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Materials' Foundry

Exploring the third dimension in magnonics

Dott. Gianluca Gubbiotti

Istituto Officina dei Materiali-Consiglio Nazionale delle Ricerche (CNR), Perugia, Italy

https://www.iom.cnr.it/

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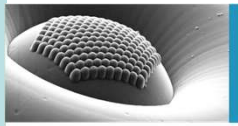
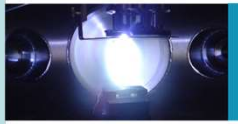
NFFA-Europe PILOT for new research infrastructure schemes

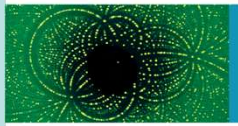
Activities are performed in 6 different types of *Installations*:



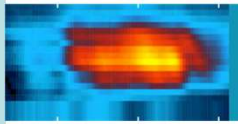
Lithography & Patterning



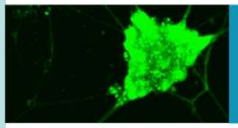
Growth & Synthesis



Structural & Morphological Characterization



Electronic, Chemical & Magnetic Characterization



From Nano to Micro/Macro

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2023: **Australia, Cina, Croatia, Spain, UK, Slovenia**

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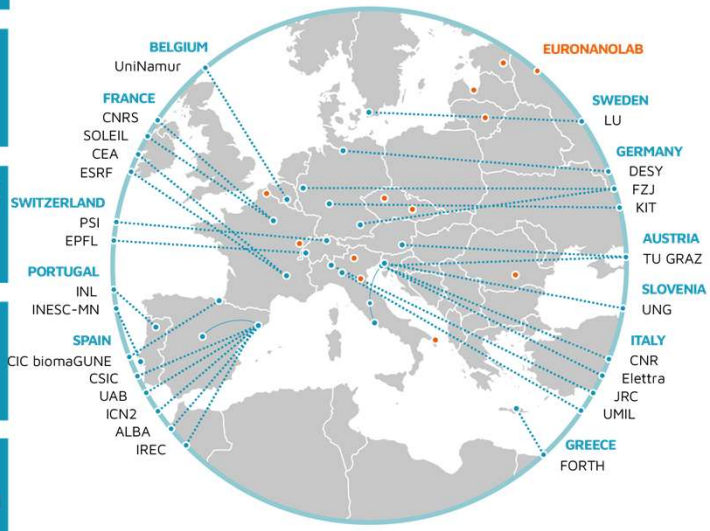

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M. Kostylev (University of Western Australia, Perth)
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R. Verba (Institute of Magnetism, Ukraine)

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Outline

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- 3D Magnonics

- Vertical Magnonic Crystals
  - *Discrete and Continuous Magnonic crystals*
  - *Single and double layers meander-shaped films*

- *Twisted magnonics*
  - *Moiré superlattices based on antidot lattices*

- Vertical magnon transport
  - *Unidirectional coupling: spin wave diode and circulator*

Conclusions

Magnonics: Beyond CMOS

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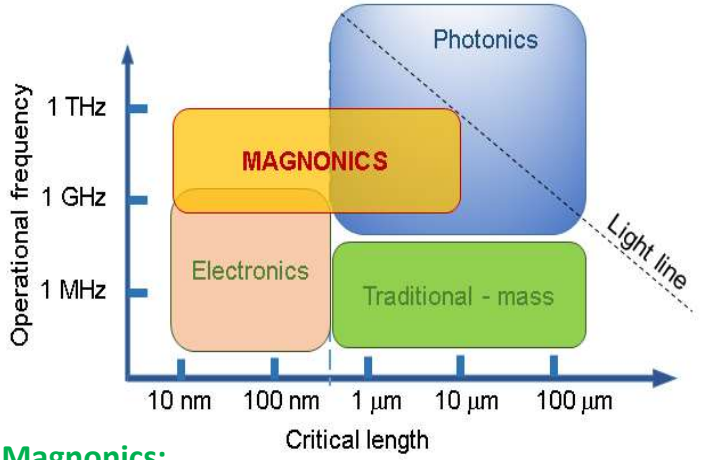
Magnonics is a well-established research field in nanomagnetism and nanoscience that addresses the use of spin waves (magnons) to transmit, store, and process information.
Is it considered as the most promising beyond-CMOS Technology (no Joule heating).

CMOS is almost at its physical limit

- End of scaling (feature size below 5nm)
- Waste energy production

Operational frequency of the different technology domains in terms of operating speed and device sizes.



Magnonics:

- **wide GHz-THz frequency range and reconfigurability.**
- **miniaturization down to 50 nm lateral feature size.**
- **reduced power dissipation.**
- **nonlinearity**

IOP Publishing — Journal of Physics: Condensed Matter
J. Phys.: Condens. Matter 33 (2021) 413001 (72pp) — https://doi.org/10.1088/1361-648X/abec1a

Topical Review

The 2021 Magnonics Roadmap

Article metrics
34728 Total downloads

Anjan Barman[1,51,•], Gianluca Gubbiotti[2,51,•], S Ladak[3],

IEEE TRANSACTIONS ON MAGNETICS, VOL. 58, NO. 6, JUNE 2022 — 0800172

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],

Journal of Physics: Condensed Matter

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The 2024 Magnonics Roadmap

Benedetta Flebus[1], Dirk Grundler[2], Bivas Rana[3], Yoshichika Otani[4], Igor Barsukov[5], Anjan Barman[6], Gianluca Gubbiotti[7], Pedro Landeros[8], Johan Akerman[9], Ursula S Ebels[10]

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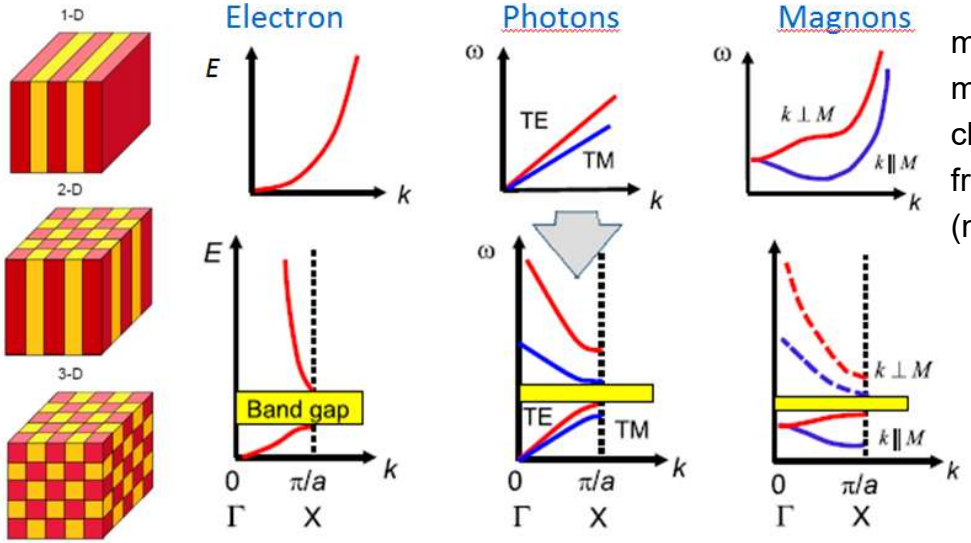
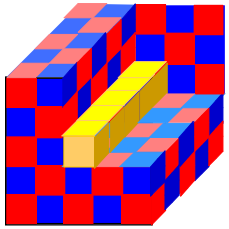
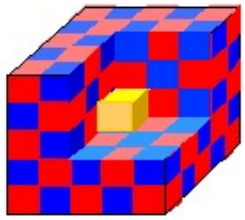
Magnonic Crystals



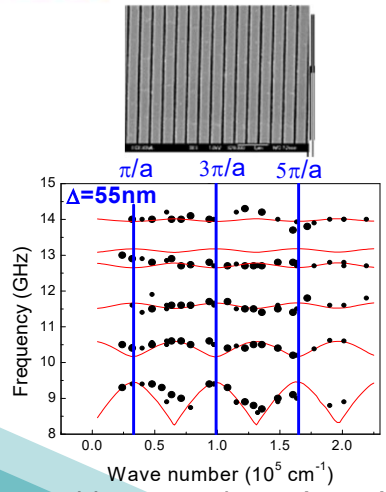
• **Magnonic Crystals** (MC) are a class of metamaterials with periodically modulated magnetic properties. The spin wave dispersion is characterized by magnonic bands separated by frequency regions where propagation is prohibited (magnonic band gap).



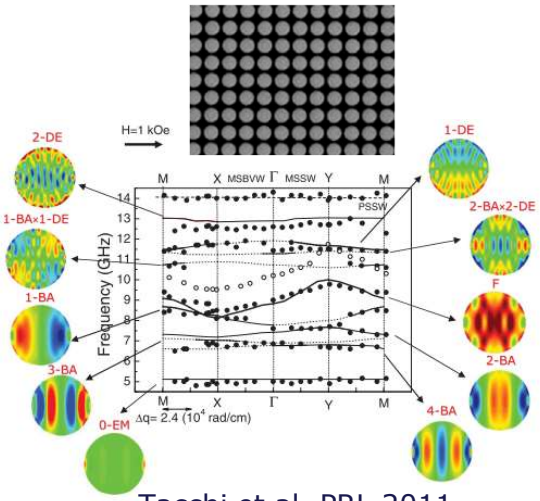
waveguides



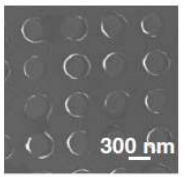
trap into cavities

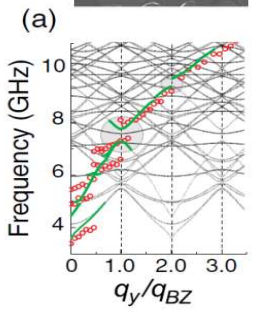


Gubbiotti et al, APL(2007)

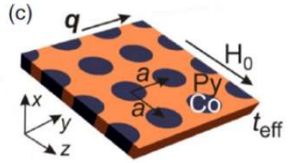


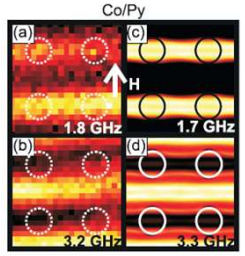
Tacchi et al, PRL 2011





Tacchi et al, PRL 2012





Duerr et al., APL (2011)

3D Magnonic crystals

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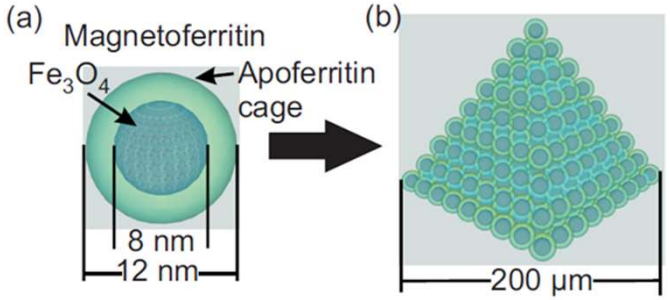
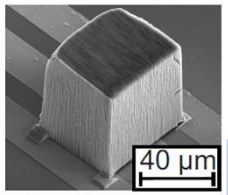
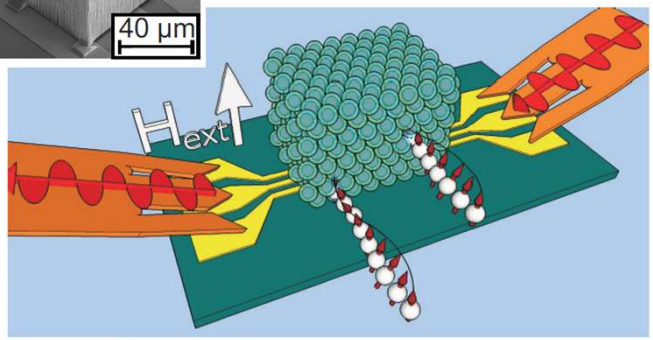
IOP Publishing Nanotechnology
Nanotechnology 28 (2017) 155301 (6pp) https://doi.org/10.1088/1361-6528/aa62f3

Top-down design of magnonic crystals from bottom-up magnetic nanoparticles through protein arrays

M Okuda[1,2,3], T Schwarze[4], J-C Eloi[1,9], S E Ward Jones[1], P J Heard[5], A Sarua[1], E Ahmad[6,7], V V Kruglyak[6], D Grundler[4,8] and W Schwarzacher[1]







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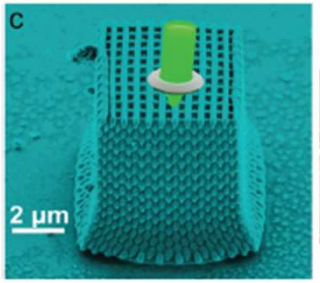
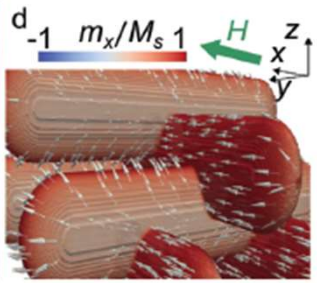
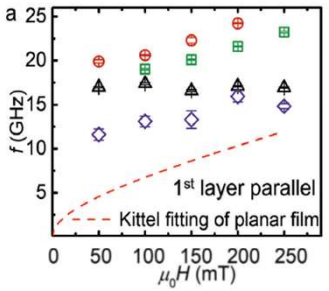
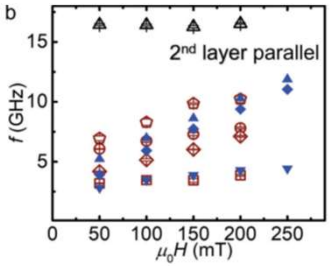
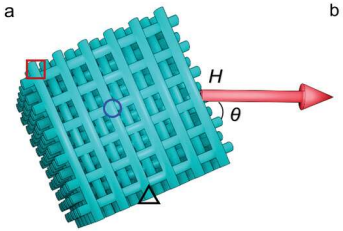
*Huixin Guo, Axel J. M. Deenen, Mingran Xu, Mohammad Hamdi, and Dirk Grundler**

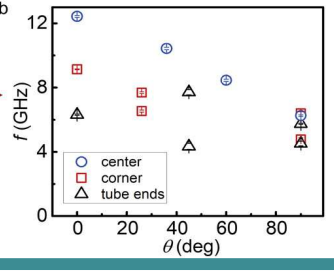












Vertical Magnonic Crystals

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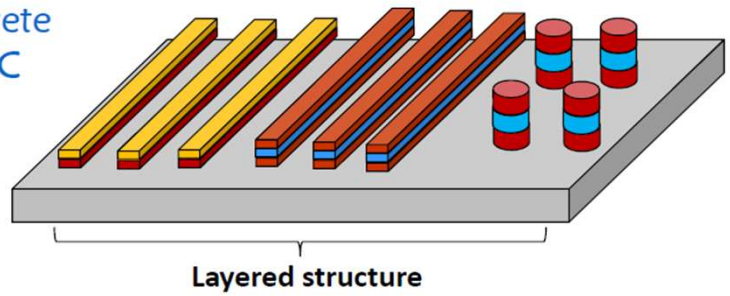
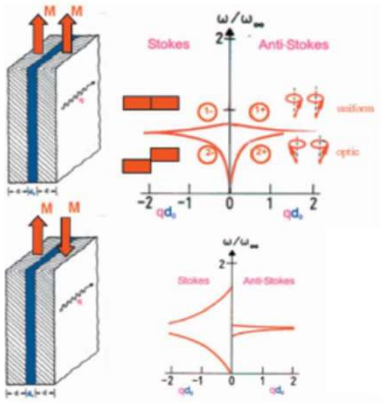
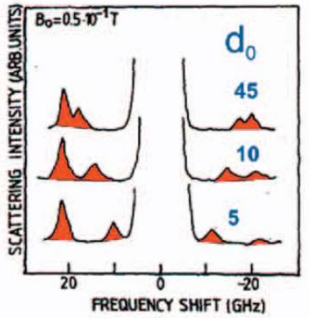
Discrete MC



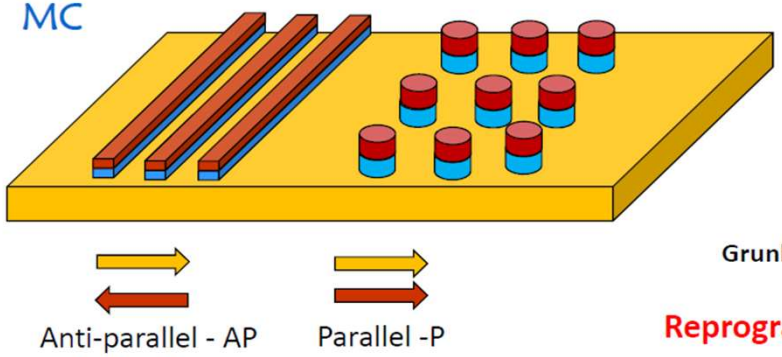
Substrate
Ferromagnet
Ferromagnet
Non magnetic film

Interplay between intra- and inter-nanowires dynamic dipolar coupling

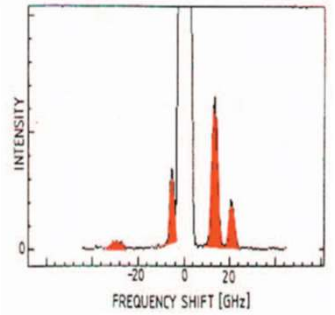




Continuous MC

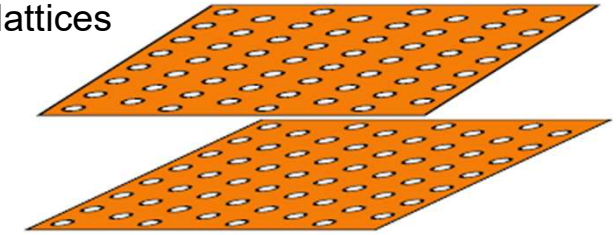


Grunberg Rev. Mod. Phys. **80**, 1531 (2008)



Reprogrammable Band structure

Twisted Magnonics: Moiré superlattices based on twisted antidot lattices



Exchange interlayer coupling $E_s = -2A_{12} \cdot \frac{M_1 \cdot M_2}{|M_1| \cdot |M_2|}$.

Reprogrammable band structure in vertical MCs

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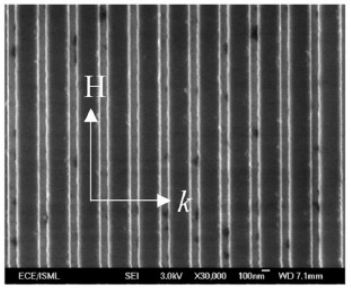
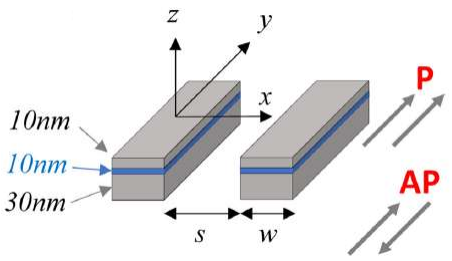
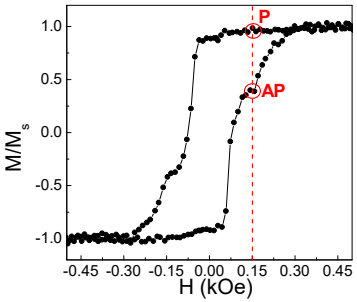
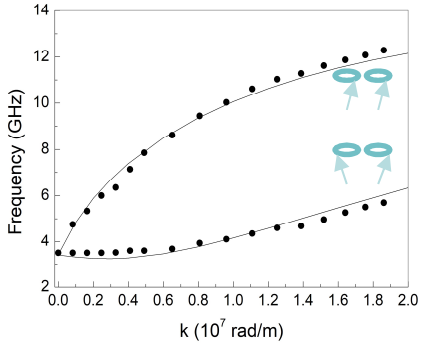


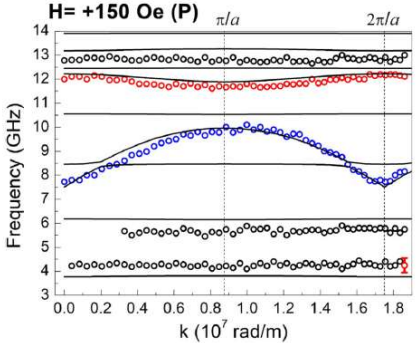


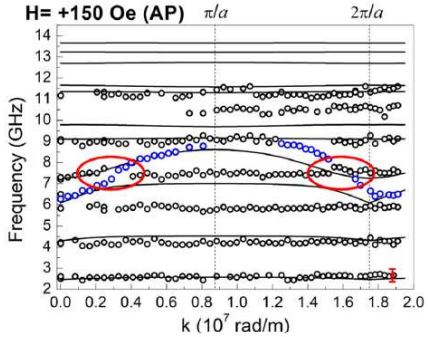
w = 280 nm; s=80 nm;
a =360 nm
$\pi/a = 0.87 \cdot 10^7$ m^{-1}

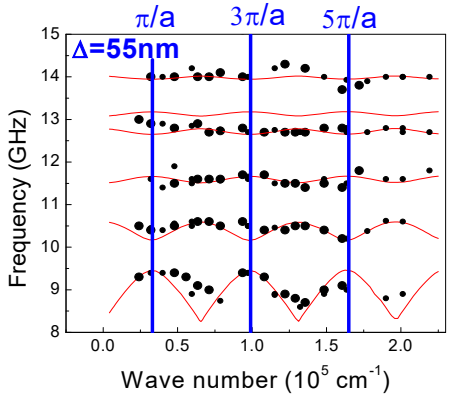


Gubbiotti et al, PRB (2018)
Gubbiotti et al, Sci. Rep. (2019)

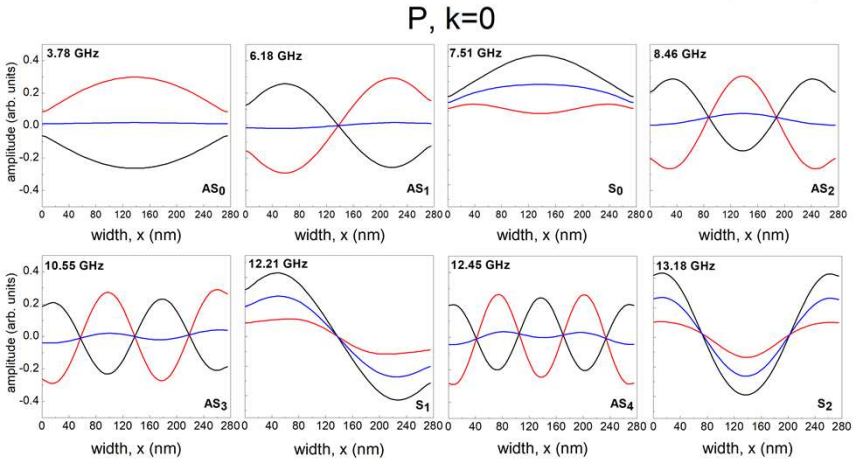








Gubbiotti et al, APL(2007)



Magnonic band gap in Py film induced by dynamic coupling with an array of permalloy ellipses

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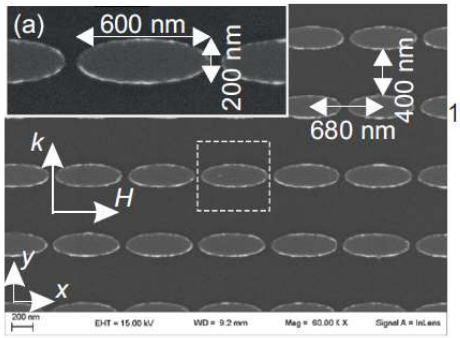

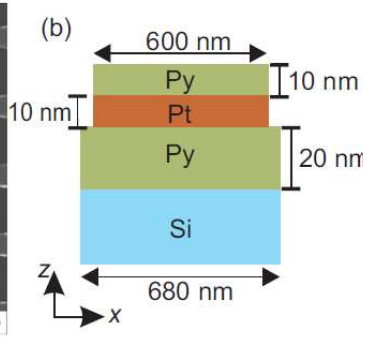

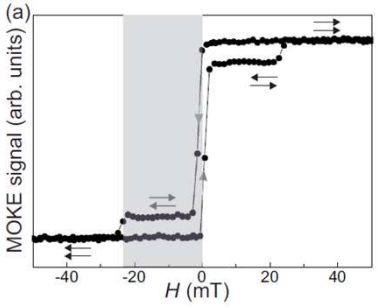

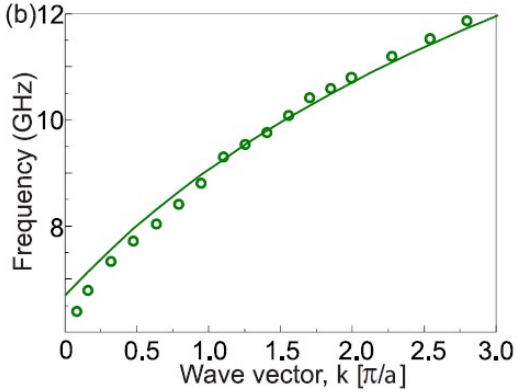

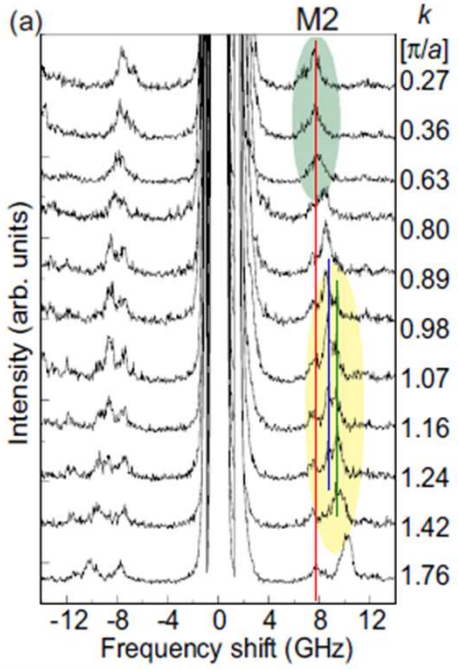

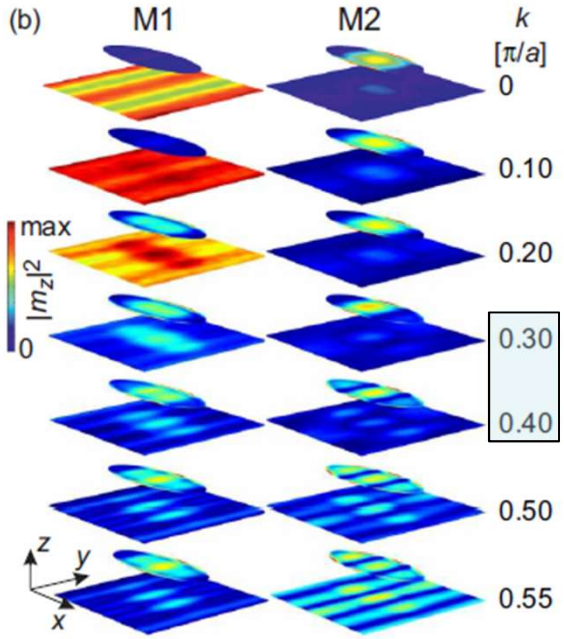

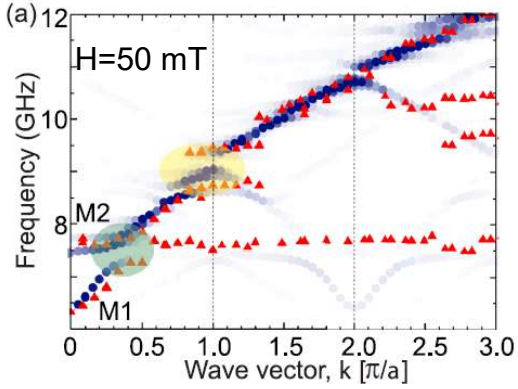

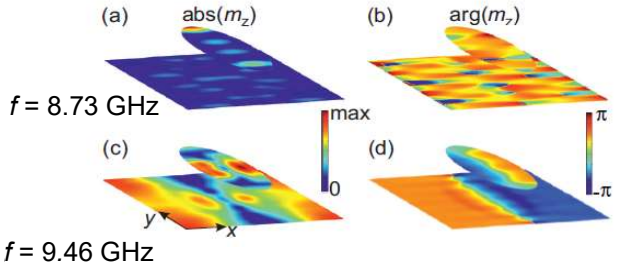

Graczyk et al , PRB (2018)

Vertical magnonic crystals: CoFeB meander-shaped film

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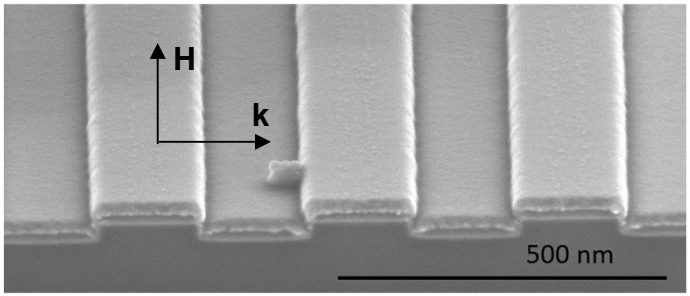
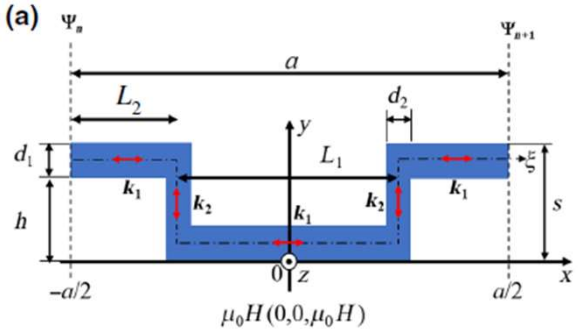
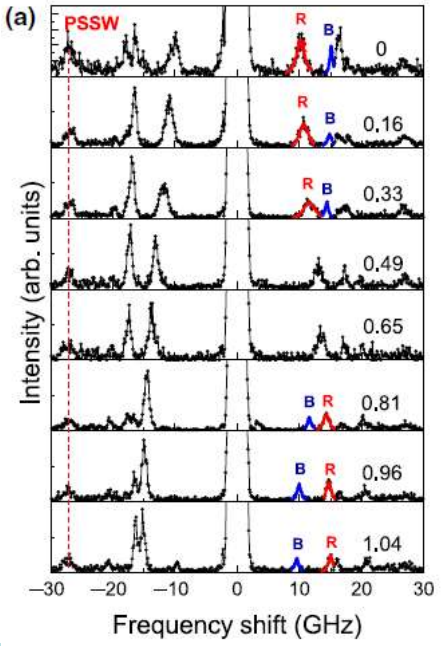
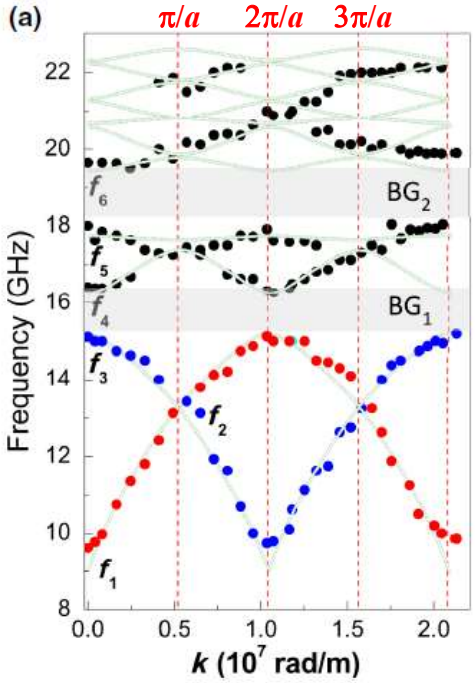
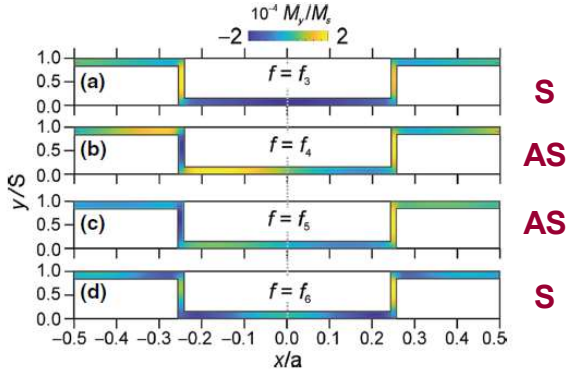


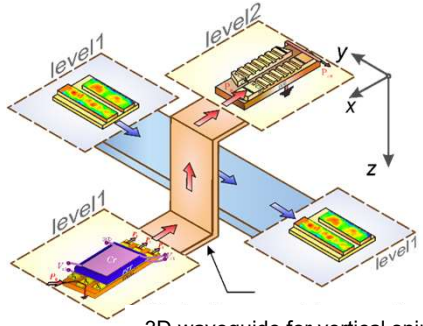
d_1=23 nm
d_2=12 nm
h=50 nm
a=600 nm











Gubbiotti et al, PRApplied (2021).

3D waveguide for vertical spin-wave transport in multilayer magnonic architectures and signal processing.

Vertical magnonic crystals: CoFeB/Ta/NiFe meander-shaped bilayer

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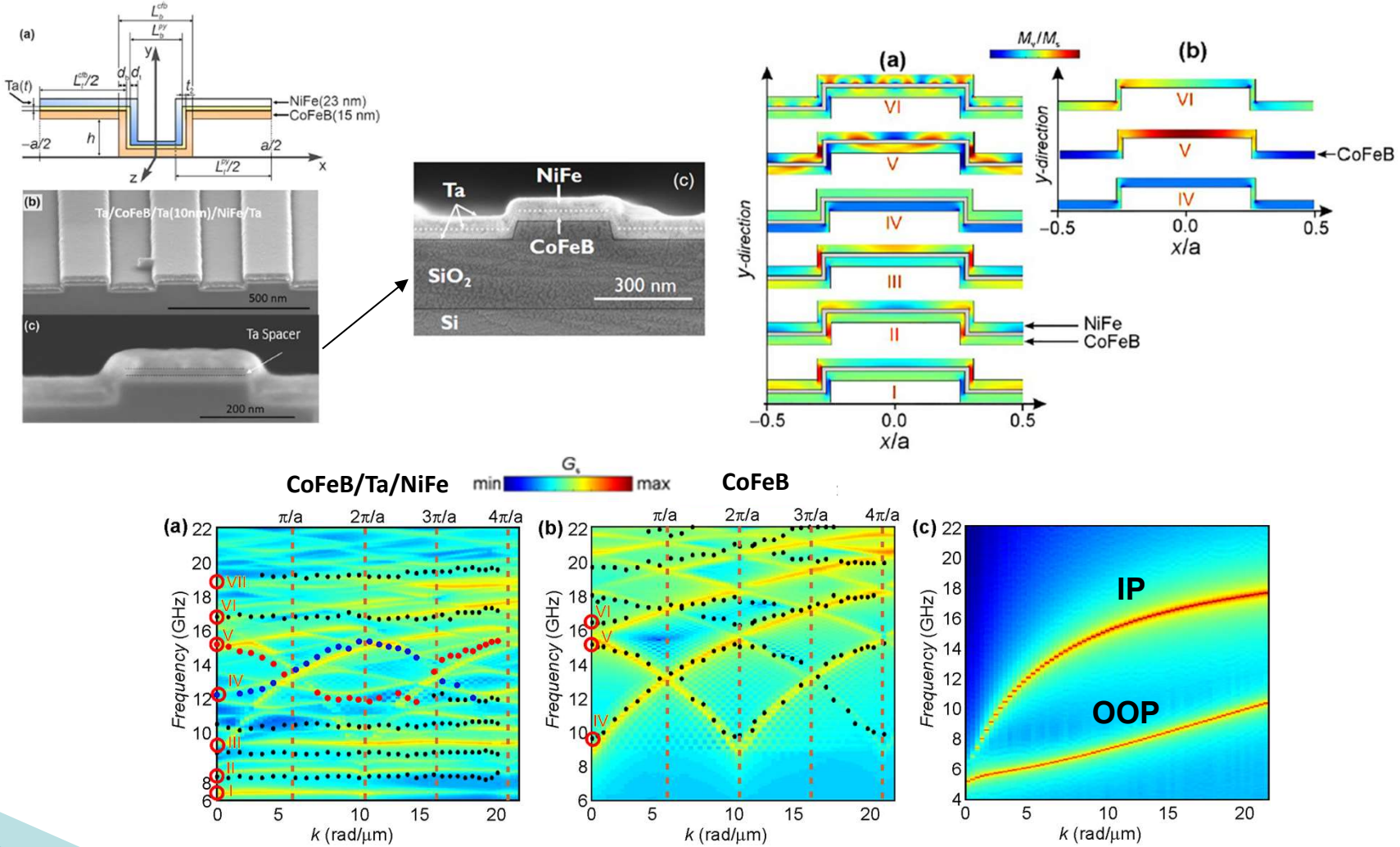

Gubbiotti et al, APL (2021)

Moiré fringes in optics and 2D materials

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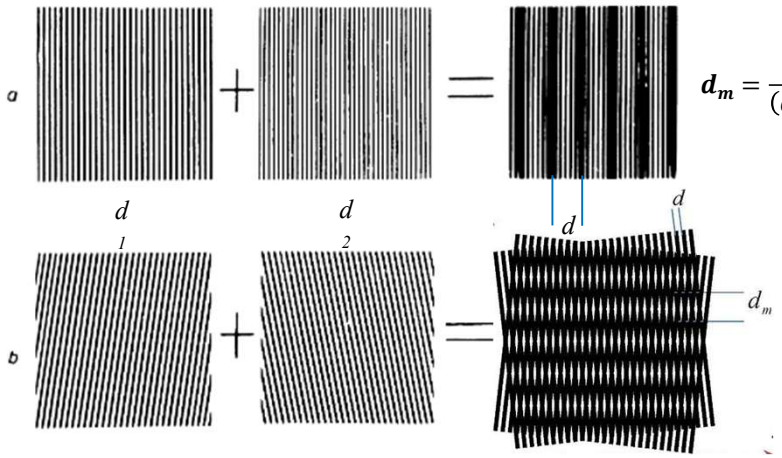
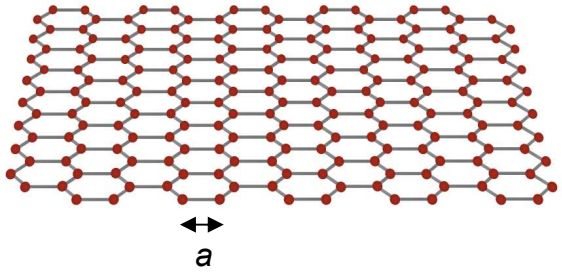
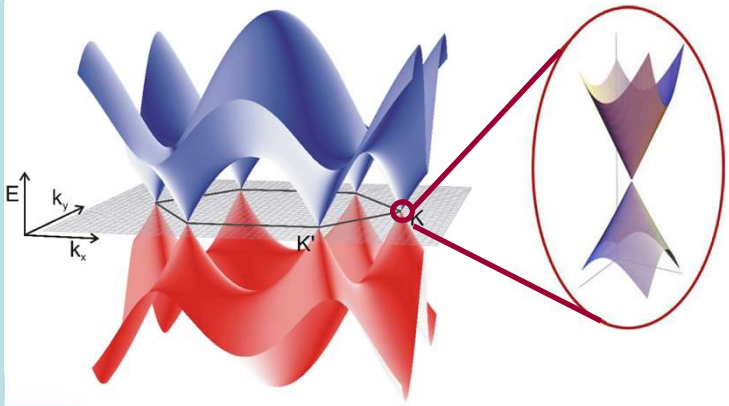
Moiré fringes in optics are large area interference patterns produced when a periodic grating is stacked on another similar one with different spacings or twist angles.

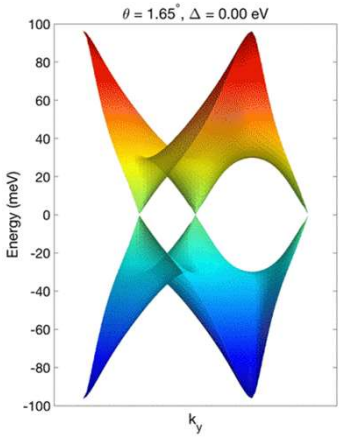


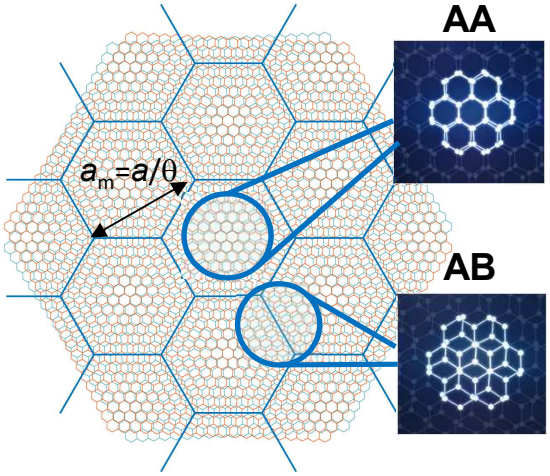
$$d_m = \frac{d_1 d_2}{(d_1 - d_2)}$$

Twistronics: how the angle between layers of 2D materials can change their electrical properties.









Moiré superlattices based on antidot lattices

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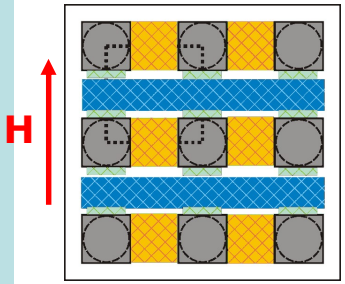
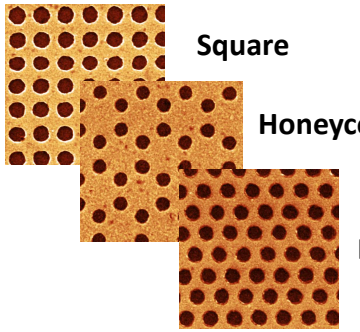


Modes Classification

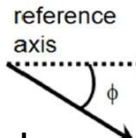
- Extended mode
- Edge mode
- Localized mode



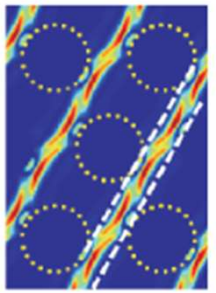
Square

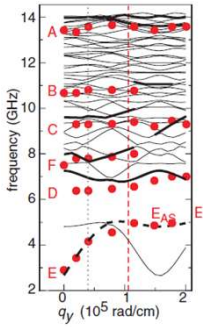
Honeycomb

Rhombic



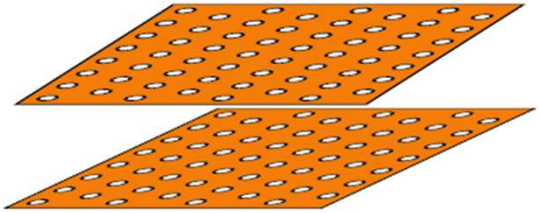
30°

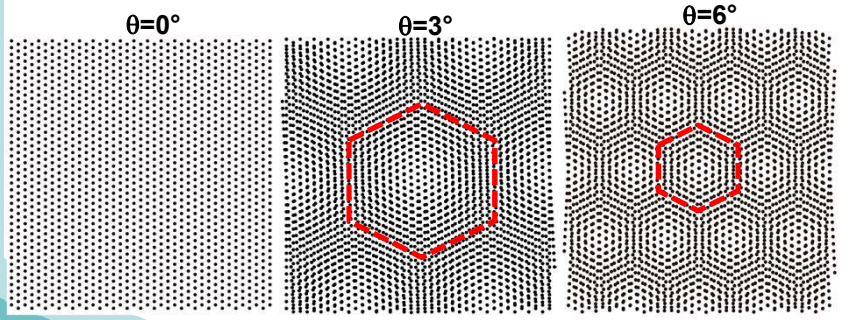




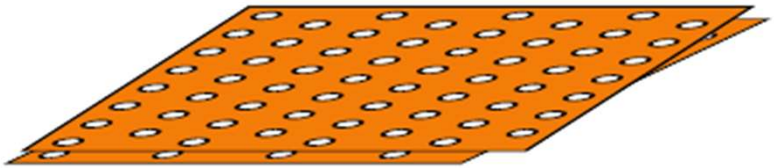
Tacchi et al., PRB **86**, 014417 (2012)

Two antidot lattices with a twist angle



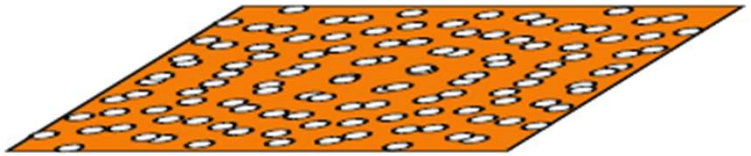


Vertical stack



J. Chen et al., **PRB 105, 094445 (2022)**

Merged into a single film



H. Wang et al., **PRX 13, 021016 (2023)**

Flat band formation in magnetic moiré superlattices

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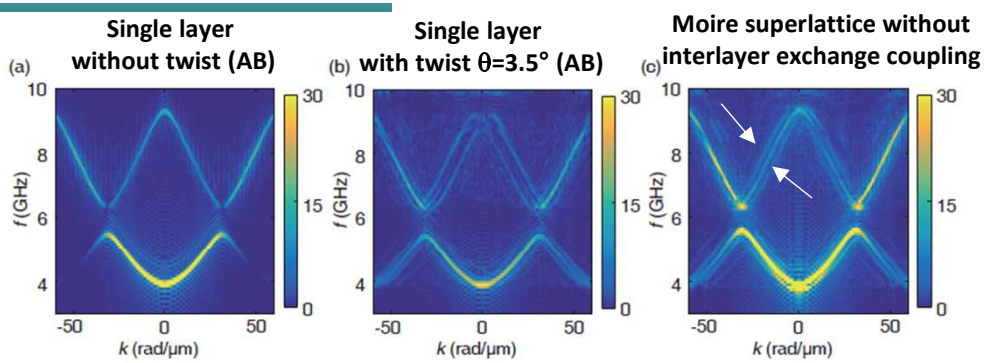
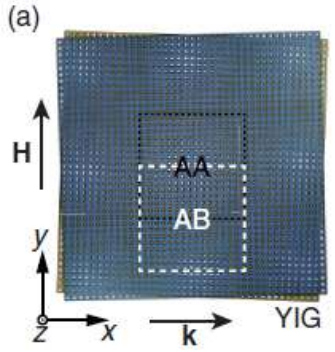
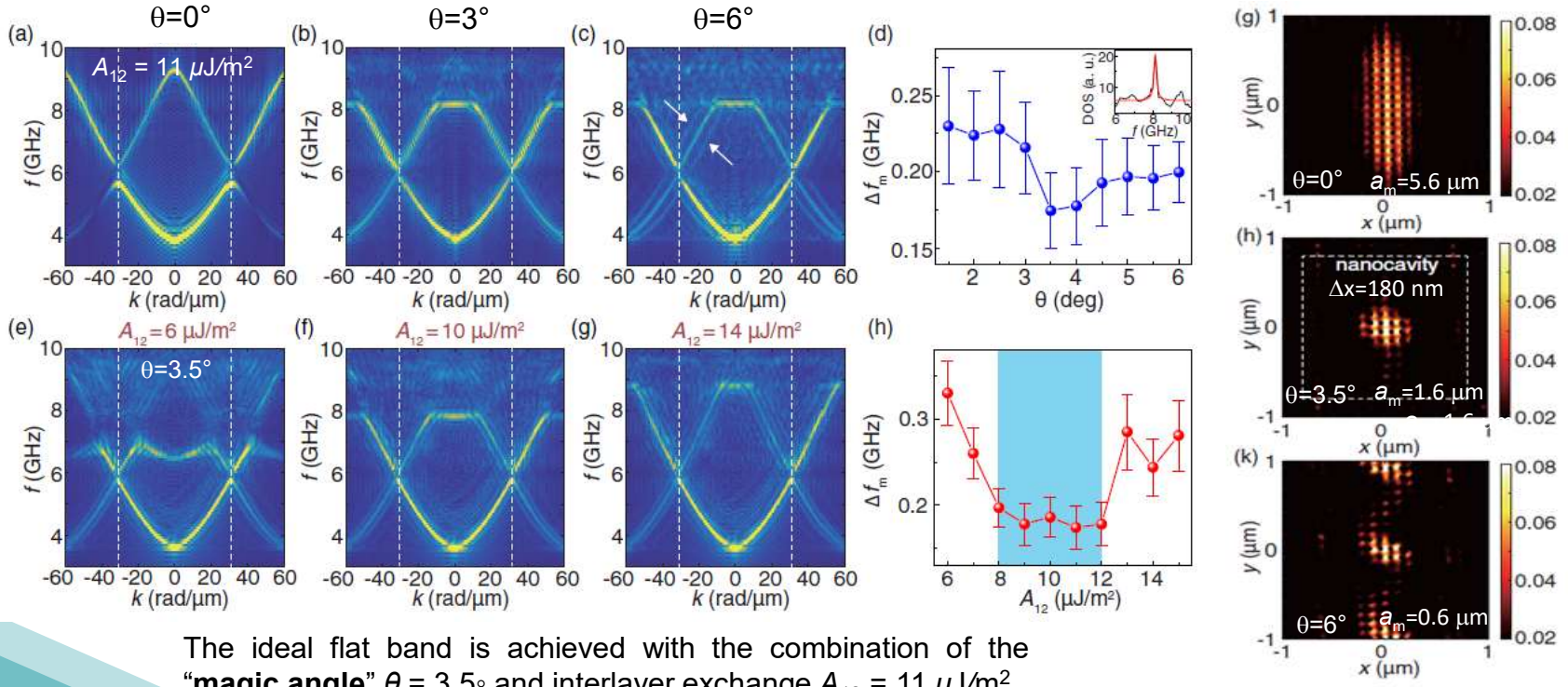
YIG antidot square lattice
***a* = 100 nm**
***d* = 50 nm**
Thickness= 2nm
H=50 mT







The ideal flat band is achieved with the combination of the "**magic angle**" θ = 3.5◦ and interlayer exchange A_{12} = 11 μJ/m^2.

Moiré magnonic antidot lattices in single layer YIG film

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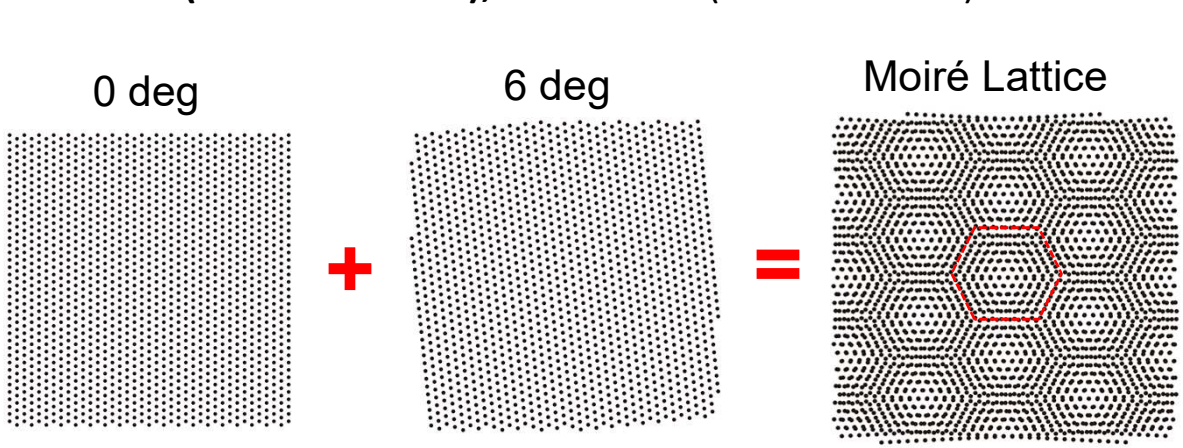
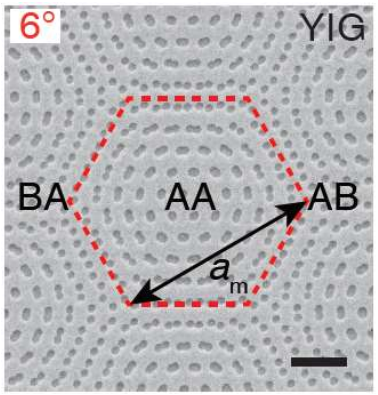
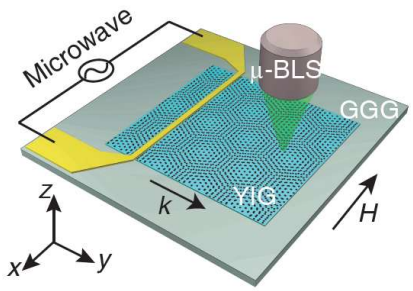
YIG thickness = 80 nm, deposited on GGG (111)

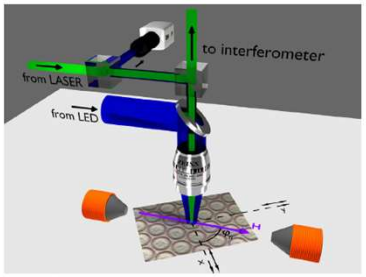
***a*=800 nm (lattice constant);** d = 260 nm (hole diameter)

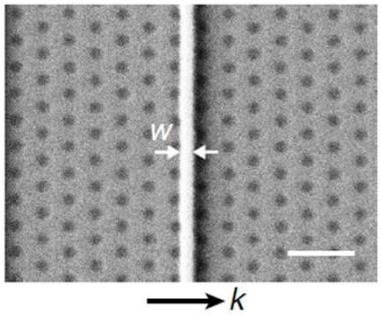


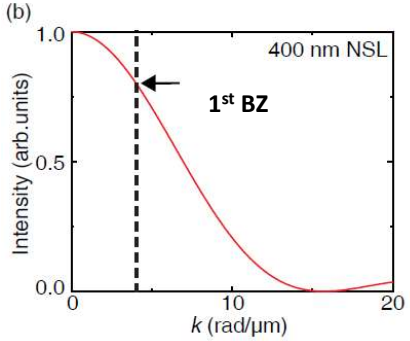
$a_m = a/\theta$











SW are exited in the DE geometry (k ⊥ H)

Gold nano strip-line (NSL) antenna (w=400 nm width)

μ-BLS setup: 250 nm of spatial resolution

μ-BLS measurements

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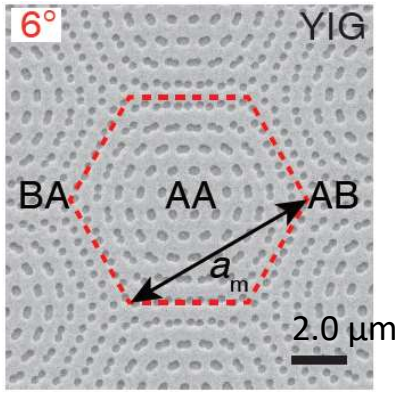
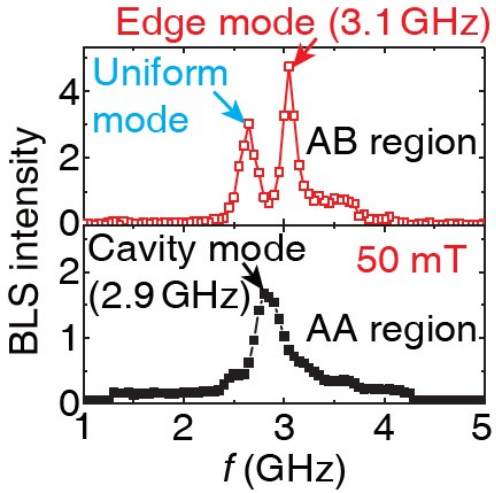
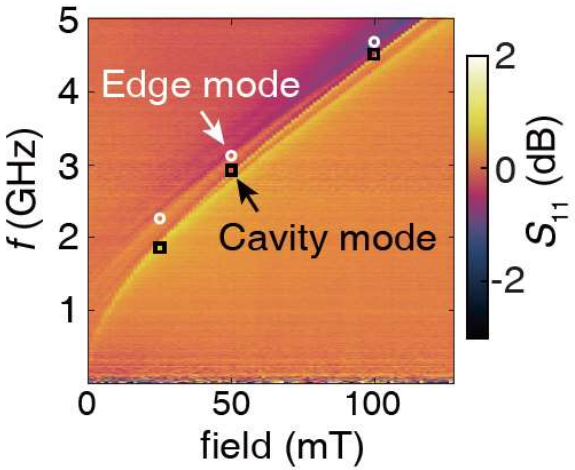
H=50 mT

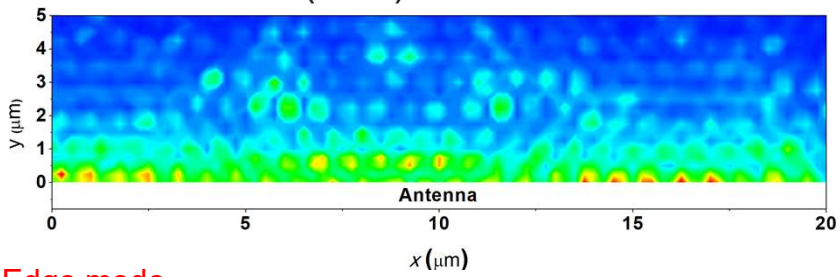


a_m=7.6 μm

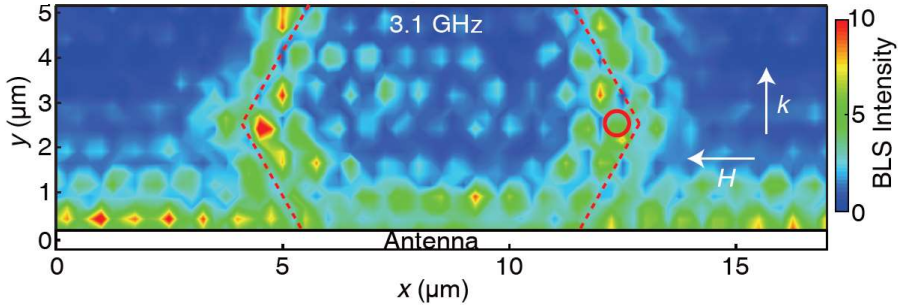




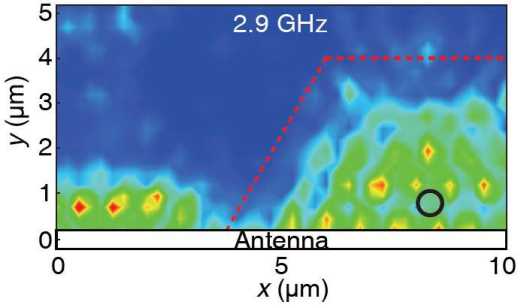
Uniform mode (2.7 GHz)



Edge mode



Cavity mode



Phase diagram of the moiré edge mode

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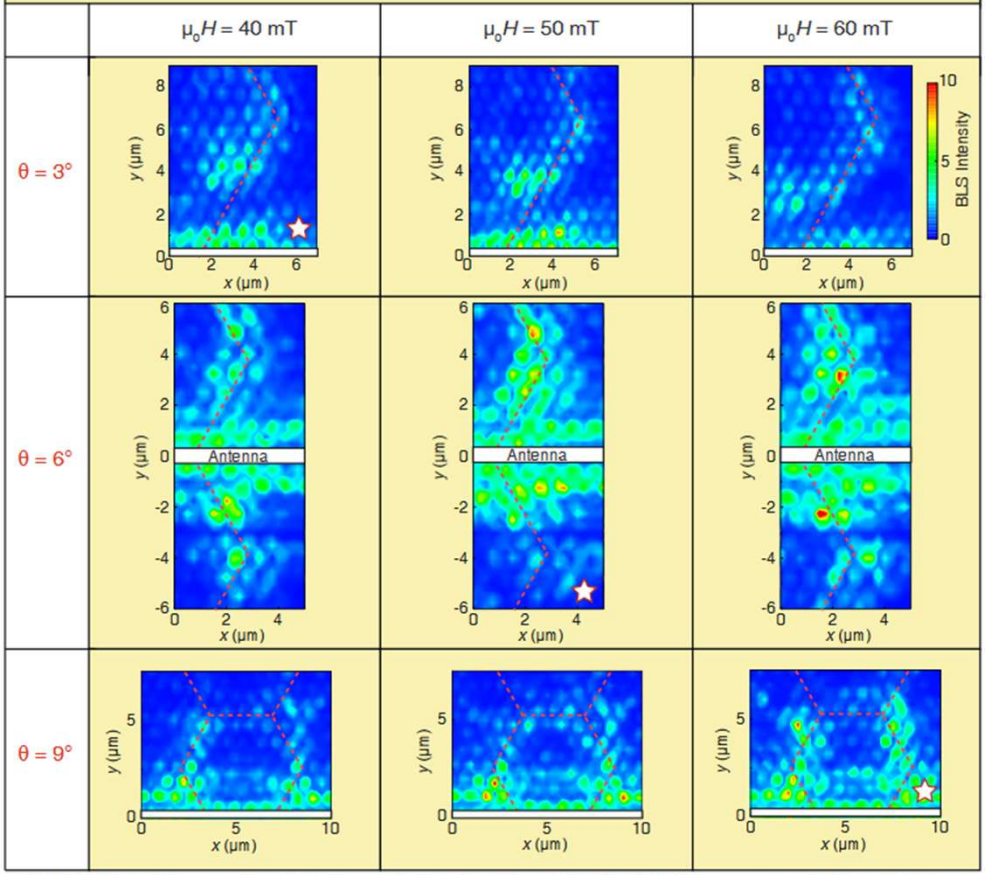
Table 1| Mode profiles obtained by μ-BLS as a function of twist angle and applied magnetic field.



Note: Red dashed lines are the guide to the eye for the edges of a moiré unit cell. Spin waves are excited by the microwave antennas (white rectangles) placed at $y = 0$. The white stars denote the optimal edge mode profile at each twist angle.

The edge mode is optimized around at ***magic-angle*** that depends on H and the twist angle:

- signal intensity
- peak linewidth
- propagation length.

Micromagnetic analysis of flat band formation

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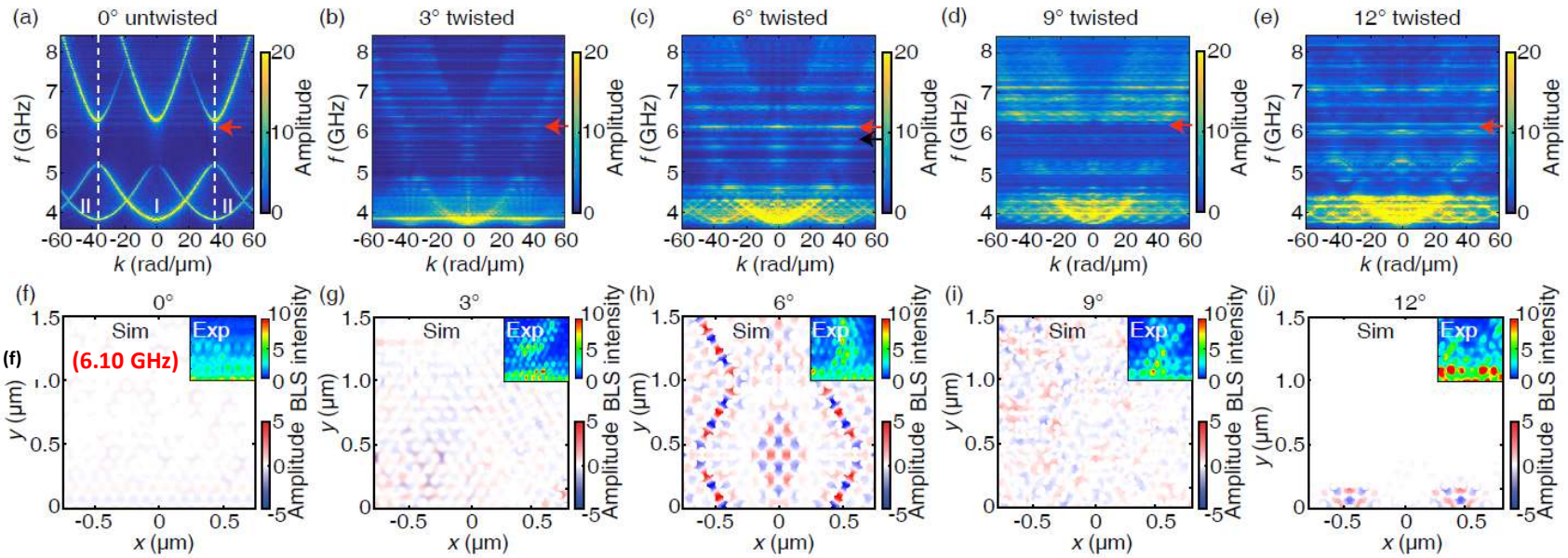
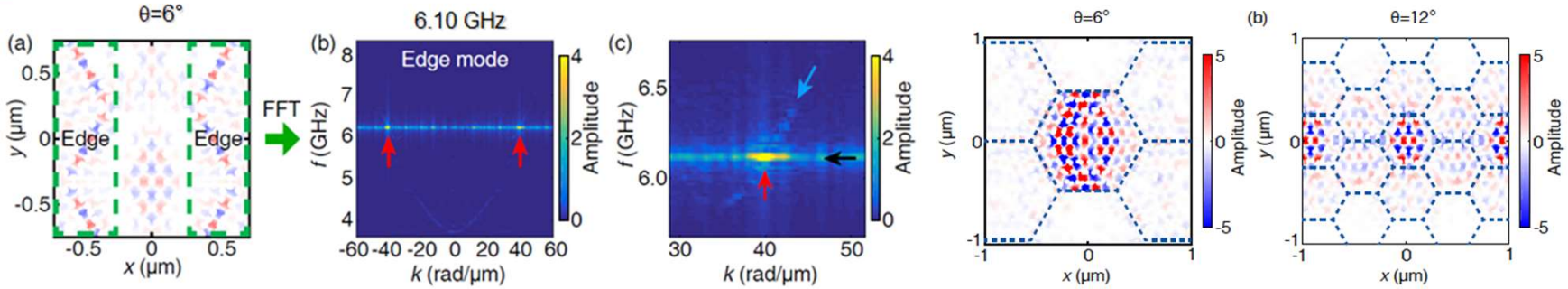


Edge-mode (6.10 GHz)

Cavity mode (5.80 GHz)



Spin-Wave devices based on Unidirectional Coupling

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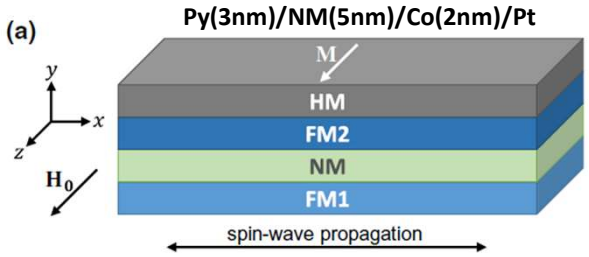
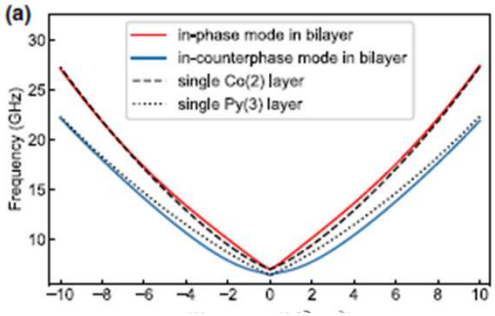
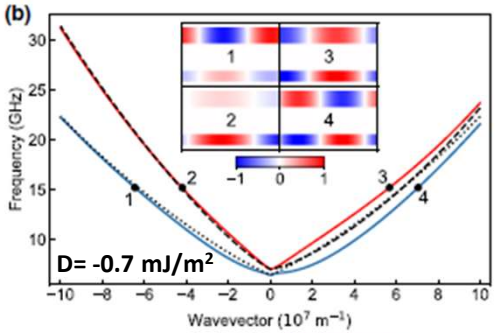
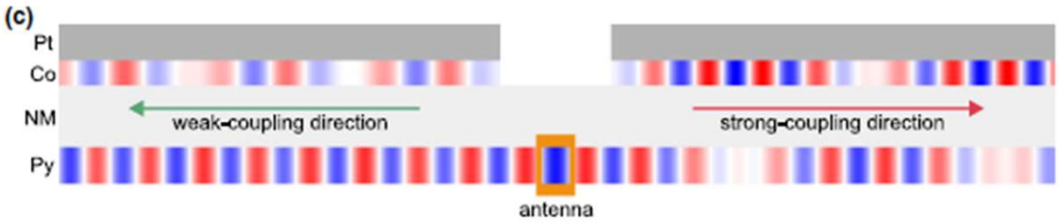
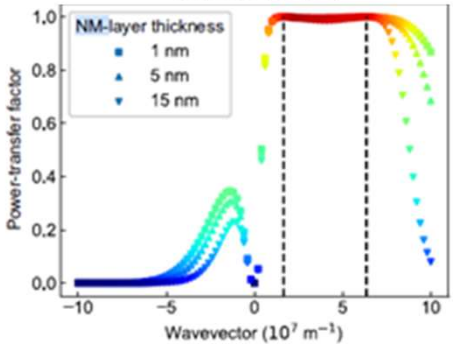


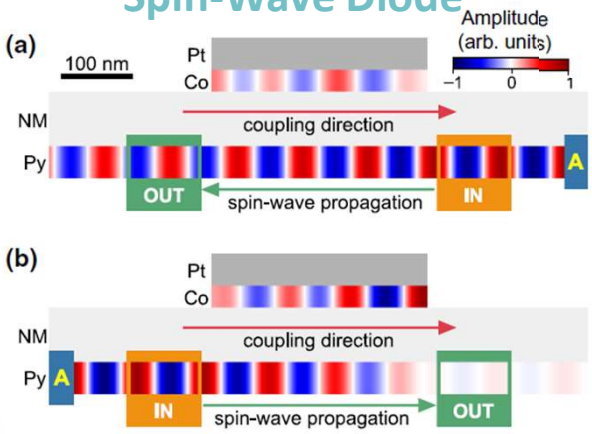








Spin-Wave Diode



Szulc et al., PRApplied (2020).

Spin-Wave devices based on Unidirectional Coupling

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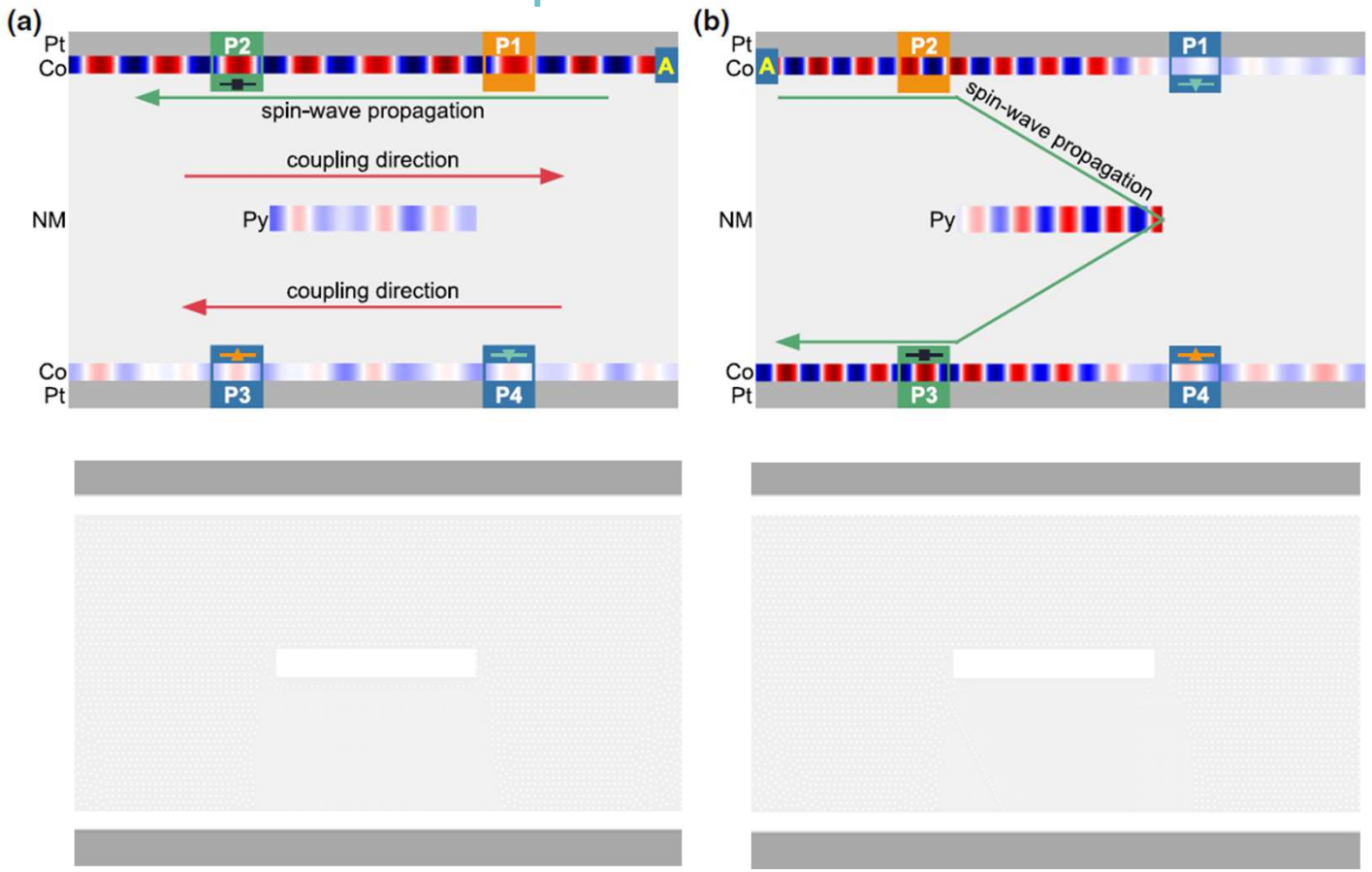
Spin-Wave Circulator



Szulc et al., PRApplied (2020).

Conclusions

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3D Magnonics enables novel functionalities that cannot be achieved in 2D structures and enables more compact device design with lower power consumption.

Twisted magnonics in the form of morié superlattices is a model system to study novel spin-wave properties.

2024- one open PhD position on 3D magnonics at the University of Perugia for three years.