Ph.D. Thesis Title: “Unravelling Spin Wave Dynamics in Artificial Spin Ice and Non-collinear Magnetic Textures”

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Abstract

Magnonics, a burgeoning field within nanomagnetism, focuses on utilizing spin waves (SW) or magnons for information transmission, storage, and processing. Magnonic crystals, typically composed of periodic and aperiodic arrangements of nanomagnetic entities with varying shapes, sizes, and materials, can be tailored to explore unique properties such as negative group velocity, anisotropic dispersion relation, nonreciprocity, and reconfigurability. These properties hold promise for developing next-generation information processing and storage technologies. To create reconfigurable magnonic devices, precise control over SW behavior and seamless integration with spintronic and electronic systems are essential. Artificial spin ice (ASI) and non-collinear magnetic textures emerge as promising candidates for achieving these objectives. ASI consists of engineered arrays of dipolar-coupled single-domain ferromagnetic nanomagnets, mimicking frustrated spins found in rare earth titanate pyrochlores like $Ho_2Ti_2O_7$ and $Dy_2Ti_2O_7$. Originally designed for studying geometrically induced magnetic frustration, phase transitions, and emergent magnetic monopoles, these structures offer multiple degenerate microstates, enabling the manipulation of SW excitations. Despite recent interest in SW behavior within these arrays and clusters of dipolar-coupled nanomagnets, a comprehensive understanding of SW excitation, propagation, and its coupling with other excitations in the presence of emergent magnetic monopole and bound monopole-polaron states remains elusive. Additionally, non-collinear magnetic textures such as radial vortex, skyrmions, etc., arising from the intricate interplay of fundamental magnetic interactions, including symmetric Heisenberg exchange, perpendicular anisotropy, and antisymmetric Dzyaloshinskii-Moriya (DM) interaction, offer advantages over simpler counterparts like nanomagnets with single-domain states in terms of reconfigurable magnonics. The SW excitations in these textures feature shorter wavelengths, non-linearity, and non-reciprocity. Exploring these properties involves stabilizing novel textures across diverse magnetic and geometrical parameter ranges and investigating their corresponding SW responses.

In this thesis, we provide an in-depth analysis of SW behavior in the building block of square ASI, finite-size square ASI, and square ASI array using micromagnetic simulations and Time-resolved magneto-optic Kerr effect (TR-MOKE) spectroscopy. We delve into the influence of magnetoelastic coupling on SWs, through the concurrent excitation of phonons induced by laser pulse irradiation on the square ASI array using TR-MOKE spectroscopy. Finally, we explore the non-trivial SW behavior in a novel non-collinear magnetic texture within a confined nanodisk with interfacial DM interaction.

Firstly, we investigated the collective SW response in the square ASI and its building blocks using micromagnetic simulations. Our study reveals key features associated with magnetization reversal in constituent nanomagnets during the evolution of microstates at varying external magnetic fields in the respective excited SW spectra. Analysis of the spatial distribution of power profiles associated with excited SW modes shows the significant influence of local magnetic charges, i.e., local converging and diverging magnetic flux lines, in the inhibition and facilitation of specific SW modes. Our comprehensive analyses of the building block and square ASI structure demonstrate that the collective excitation of SWs and their behavior in square ASI can be understood by examining their corresponding building blocks. Further, we demonstrate that limited efficient and anisotropic transmission of SWs can occur between nanomagnets solely due to the dipolar interaction inherent in square ASI configurations. Our study underscores the critical role of local magnetic charges in facilitating this anisotropic transmission of SWs to neighboring nanomagnets when a spatially localized magnetic field perturbation

is applied at the magnetically uncharged vertex. Our findings reveal distinctive features in the spectral attributes of SWs when magnetically charged states, such as emergent magnetic monopoles and anti-monopoles, and bound monopole-polaron states, are present within finite-size square ASI systems.

Based on our simulation findings, we explore the collective SW response in a square ASI lattice using TR-MOKE spectroscopy. Here, we employ a highly focused pump pulse to excite a single ASI vertex during irradiation. Our experimental investigation reveals that in large arrays of such ASI vertices, viz., square ASI lattice, magnetoelastic coupling emerges as a critical factor influencing the collective SW response. Magnetoelastic coupling arising due to the concurrent excitation of phonon modes through pump pulse irradiation results in the observation of non-dispersive SW modes, which are independent of the magnetic field due to magnetoelastic coupling. We show that the influence of magnetoelastic coupling can be tuned by controlling the underlying magnetic state through external magnetic orientation relative to lattice symmetry or by introducing defects like misaligned nanomagnets to break the symmetry of the square ASI lattice. To corroborate our experimental findings, we employ a multistep modeling approach to simulate coupled magnetoelastic modes induced by ultrafast laser pulse irradiation on square ASI samples. Details of the multi-step model and its outcomes are presented alongside the experimental findings.

Finally, we present our analysis of SW modes in non-collinear magnetic textures by conducting detailed micromagnetic simulations in Co/Pt bilayer nanodisks. The simulated ferromagnetic/non-magnetic bilayer nanodisks exhibit interfacial DM interaction, thereby facilitating the stabilization of non-collinear magnetic textures with specific chirality. Our study demonstrates the stabilization of a novel magnetic texture through a series of magnetic texture transitions induced by sweeping an external magnetic field. The SW studies conducted in these textures highlight the non-reciprocal nature of the excited SW mode, which is exclusively observed in the novel texture. Furthermore, our study demonstrates efficient switching of this novel state into a target-skyrmion state within a few nanoseconds timescales by resonating the equilibrium magnetic state at the eigenfrequency of its radial SW mode. This finding holds promise for developing power-efficient spintronic memory devices.