Pulsed OPM in Magnetorelaxometry of Magnetic Nanoparticles: Analyzing OPM's Free Precession Signals

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Magnetic nanoparticles (MNP) offer a large variety of promising applications in medicine, for which it is crucial to quantify the amount of MNP in their specific binding state. This information can be obtained by means of magnetorelaxometry (MRX). However, current OPM-MRX is limited by OPM bandwidth and OPM recovery time after the shut-off of the external magnetic field for MNP alignment, therewith preventing the detection of fast relaxing MNP. Novel pulsed OPM enable a very short system recovery time in the microsecond range due to the use of a high power pulsed pump laser in the sensor. After a strong pump pulse (795 nm, 1 W, 1 µs), the free spin precession is monitored by a polarimeter and a linear polarized probe laser (795 nm, detuned by 20 GHz, 100 µW). The magnetic field amplitude can be extracted by frequency estimation. However, limited data availability (to reach high bandwidths), several nonlinearities, harmonics and noise in the precession signal lead to uncertainities. In addition to the magnetic field amplitude estimation [1,2], also other information can be extracted from the OPM precession signal, e.g. the direction of the magnetic field [3]. However, the frequency estimation methods can still be improved by modeling and thus taking into account physical processes occuring in the system, e.g. transit relaxation and repopulation.
We will present, compare and discuss several techniques for frequency estimation, including FPGA zero crossing detection, harmonic inversion, curve fitting and density matrix assisted frequency estimation. Additionally, we will show that fast relaxing MNP can now be detected by exploiting pulsed OPM-MRX.
While FPGA timestamping can be achieved with high temporal resolutions, no model parameters, e.g. the out of phase harmonics are taken into account. Harmonic inversion is well suited for frequency estimation of exponentially decaying sinusoids, but here nonlinearities, e.g. hyperfine relaxation introduce errors. While curve fitting is often used and is well suited for frequency estimation, specific care (especially on initial parameters) must be taken to avoid a non-global convergence. Also, the fit function must be selected to include harmonics, exponential amplitude decaying, frequency chirping and an exponentially decaying offset. Using density matrix simulations, additional physical dynamics affecting the precession signal can be investigated to improve the magnetic field measurements, reaching $< 1\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$ with the current setup.

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