Spin wave computing and mode engineering using hard media bias field

(in-depth report)

R. Mehta,[a] J. Zhou,[b,c] M. Moalic,[d] M. Zelent,[d] Z. Luo,[b,c] V. Scagnoli,[b,c] S. Parchenko,[b,c]
M. Krawczyk,[d] L. J. Heyderman,[b,c] S. Saha[a,b,c]
a: Department of Physics, Ashoka University, Hariyana, India;
b: Laboratory for Mesoscopic Systems, Department of Materials, ETH Zurich, Switzerland;
c: Laboratory for Multiscale Materials Experiments, Paul Scherrer Institute, Villigen PSI, Switzerland;
d: Faculty of Physics, Adam Mickiewicz University, Poznan, Poland

Spin-wave band structures can be engineered by varying the crystal geometries and this is important to facilitate the realization of many functional magnonic devices [1], such as band stop filters and magnonic transistors. Recently, we have shown [2,3] the magnetostatic mode formation in an artificial magnetic structure, going beyond the crystal geometry to a fractal structure, where the mode formation is related to the geometric scaling of the fractal structure. Fractals are composed of self-similar structures across different length scales, which look similar under different magnifications. This property is commonly referred to as dilation symmetry. Snowflakes, Romanesco broccoli, and coastlines are popular examples of fractals observed in nature.

We have studied the magnetization dynamics of magnetic fractals by both using experiment and simulation. First, we have determined the evolution of the magnetostatic spin-wave modes from a simple geometric structure toward a Sierpinski carpet and Sierpinski triangle by imaging the precessional dynamics using time resolved scanning Kerr microscope. We reported on the magnetostatic mode formation in an artificial magnetic structure, going beyond the crystal geometry to a fractal structure, where the mode formation is related to the geometric scaling of the fractal structure. Specifically, the precessional dynamics was measured in samples with structures going from simple geometric structures toward a Sierpinski carpet and a Sierpinski triangle. The experimentally observed evolution of the precessional motion could be linked to the progression in the geometric structures that results in a modification of the demagnetizing field. Furthermore, we have found sets of modes at the ferromagnetic resonance frequency that form a scaled spatial distribution following the geometric scaling. Based on this, we have determined the two conditions for such mode formation to occur. One condition is that the associated magnetic boundaries must scale accordingly, and the other condition is that the region where the mode occurs must not coincide with the regions for the edge modes [2]. But the application of the magnonic fractals were not discussed yet. To show the application of magnonic fractals in spiwave transmission, we have performed micromagnetic simulations on Sierpinski triangles. A wide frequency gap is observed for a structure with an iteration number exceeding some value and plenty of mini-frequency bandgaps at structures with high iteration number. The frequency gap could be controlled by varying the strength of the magnetic field. A sixfold symmetry in the frequency gap is observed with the variation of the azimuthal angle of the external magnetic field. The spatial distributions of the spin-wave modes allow to identify the bands surrounding the gap [3]. Please check the supplementary information for more details. This established relationship between fractal geometry and the mode formation in magnetic fractals provides guiding principles for their use in magnonics applications.

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[1] M. Krawczyk and D. Grundler, J. Phys.: Condens. Matter **26**, 123202 (2014).
[2] J. Zhou, M. Zelent, Z. Luo, V. Scagnoli, M. Krawczyk, L. J. Heyderman, and S. Saha, *Precessional dynamics of geometrically scaled magnetostatic spin waves in two-dimensional magnonic fractals*, Phys. Rev. B **105**, 174415 (2022).
[3] R. Mehta, M. Moalic, M. Krawczyk, and S. Saha, *Tunability of spin-wave spectra in a 2D triangular shaped magnonic fractals*, J. Phys.: Condens. Matter **35**, 324002 (2023).

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