Efficient generation of the second-harmonic propagating spin-waves in a thin out-of-plane magnetized ferromagnetic film

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Spin waves are promising carriers of information due to their high frequencies, short wavelengths, low energy cost of manipulation, and associated angular momentum transfer. However, exciting exchange-dominated spin waves, which inherently have short wavelengths and higher frequencies, remains challenging. To gain a comprehensive understanding of the dynamic interactions behind this process, we employ micromagnetic simulations using Amumax[1], a fork of Mumax3[2], to implement a 4000 nm long, 1000 nm wide, and 13.2 nm thick waveguide. Absorbing boundary conditions are applied to each wall to isolate planar spin waves. The material used is a Co/Pd multilayer[3], forming a thin film with strong perpendicular magnetic anisotropy (450e3 J/m³). A single singular antidot is introduced in the middle of the waveguide with 50 nm rims where the magnetic anisotropy is removed, stabilizing the magnetization in-plane. A bias field, B0, is applied along the out-of-plane direction to tune the interface resonance frequency, thereby controlling the frequency of the generated spin waves.

To quantify the efficiency of this process, simplified one-dimensional simulations were performed, replacing the antidot with a 70 nm wide anisotropy-free strip at one end of the waveguide, where magnetization stabilizes in-plane. Efficiency was calculated as the ratio of the spin wave amplitude in the rim, oscillating at the driving frequency f0, to the generated spin waves in the waveguide oscillating at 2f0. Stronger excitation fields resulted in higher efficiency, reaching up to 42% for a sinusoidal amplitude of 70 mT. Tuning B0 allowed precise control over the generated frequencies, where 2f0 is 14.27 GHz at 145 mT and increases to 17.20 GHz at 360 mT. We propose a hybrid structure consisting of an in-plane magnetized area coupled with an out-of-plane magnetized ferromagnetic strip. We demonstrate that, under a homogeneous microwave magnetic field polarized out-of-plane, spin waves can be excited in the area of non-uniform magnetization and transferred into the waveguide as propagating waves at integral multiples of the base frequency, as seen in Fig. 1. This highly efficient process is governed by exchange interactions at the interface between the in-plane and out-of-plane magnetized areas.

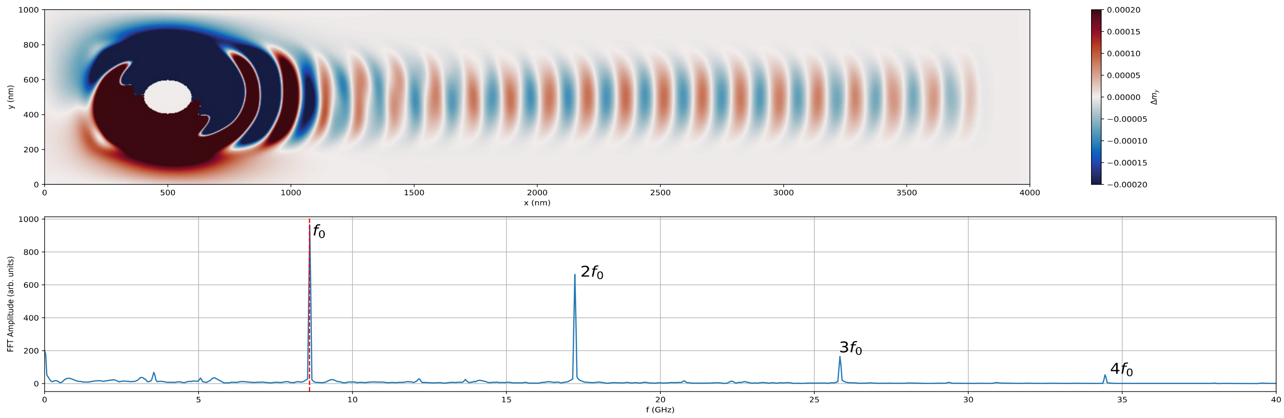

Figure 1: top: Dynamic y component of the magnetization in the waveguide with the antidot on the left and the propagating spin waves on the right. Bottom: Fourier transform of the m_y magnetization in the strip over time.

Acknowledgements: The research has received funding from the National Science Centre of Poland, Grant No.UMO–2020/37/B/ST3/03936 and 2023/49/N/ST3/03538. The simulations were partially performed at the Poznan Supercomputing and Networking Center (Grant No. 398).

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