Injection-locking in spin-Hall nano-oscillators investigated by Brillouin light scattering using the THATec Innovation optical scanning microscope in combination with *thaTEC:OS*.

Spin-Hall nano-oscillators (SHNO) are spintronic devices which can convert DC currents into oscillations with frequencies in the GHz regime. Thus, they are a very promising link for the integration of spintronic devices into CMOS circuits. One of the most powerful techniques to investigate SHNOs is Brillouin light scattering microscopy. The presented results were conveniently obtained in fully automated measurement sequences using the software modules *thaTEC:TFPDAS5*, *thaTEC:Microscopy* and *thaTEC:OS* in the group of Helmut Schultheiss at the Helmholtz-Zentrum Dresden-Rossendorf. More details can be found in [1].

The field of spintronics is dedicated to the development of novel logic devices using the electron spin. Promising for such novel devices is the application of spin-waves - collective oscillations of the electron spins which show frequencies in the GHz range. However, the generation of GHz frequencies for the precise excitation of spin-waves is quite challenging and, in general, requires additional external devices. To overcome this, in the last years, many experiments investigated so-called auto-oscillations in magnetic systems where spin-waves in the GHz range were excited using DC currents. Besides the simple generation of DC currents, this conversion also allows for an easy integration into existing CMOS circuits.

Physical background

For the presented measurements, a DC current is applied to a magnetic nanostructure. This DC current generates a spin current in an adjacent Pt layer via the spin-Hall effect which is a spin dependent scattering process. When this spin current enters the magnetic layer of the nanostructure, depending on the spin-orientation, it acts a torque on the magnetization which can counteract to the spin-wave damping torque. In particular, if the damping torque is overcome by the torque caused by the injected spin current, the spin-wave intensity will increase exponentially in time. This scenario is referred to as auto-oscillation, thus, the investigated devices are called Spin-Hall Nano-Oscillators (SHNO).

Measurement setup

One of the most powerful techniques to investigate magnetization dynamics in nanostructures is Brillouin light scattering (BLS) microscopy, which is an inelastic scattering process of photons on spin-waves [2]. A sketch of the here-used setup is depicted in Fig. 1 and consists of the THATec Innovation optical scanning microscope including a railing system for an electromagnet to give easy access to the sample, a 3D sample positioning system, and a Probe station to apply DC- and RF-currents to the sample. Via the integrated 2-port viewing system in combination with the microscopy software thaTEC:Microscopy, the RF- and DC-probes can be individually 3D positioned relative to the sample and landed on the sample without a wirebonding process. During an automated measurement, the sample can be positioned relative to the laser spot using different scan areas, i.e., lines or rectangles. Furthermore, the software compensates thermal drifts of the sample during long-term measurement using a pattern recognition algorithm.

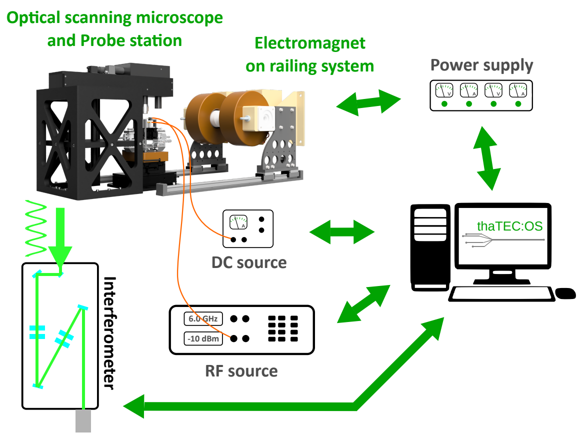

Figure 1: Sketch of the experimental setup. All devices are controlled by the thaTEC:OS software platform in order to perform automated measurements.

THATec Innovation GmbH | Augustaanlage 23 | 68165 Mannheim | Germany
contact@thatec-innovation.com | Fax: +49-621-40041-40
www.thatec-innovation.com

Obviously, for the measurements presented here, many different devices are required resulting in a huge parameter space (magnetic field, DC current, RF frequency, RF power, 2D position of the laser spot, ...). Thus, to map the properties of the structure and in order to find an optimal working point, the automation of these measurements is inevitable. This is easily achieved by using the modular software platform thaTEC:OS. This software acts as a server to which all required devices like the microscope, power supply for the electromagnet, interferometer and current sources, are connected to via simple device software modules. To perform fully automated measurements, the desired parameter space and the required detectors and loggers are defined via drag & drop in thaTEC:OS. Furthermore, thaTEC:OS will also take care of the documentation. All device parameters and numerous meta-data are saved as a digital labbook in the measurement file (HDF5 file format, for more details, check out our Knowledge Base). Optionally, all measurements can be stored in a measurement database which allows to sort and filter all measurements later on in order to achieve a complete overview over all performed measurements on a specific sample or structure.

Exemplary measurements

Figure 2 (a) shows the current-dependent spin-wave intensity in the investigated SHNO for an externally applied magnetic field of 50 mT. In particular, after reaching the threshold value of around +0.7 mA, auto-oscillations set in and the amplitude of these oscillations quickly increases if the DC current is further increased. The symmetry of the spin-Hall effect predicts that this anti-damping effect flips to an increase of effective damping by switching the polarity of the DC current. This can clearly be seen since no auto-oscillations are excited for -0.7 mA or larger negative DC current values.
For potential applications, in particular applications which employ interference effects, a frequency synchronization of multiple SHNOs is required. To investigate this, in an injection-locking experiment an additional microwave current is applied to the SHNO and the experimental results are shown in Fig. 2 (b). For an applied DC current of +1.5 mA and an applied magnetic field of 50 mT, the auto-oscillation frequency is about 6 GHz. For externally applied RF current frequencies which are too far from this value, no injection-locking can be achieved and the auto-oscillation frequency is constant or only slightly shifted. Only in a range of about 500 MHz the auto-oscillations can be locked to the external stimulus which allows for a precise control of the oscillation frequency and a frequency-locking of multiple SHNOs for future spintronic applications.

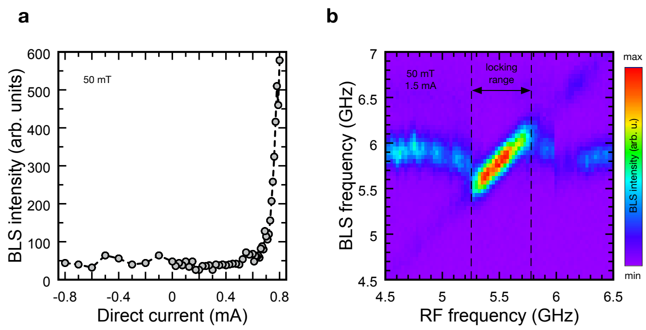

Figure 2: (a) Current-dependent spin-wave intensity in the SHNO. Only for positive currents above the threshold at about +0.7 mA, auto-oscillations occur. (b) Injection locking characteristics. Within the locking range, the frequency of the auto-oscillations is locked to the external stimulus.

Further Reading

For more information on our hard- and software and a detailed list of features, visit our homepage and check out the section about Brillouin light scattering spectroscopy: www.thatec-innovation.com

References

[1] Combined frequency and time domain measurements on injection-locked, constriction-based spin Hall nano-oscillators, T.Hache, H.Schultheiss *et al.*, Appl. Phys. Lett. **114**, 102403 (2019). DOI: 10.1063/1.5082692

[2] Micro-focused Brillouin light scattering: imaging spin waves at the nanoscale, T. Sebastian *et al.*, Front. Phys. **3**, 35 (2015). DOI: 10.3389/fphy.2015.00035