Toward machine learning with nonlinear magnonic hardware

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Combining spin waves with magnetic textures offers a promising route toward compact hardware for neuromorphic computing. Recent studies have demonstrated a variety of unconventional computing concepts that exploit the intrinsic nonlinearity of spin-wave dynamics together with the high information density and robustness of magnetic textures. Bringing these two ingredients together—nonlinear spin waves confined by magnetic textures—not only advances magnonics toward functional computing hardware but also gives rise to unexpected dynamical phenomena.

We demonstrate that a single magnetic vortex can serve as a magnon-scattering reservoir for processing temporal information. Nonlinear coupling between its spin-wave eigenmodes enables the recognition of pattern sequences embedded in a serial microwave data stream [1]. Frequency-domain multiplexing of the spectrally discrete yet spatially delocalized spin-wave modes provides a large number of virtual nodes without requiring an extended network of physically interconnected elements. At the same time, it mitigates limitations associated with the finite propagation length and lifetime of spin waves.

More recently, we have shown that the same magnonic reservoir concept can also be used to forecast chaotic time series [2]. Trained on the Mackey–Glass benchmark, the frequency-resolved response of magnetic vortices enables accurate prediction of the future evolution of the system. Combining the responses of vortices with different geometries further increases the available reservoir dimensionality and improves the forecasting performance. Together, these results demonstrate that nonlinear magnonic hardware can address both classification and prediction tasks.

The effective dimensionality of the reservoir originates from stimulated magnon–magnon scattering, which establishes nonlinear transitions between different spin-wave eigenmodes [3]. It can be further increased through the generation of spin-wave frequency combs. In magnetic vortices, such combs arise from the mutual interaction between the low-frequency gyration of the vortex core and higher-frequency spin-wave modes, giving rise to self-induced Floquet magnons [4]. These effects provide a route toward compact, frequency-multiplexed neuromorphic hardware in which nonlinear dynamics, memory, and high-dimensional information processing are realized within a single magnetic element.

References
[1] L. Körber, C. Heins, T. Hula, J.-V. Kim, S. Thlang, H. Schultheiss, J. Fassbender, and K. Schultheiss, “Pattern recognition in reciprocal space with a magnon-scattering reservoir,” Nature Communications 14, 3954 (2023).
[2] Z. Xiong, C. Heins, T. Devolder, F. Kammerbauer, M. Kläui, J. Fassbender, H. Schultheiss, and K. Schultheiss, “Predicting the future with magnons: Forecasting

chaotic time series with reservoir computing," Physical Review Applied 25, 044047 (2026).
[3] L. Körber, K. Schultheiss, T. Hula, R. Verba, J. Fassbender, A. Kákay, and H. Schultheiss, "Nonlocal stimulation of three-magnon splitting in a magnetic vortex," Physical Review Letters 125, 207203 (2020).
[4] C. Heins, L. Körber, J.-V. Kim, T. Devolder, J. H. Mentink, A. Kákay, J. Fassbender, K. Schultheiss, and H. Schultheiss, "Self-induced Floquet magnons in magnetic vortices," Science 391, 190–194 (2026).