Dynamics of edge and bulk modes in an antidot lattice with perpendicular magnetic anisotropy

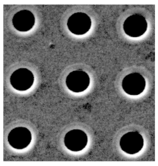
M. Moalic, M. Zelent, K. Szulc and M. Krawczyk

Institute of Spintronics and Quantum Information, Faculty of Physics, Adam Mickiewicz University, Poznań, Poland

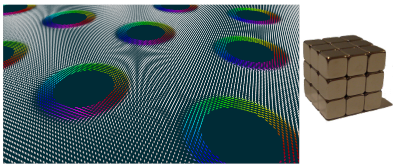
We numerically investigate spin-wave dynamics in a Co/Pd multilayer antidot lattice with reduced perpendicular magnetic anisotropy at the antidot edges. This structure forms a magnonic crystal with periodic magnetization, featuring out-of-plane magnetized bulk and in-plane magnetized rims. Our results show distinct spin-wave behaviors under varying magnetic fields, revealing complex spectra and mode hybridizations. Strong magnon-magnon coupling, driven by exchange interactions, occurs between the fundamental bulk mode and second-order radial rim modes. This study highlights the role of exchange interactions in achieving strong mode coupling through structural patterning and non-collinear magnetization.

A multilayered thin film in Amumax

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

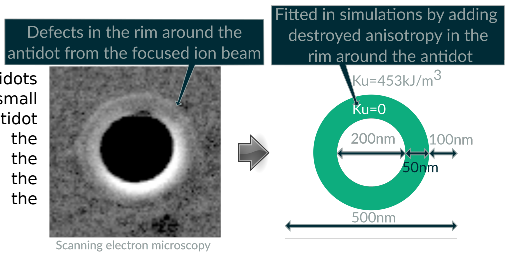


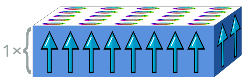
Scanning election microscropy image.



3D visualization of the magnetization from using *mumax-view.*

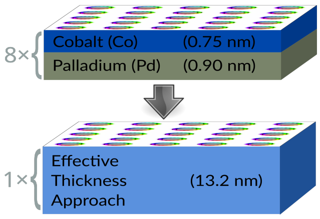
During the making of the antidots with Ga^{+} bombarding, a small crater is created around the antidot and gallium ions are entering the magnetic layers, changing the initial magnetic properties of the thin film in the rim around the antidots.



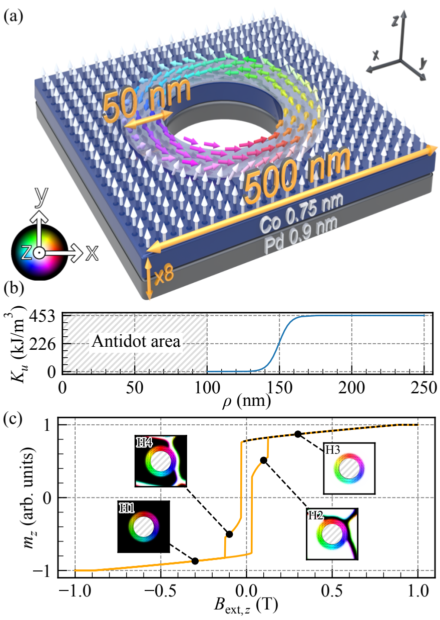


8 repetitions of Cobalt/ Palladium bilayers create a thin film with high magnetization and perpendicular magnetic anisotropy

Magnetization Saturation	= 810 kA/m
Exchange Stiffness	= 13 pJ/m
Out-of-Plane Anisotropy	= 453 kJ/m3

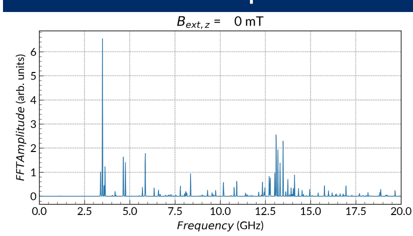


Hysteresis



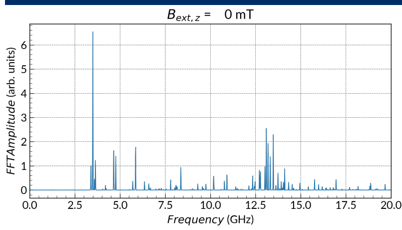
(a) Schematic illustration of the investigated structure showing the Co/Pd unit cell of the Antidot lattice with modified rims (ADL-MR). Note that the figure is not to scale. The light gray area around the hole represents the rim with the reduced PMA. The arrows roughly indicate the orientation of the magnetization for Bextz=0 T. (b) Variation of the PMA constant along the radial direction, starting at the center of the antidot. (c) Hysteresis loop along the z-axis. The dashed black line marks the regime where the demagnetization process is reversible, and within which the SW spectra are calculated. In the insets, the static magnetization configuration at selected field values is illustrated. The non-magnetic areas are hatched in gray. (a) and (c) The hue represents the in-plane orientation of the magnetization, while the brightness indicates the out-of-plane value, with black being fully down and white fully up.

Spin wave spectrum



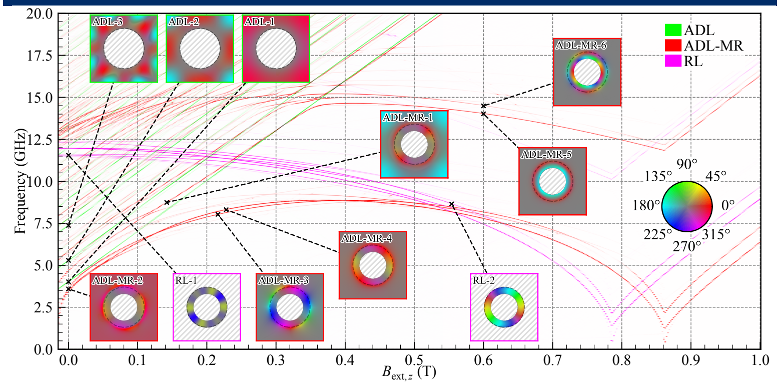
To obtain the spin wave spectrum, we first stabilize the system with the desired film (0 mT in this case) and excite the spin waves with a global external in-plane field. The field has a *sinc* profile in time and a low peak amplitude of 5 mT to ensure we stay in the linear regime and a cut-off frequency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

Spin wave spectrum



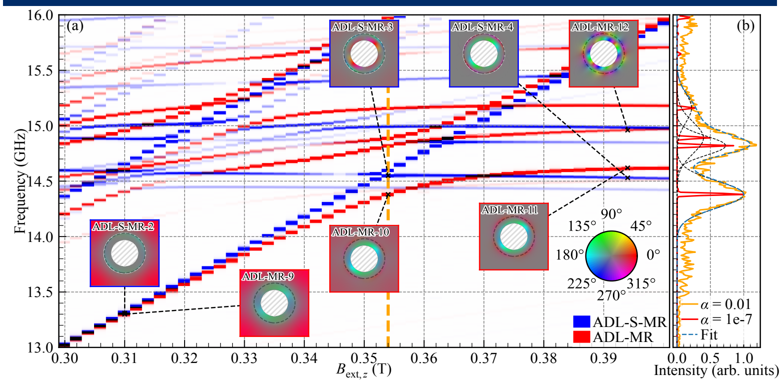
To obtain the spin wave spectrum, we first stabilize the system with the desired film (0 mT in this case) and excite the spin waves with a global external in-plane field. The field has a *sinc* profile in time and a low peak amplitude of 5 mT to ensure we stay in the linear regime and a cut-off frequency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

Increasing the external field



Evolution of the SW resonance spectra for the ring lattice, antidot lattice, and ADL-MR in dependence on the external out-of-plane magnetic field. The line intensity correlates with the SW amplitude. In the insets, the hue represents the phase of the in-plane dynamic magnetization, while the saturation indicates its spatial amplitude. The circular dashed line represents the outer edge of the modified rim. The border color of each inset specifies the corresponding geometry. Non-magnetic areas are hatched in gray.

Hybridization



(a) The evolution of the SW resonance spectra for the ADL-MR and ADL-S-MR in dependence on the external out-of-plane magnetic field at a higher-frequency range. The vertical dashed orange line indicates the value for which (b) was plotted. The line intensity correlates with the SW amplitude. In the insets, the hue represents the phase of the in-plane dynamic magnetization, while the saturation indicates its spatial amplitude. The circular dashed line represents the outer edge of the modified rim. The border color of each inset specifies the corresponding geometry. Non-magnetic areas are hatched in gray. (b) Ferromagnetic resonance spectra of ADL-MR for Bextz=0.354 T with low damping in red and realistic damping (α = 0.01) in orange. The dashed lines are Gaussian fits of the peaks with frequencies 14.38, 14.82, 14.89, and 15.16 GHz.

Cooperativity

$$C = \frac{g^2}{\kappa_{f_{\text{low}}} \times \kappa_{f_{\text{high}}}} = 4.698.$$

Even though the system was not optimized for it, this value of the cooperativity indicates a strong magnon--magnon coupling in the ADL-MR between the second-order radial, first-order azimuthal rim mode and the fundamental bulk ADL mode.

In the context presented, the coupling between rim and bulk modes in the ADL-MR system based on PMA material, as demonstrated above, explores a new type of rather strong dynamic coupling between planar regions of non-collinear magnetization, which is mainly mediated by exchange interactions and turns on a higher-order azimuthal mode. The influence of the lattice type, as indicated by the hybridization selection rules, suggests a possibility for further optimiza-

Aknowledgement

The research has received funding from the National Science Centre of Poland, Grant No. UMO-2020/37/B/ST3/03936 and 2023/49/N/ST3/03538. The simulations were partially performed at the Poznan Supercomputing and Networking Center (Grant No. 398).