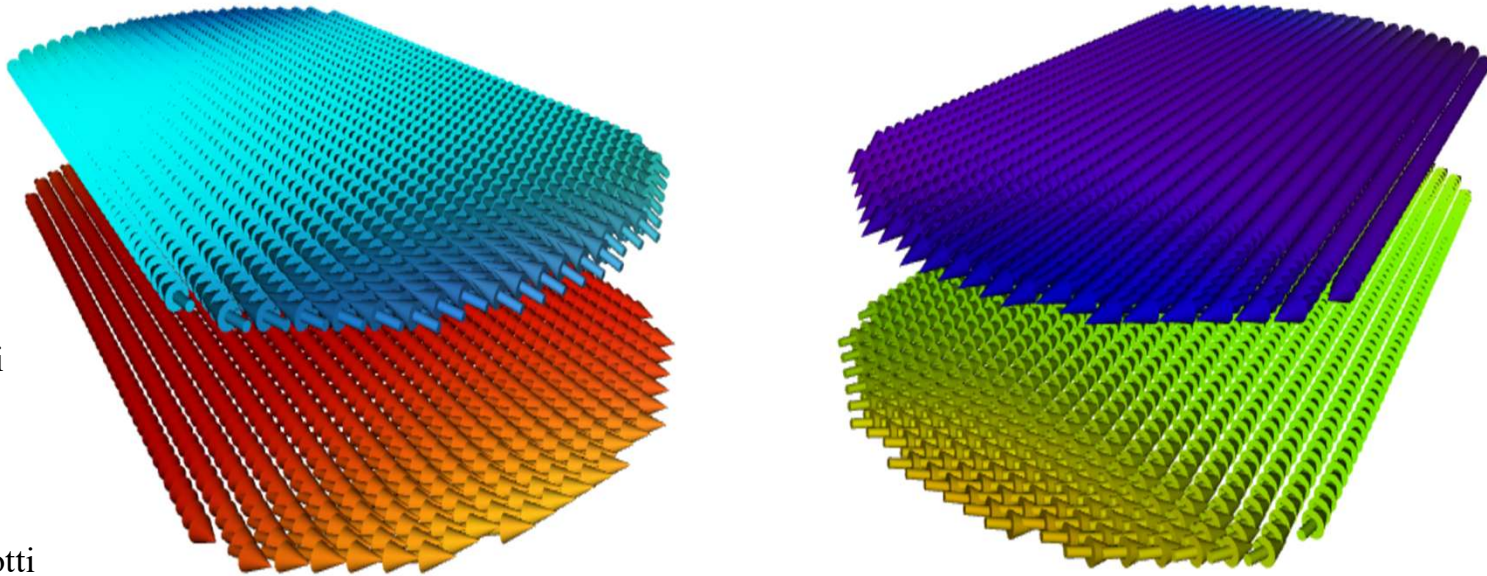


PhD in Physics

XLI cicle

Research Project

Spin Wave Properties in 3D Magnetic Nanostructures



Student:

Riccardo Fornari

Supervisors:

Marco Madami

Gianluca Gubbiotti



1-Education and Research Group

Education

Bachelor's Degree in Physics – Università degli Studi di Perugia

'Spin Waves in the Dipolar regime and Magnonic Crystals'

Master's Degree in Physics– Università degli Studi di Perugia

'Static and dynamic properties of exchange-coupled Artificial-Spin-Ice
CoFe/Ru/NiFe multilayers'

Research group



Group of High resolution Optic Spectroscopy and related Techniques



Overview of the Master's thesis work

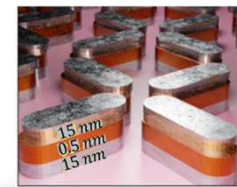
- Characterization of the magnetic properties

$Co_{90}Fe_{10}(15nm)/Ru(0.5nm)/Ni_{80}Fe_{20}(15nm)$

Continuous trilayer

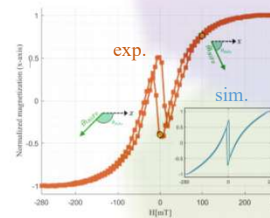


Artificial – Spin - Ice (ASI)

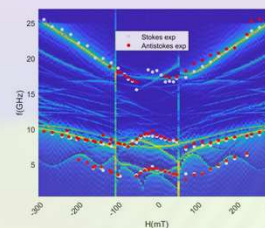


- Techniques: MOKE magnetometry and BLS

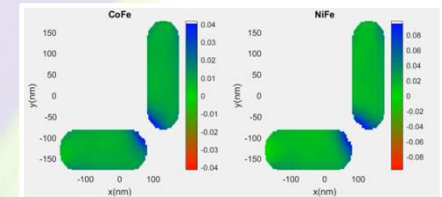
Trilayer MOKE



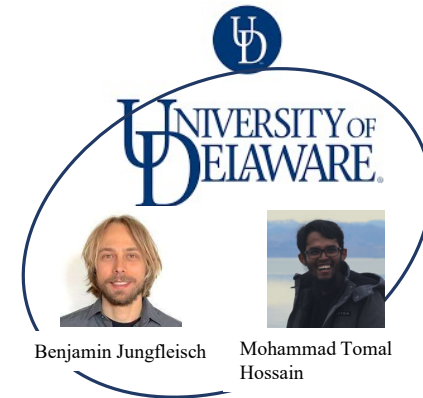
Artificial-Spin-Ice BLS



Spatial profile

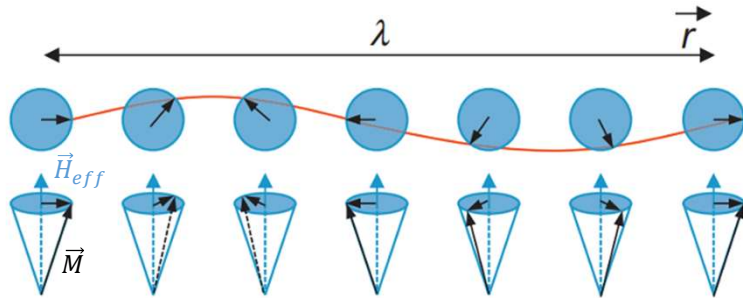


- Interpretation of the results through micromagnetic simulations:



2-State of the art in magnonics reasearch

Magnonics



Landau-Lifshitz equation:

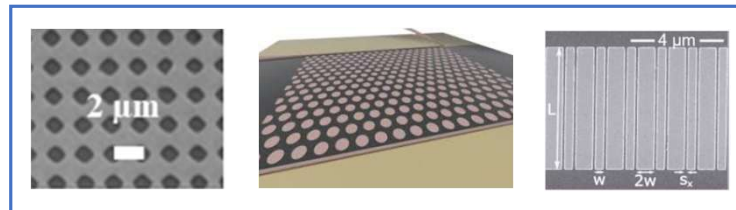
$$\frac{d\vec{M}}{dt} = -\gamma\mu_0\vec{M} \wedge \vec{H}_{eff} , \quad \vec{H}_{eff} = \vec{H}_{ext} + \vec{H}_{ex} + \vec{H}_{dem} + \vec{H}_{anis} + \dots$$

- 1930 Bloch
- ~~Joule heating~~
- Signals control by external magnetic fields, different geometries, different materials
- Wide frequency range (GHz – THz)
- Small wavelengths (nm – mm) → [Miniaturization]

Traditional Magnonics (planar geometry)

- Dipolar coupling (weak)
- Non-reciprocal effects induced by *iDMI*
 $\omega(k) \neq \omega(-k)$

Examples:

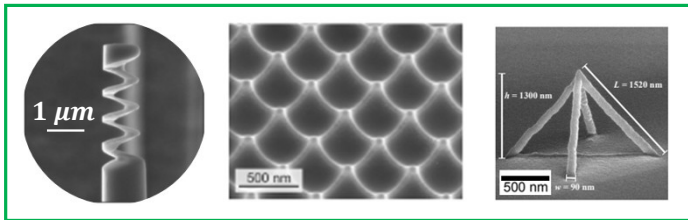


3-Beyond the planar geometry

3D Magnonics

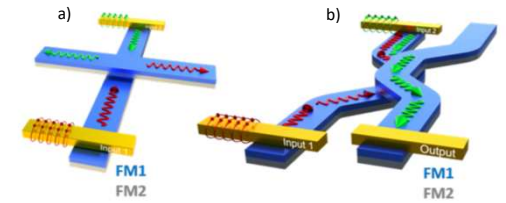
- Increase in the number of **transport channels**
- Increase in device **density** (reduction of footprints)
- New **mechanisms** for Spin Waves manipulation
 - Geometric curvature
 - Exchange interlayer interaction (strong)

Examples:



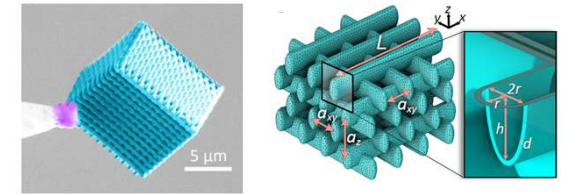
Non-reciprocal directional couplers

- **Vertical transport**
 - a) 90° vertical shift
- Non-reciprocal effects induced by **curvature**
 - b) Change in spin wave height for a single propagation direction



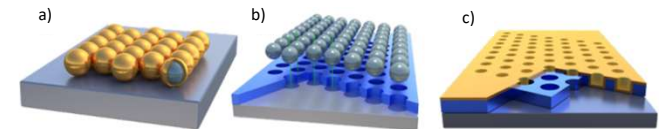
Vertically modulated magnonic crystals

- Significant differences in the **band structure**
- Spin waves **reprogrammable** filters
- **Reconfigurable** devices



Advanced nanofabrication techniques

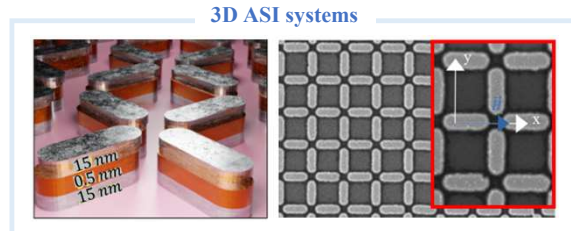
- Lithography techniques
 - a) **Self-assembling** structures
 - b) Antidot lattices fabricated by lift-off
 - c) New systems **not yet investigated**



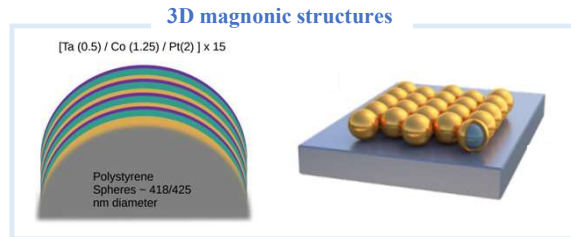
4-Project perspectives

International collaborations in the field of 3D magnonics

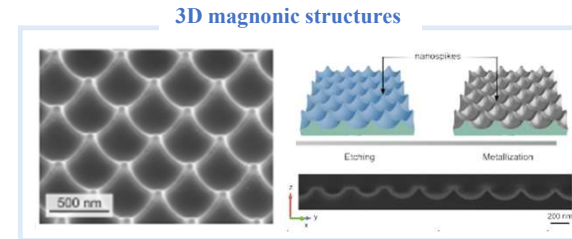
- Department of Physics and Astronomy, University of Delaware, Newark (*USA*)



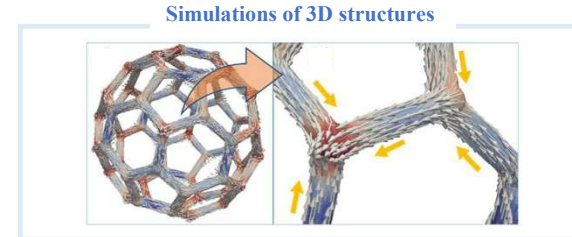
- Institute of Applied Physics, TU Wien (*Austria*)



- Leibniz Institute for Solid State and Materials Research, Dresden (*Germany*)



- Politecnico di Bari and Università Federico II di Napoli (*Italy*)



Final objectives of the project

- Deepen the experience in modern experimental techniques and in the development of micromagnetic simulation codes
- Develop skills in modern nanofabrication processes for 3D magnetic structures.
- Contribute robust scientific results to the understanding and future applications of the emerging field of 3D magnonics.

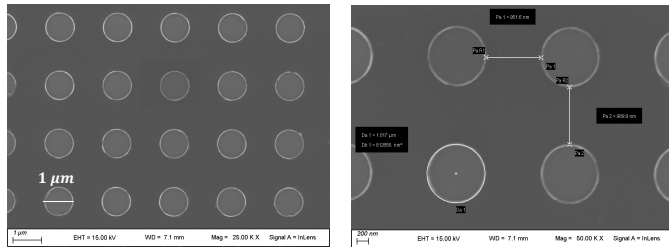
APPENDIX

Research activity carried out last month

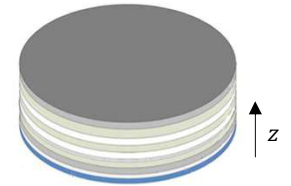


Multilayer disks characterization

SEM images and list of the samples:

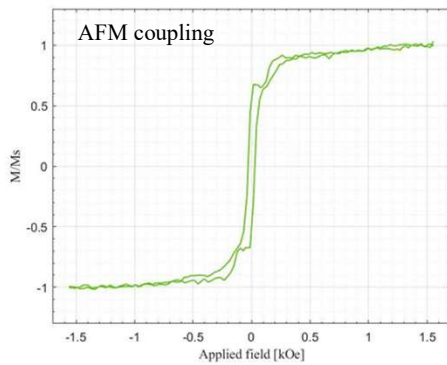


- \xrightarrow{z}
- Sample 1: Si / Py(20nm) / Ru(0.7nm) / Py(5nm) AFM
 - Sample 2: Si / Py(20nm) / Ru(1.4nm) / Py(5nm) FM
 - Sample 3: Si / Py(5nm) / Ru(0.7nm) / Py(10nm) **AFM**
 - Sample 4: Si / Py(5nm) / Ru(1.4nm) / Py(10nm) FM
 - Sample 5: Si / Py(20nm) / Ru(0.7nm) / Py(5nm) / Ru(0.7nm) / Py(10nm) **AFM-AFM**
 - Sample 6: Si / Py(20nm) / Ru(0.7nm) / Py(5nm) / Ru(1.4nm) / Py(10nm) AFM-FM
 - Sample 7: Si / Py(20nm) / Ru(1.4nm) / Py(5nm) / Ru(0.7nm) / Py(10nm) FM-AFM
 - Sample 8: Si / Py(20nm) / Ru(1.4nm) / Py(5nm) / Ru(1.4nm) / Py(10nm) FM-FM
 - Sample 9: Si / Py(35nm) Film

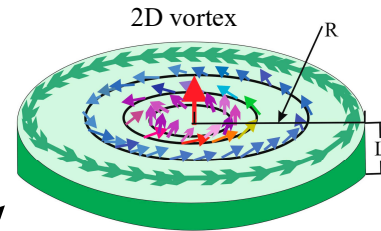
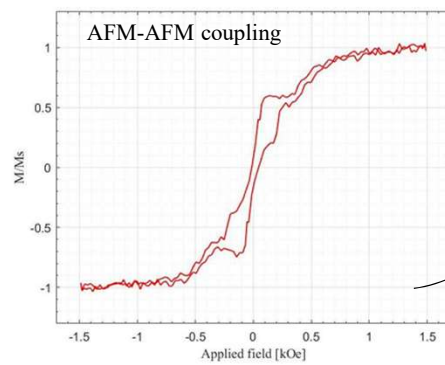


MOKE magnetometry preliminary measurements:

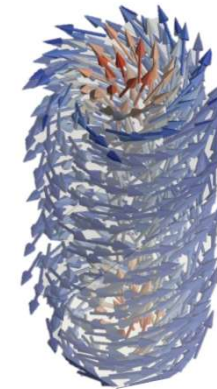
Sample3:
AFM Si/Py(5nm)/Ru(0.7nm)/Py(10nm)



Sample5:
AFM-AFM Si/Py(20nm)/Ru(0.7nm)/Py(5nm)/Ru(0.7nm)/Py(10nm)



3D vortex



Thank you for your attention

