Hysteresis and bistability in the injection locking of spin-transfer nano-oscillators

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The power emitted from a single spin-transfer nano-oscillator is typically too low (in the order of 1 nW) to be useful for technological applications. However, enhanced emitted powers can be obtained when multiple spin-transfer oscillators are mutually synchronized and phase locked [1]. The simplest technique to phase-lock a spin-torque oscillator to a precisely controlled frequency is the injection locking [2]. This technique consists in injecting in the device a weak microwave current with a frequency close to its self-oscillation frequency. This problem is usually treated by using the simple Adler theory [3] which is based on the assumption that the amplitude of magnetization self-oscillation is not modified by the injection of the microwave current. In this paper, by using the Landau-Lifshitz (LL) equation with the Slonczewski spin-torque term as equation governing magnetization dynamics, we obtain results which qualitatively deviates from the Adler theory. In the case of a spin-torque oscillator subject to moderately large injected microwave currents, we obtain that the magnetization oscillation amplitude variations lead to hysteresis and bistability in the injection locking. This novel result, which has not been considered in the theoretical studies on this topic so far [4], is suggestive of further experimental studies of injection locking. In the paper, we analyze a classical spin-valve trilayer structure with current perpendicular to plane configuration. We consider the case where both the free and fixed layers are uniformly magnetized. The injected time-varying current I(t) is composed of a DC component I_{DC} and a time harmonic microwave component I_{RF} (t). The external magnetic field is applied in the out-of-plane direction and it is assumed to be strong enough that both the free and the fixed layer magnetization are tilted out-of-plane. In the analysis, we also assume that the frequency of time-harmonic injected current is close to the frequency of magnetization precessional oscillations which is the situation relevant to the study of synchronization and phase locking.

Magnetization dynamics in the free layer of the spin-valve structure under the external excitation conditions discussed above, is characterized by two time scales. Magnetization precessional oscillations occur on a fast time scale comparable with the time-scale of the external microwave excitation. On the other hand, changes of the amplitude of the magnetization self-oscillations and the change of the phase difference between magnetization oscillations and external current oscillations occur on a much lower time scale. By using appropriate perturbation technique and averaging, it is possible to derive the equation which governs only the slow variables in the magnetization dynamics. In this respect, the amplitude of magnetization precessions can be described by the tilt angle θ of the free layer magnetization with respect to the perpendicular to plane direction, while the phase shift between magnetization precessions and the microwave injected current by an appropriate azimuthal angle φ. The equilibria of the (θ, φ)-dynamics are periodic solution of magnetization dynamics and for this reason are called P-modes. Self-oscillations (limit cycles) in the (θ, φ)-dynamics are quasi-periodic magnetization motions and are referred to as Q-modes. In connection with the synchronization of the spin-torque oscillator by the external current, the P-modes correspond to synchronized motions while Q-mode correspond to nonynchronized motions. In this framework the process of synchronization can be viewed as a bifurcation process. In Fig.1(left) a portion of the stability diagram in the control plane (I_{DC}, I_{RF}) is reported. Each region is labelled by the associated stable steady states. The red and blue lines represent bifurcation lines. By changing the DC-current from I_1, to I_3, at a given value of I_{RF}, the system passes from a stable P-mode to a stable Q-modes. This requires to traverse the region of bistability P/Q in which both a stable P-mode and a stable Q-mode exist. This bistability manifests itself in the plot of the average time derivative of the phase difference between the oscillator and the external source vs I_{DC}, as sketched in Fig.1(right). This discussion shows that the process of synchronization is considerably more complicated with respect what is usually obtained with the Adler model in which no hysteresis is present. In the full paper, the analytical derivations of the discussed result will be reported in detail.

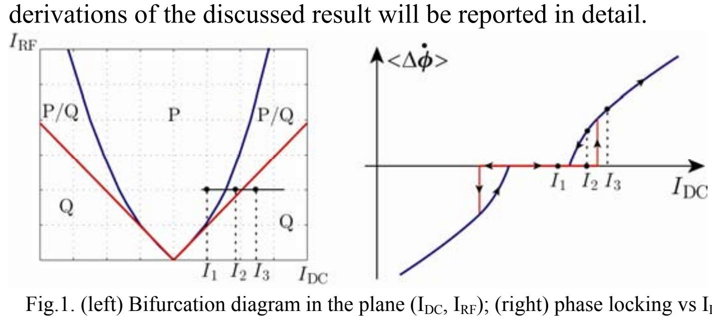

Fig.1. (left) Bifurcation diagram in the plane (I_{DC}, I_{RF}); (right) phase locking vs I_{DC}

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