Spin, lattice, and ac-field couplings in magnetic materials and devices

In this project, we studied new developments in spintronics related to the coupling between spins and magnetic order parameter with other degrees of freedom, specifically mechanical and electromagnetic fields. The present collaboration was carried out with contributions from the IMR experimental groups Saitoh and Takanashi and many theoretical and experiment groups from oversea, most importantly the Walter Meissner Institute of the Technical University Munich and the Kavli Institute of NanoScience of the Technical University Delft.

In this project, we studied many different phenomena, of which we present here three highlights, *viz*. the progress of our understanding the coupling with phononic and electromagnetic fields.

Spin Mechanics

The magnetization order parameter couples to the lattice by magnetic form and crystal anisotropies. In the past we investigated the effects of the coupled motion of the magnetic and the elastic fields for rigid systems. The other extreme, the magnon-phonon interaction in bulk ferromagnets, has been studied intensively many decades ago. Several modern developments, such as the ultrasound induced spin pumping discovered at the IMR, requires the development of new theoretical techniques. We developed a scattering theory for ultrasound actuation of magnetization dynamics [1]. By the spin pumping technique it should be possible to detect strongly coupled quasiparticle, the "magnon-polarons" as demonstrated in Fig. 1.

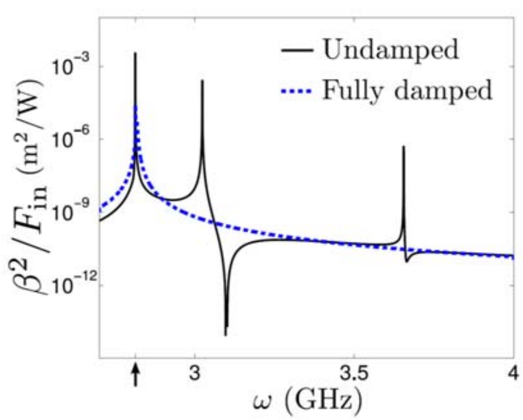

Fig. 1: *Normalized acoustically actuated spin pumping signal as function of the sound frequency for thin magnetic films (dashed line: thick films) [1].*

Strong coupling of microwaves with magnetic order parameter

We formulated a scattering theory to study magnetic films in microwave cavities beyond the independent-spin and rotating-wave approximations of the Tavis-Cummings model that is based on the coupled LLG and Maxwell equations [2]. When the coupling between spin and microwaves becomes larger than the losses of the cavity and by Gilbert damping, magnons and photons become indistinguishable and form new quasi-particles, so-called "magnon-polaritons". We demonstrate that strong coupling can be achieved not only for the ferromagnetic resonance mode, but also for spin-wave resonances; the coupling strengths are mode dependent, as demonstrated in Fig. 2, and decrease with increasing mode index. The strong-coupling regime can be accessed electrically by spin pumping into a metal contact.

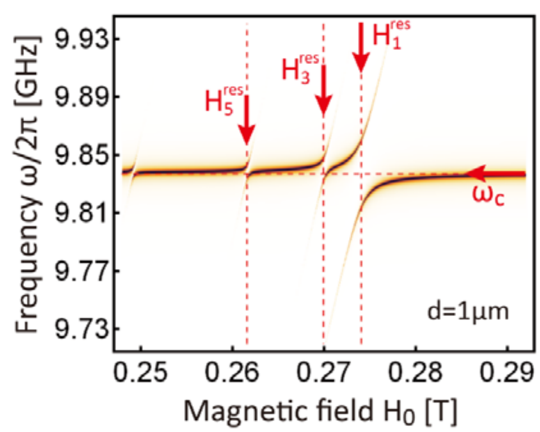

Fig. 2: *Microwave reflection generated by a magnetic film in a cavity, illustrating strong coupling of spin waves with the ac magnetic field [2].*

Strong coupling of microwaves with magnetic order parameter

T. Chiba *et al*. [3] predicted that the current-induced magnetization dynamics in magnetic insulators can be measured by down-conversion of an ac voltage in Pt contacts. The theory was based on the recently discovered spin Hall magnetoresistance (SMR) [4] and tested by the Munich group to unequally prove the actuation of the magnetic order parameter by the spin transfer torque [5].

Experiments were carried out in yttrium iron garnet/ platinum bilayers. An alternating charge current at GHz frequencies in the platinum gives rise to DC spin pumping and spin Hall magnetoresistance rectification voltages, induced by the Oersted fields of the AC current and the spin Hall effect-mediated spin transfer torque. In ultrathin, yttrium iron garnet films, we observed spin transfer torque actuated magnetization dynamics that can be significantly larger than those generated by the AC Oersted magnetic field. The different effects can be shown to dominate for samples with different thicknesses as illustrated in Fig. 3, which compares experiments and theoretical modelling [3] Spin transfer torques thus efficiently couple charge currents and magnetization dynamics also in magnetic insulators, enabling charge current-based interfacing of magnetic insulators with microwave devices.

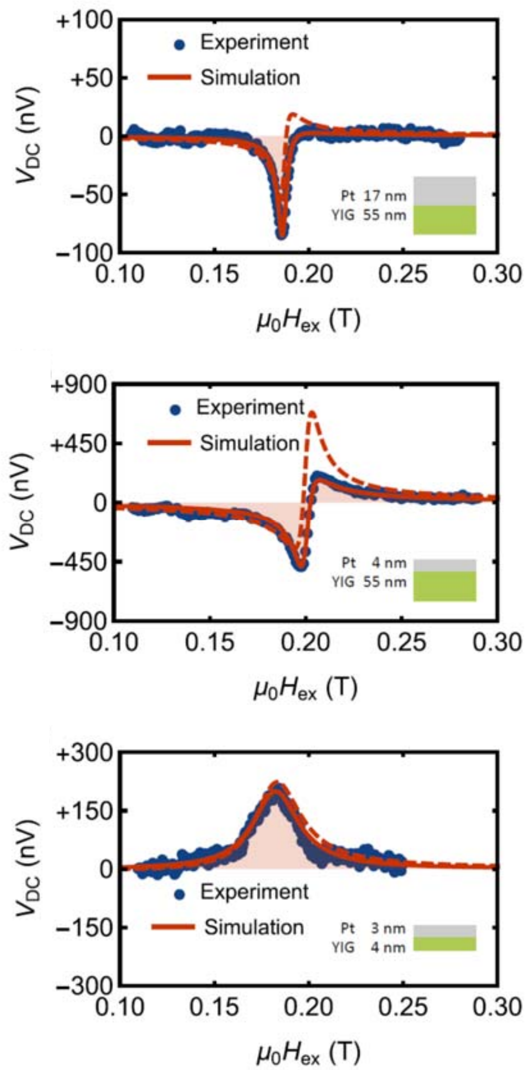

Fig. 3: *Measured (dots) and simulated (lines) of the dc voltage generated under and ac applied current for three different YIG|Pt samples with thicknesses indicated in the insets [5]. The dashed lines correspond to zero phase shift between the Oersted magnetic fields and the applied current.*

References

[1] A. Kamra, H. Keshtgar, P. Yan, G. E. W. Bauer, *Coherent elastic excitation of spin waves*, Phys. Rev. B **91**, 104409 (2015).

[2] Y. Cao, P. Yan, H. Huebl, S. T.B. Goennenwein, G.E.W. Bauer, *Exchange Magnon-polaritons in Microwave Cavities*, Phys. Rev. B **91**, 094423 (2015).

[3] T. Chiba, G. E. W. Bauer, S. Takahashi, *Current-induced spin torque resonance for magnetic insulators*, Phys. Rev. Applied 2, 034003 (2014)

[4] H. Nakayama, M. Althammer, Y.-T. Chen, K. Uchida, Y. Kajiwara, D. Kikuchi, T. Ohtani, S. Geprägs, M. Opel, S. Takahashi, R. Gross, G. E. W. Bauer, S. T. B. Goennenwein, and E. Saitoh, *Spin Hall Magnetoresistance Induced by a Nonequilibrium Proximity Effect*, Phys. Rev. Lett. **110**, 206601 (2013).

[5] M. Schreier, T. Chiba, A. Niedermayr, J. Lotze, H. Huebl, St. Geprägs, S. Takahashi, G. E. W. Bauer, R. Gross, S. T. B. Goennenwein, *Current-induced spin torque resonance of a magnetic insulator*, arXiv:1412.7460.

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