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Recent advances in magnonics FREE

Special Collection: Recent Advances in Magnonics

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Magnonics is an exciting and rapidly growing field revolving around the study and manipulation of magnons, the low-lying collective excitations of magnetically ordered systems. This field has emerged in response to both fundamental physics interests and the growing demand for faster, more efficient, and more reliable signal processing and computation up to THz frequencies, i.e., beyond clock frequencies of current computer technology.

Magnonic devices promise to transmit and process information in ways that are fundamentally different from traditional electronic devices that exploit the flow of charges. Low-frequency spin waves can propagate through magnetic materials with minimal energy loss, transmit information via angular momentum flow instead of charge motion, and can be easily manipulated using magnetic fields, electric fields, spin currents, or thermal gradients. High-frequency magnons offer wave-based in-memory computation at wavelength much shorter than light, contributing to the emerging request for beyond von Neumann computer architectures. Consequently, numerous efforts are focused on developing spin-wave-based approaches to information processing that encode information in the amplitude and phase of spin waves and manipulate it via spin-wave gates and spin-wave interferometers. Magnons also give rise to the new burgeoning field of hybrid magnonics, which aims at leveraging the interactions between magnons and other degrees of freedoms to unlock unprecedented functionalities and physical regimes. In particular, the integration of magnons with other quantum systems, such as superconducting circuits, quantum dots, or nitrogen-vacancy centers in diamond, leads to several advantages for quantum information processing and quantum sensing and opens new avenues for research into the quantum properties of magnons.

This "Recent Advances in Magnonics" Special Topic in the *Journal of Applied Physics* offers an overview of the most active research areas currently under investigation in the broad field of magnonics. In particular, featured topics include theoretical modeling of spin-wave dynamics,[1–5] magnonic crystals,[6–10] magnetic bilayers,[11] developments in spin-wave sensing[6,12] and spin-wave computing,[13,14] hybrid magnonic systems,[3,4,15–18] interactions between spin waves and topological spin textures,[19,20] nuclear spin waves,[21] and novel theoretical approaches to the dissipative nature of magnons in magnetic and hybrid magnonic systems.[22]

The optimization of magnonic devices critically relies on a comprehensive understanding of the spin-wave properties, which can be developed through a combination of theoretical modeling and experimental advancements in spin-wave sensing techniques. Modeling systems with arbitrary geometry and spatially inhomogeneous magnetization is often not amenable to analytical techniques and instead requires advanced numerical methods. Among several numerical approaches, micromagnetic simulations have emerged as a crucial tool in designing and optimizing magnetic devices and continued in providing essential guidance for interpreting experimental results. In this collection, d'Aquino and Hertel[1] present a comprehensive overview of the current state-of-the-art in micromagnetic frequency-domain simulation methods and their applications to three-dimensional micromagnetic systems. Copus *et al.*[2] and Moalic *et al.*[8] illustrate the effectiveness of micromagnetic simulations in calculating eigenmodes and the dispersions of spin waves in complex magnetic structures. Iyaro and Stamps[3] show that integrating a newly developed semi-classical cavity magnonics theory with micromagnetic simulations enables a comprehensive description of a broad range of linear and nonlinear magnetization dynamics. Hamadeh and co-authors[4] utilize micromagnetic simulations to showcase that a hybrid magnonic-oscillator system consisting of a spin transfer auto-oscillator and a magnonic waveguide can be engineered to achieve coherent and adjustable generation of propagating spin waves. Despite the widespread applications of micromagnetic methods, there are still certain physical scenarios where other theoretical approaches can be devised to surpass the efficiency of these simulations. An example is provided by Vlaminck and co-authors,[5] i.e., a near-field diffraction model that can replicate the diffraction patterns of spin waves in perpendicularly magnetized films at a faster pace than the equivalent micromagnetic simulations.

This collection contains several examples of the applications of Brillouin light scattering (BLS) microscopy, which is widely recognized as one of the leading probes for accessing the spectroscopic properties of magnetic excitations. In Ref. 10, Schweizer and co-authors demonstrate via BLS measurements the spatiotemporal control of a magnon Bose-Einstein condensate density distribution through the excitation of magnon supercurrents in an inhomogeneously magnetized yttrium iron garnet film. Montoncello and co-authors[15] show that the synergy of Brillouin light scattering and micromagnetic simulations can resolve the complex spin-waves dynamics of a Permalloy artificial spin-ice system deposited over an unpatterned Permalloy film. The same technique is used by Gubbiotti and co-authors[9] to investigate the nonreciprocal spin-wave propagation in stepped ferromagnetic heterostructures that contribute to enhanced interconnectivity in 3D magnonics.

Similarly to any other probe, BLS spectroscopy exhibits drawbacks, most notably the involvement of time-consuming measurement, advanced equipment, and the limitations set by the wavelength of the laser on the minimum detectable spin-wave wavelength. In this Special Collection, the works of Lucassen *et al.*[12] and Iguchi *et al.*[6] offer alternative approaches to bypass these constraints in probing the spin-wave dynamics. In Ref. 12, Lucassen and co-authors demonstrate magneto-optical detection of spin waves beyond the diffraction limit, which can yield unprecedented insights into the fundamental physics of spin waves in the exchange-wave regime and towards the integration of the photonic and magnonic platforms. Iguchi and co-authors[6] present a study of the propagation of spin waves in magnonic crystals using lock-in thermography, a non-destructive low-cost technique for measuring temperature oscillations at different frequencies and positions in a material. The authors show that the spin-wave dispersion relation and the bandgap structure of magnonic crystals can be reconstructed from the spatially resolved temperature data with high sensitivity. Spin-wave dynamics in magnonic crystals is also discussed in the work of Kuznetsov *et al.*,[7] in which the authors study spin-transport in yttrium iron garnet (YIG) waveguides with integrated magnonic crystals using broadband spin-wave spectroscopy and SNS-MOKE microscopy.

Further articles in this Special Collection are dedicated to hybrid systems relevant to cavity magnonics.[3] The works of Kondrashov and Ustinov[16] and Bhoi *et al.*[18] focus on the magnon-photon coupling and discuss how its optimization might yield innovative quantum devices characterized by high-frequency operation, low energy consumption and robust coherence. Barbhuiya and Bhattacherjee[17] provide a theoretical study of the non-linear behavior of a hybrid quantum magnomechanical system based on superconducting qubit coupled dispersively to a magnon-phonon mode.

Li *et al.*[19] and Froes *et al.*[20] investigate the coupling between spin-waves and topological spin textures, i.e., skyrmions and domain walls, respectively. This collection includes also a pedagogical introduction to nuclear spin waves,[21] i.e., the collective oscillations of the nuclear spins, in ferromagnetic and antiferromagnetic systems. In his work, Rezende provides an in-depth introduction to the properties of nuclear spin waves while highlighting the relationship between theory and the latest experimental findings on the nuclear spin pumping and nuclear spin Seebeck effects.

Hurst and Flebus[22] introduce the reader to novel non-Hermitian theoretical approaches to magnonic and magnon hybrid spin systems. Non-Hermitian theories have gained increasing attention in recent years, leading to the experimental discovery of a number of counterintuitive phenomena in photonic systems and metamaterials. Magnonic and hybrid magnonic systems are also, in many ways, a natural, yet largely unexplored, platform for non-Hermitian phenomena due to the tunability in the parameters controlling their degree of non-Hermiticity, i.e., gain and loss. As Hurst and Flebus suggest, exploring magnetization dynamics under non-Hermitian lenses will likely yield a plethora of new phenomena and functionalities.

It is clear that the current research in magnonics is thriving and presents new and exciting opportunities for exploration. This area of study continues to captivate the scientific community and industry alike, as it holds the potential to unlock previously unexplored pathways for research and technological advancement.

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