Magnon-magnon coupling in an antidot lattice with perpendicular magnetic anisotropy

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We investigate the spin-wave dynamics in the antidot lattice in Co/Pd multilayered structure with reduced perpendicular magnetic anisotropy close to the antidot edges. Our results delineate the distinct behavior of spin waves in the bulk and reduced anisotropy regions revealing complex spin-wave spectra with hybridization of modes. Our research expands the horizons of magnonic crystals by combining periodic patterning and magnetization texture to enhance magnon-magnon coupling quantified by a high cooperativity value of 2.757.

Index Terms—**Magnonics, Magnonic crystals, Spin wave coupling.**

MAGNONIC CRYSTALS (MCs), magnetic metamaterials with a periodic structure influencing spin-wave (SW) band formation, are similar to photonic crystals in manipulating wave propagation. [citation] These MCs, made from various material combinations like ferromagnetic dots in non-magnetic matrices or antidot lattices (ADLs), guide SWs and have diverse applications. Recent expansions include atomic spin lattices, contributing to SW bands into the THz range. However, the flexibility in customizing these structures remains limited.

Recent works highlight strong magnon-magnon coupling in nanomagnonic devices, crucial for advanced device designs, and reveal tunable coupling strength through external parameters [1]. Our prior research showed that multilayer ADLs with perpendicular magnetic anisotropy (PMA), like $[Co/Pd]_8$ multilayers, control SW propagation via periodic magnetization texture [2]. Using micromagnetic simulations, we calculated the SW spectra in ADLs, revealing low-frequency modes from modified magnetic properties in rims post-ion beam patterning [3], [4]. In our case, the focused ion beam has the side effect of modifying the edge of the antidot, the rim, which we modeled in our simulations by reducing the PMA in these areas.

In this talk we plan to present our work on the study the SW spectra in ADLs with modified rims (ADL-MR) shown in Fig. 1(a) and focus on the effects of the external magnetic field strength $B_{\text{ext},z}$ on the SW spectra.

Investigating the hysteresis loop of the ADL-MR (Fig. 1(c)), we observe distinct magnetization states in bulk and rim regions under an out-of-plane magnetic field. At remanence, the bulk maintains out-of-plane saturation, while the rim stabilizes into a vortex-like state. Switching the external magnetic field initiates domain wall formation within the bulk at $B_{\text{ext},z} = 0.014$. At $B_{\text{ext},z} = 0.124$ T, the domain evolves to full saturation in the opposite direction. Rim magnetization reaches full saturation when the magnetic field intensity exceeds $B_{\text{ext},z} = 0.86$ T or falls below $B_{\text{ext},z} = -0.86$ T, resulting in out-of-plane saturation. The next section explores spin wave (SW) dynamics in the field range marked by the dashed line in Fig. 1(c) (between 1 and -0.014 T), signifying full bulk saturation.

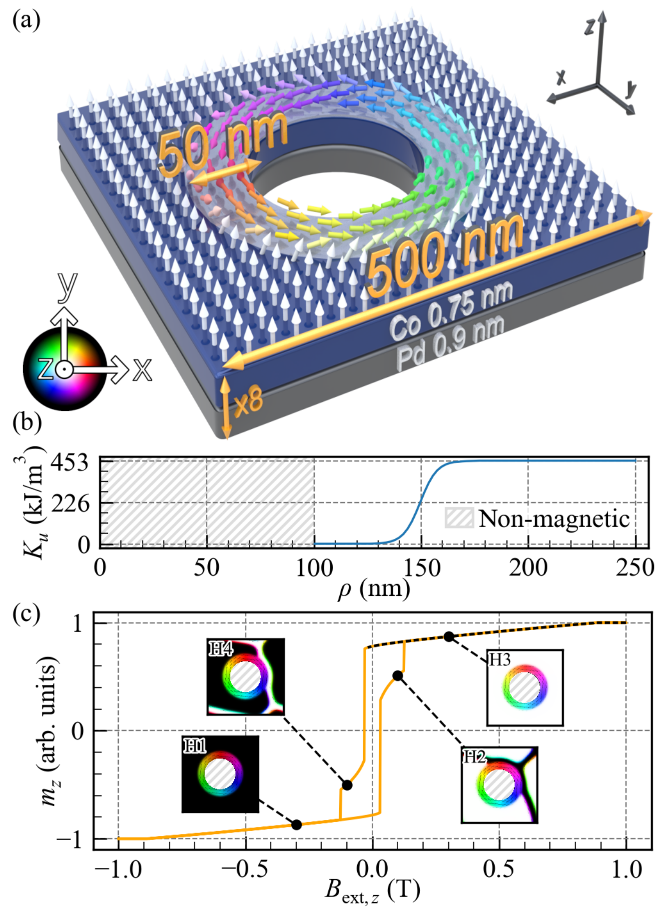

Fig. 1. (a) Schematic illustration of the investigated structure showing the Co/Pd super-cell of the ADL-MR. Note that the figure is not to scale. The light gray area around the hole represents the rim with the reduced PMA. The arrows roughly show the orientation of the magnetization for $B_{\text{ext},z}$ = 0 T. (b) The variation of the PMA constant along the radial direction starting at the antidot center. (c) Hysteresis loop along the z-axis. The dashed black line indicates the regime in which the demagnetization process is reversible and the SW spectra are calculated. In the insets, the static magnetization configuration in selected field values is shown. The hue gives the in-plane orientation of the magnetization, and the brightness gives the out-of-plane value, black being fully down and white fully up. The non-magnetic areas are hatched in gray.

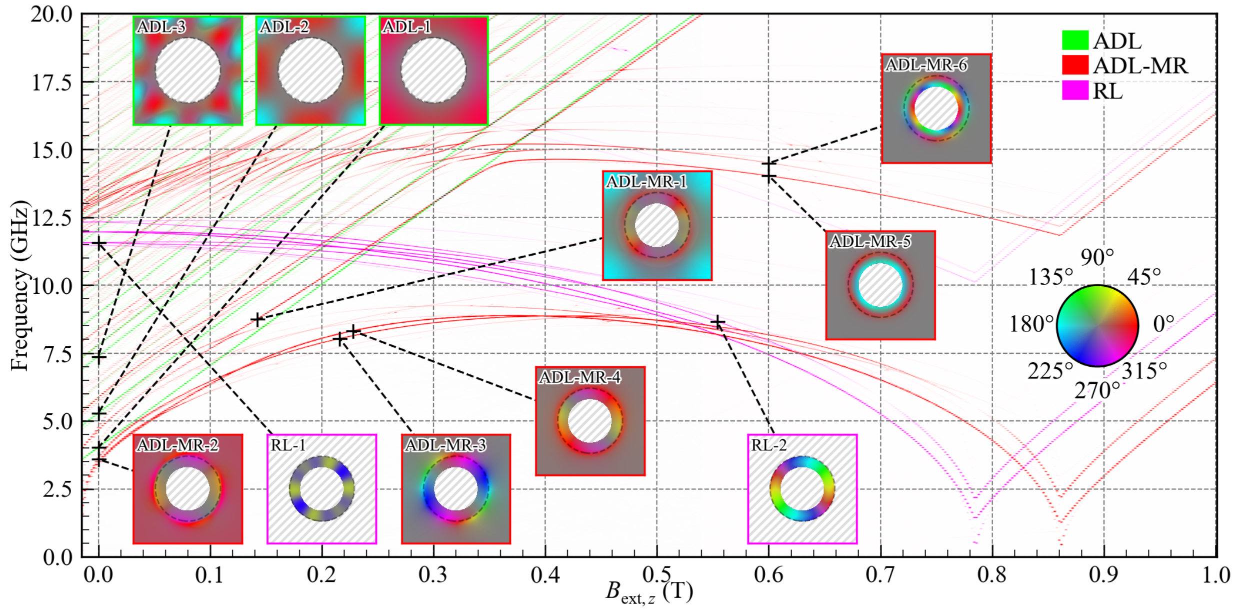

Fig. 2. Evolution of the SW resonance spectra for the RL, ADL, and ADL-MR in dependence on the external out-of-plane magnetic field. The color intensity corresponds to the maximum amplitude value of the SW spectra. In the insets, the hue gives the in-plane orientation of the magnetization and the saturation gives the spatial amplitude. The circular dashed line represent the outer edge of the modified rim. The color of the inset borders indicate which geometry it belongs to. The non-magnetic areas are hatched in gray.

We analyze two complementary subsystems: a ring lattice (RL) without PMA, plotted in purple in Fig. 2; and a simplified antidot lattice (ADL) utilizing PMA but without rims, plotted in green in Fig. 2. The ADL system exhibits a standard linear relationship between the spin wave (SW) frequency and the external field [3], leading to no observed interaction between modes as the field increases.

In the RL system, in purple, with a counterclockwise vortex-like magnetization texture, the lowest frequency curves at $B_{\mathrm{ext},z} = 0$ T correspond to low order azimuthal modes (*RL-1*). These modes result from the degeneration of clockwise and counterclockwise azimuthal modes of the same order. As the magnetic field increases, the degeneration splits. We then compared the RL with the ADL-MR system.

At low frequencies (3-12.5 GHz), the first-order radial rim modes in ADL-MR exhibit a strong interaction with the bulk, leading to mode localization transitions from bulk to rim with increasing magnetic field. The coupling is attributed to the exchange interaction between the rim and bulk, resulting in significant mode softening. The magnetization reorientation within the rim and the static stray magnetic field from the bulk contribute to this behavior.

At higher frequencies (12.5-17.5 GHz), second-order radial rim modes in ADL-MR show hybridization with bulk modes, resulting in large gaps and deviations from linear frequency-field dependencies. The exchange interaction between the rim and bulk is identified as the main contributor to this magnon-magnon coupling. The coupling strength is quantified by cooperativity, reaching a value of 2.757 at 0.354 T, indicating a strong dynamic coupling between the rim and bulk modes.

Comparative simulations with a spacer layer between the rim and bulk (ADL-S-MR) demonstrate that the exchange interaction significantly influences the azimuthal modes' behavior, supporting the conclusion that it plays a crucial role in the observed effects in ADL-MR. The results highlight the unique coupling mechanisms in ADL-MR, revealing a new type of strong dynamic coupling between planar regions of non-collinear magnetization, mediated primarily by exchange interactions. This understanding of rim-bulk interactions in ADL-MR opens avenues for designing magnonic devices with tunable coupling strengths and frequencies.

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