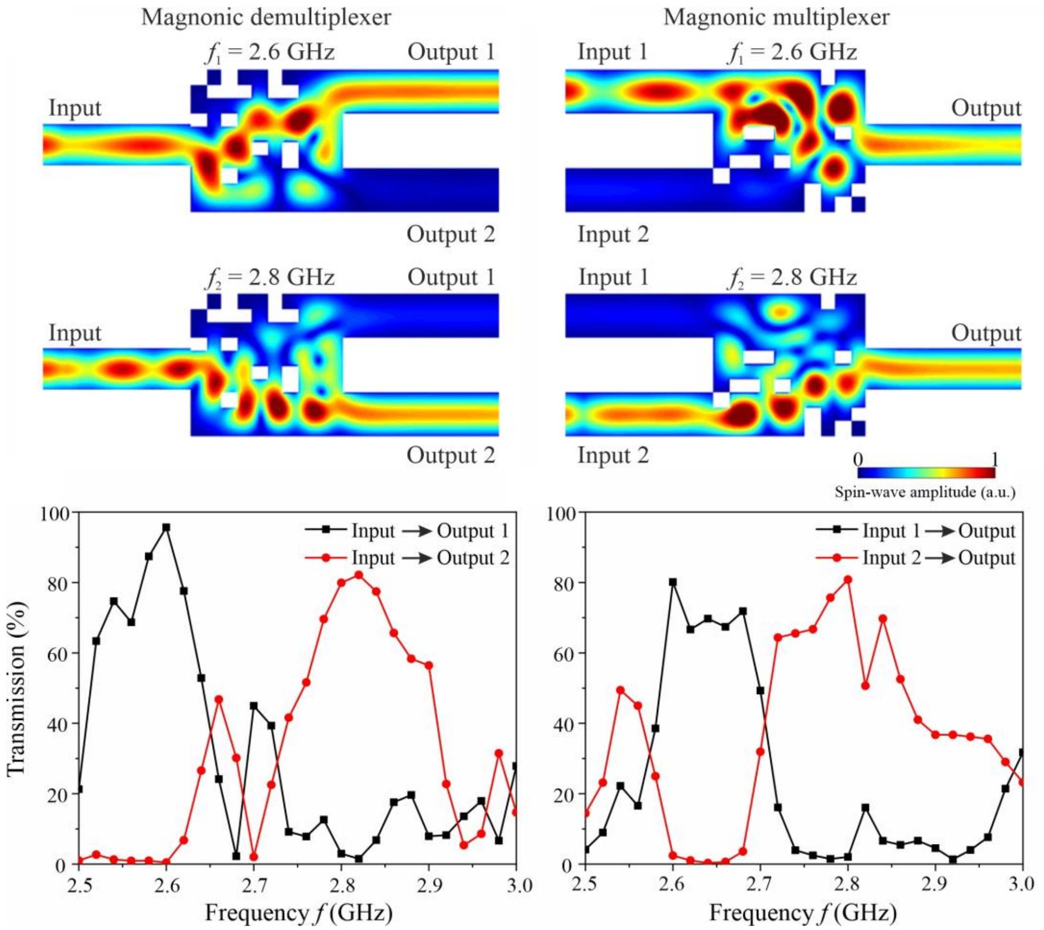
Cell size: 20 nm

Q. Wang, A. Chumak, P. Pirro, *Nature Commun.*, ***12***, *2636 (2021)*

Inverse design magnonics

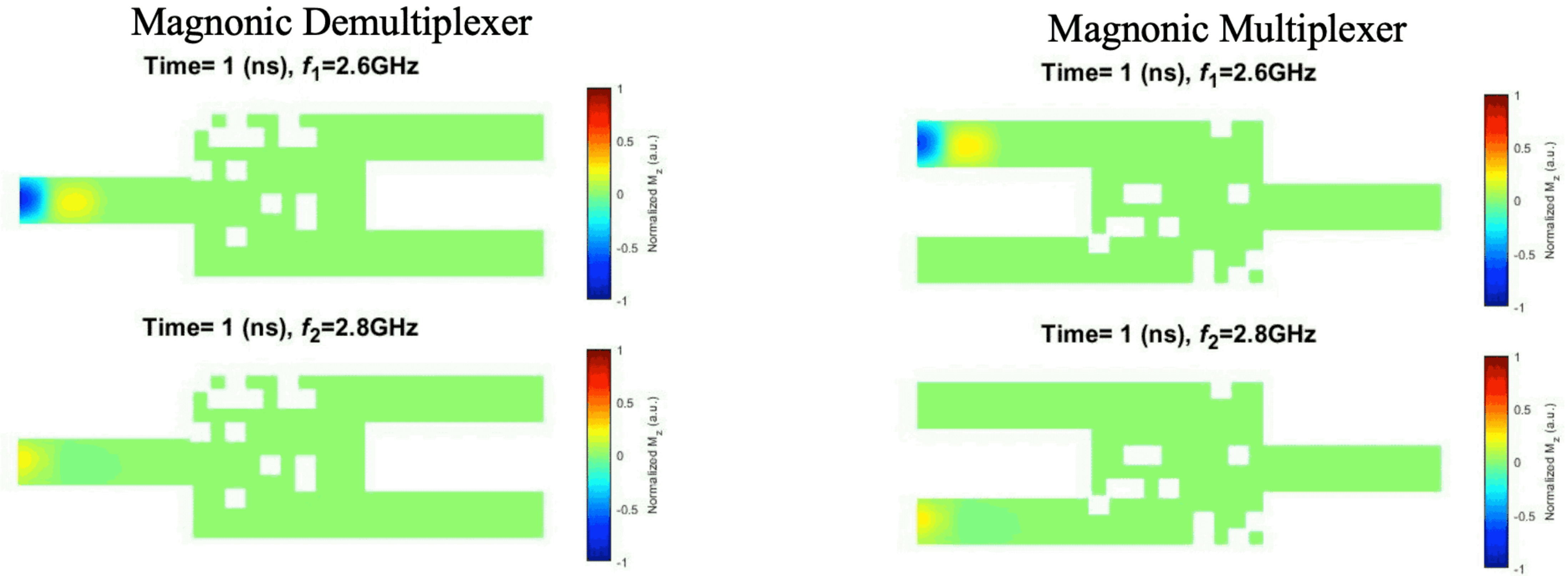






Q. Wang, A. Chumak, P. Pirro, *Nature Commun.*, ***12***, *2636 (2021)*

Inverse design magnonics: frequency multiplexer



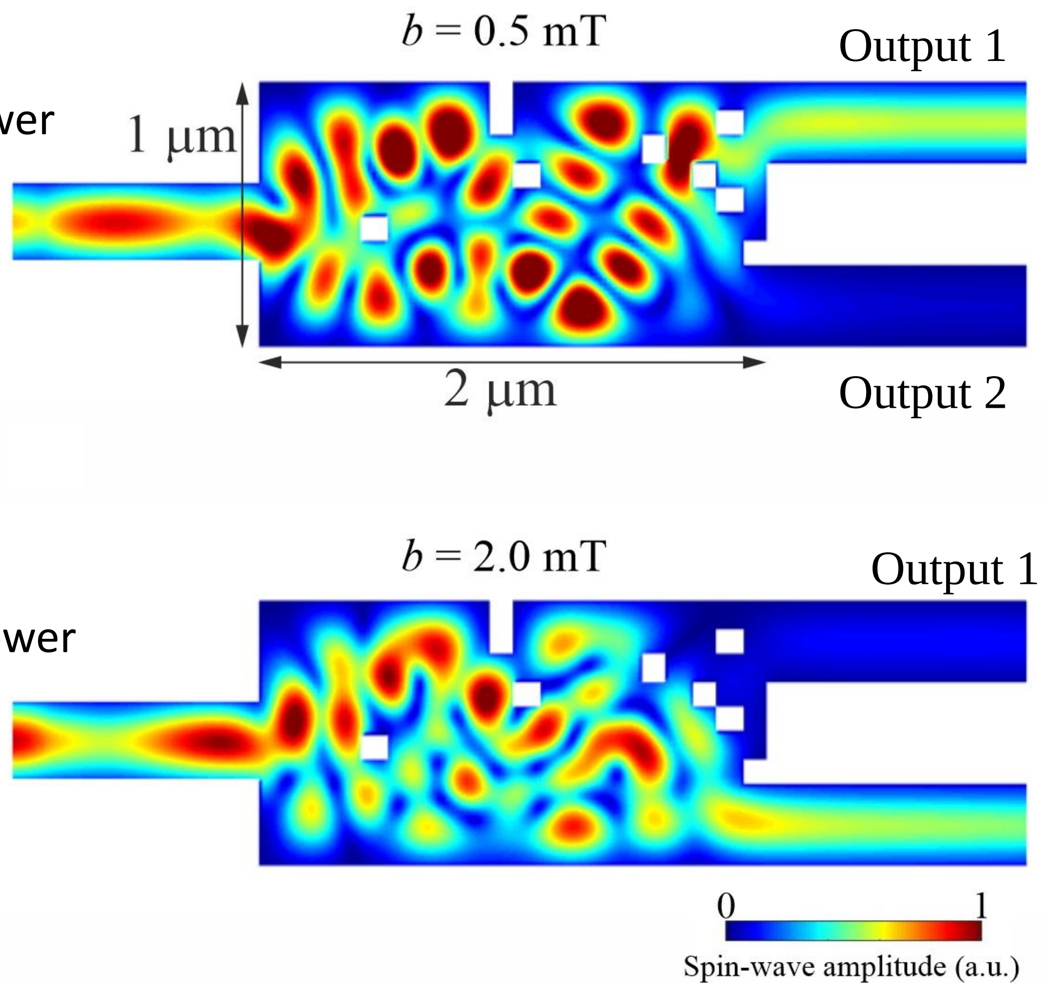
Q. Wang, A. Chumak, P. Pirro, *Nature Commun.*, ***12***, *2636 (2021)*

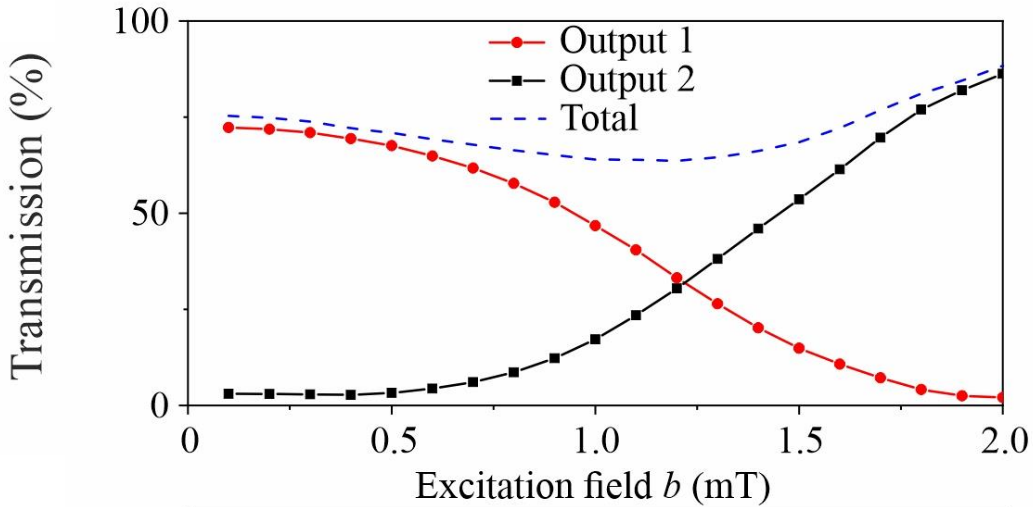
Inverse design magnonics: nonlinear systems

Objective function: $O = (I_{low,o_1} - I_{low,o_2})(I_{high,o_2} - I_{high,o_1})$

Low power

High power





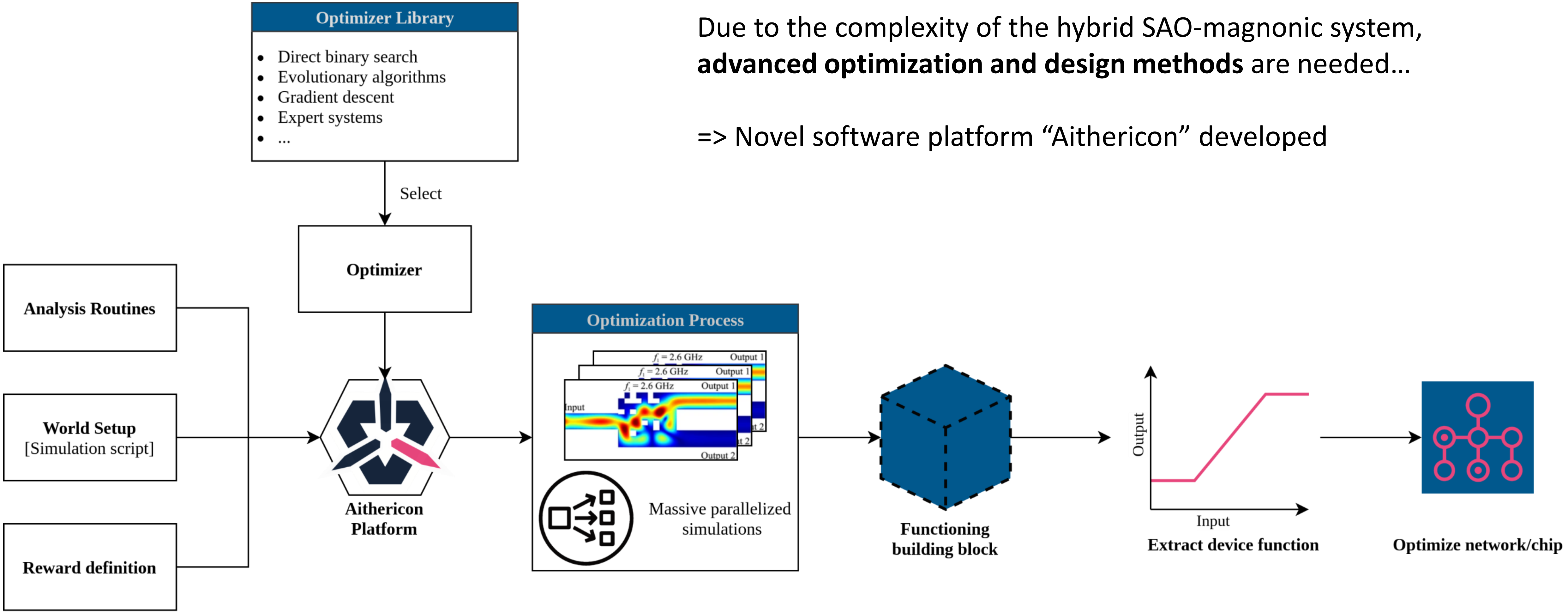
Inverse design magnonics can design linear and nonlinear magnonic devices (almost) completely automatized

Q. Wang, A. Chumak, P. Pirro, *Nature Commun.*, ***12***, *2636 (2021).*

Inverse design: next steps

Due to the complexity of the hybrid SAO-magnonic system, **advanced optimization and design methods** are needed…

=> Novel software platform "Aithericon" developed



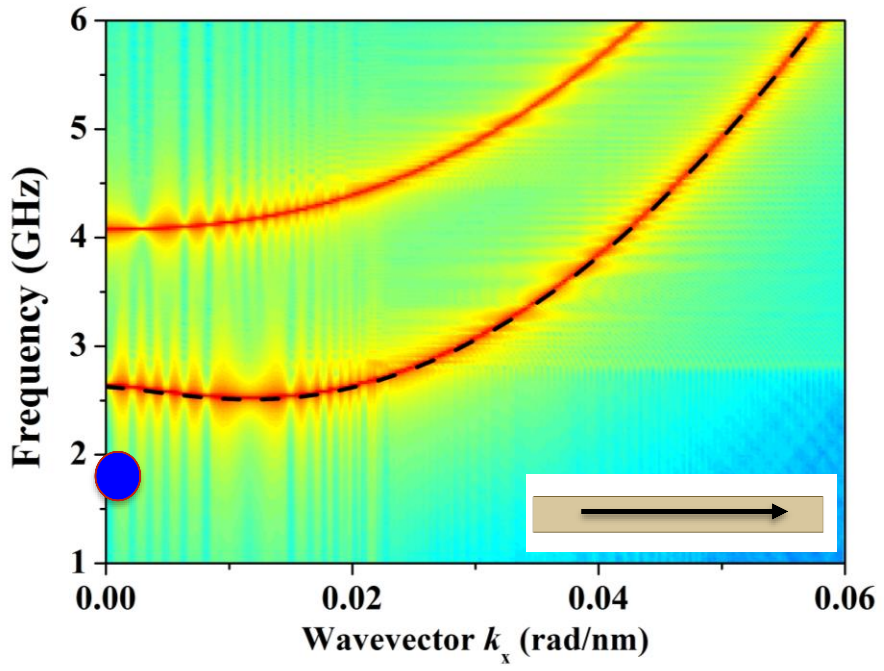
https://aithericon.com

Matching the SAO and the magnonic system

- **Frequency mismatch**: large precession amplitudes of SAO → associated nonlinear frequency shift: SAO are not well matched in their frequency to the spin-wave system in the same structure.

- Materials, film thicknesses and geometries **cannot be optimized for both systems simultaneously**

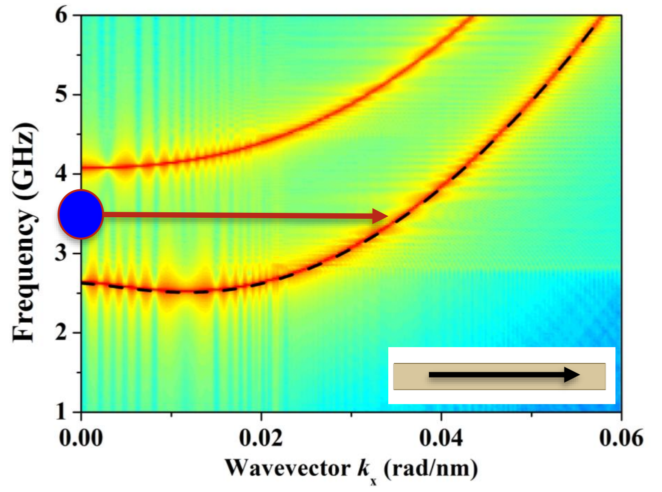
→ **Create a hybrid system with tunable coupling**



YIG spin-wave waveguide (100nm width): spin-wave dispersion relation and frequency of an auto-oscillation (blue dot) induced, e.g., by Spin Hall effects

Matching the SAO and the magnonic system

→ **Create a hybrid system with tunable coupling**



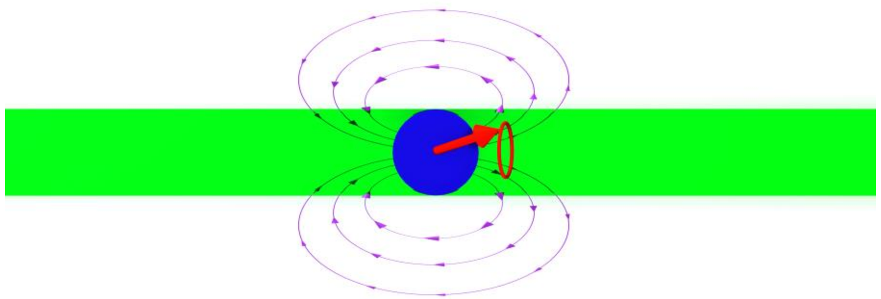
Example: NiFe-base auto-oscillator coupled to a YIG nanowaveguide

M_s=800 kA/m

M_s=140 kA/m

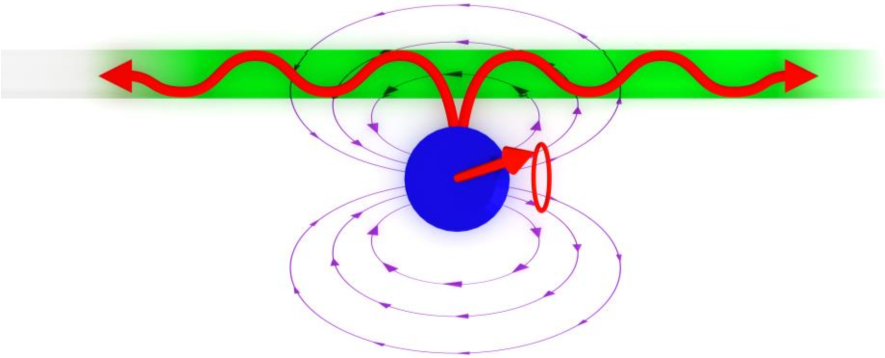
→Very different M_s lead to very different ferromagnetic resonance frequencies allow for easier matching

"SAO on waveguide"



Strong coupling, low tunablity

"SAO beside waveguide"

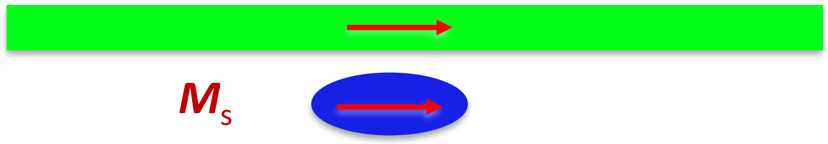


Weaker coupling, tunablity by gap

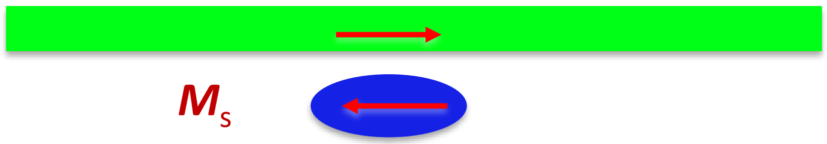
Tuning the coupling and SAO frequency

- **Dipolar coupling**: excitation strength of spin waves depends on the
  - Gap between SAO and waveguide,
  - SAO size and excited spin-wave wavelength
  - Relative orientation of the SAO and the spin-wave waveguide

- Spin-wave excitation is a radiation loss mechanism for the SAO: it **increases the threshold current** and **changes the auto-oscillation frequency**.

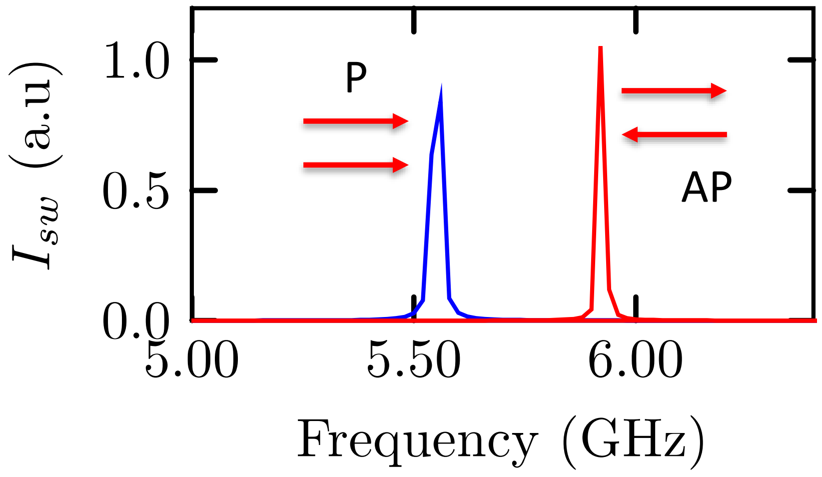


Parallel M_s
→ **weak dipolar coupling**
→ low spin-wave emission amplitude
→ high SAO amplitude
→ high (negative) nonlinear shift



Antiparallel M_s
→ **strong dipolar coupling**
→ high spin-wave emission amplitude
→ low SAO amplitude
→ small (negative) nonlinear shift

SWs emitted from a NiFe SHNO, into a 5 nm thick YIG waveguide

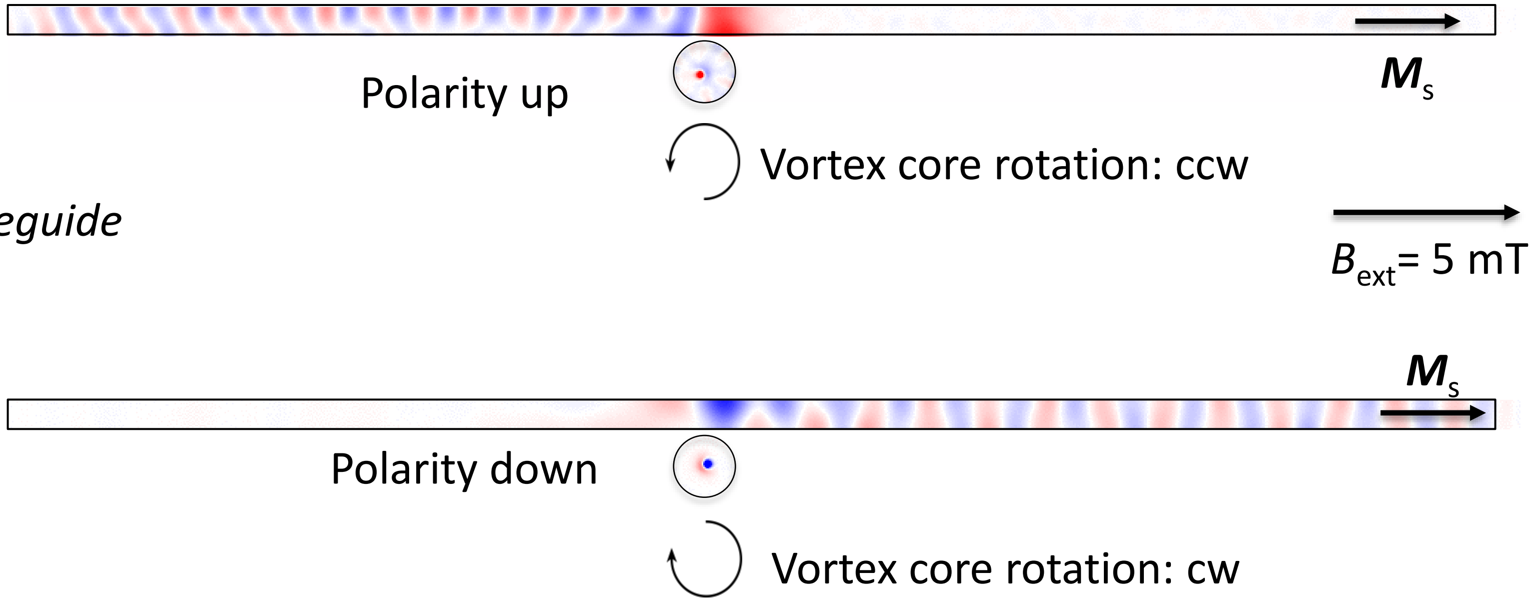


j_{DC}= 1.9·10^{11} A/m^2, B_{ext}= 10 mT

Tuning the spin-wave emission

- Uniform oscillators emit reciprocally, but **vortex oscillators** have a particular rich reconfigurability since the spin-wave emission depends on the **chiralit**y and the **polarity** of the oscillator.

Vortex oscillator:
200 nm diameter
20 nm gap to waveguide
j_{DC}= 1.9·10^{11} A/m^2



YIG waveguide
50 nm thickness,
100 nm width

- **Non-reciprocal emission** into a completely reciprocal magnonic system (Backward-Volume geometry) due to the **interplay of the different in-plane and out-of-plane components of the dynamic fields** created by the vortex

→ Enables directionality in a network, can be tuned by the ellipticity of the oscillator

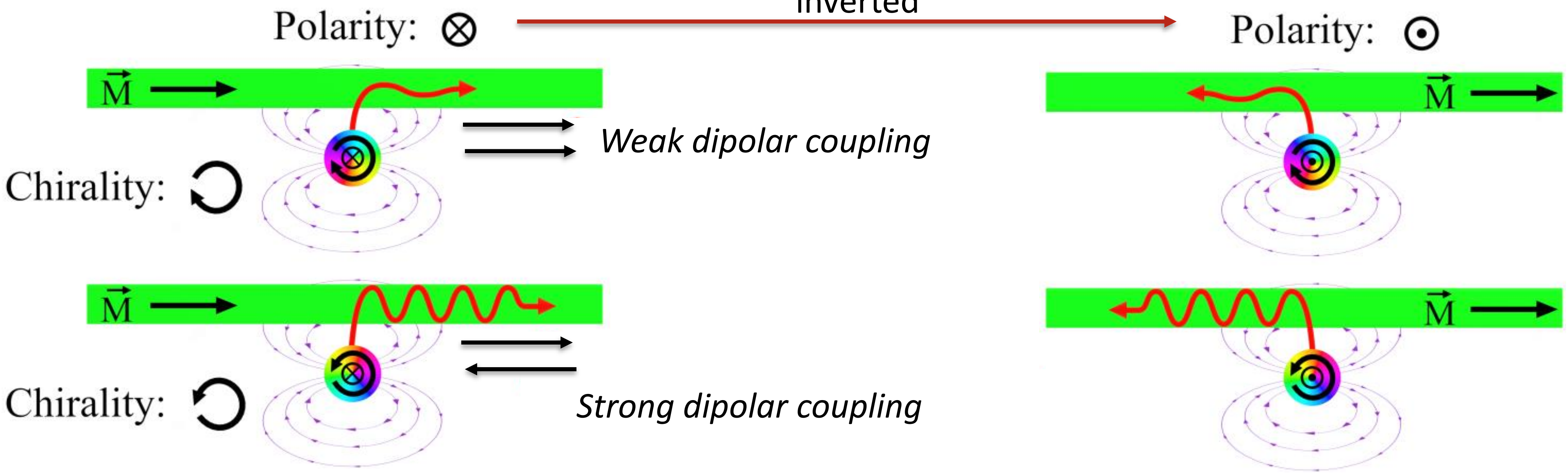
Tuning the spin-wave emission

- Summary: Vortex oscillator coupled to a Backward Volume spin-wave waveguide

Chirality changes the **amplitude** and **frequency** of the emitted waves

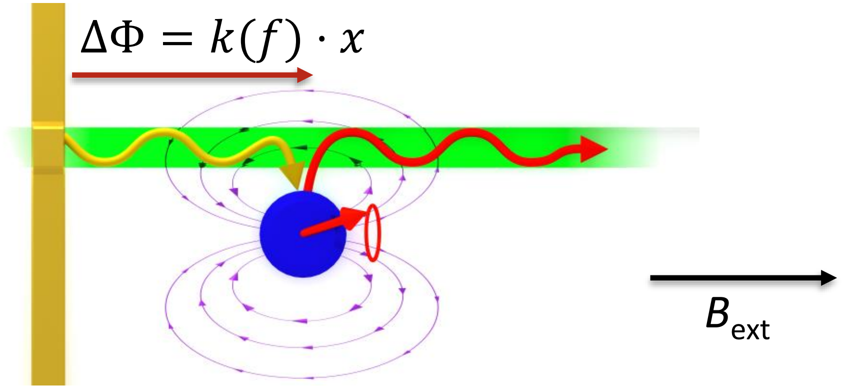
Polarity changes the **direction** of the emitted waves

Sense of vortex rotation is inverted

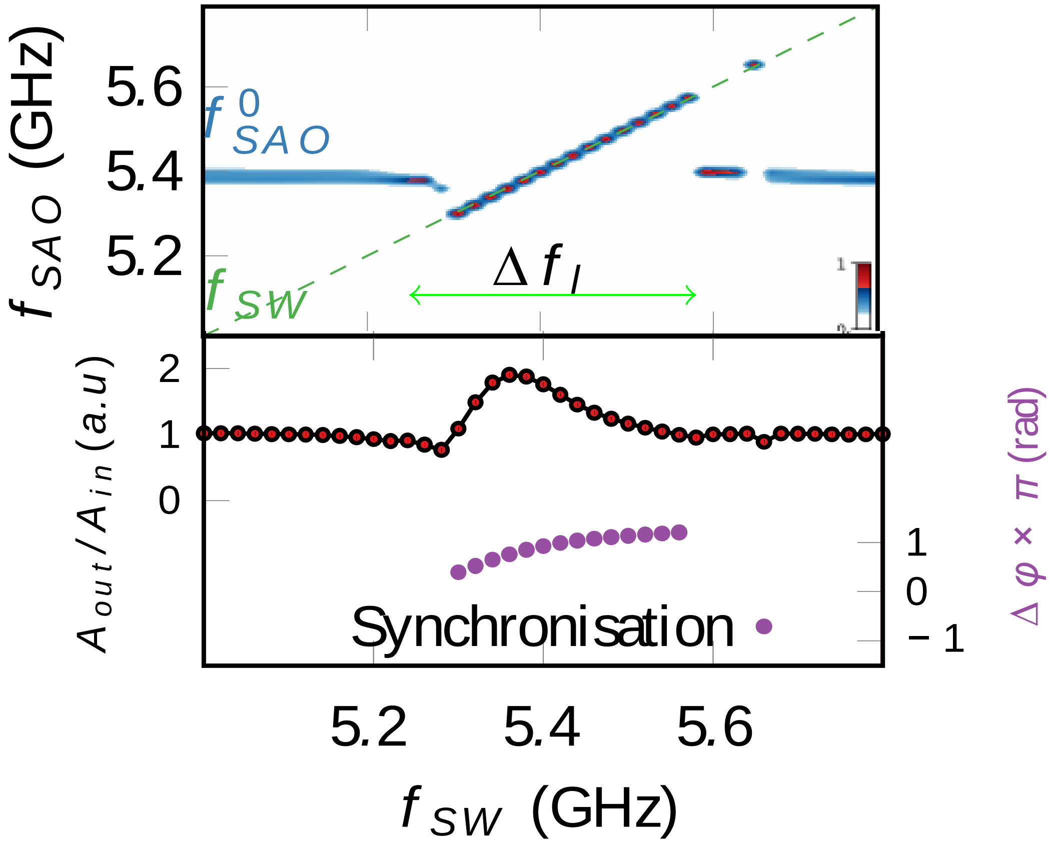


Synchronization to a magnonic signal

- Inverse process to the emission of spin waves: SAO synchronizes to magnonic signal in the waveguide:



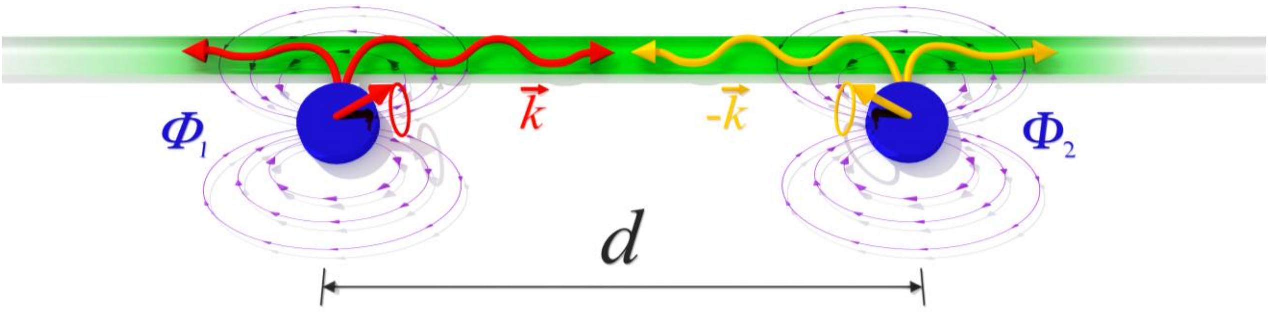
Elliptical NiFe SHNO (80x40x5 nm) coupled to a 10 nm thick, 100nm wide YIG waveguide



j_{DC}= 1.9·10^{11} A/m^2, B_{ext}= 50 mT, distance x = 1280 nm

- SAO synchronizes to the magnonic input signal ✓
- Phase of the SAO depends on the spin-wave wavelength ✓
- Amplification depends on spin-wave frequency, can be enhanced by frequency selective elements

Synchronization of SAO via spin waves



Most efficient synchronization:

$$\beta = k(f) \cdot d = \arctan(\nu) + l \cdot \pi,$$
$$l \in 0,1,2 \ldots$$

ν: normalized nonlinear frequency shift of the oscillators

Two possibilities for the phase difference between oscillators:

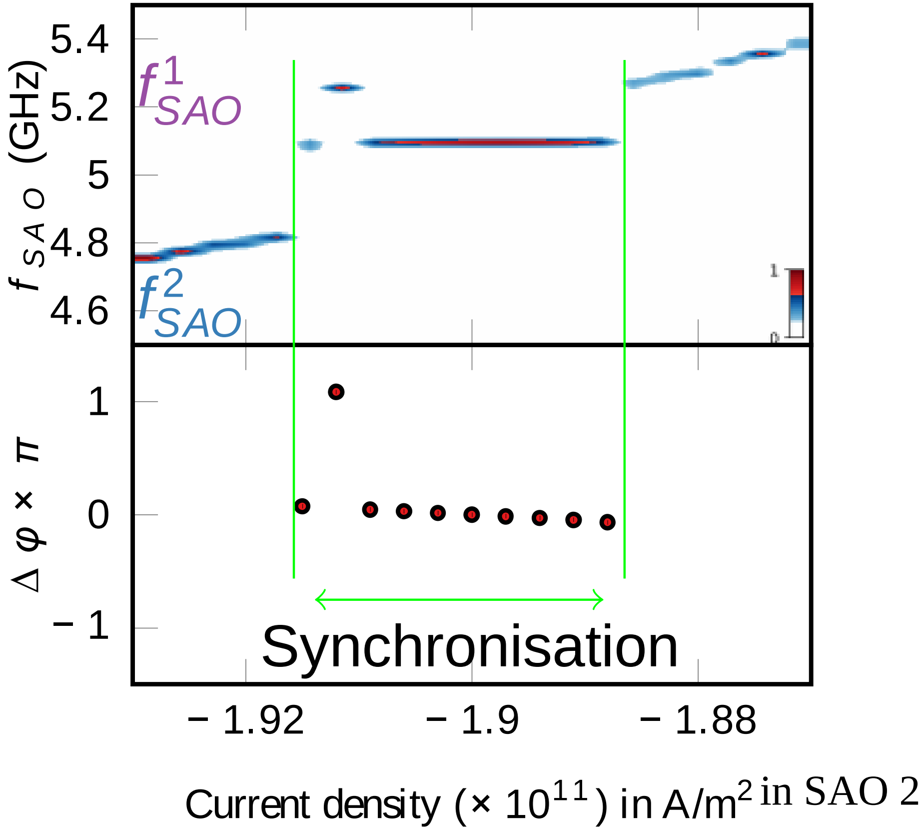
$$\Delta\Phi = \arcsin(\delta\omega/\Delta_2) \text{ or } \Delta\Phi = \pi - \arcsin(\delta\omega/\Delta_2)$$

$\delta\omega$: frequency mismatch to the free running oscillator

Δ_2: synchronization bandwidth

Stable solution depends on β and ν

Two elliptical NiFe SHNO (80x40x5 nm), distance *d*=2 µm coupled to a 10 nm thick, 100 nm wide YIG waveguide,

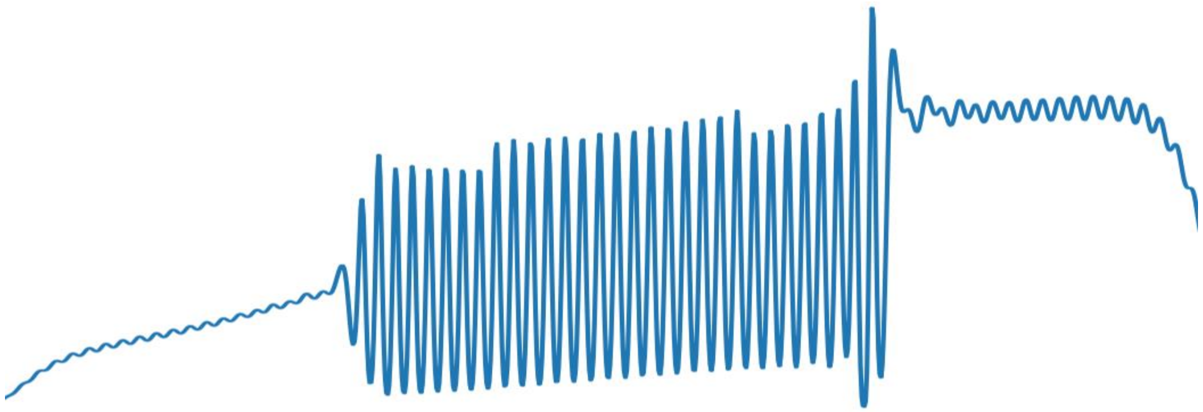


Synchronization for larger distances *d* achievable without further optimization.

A. Slavin and V. Tiberkevich, IEEE Trans. on Magn, **45**, 1875–1918 (2009).

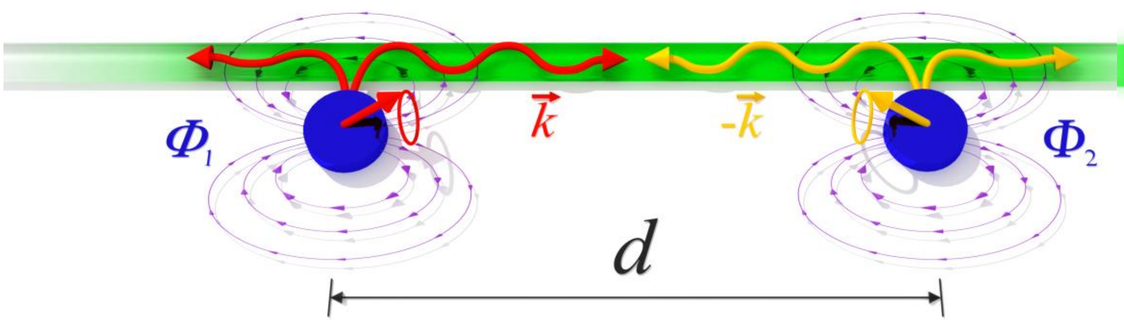
Synchronization patterns

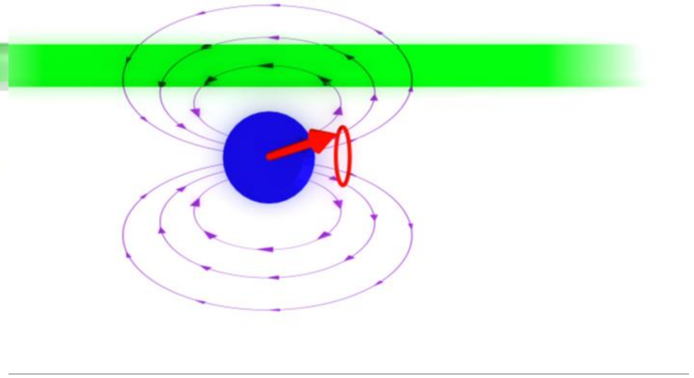
- If synchronization is reached, the resulting interference pattern depends on the realized wavelength, the relative phase- and spatial difference of the oscillators:



Spin-wave intensity (time averaged)
In this case (uniform SHNO), the non-synchronized system is completely reciprocal (emission of spin waves etc).

Where does the non-reciprocity come from?





Synchronization patterns

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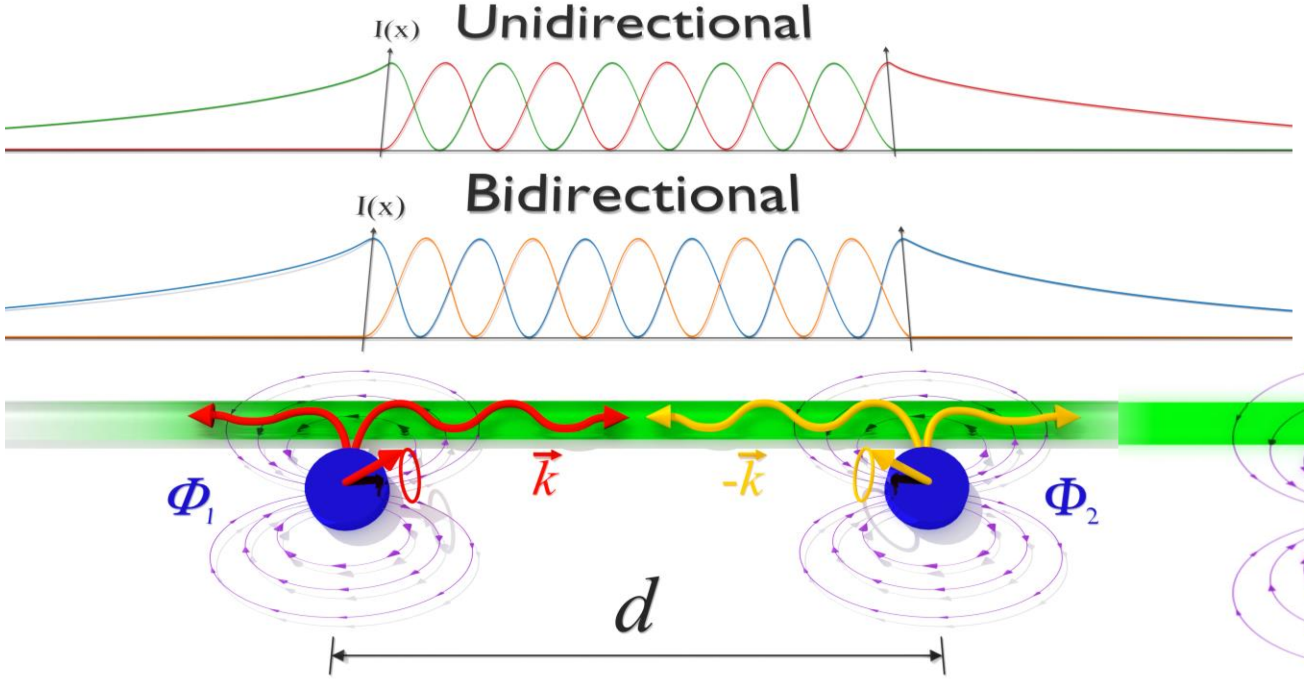
Spin-wave intensity (time averaged)

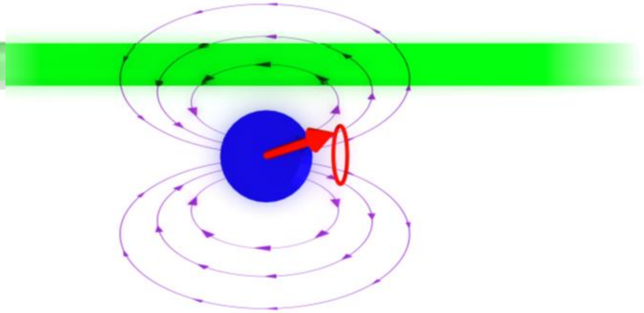


$$d = \lambda(f_{Osci}) \cdot \left(n + \frac{1}{4}\right)$$

$$\Delta\Phi = \Phi_1 - \Phi_2 = \pm\pi/2$$

$$d = \lambda(f_{Osci}) \cdot \left(n + \frac{1}{2}\right)$$

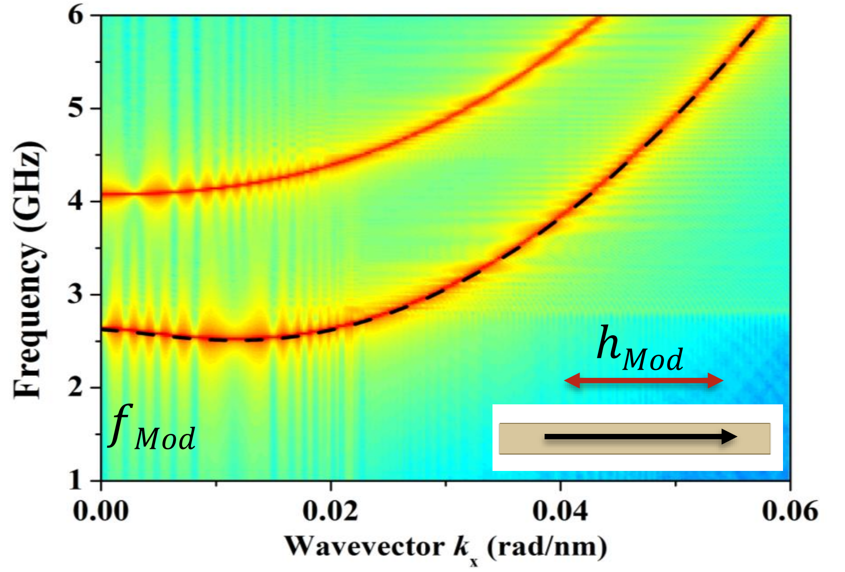
$$\Delta\Phi = \Phi_1 - \Phi_2 = \pi, 0$$

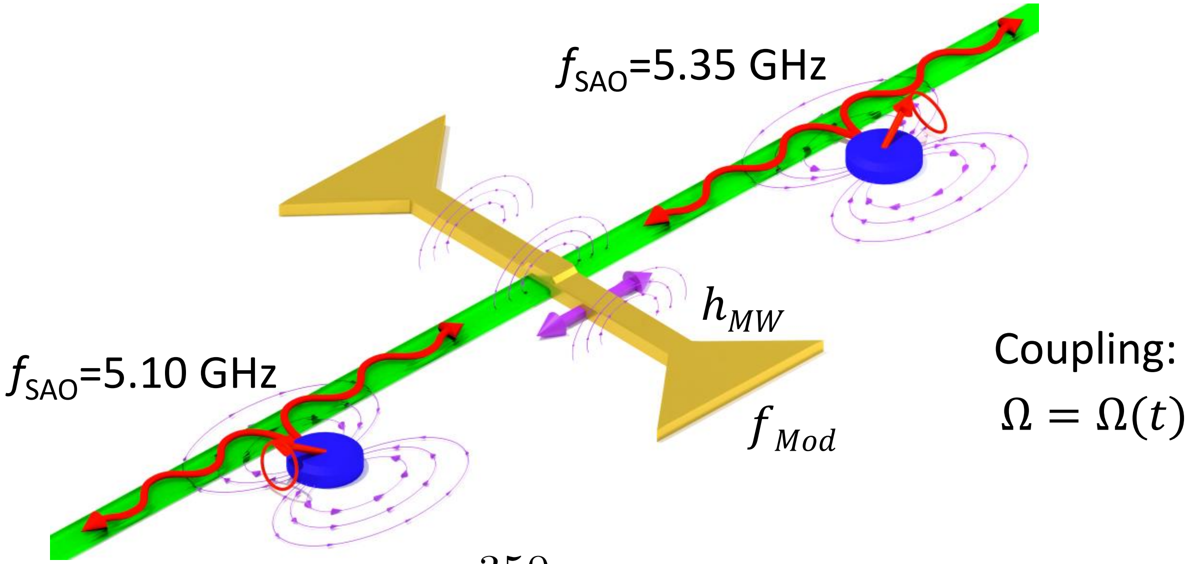


Transition to the **synchronized state**:
phase transition with **ordering parameter ΔΦ** which **decides on the intensity pattern** outside the oscillator pair
→defines the direction in which an initial **synchronization spreads through the network**

Time-modulation of the spin-wave coupling

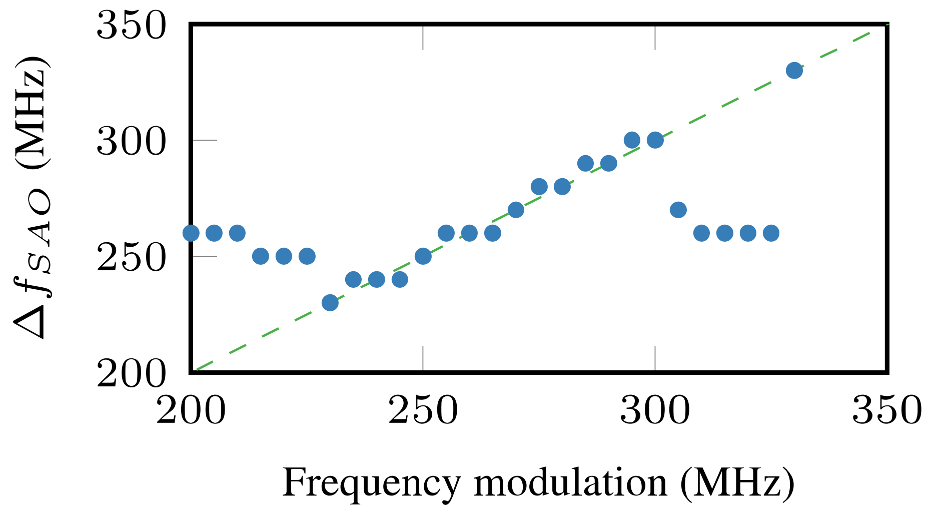
What happens if we time-modulate the connecting spin-wave band structure with a frequency below the magnon gap?





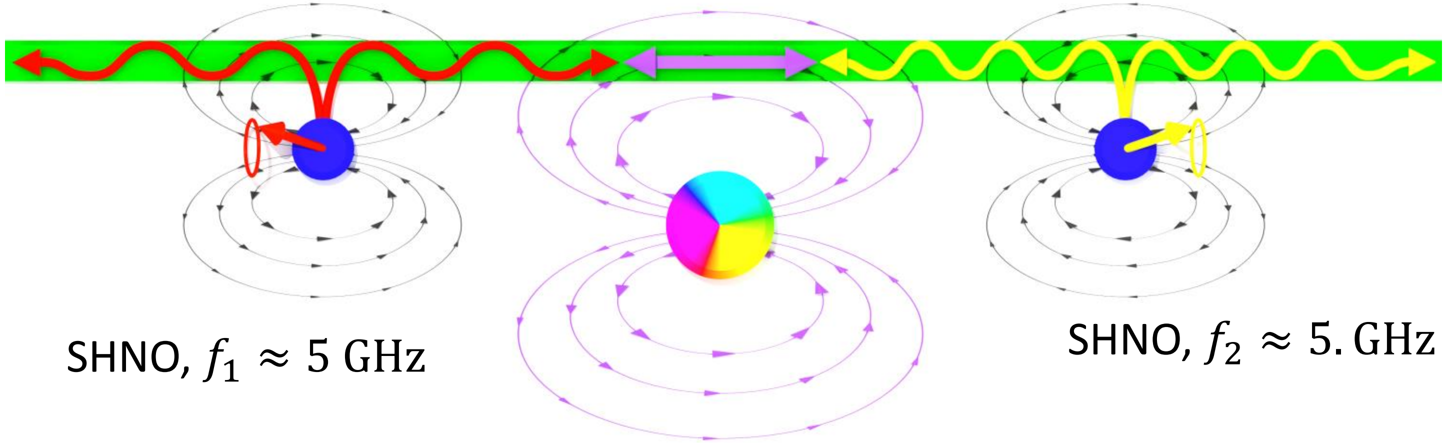
Coupling:
$\Omega = \Omega(t)$

- Modulation of the spin waves leads to **coherent mode-locking** of SAOs running at different f_{SAO}
- **Spin waves pulses** develop whose duration decreases if more SAOs are locked with different f_{SAO}



Time-modulation of the spin-wave band structure

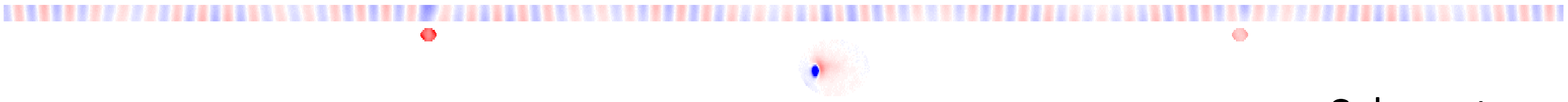
Modulation of the spin-wave band structure can **couple very different oscillator types**:



SHNO, $f_1 \approx 5\ \mathrm{GHz}$

SHNO, $f_2 \approx 5.\,\mathrm{GHz}$

Vortex oscillator, $f_{Vor} \approx 350\ \mathrm{MHz}$

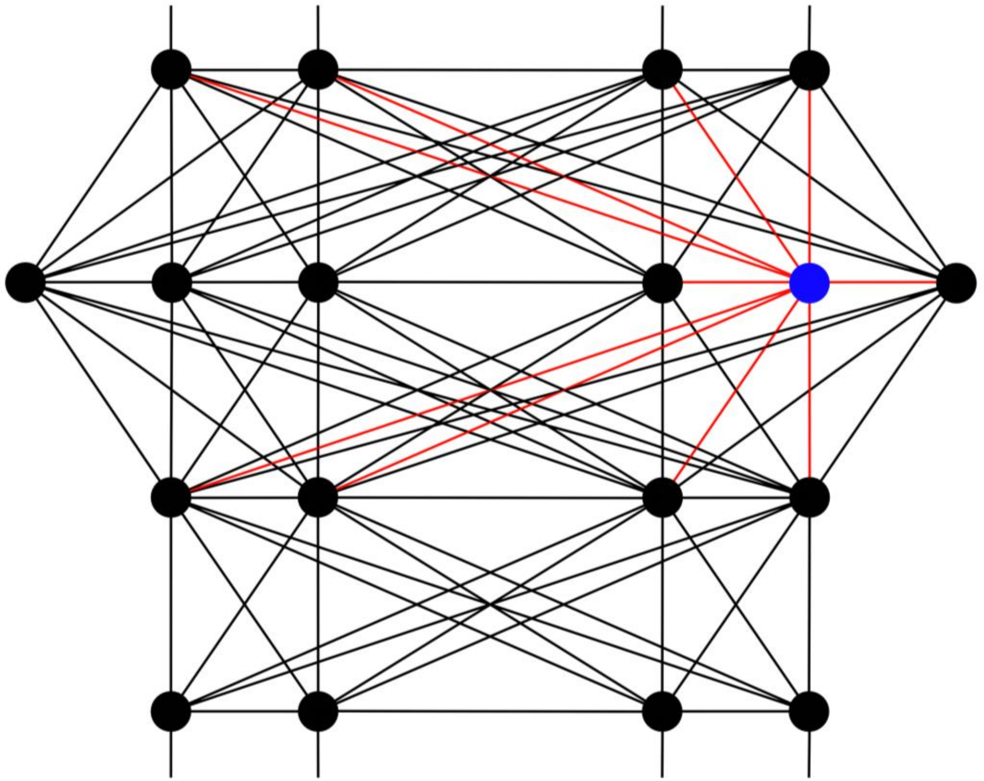


$$f_1 + f_{Vor} = f_2$$

Coherent, mode-locked operation of all three SAOs

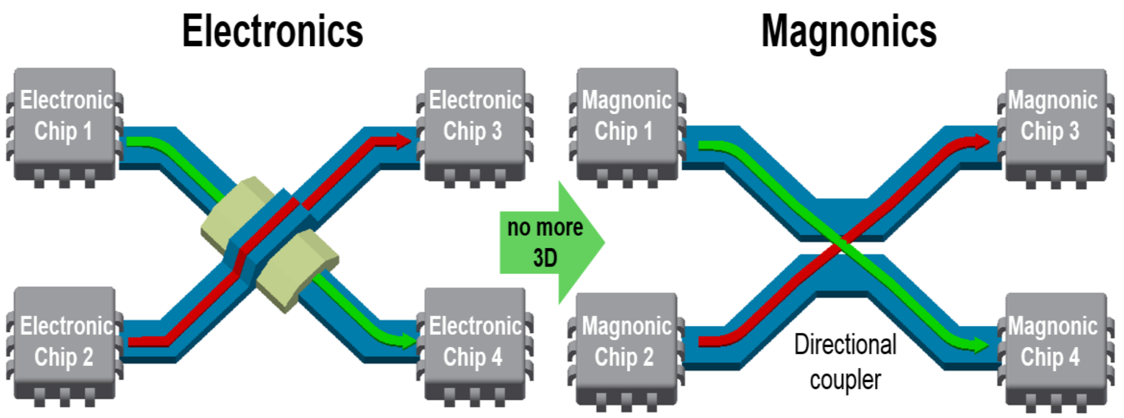
→There are plenty of coherent phenomena for coupled SAO which go beyond simple synchronization.

Last but not least: connectivity challenge



Connection by waves

Use of **coherent coupling effects** allows to use 2D systems



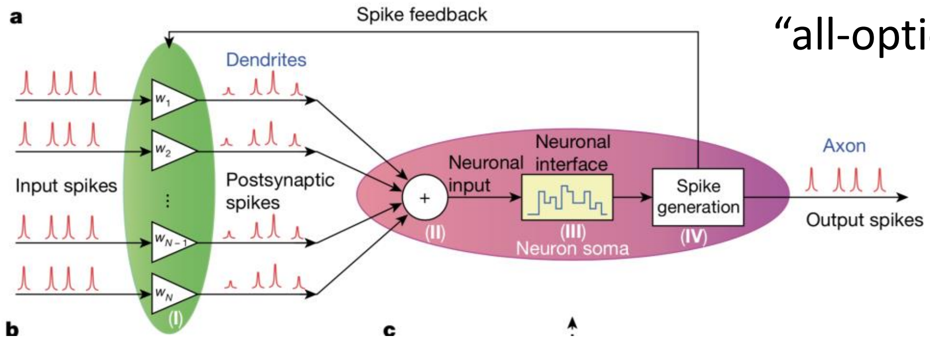
Additional reduction of physical interconnects by **frequency multiplexing**

Optical neuronal networks

All-optical spiking neurosynaptic networks with self-learning capabilities

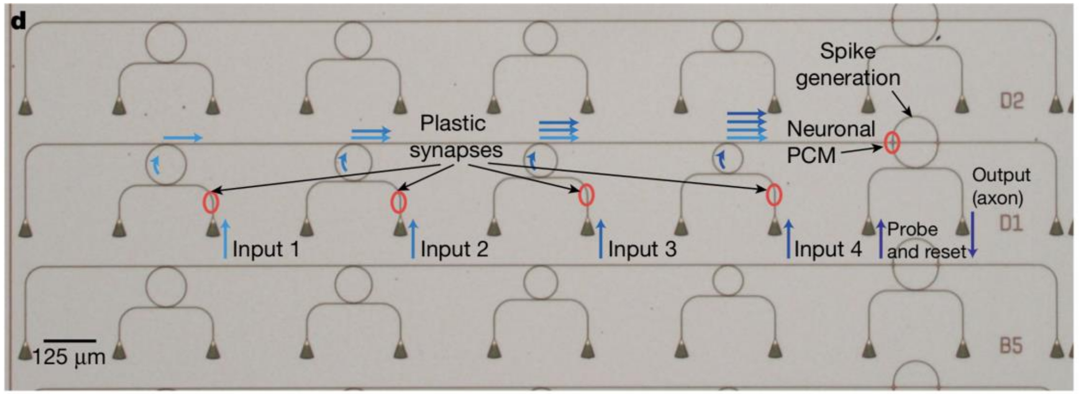
J. Feldmann[1], N. Youngblood[2], C. D. Wright[3], H. Bhaskaran[2] & W. H. P. Pernice[1]*

J. Feldmann, *et al.*,
Nature **569**, 208–214 (2019).



“all-optical neuron”

Perform in the optical domain:
pattern recognition,
supervised and unsupervised learning



Main ingredients:

- Photonic ring resonators
- Nonlinear functionality (phase change material)
- **Multiplexing und Demultiplexing**
- Embedded memory (phase change material)

Main problem in optics:
scalability of the individual elements

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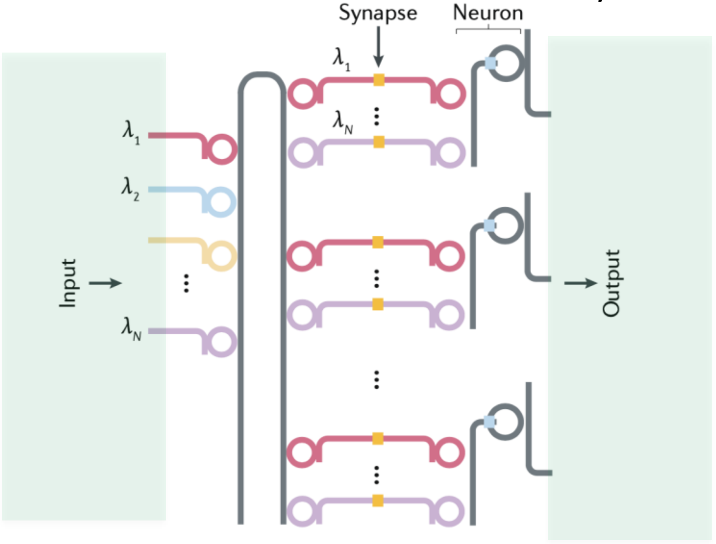
Frequency-division multiplexing

Photonic neural network using N different frequencies/wavelengths

Input from previous layer

Output to next layer



collector distributor

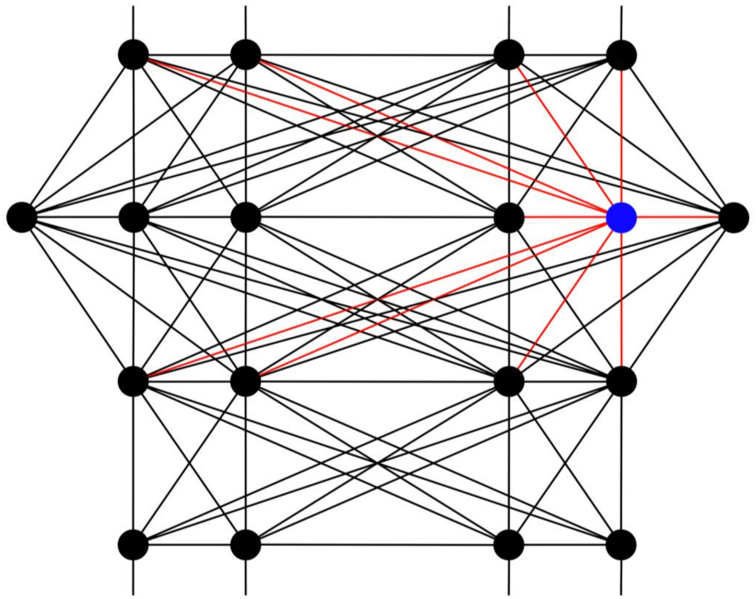
The use of frequency-dependent elements creates an *all-to-all connection* of neurons in a 2D structure using a *linear scaling* number of connecting elements.

J. Feldmann, *et al.*, *Nature* **569**, 208–214 (2019).

D. Marković, et al., *Nat. Rev. Phys*. **2**, 499–510, (2020).

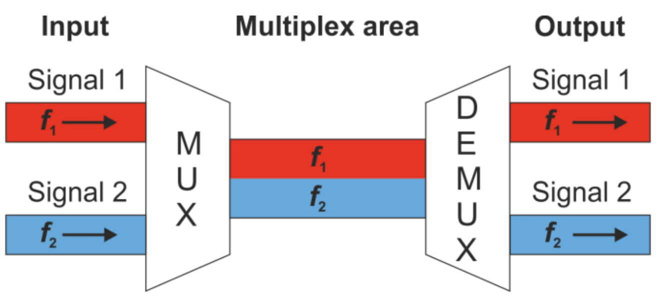
Wiring scheme

needs $\frac{N(N-1)}{2}$ physical connections to create *all-to-all connectivity*

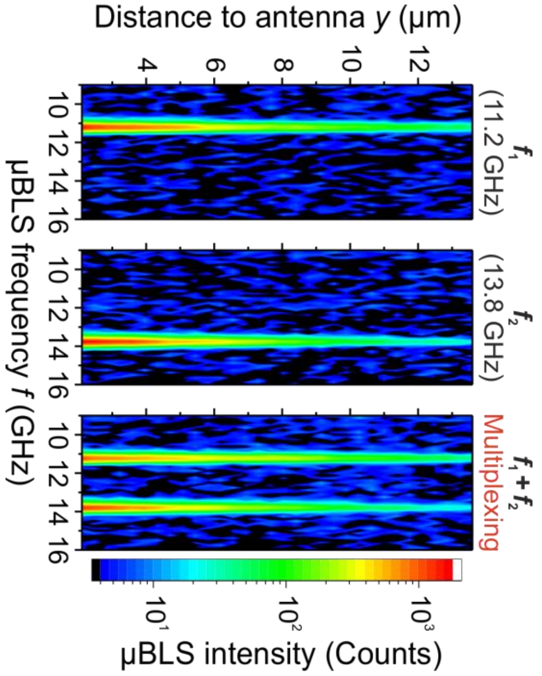


Frequency-division multiplexing (FDM) for spin-waves

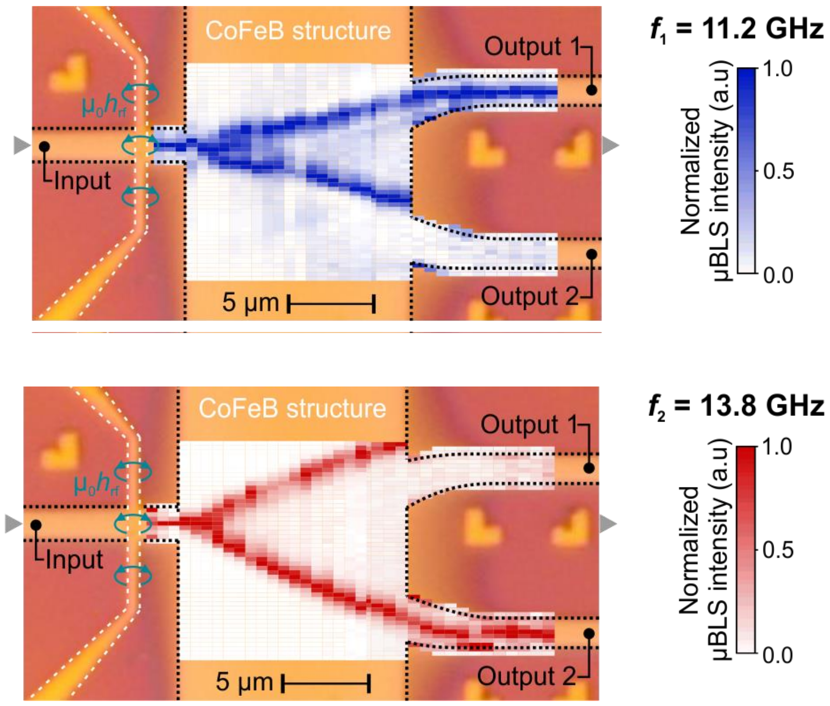
"Several spin-wave frequencies in the same device"



µBLS measurement

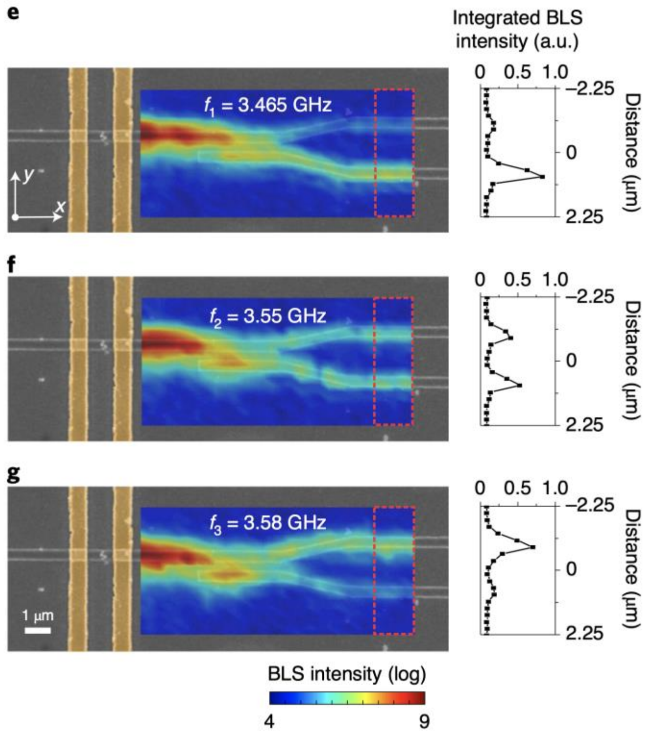


Caustic-based demultiplexer



F. Heussner, PP, *et al.*, *Phys. Status Solidi RRL*, **7**, 1800409 (2018).
F. Heussner, PP, *et al.*, *Phys. Status Solidi RRL*, **14**,1900695 (2020).

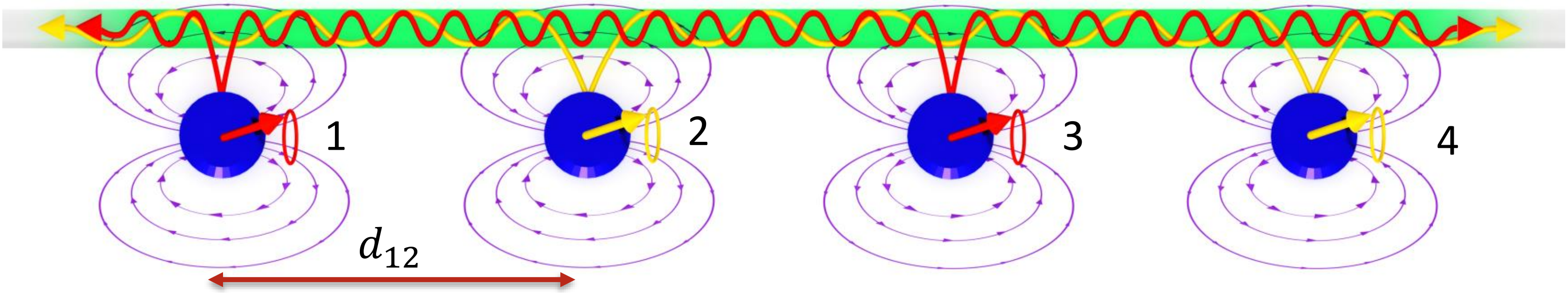
Coupler-based demultiplexer



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

Synchronization of SAO via frequency multiplexing

Four individual SAOs coupled to the same waveguide:



How will they synchronize?

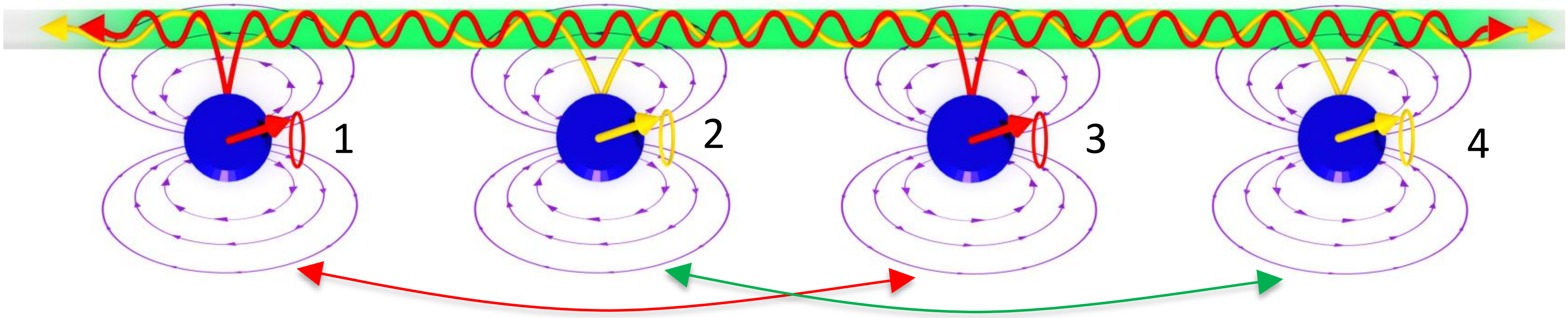
Most efficient synchronization:

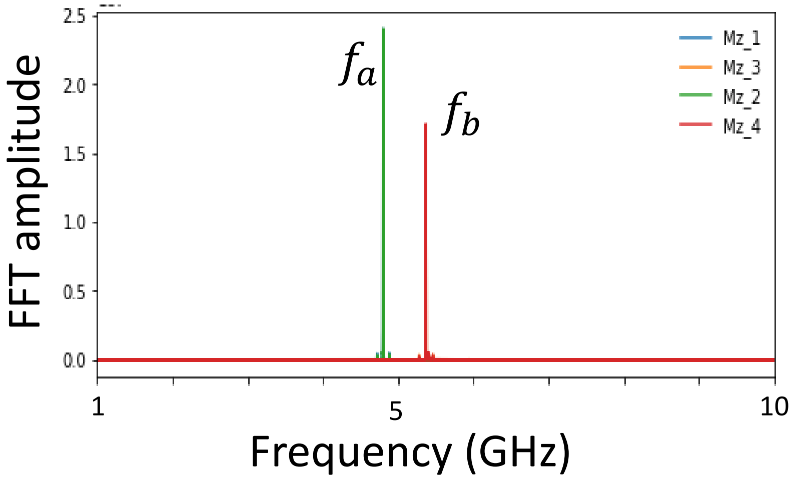
$$k(f) \cdot d_{mn} = \arctan(\nu) + l \cdot \pi, \mathrm{l} \in 0,1,2 \ldots$$

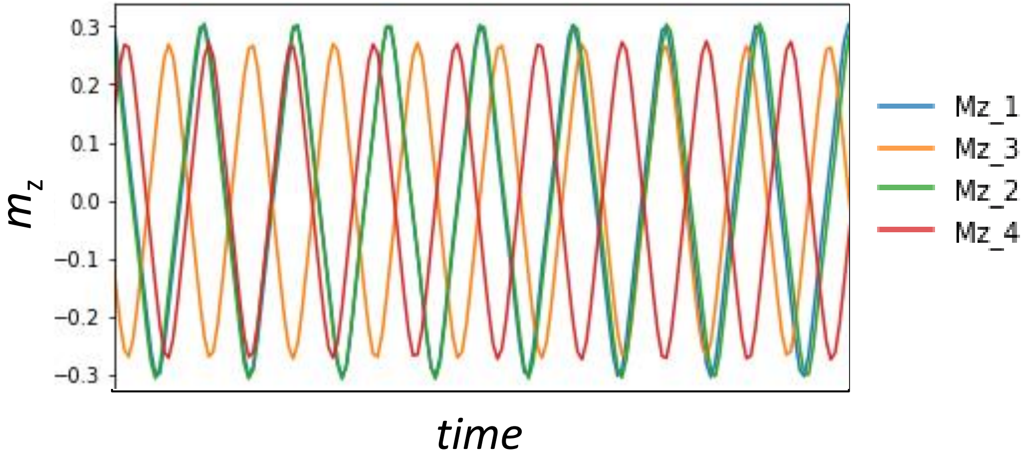
This condition might be fulfilled for a distant oscillator, whereas it is not fulfilled for the next neighbor….

Synchronization of SAO via frequency multiplexing

Four different SAOs coupled to the same waveguide:







SAO 1 and SAO 3 synchronize in phase with f_a,
SAO 2 and SAO 4 synchronize out-of-phase with f_b

Four different SAO coupled by a single magnetic nanowire forming two synchronization clusters.

Additional effect: **nonlinear magnon interaction** seems to mode-lock the clusters
→ Spin-wave pulses develop, network starts to spike with shorter pulses if more clusters are involved

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

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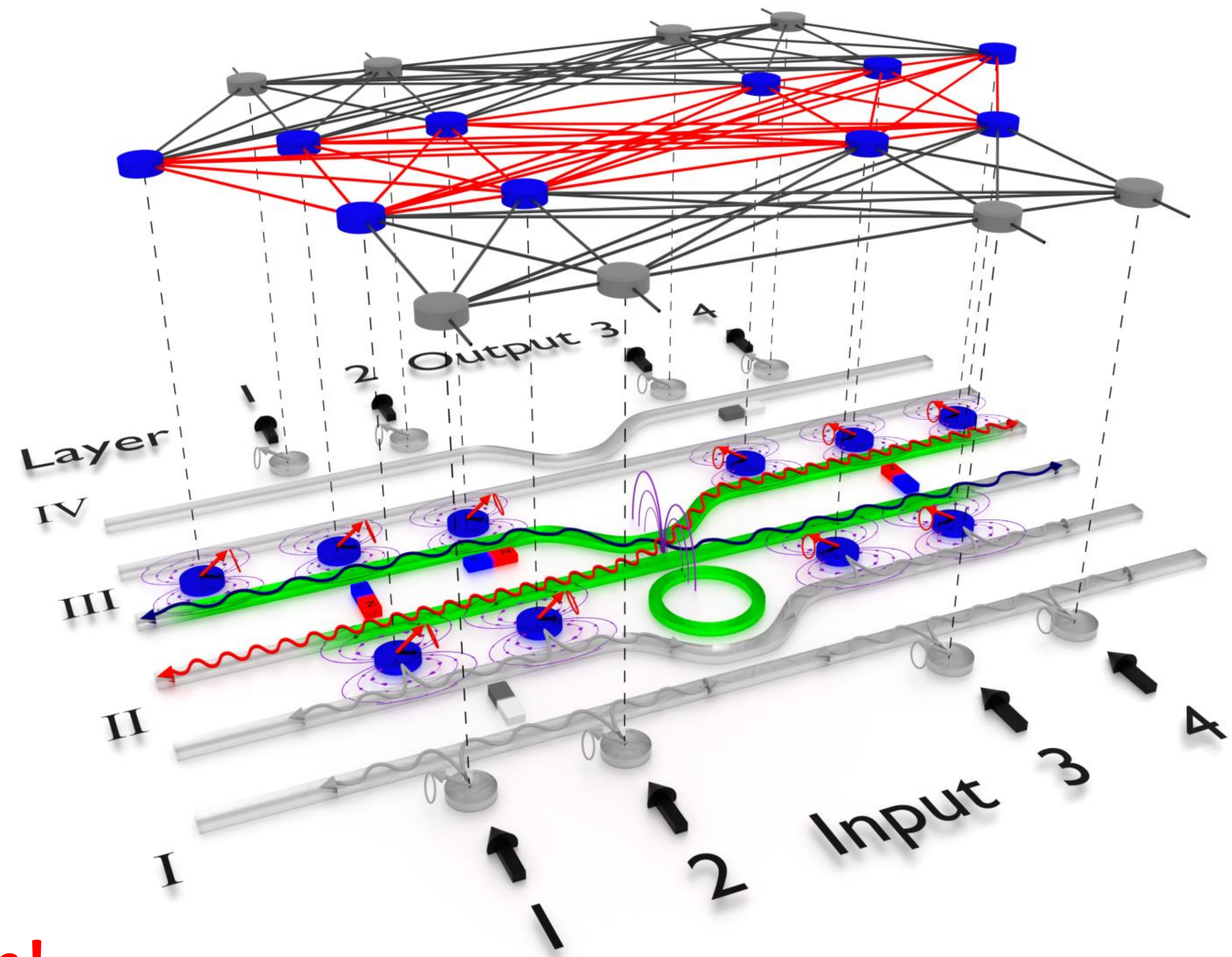
Conclusions

- Proposition of an **all-spintronic neural network** based on **spintronic auto-oscillators** as artificial neurons connect by **spin-waves in nano-waveguides** acting as artificial synapses
- **Oscillators** can be efficiently coupled to ultralow damping magnonic structures and **synchronize over large distances**
- Manipulation of the connecting spin waves allows to **modify the synchronization properties,** create phase-locked states…
- **Frequency-multiplexing** in the spin-wave domain allows to reduce the number of physical interconnects in a scalable and efficient way



Thank you for your attention!