

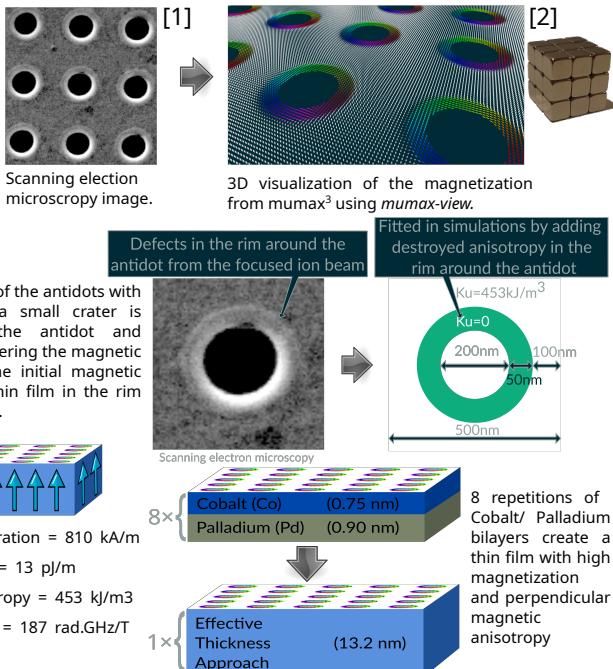
Hybridizations between edge and bulk modes in an antidot lattice with perpendicular anisotropy

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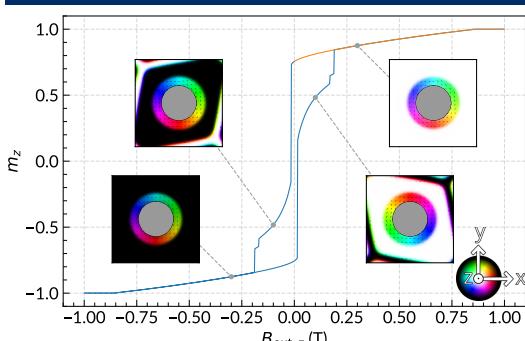
In this investigation, we will use Mumax³ to study the spin wave dynamics of antidot lattice with modified magnetic properties in the rims. Such structures are called magnonic crystals and can be used to control the propagation of spin waves. The ultimate goal would be to use magnonic devices to design magnonic logic units which have the potential to be an energy efficient alternative to conventional electronics. However, we must first study the fundamental spin waves interactions that are happening in the magnonic crystal before studying more complicated devices.

Implementation of a multilayers thin film in Mumax

The thin film we study are based on samples studied by the group of Prof. Barman [1].



Hysteresis



The insets show the magnetization configuration at different points of the hysteresis loop with the color legend on the bottom right corner. When starting from a 1T perpendicular global external field, the film is entirely saturated. As the field is decreased, the magnetization in the rim will start to orientate in plane due to the shape anisotropy and dipolar field from the bulk. As the external field reaches -10 mT, the magnetization in the bulk changes from uniform to domain walls until -200 mT where the bulk saturates again but in the negative direction.

The magnetization in the rim has three main configurations. The "onion" or head-to-head state is a possible state but requires an in-plane field to first stabilize. The vortex-like state will appear when the system is first saturated out-of-plane and the field is removed. The clockwise and counter-clockwise configurations are as likely and degenerated.

In this study, we will operate only in the regime shown by the orange line where the bulk is saturated positively out-of-plane. Also, the magnetization in the rim will be set to always be in a vortex-like counter-clockwise state.

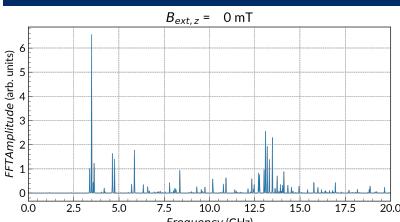
Acknowledgement

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[1] Pal, S., et al. "Tunable magnonic frequency and damping in [Co/Pd] 8 multilayers with variable Co layer thickness." *Applied Physics Letters* 98.8 (2011): 082501.

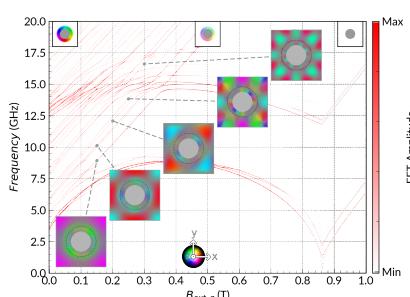
[2] J. Leliaert, M. Dvornik, J. Mulkers, J. De Clercq, M. V. Milošević, and B. Van Waeyenberge, "Fast micromagnetic simulations on GPU - Recent advances made with mumax3," *Journal of Physics D: Applied Physics* 51, 123002 (2018).

Spin wave spectrum



To obtain the spin wave spectrum, we first stabilize the system with the desired film (0 mT in this case) and excite the spin waves with a global external in-plane field. The field has a sinc profile in time and a low peak amplitude of 5 mT to ensure we stay in the linear regime and a cut-off frequency of 20 GHz. Each peak will correspond to a specific spin-wave resonant mode.

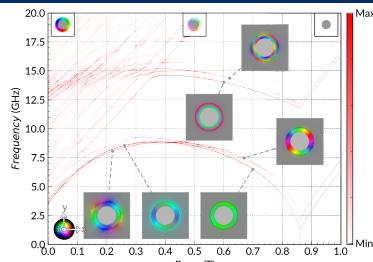
Increasing the external field



Spin wave spectra as we increase the out-of-plane external field from 0 to 1 T. We can see in the small insets at the top, the configuration of the magnetization for the fields of 0, 0.5 and 1 T from left to right respectively.

In red are the resonant spin waves modes. In the upper left corner, we can see the evolution of the bulk modes. The bulk modes are very close to the ferromagnetic resonant modes also called Kittel modes. They increase almost linearly with the external field

Rim modes

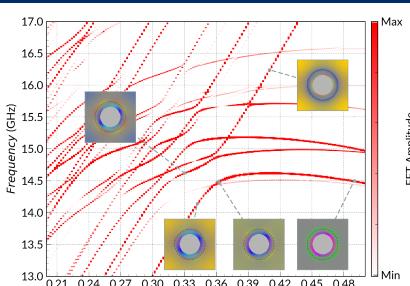


The mode branches that don't have a linear evolution are the rim modes. In this frequency range we can see two groups of rim modes. The group with higher frequency contains the spin waves modes with the radial second order modes. As we increase the field, these branches increase frequencies until around 470 mT, then the frequency decreases until the rim is saturated by the external field which then follows a linear dependency. The reason this branch has such a field dependence is due to the location of the mode to be located on the 90 degree domain wall that is at the junction of the rim and the bulk.

Hybridization

One of the most interesting part is the bulk-rim hybridisation of the spin wave modes happening around $B_{ext,z} = 0.35\text{ mT}$ at 14 GHz. This figure is a zoom in to better have a look at the hybridization conditions.

We find that the bulk and the rim modes need to have a matching number of nodes. This means that the resonant spectrum of the spin wave depends on the lattice type.



Conclusion

The bulk-rim coupling depends on the lattice type and the mode orders

We observe complex rim modes even with a simple unidirectional excitation

Next step is to study the spin wave propagation and studying the magnonic band structure of the magnonic crystal