Hysteretic synchronization in magnetic vortex spin-torque nano-oscillators

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Spin Torque Nano-Oscillators[1] (STNOs) have a strong potential to be used in the information and communication technologies because they present some attractive features, such as the current tunability, thermal stability and scalability, but a single device has low output power and poor quality factor. Recently, STNOs based on oscillating magnetic vortex configurations have been demonstrated to produce larger microwave power and improved thermal stability and linewidth[2-4]. Nevertheless, the most effective strategy to increase the emitted power is the synchronization of multiple STNOs[4], which is a strongly nonlinear dynamical phenomenon.

In this work, we theoretically study the synchronization in STNOs between the magnetic vortex core oscillations and a weak microwave excitation (microwave field/current). The free layer is disk-shaped with radius R and thickness L. We consider STNOs based on both nanopillar[3] and nanocontact[2] geometries. In our study, the vortex dynamics is modelled in terms of the vortex core position by using a combined analytical-numerical approach. The analytical part consists in a collective variables description[5] of the vortex core dynamics. The numerical one is based on few simple micromagnetic simulations, which are instrumental to extract the intrinsic parameters of the STNO (natural oscillation frequency, free linear vortex core decay rate, degree of nonlinearity). By using the aforementioned approach, we derive phase locking diagrams which predict the same three possible dynamical regimes for nanopillar (fig. 1) and nanocontact STNOs: vortex core oscillations synchronized with the microwave source (P-region), unsynchronized quasi-periodic oscillations (Q-region), coexisting synchronized and unsynchronized oscillations (P/Q-region). The coexistence of P/Q modes is the fingerprint of hysteretic synchronization. In fact, let us keep, for instance, the microwave source amplitude constant while the frequency is varied back and forth in a sufficiently large range (e.g. horizontal line crossing all the critical lines of fig. 1(a)). Then, one can clearly infer that the occurrence of synchronized regimes is different depending if one starts decreasing (increasing) the frequency from sufficiently large (small) frequencies (right/left Q regions). This circumstance is elucidated in figure 1(b) where the output frequency of a nanopillar vortex STNO is reported as function of the driving microwave current. As validation test for the analytical models, micromagnetic simulations of injection locking experiments on nanopillar/nanocontact STNOs have performed showing good quantitative agreement (fig. 1(a)). These results confirm the universal nature of the hysteretic synchronization in STNOs regardless of their physical realization.

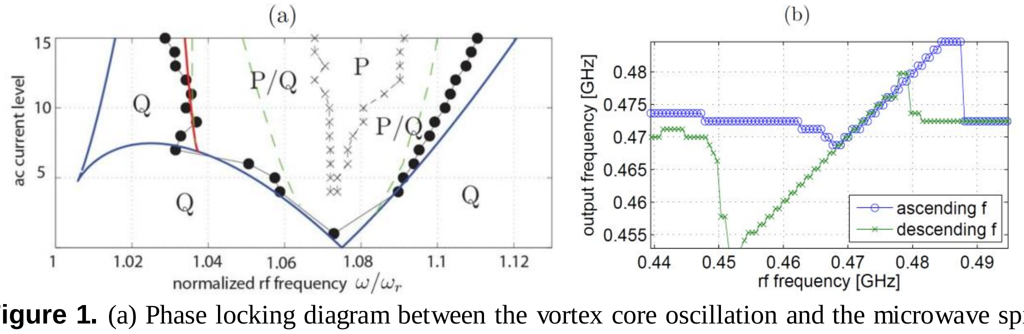

Figure 1. (a) Phase locking diagram between the vortex core oscillation and the microwave spin-polarized current injected in a nanopillar STNO. The dimensions of the nanodisk are R=100 nm, L=10 nm. Blue (red) solid lines refer to saddle-node (Hopf) bifurcations. Dashed green lines refer to homoclinic bifurcations. Black dots (cross symbols) refer to P→Q (Q→P) transitions observed in micromagnetic simulations; (b) output frequency of the STNO as function of increasing (blue) and decreasing (green) driving frequency at constant ac current amplitude (ac level = 15 means I_{ac} = 1.4 mA). The polarizer is tilted 45 degrees out-of-plane.

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