Realization and Control of Bulk and Surface Modes in 3D Nanomagnonic Networks by Additive Manufacturing of Ferromagnets

(in-depth report)

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The field of 3D nanomagnetism has gathered significant attention recent years. The 3D ferromagnetic devices are promising for multiple functionalities in nonvolatile data storage, high-speed data processing, and non-charged-based logic operations. However, the challenging 3D nanofabrication hinders thorough exploration of 3D spintronics and magnonics [1]. We have developed an additive manufacturing methodology by which we fabricate complex 3D ferromagnetic

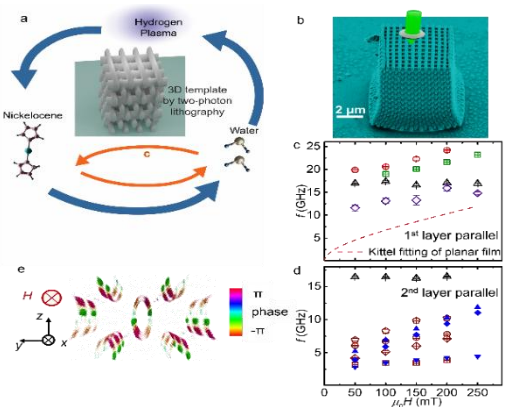

Fig. 1. (a) Sketch of ALD process for fabricating 3D nanomagnonic networks. (b) Colored SEM image of the 3D Ni nanonetwork. The green laser and lens represent the µ-BLS measurement configuration. Extracted magnon modes detected on a 3D Ni nanonetwork in dependence of an external magnetic field when the magnetic field is parallel to the tubes of the top (c) and second (d) layer. (e) Higher-order azimuthal mode around longitudinally magnetized tube segments on 3D Ni nanonetwork extracted from micromagnetic simulations.

nanonetworks. We combine two-photon lithography (TPL) which offers possibilities to create 3D nanotemplates with atomic layer deposition (ALD) sketched in Fig. 1a [2] which supplies a conformal ferromagnetic coating without shadowing effect. We particularly deposit thin Ni shells (Fig. 1b) exhibiting unprecedentedly low damping. The collective spin dynamics of the 3D Ni nanomagnonic networks were detected by micro-focus Brillouin Light Scattering (BLS) performed from the top at room temperature (Fig. 1b). The networks contained woodpile structure unit cells. Thermal magnon modes at frequencies up to 25 GHz were found on the topmost layer (Fig. 1c) in case of a lattice period of 1 µm. A clear discrepancy of about 10 GHz is found between the topmost (first) and second layer of the 3D superstructure (Fig. 1c and 1d), which we attribute to surface and bulk modes, respectively. We engineer the modes by different unit cell sizes in the Ni-based nanonetworks. By means of micromagnetic simulation, the microscopic nature of excited bulk magnon modes are visualized (Fig. 1e). Our work demonstrates that the additive manufacturing methodology enables engineered GHz responses in 3D ferromagnetic nanonetworks. It offers a technology platform for 3D magnonic devices with complex unit cells which might give rise to magnetochiral properties and topologically protected surface modes. Financial support by SNSF via grant number 197360 is acknowledged.

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[1] H. Guo, et al, *Realization and Control of Bulk and Surface Modes in 3D Nanomagnonic Networks by Additive Manufacturing of Ferromagnets*, Adv. Mater., 2303292 (2023); https://doi.org/10.1002/adma.202303292
[2] M. C. Giordano, et al, *Plasma-Enhanced Atomic Layer Deposition of Nickel Nanotubes with Low Resistivity and Coherent Magnetization Dynamics for 3D Spintronics*, ACS Appl. Mater. Interfaces, **12**, 36 (2020).