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# Micromagnetic simulations of magnetization dynamics in a nanowire induced by a spin polarized current injected via a point contact

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## **Abstract**

We present a detailed numerical analysis of the magnetization auto-oscillations induced in a thin NiFe nanowire by a direct spin polarized current injected via a square-shaped CoFe nanomagnet (a system experimentally studied in C. Boone et al., *Phys. Rev. B* **79**, 140404 (2009)). We demonstrate that all auto-oscillation modes in the nanowire are localized under the nanocontact for magnetic field applied in the plane of the nanowire. This mode localization is induced by a strong stray magnetic field acting on the NiFe nanowire from the CoFe current injector. We find that the auto-oscillation frequency, power and the frequency shift with the current strongly depend on the exchange constant of NiFe. We also find that the auto-oscillation power depends non-monotonically on the CoFe saturation magnetization, and demonstrate that this effect has its origin in resonant excitation of the CoFe eigenmodes by magnetization oscillations in the NiFe nanowire. The calculated dependence of the oscillation frequency on current is in a good agreement with the experiment. However, the agreement between theory and experiment for the oscillation power is unsatisfactory. Finally, we have shown that an auto-oscillatory mode propagating along the nanowire in the system under study is possible when a sufficiently strong out-of-plane field is applied.

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## I. INTRODUCTION

Spin torque (ST) from spin-polarized current applied to a metallic ferromagnet<sup>1,2,3,4</sup> can induce steady-state oscillations of this magnetization and thereby generate a microwave signal<sup>5,6,7</sup>. The frequency of the microwave signal is tunable by the direct current bias, and thus such nanostructures function as microwave voltage-controlled oscillators of nanoscale dimensions. Practical applications of spin torque nano-oscillators (STNOs) require high output power levels and low phase noise<sup>8,9,10</sup>. Several approaches pursuing these goals, such as phase locking of arrays of STNOs<sup>11,12,13,14</sup> and development of STNOs based on magnetic tunnel junctions<sup>15,16,17,18</sup> are active areas of research.

STNOs also form a peculiar class of nonlinear dynamical systems. The nonlinearity of a STNO (the dependence of its frequency on power) can be tuned from nearly zero to very large values by changing the direction and magnitude of the external magnetic field<sup>19,20</sup>. For many STNO geometries, the nonlinearity reaches values far exceeding<sup>19,21,22,23,24</sup> those observed in other auto-oscillatory systems. Owing to their nanoscale dimensions, the magnetic energy of STNOs is comparable to the ambient temperature and thus the STNO dynamics are strongly affected by random thermal torques<sup>25,26</sup>. Therefore, STNOs provide a unique testing ground for studies of stochastic auto-oscillatory systems in the strongly nonlinear regime.

Up to date, two major STNO geometries have been studied: (i) spin valve nanopillars in which propagation of magnetic excitations is restricted by the ferromagnet boundaries in all three spatial dimensions (zero-dimensional systems, 0D)<sup>5,27,28</sup> and (ii) point contacts to spin valves in which magnetic excitations can propagate in the plane of the spin valve (two-dimensional systems, 2D)<sup>6,8,11,12,29</sup>. The two-dimensional systems offer the advantage of phase locking of nearby STNOs via interaction by spin waves propagating in the common ferromagnetic free layer<sup>11,12</sup>. The phase locking regime is attractive from the practical point of view because the output power of STNOs increases and their phase noise decreases in this regime<sup>11,12,13</sup>.

Another recently studied SNTNO system is a nanowire spin valve with a point contact for spin-polarized current injection<sup>30</sup>. In this system, schematically shown in Fig. 1, magnetic excitations can, in principle, propagate only in the direction parallel to the nanowire axis. This one-dimensional (1D) STNO system can potentially improve the phase locking properties of SNTNO arrays compared to the 2D point contact systems. Indeed, in 2D systems, the coupling between neighboring oscillators is weakened by the  $1/R$  geometric decay of the amplitude of spin waves mediating the coupling ( $R$  is the distance between the neighboring STNOs). In this paper, we numerically study auto-oscillations of magnetization in such 1D STNO systems. We examine the factors that determine the 1D STNO performance and discuss pathways to practical realization of phase locked 1D STNO arrays.

## II. EXPERIMENTAL SETUP

Fig. 1 schematically shows the structure of the 1D nanowire STNO experimentally studied in Ref. 30. In this work, we make micromagnetic simulations of magnetization dynamics in this nanowire STNO using the exact geometry and the material parameters of the experimentally studied system<sup>30</sup>. The free layer of this 1D STNO is a 6-nm thick, 50-nm wide Permalloy ( $\text{Py} \equiv \text{Ni}_{86}\text{Fe}_{14}$ ) nanowire lithographically defined on top of a Cu/Ta multilayer that serves as the bottom electrical lead. Spin-polarized current is injected into the nanowire through a  $50 \times 50 \text{ nm}^2$   $\text{Co}_{50}\text{Fe}_{50}$  (15 nm)/ Cu (8 nm) bilayer patterned on top of the Py nanowire. The top Au/Ta bilayer lead is connected to the  $\text{Co}_{50}\text{Fe}_{50}$  nanomagnet, and spin-polarized current is injected from the  $\text{Co}_{50}\text{Fe}_{50}$  polarizer into the Py nanowire by applying direct current

between the top and the bottom leads. The value of saturation magnetization of the Py ( $M_{Py} = 580 \text{ emu/cm}^3$ ) film was measured by vibrating sample magnetometry.

Persistent auto-oscillations of magnetization in the Py nanowire are excited by applying a direct current,  $I_{dc}$ , between the top and bottom leads of the device with electrons moving from Py to  $\text{Co}_{50}\text{Fe}_{50}$ . These GHz-range auto-oscillations of magnetization give rise to resistance oscillations due to the giant magnetoresistance effect (GMR). As a result, a microwave voltage is generated by the current-biased STNO device<sup>5</sup>. In the experiment, this microwave voltage is amplified and its power spectrum is measured using a microwave spectrum analyzer<sup>5</sup>.

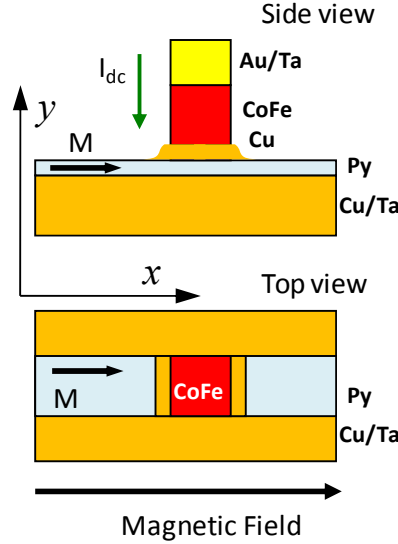


Fig. 1. (color online) Schematic of the 1D STNO device (side and top views). The free layer of this STNO is a Py nanowire and the fixed layer is a square  $\text{Co}_{50}\text{Fe}_{50}$  nanomagnet.

### III. NUMERICAL SIMULATIONS METHOD AND STATIC HYSTERESIS LOOPS

#### A. Simulation details

Numerical simulation have been carried out used the MicroMagus software package<sup>31</sup> supplemented by a special routine allowing the introduction of a site-dependent damping in order to avoid the spin wave reflections from the wire ends<sup>37</sup>. Both the Py nanowire and CoFe square nanomagnet were included in the simulated system and discretized in-plane using lateral cell sizes  $3.125 \times 3.125 \text{ nm}^2$ , so that, e.g., the CoFe square was subdivided in-plane into  $16 \times 16$  cells. Test runs have shown that finer discretization did not lead to noticeable changes in the simulated power spectra and that no discretization of Py and CoFe layers perpendicular to the sample plane was necessary. We direct the  $x$ -axis of the coordinate system in-plane along the long nanowire axis, the  $y$ -axis - perpendicular to the film plane, so that the  $z$ -axis is directed in-plane perpendicular to the long nanowire axis.

For quasistatic simulations of hysteresis loops, we start from the saturated state in a large external field  $H_{\text{ext}}^{\text{max}} = +2000 \text{ Oe}$  directed nearly parallel to the  $x$ -axis (we have introduced a small angle of  $2^\circ$  between the field direction and the nanowire axis to avoid artificial degeneracies arising in simulations when  $H_{\text{ext}}$  is exactly parallel to the  $x$ -axis). Then we decrease the field in small steps to the negative saturation  $H_{\text{ext}}^{\text{min}} = -2000 \text{ Oe}$  to obtain the decreasing-field loop branch. Then we increase the field to the initial value to check that the hysteresis loop is centrally symmetric with respect to the  $(M_x, H_x)$ -coordinate origin. **GMR**

curves  $\Delta R(H_x)$  shown in Fig. 2(b) were calculated from equilibrium magnetization states in a standard way, assuming that (i) the current density (current flows perpendicular to the layer planes) is homogeneous across the CoFe nanomagnet, (ii) the vertical cell stacks (CoFe/Py cell pairs along the  $y$ -direction) are connected as parallel resistors and (iii) the magneto-resistance change of such a vertical stack depends on the angle  $\theta$  between the magnetizations of CoFe and Py stack cells as<sup>30</sup>  $\Delta R(\theta) = \Delta R_{\max} \cdot \sin^2(\theta/2)/(1 + \chi \cos^2(\theta/2))$ . The value of the magnetoresistance asymmetry parameter  $\chi$  was set to  $\chi=1$  as determined in Ref. 30.

To perform dynamic simulations at a fixed external field, we first find the equilibrium magnetization state in this field ( $H_x = 500$  Oe used in the experiment)<sup>30</sup> and then turn on the direct current,  $I$ , to obtain the dependences of the oscillation frequency  $f(I)$  and power  $p(I)$  on the current. For the spin torque we use the standard Slonczewski term as in our previous publications<sup>37,39</sup>. The spin torque magnitude is proportional to  $P \cdot I$ , where  $P$  is the degree of spin polarization of the electrical current. We plot all current-dependent quantities as functions of the reduced current  $I/I_{\text{cr}}$ , with  $I_{\text{cr}}$  being the auto-oscillation onset current (the lower critical current). Comparing the value  $I_{\text{cr}}$  obtained in simulations with the corresponding experimental value, we can extract the degree of current polarization  $P$ . In our simulations, spin torque was assumed to act only on the Py magnetization directly under the CoFe nanomagnet. The direction of the spin polarization acting on the Py magnetization was dynamically adjusted to the local direction of the CoFe magnetization, which was time-dependent due to the magnetodipolar interaction between the Py and CoFe layers.

We have also verified that spin torque<sup>32</sup> acting on the CoFe magnetization from the Py layer did not have a significant effect on the dynamics of the system. This torque can be neglected due to much larger values of the saturation magnetization and the thickness of the CoFe nanomagnet compared to the Py nanowire.

The Oersted field was neglected in our simulations because for the typical currents used in the experiment,  $\sim 2$  mA, and the lateral CoFe nanomagnet dimensions,  $50 \times 50$  nm<sup>2</sup>, its maximum value is  $H_{\text{Oe}}^{\max} \approx 130$  Oe (for this estimate, we assumed that the Oersted field is produced by a current in an infinitely long wire with the  $50 \times 50$  nm<sup>2</sup> square cross-section). This maximal value is already significantly smaller than the applied field value of 500 Oe, and the Oersted field magnitude averaged over the CoFe cross-section is even smaller. Furthermore, in the experiment, the magnetic multilayer stack height is of the same order of magnitude as the CoFe lateral dimensions and thus the infinite wire approximation significantly overestimates the Oersted field magnitude.

## B. Results of quasistatic simulations

We simulated the quasistatic hysteresis behavior of our system and compared it to the experimentally measured magneto-resistance loops (see Fig. 1 in Ref. 30). In our quasistatic simulations we used the experimental system geometry: Ni<sub>86</sub>Fe<sub>14</sub> (Py) nanowire with width  $w = 50$  nm, thickness  $h_{\text{Py}} = 6$  nm separated by the Cu layer with thickness  $h_{\text{Cu}} = 8$  nm from the Co<sub>50</sub>Fe<sub>50</sub> square nanomagnet with the lateral dimensions  $50 \times 50$  nm<sup>2</sup> and thickness  $h_{\text{CoFe}} = 15$  nm. For magnetic parameters we employed the experimentally measured value of the Py magnetization  $M_{\text{Py}} = 580$  emu/cm<sup>3</sup> and the standard parameter values for the Co<sub>50</sub>Fe<sub>50</sub> alloy:  $M_{\text{CoFe}} = 1800$  emu/cm<sup>3</sup> and  $A_{\text{CoFe}} = 3 \times 10^{-6}$  erg/cm. Since the value of the exchange constant,  $A_{\text{Py}}$ , for ultrathin Ni<sub>86</sub>Fe<sub>14</sub> is not known, we performed simulations for a number of values of  $A_{\text{Py}}$  smaller the bulk Py exchange constant ( $A_{\text{Py}} = (1 - 1.3) \times 10^{-6}$  erg/cm).

We have also taken into account the random magnetocrystalline anisotropy present both in Py and CoFe layers. For this purpose we have used the ability of the MicroMagus package to create random grain structures and to assign to each crystal grain its own set of the

anisotropy axes. We have assumed that the averaged grain size in both magnetic layers is  $\langle D \rangle = 10$  nm. A cubic magnetocrystalline anisotropy was assigned to grains of both Py and CoFe, with the standard anisotropy constant  $K_{\text{Py}} = 5 \times 10^3$  erg/cm<sup>3</sup> for Py and  $K_{\text{CoFe}} = -2 \times 10^5$  erg/cm<sup>3</sup> for Co<sub>50</sub>Fe<sub>50</sub> (see Ref. 42). Anisotropy axes were oriented randomly for different grains. Due to the self-averaging of the random anisotropy contributions for systems with small crystallites and randomly oriented anisotropy axes we have found that the contribution of the anisotropy field to the magnetization dynamics is negligible, i.e., oscillations frequencies and powers for systems with different realizations of crystal grains anisotropy axes directions did not demonstrate any significant differences.

In principle, thin ferromagnetic layers may also exhibit some surface anisotropy. However, lacking the exact information concerning this anisotropy of magnetic layers used in our study, we have set the surface anisotropy constants of both magnetic layers to zero.

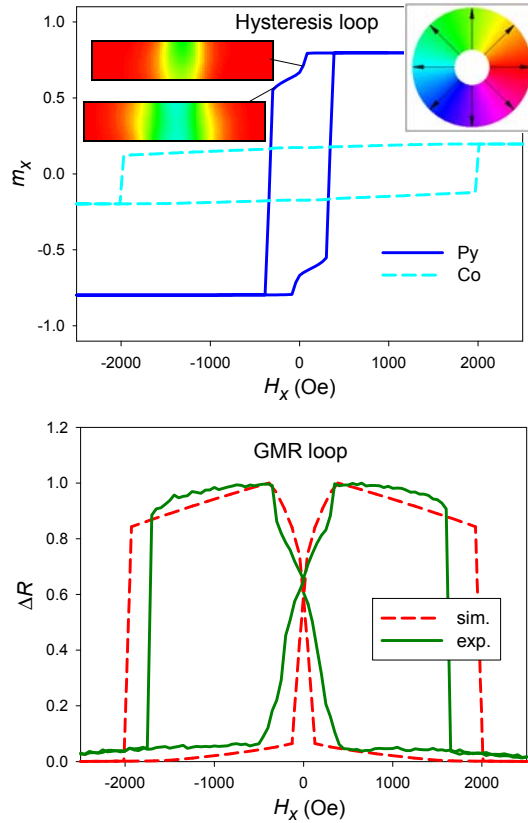


Fig. 2. (color online) Magnetization (upper panel with the color wheel representing the magnetization direction) and magneto-resistance (lower panel) hysteresis loops of the studied system calculated for  $M_{\text{Py}} = 580$  emu/cm<sup>3</sup>,  $A_{\text{Py}} = 1 \times 10^{-6}$  erg/cm,  $M_{\text{CoFe}} = 1800$  emu/cm<sup>3</sup> and  $A_{\text{CoFe}} = 3 \times 10^{-6}$  erg/cm.

Simulation results for our system are presented in Fig. 2 and 3 together with the magneto-resistance loop measured experimentally. Comparison of the simulated magnetization and GMR loops shown Fig. 2 reveals that the continuous resistance increase with decreasing field is due to formation of a 90° domain in the region of the Py nanowire directly under the CoFe nanomagnet. This domain formation under the CoFe nanomagnet is assisted by the large stray field of the CoFe nanomagnet. For  $A_{\text{Py}} = 1 \times 10^{-6}$  erg/cm, this domain appears at  $H_x \approx 50$  Oe and rapidly expands (see magnetization color maps in Fig. 2(a)) leading to the complete magnetization reversal of the Py nanowire at  $H_x \approx -400$  Oe. At this field, resistance reaches its maximal value and remains approximately constant until the abrupt magnetization reversal

of the CoFe nanoelement occurs at  $H_x \approx -2000$  Oe. We also note that the magnetization state of the CoFe nanomagnet in positive fields is the so called *C*-state, so that its stray field acting on the Py nanowire is strongly asymmetric with respect to the long nanowire axis. This stray field asymmetry is important for understanding of the dynamic mode localization pattern discussed in Sec. IV.

Comparison of the experimental and simulated magneto-resistance loops (lower panel in Fig. 2) shows that for the assumed standard Py exchange stiffness  $A_{Py} = 1 \times 10^{-6}$  erg/cm the simulated GMR loop is only qualitatively similar to the experimentally measured loop. To achieve better agreement with the experimental MR loop, we use the poorly known exchange stiffness of the thin Py film,  $A_{Py}$ , as a fitting parameter. We performed simulations for  $A_{Py} = 0.8 \times 10^{-6}$ ,  $0.7 \times 10^{-6}$  and  $0.6 \times 10^{-6}$  erg/cm. The results are shown in Fig. 3, which illustrates that smaller  $A_{Py}$  indeed leads to a better agreement with the measured GMR loop. For smaller values of  $A_{Py}$ , the nucleation field of the central  $90^\circ$ -domain in Py increases with decreasing  $A_{Py}$ , leading to a more gradual resistance increase near zero field in agreement with the experiment. We also note that the discrepancy between simulated and measured CoFe switching fields is eliminated if a small CoFe edge roughness is taken into account. This roughness was simulated as a magnetization decrease of the outmost rows of the CoFe discretization cells, in which normalized magnetization was changed randomly in the interval  $[0.5 - 1.0]$ . Fig. 3(b) shows that this procedure leads to a perfect agreement for CoFe switching fields for  $A_{Py} = 0.7 \times 10^{-6}$  erg/cm.

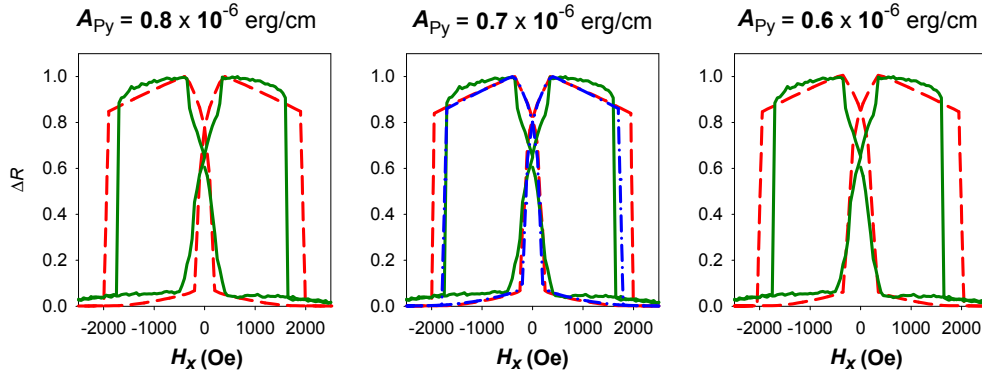


Fig. 3. (color online) Magnetoresistance loops for  $M_{Py} = 580$  emu/cm<sup>3</sup>,  $M_{CoFe} = 1800$  emu/cm<sup>3</sup>,  $A_{CoFe} = 3 \times 10^{-6}$  erg/cm and three values of Py exchange stiffness constants  $A_{Py}$  (solid lines - experiment, dashed lines - simulations). Smaller values of the Py exchange constant significantly improve the agreement with the experiment for the inner part of the magnetoresistance loop corresponding to the Py layer reversal. The dash-dotted blue line for  $A_{Py} = 0.7 \times 10^{-6}$  erg/cm (central panel) shows that the CoFe switching field can be reduced to the measured value by introducing a small edge roughness at the CoFe edges (see text for details).

#### IV. SIMULATED SYSTEM DYNAMICS AND COMPARISON WITH EXPERIMENTAL FINDINGS

Since the Oersted field is neglected in our simulations, the current  $I$  and the current spin polarization  $P$  enter the theoretical description of current-induced magnetization dynamics only as the product  $I \cdot P$ . For this reason we calculate all current-dependent quantities as functions of reduced current  $I/I_{cr}$ , where  $I_{cr}$  is the critical current for the onset of magnetization auto-oscillations. The value of the current polarization  $P$  can be calculated by setting the simulated critical current equal to the experimental value. All results presented in this section are calculated for a static applied field  $H_x = 500$  Oe (along the nanowire axis). Thermal fluctuations of magnetization are not included in our simulations.

## A. General features of the magnetization oscillations

For the geometry under study (see Fig.1) and all sets of magnetic parameters used in our simulations, the ST-induced magnetization dynamics exhibits the following general features:

- 1) There are two qualitatively different auto-oscillation regimes: low and high current regimes.
- 2) The *low current regime* starts at the onset current  $I_{cr}$  and persists to  $I/I_{cr} \approx 3 - 5$ . In this regime, the magnetizations of both Py and CoFe layers precess approximately around the external field direction and magnetization oscillations are highly phase-coherent. The power spectrum exhibits spectral peaks with a width smaller than our spectral resolution ( $\sim 10$  MHz), which is limited by the simulation time.
- 3) In the Py nanowire, the coherent oscillations of magnetization are always localized within the area under the CoFe nanomagnet (see spatial power maps in Fig. 6). This localization is due to the strong inhomogeneity of the CoFe stray field acting on the Py wire. In this sense, our system differs qualitatively from extended multilayer devices employing the point contact current injection<sup>8</sup>, where the localization of the ST-induced oscillations is caused by the strong non-linearity of the auto-oscillation modes (e.g., bullet<sup>33</sup>, vortex<sup>34</sup> or vortex-antivortex pairs<sup>35,36,37</sup>). In our case, magnetization oscillations in the linear regime are already localized within the Py nanowire area under the CoFe nanomagnet due to the stray field from the CoFe nanomagnet. Analogous localization of thermal spin waves was observed in patterned nanoelement arrays<sup>38</sup>.

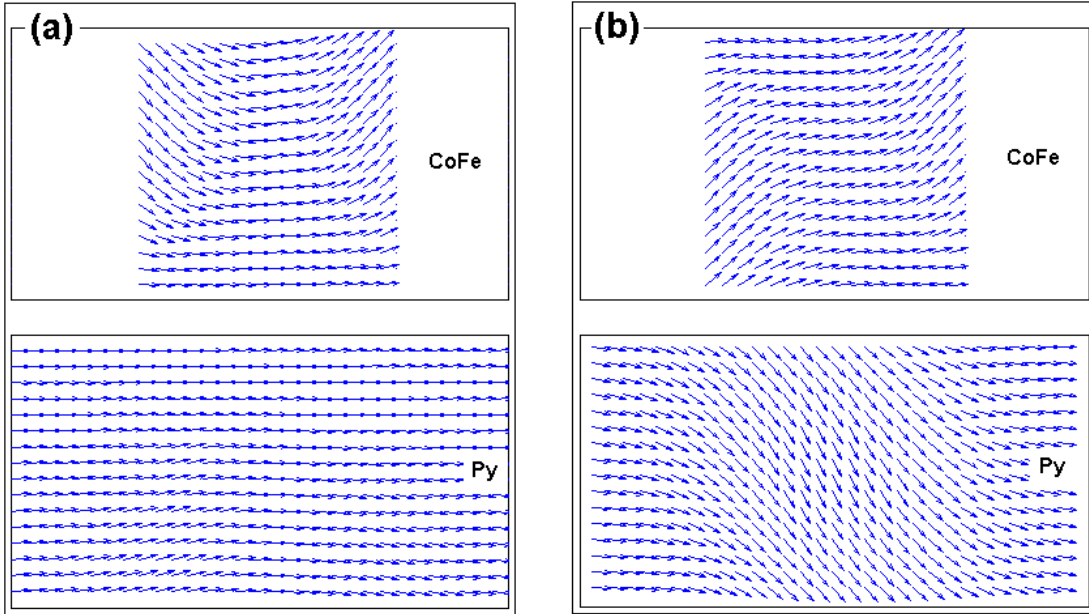


Fig. 4. (color online) Equilibrium magnetization configurations of Py and CoFe layers in the external field  $H_x = 500$  Oe at zero current (a) and after switching in the high-current regime (b). To compute the static equilibrium state (b), spin torque was turned off after the magnetization switching.

- 4) At a relatively high current,  $I_{sw}$ , the system switches to a qualitatively different magnetization state. In the zero-current (equilibrium) state, the CoFe nanomagnet magnetization is in the so called C-state and the CoFe stray field causes only a small deviation of the Py layer magnetization from the uniform state (Fig. 4(a)). For  $I > I_{sw}$ , the CoFe magnetization jumps into an S-state, and its stray field leads to a large-angle rotation of the Py magnetization directly under the CoFe nanomagnet. As the result of this process,



magnetizations of CoFe and Py are directed approximately *perpendicular* to each other. If after this magnetization jump we turn the spin current off, the system magnetization remains trapped in the state shown in Fig. 4(b), which we shall call the 90°-state. ST-induced oscillations in this regime (present if we do not switch the current off) are quasichaotic, have a much lower power and broad spectral lines, and thus they cannot be detected experimentally. For this reason, in what follows we concentrate on the coherent low-current regime.

### B. Effect of the Py exchange constant $A_{\text{Py}}$

The exchange constant  $A_{\text{Py}}$  of our thin  $\text{Ni}_{86}\text{Fe}_{14}$  film is not well known, and its relatively low saturation magnetization  $M_{\text{S}} = 580$  Oe indicates that its exchange stiffness may be significantly lower than the ‘standard’ value for bulk Py (which is usually reported within the interval  $(1-1.3)\times 10^{-6}$  erg/cm). For this reason, we first studied the dependence of the system dynamics on the  $\text{Ni}_{86}\text{Fe}_{14}$  exchange constant. The results of this study are summarized in Fig. 5, which shows the dependences of the simulated auto-oscillation frequency and power on the reduced current  $I/I_{\text{c}}$  for several values of  $A_{\text{Py}}$ , along with the experimental results<sup>30</sup>.

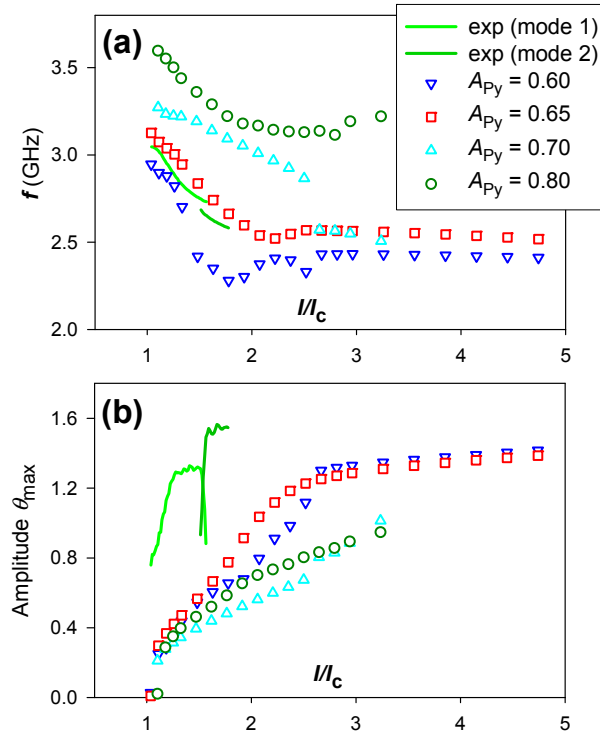


Fig. 5. (color online) Effect of the Py exchange constant  $A_{\text{Py}}$  on the dependences of the oscillation frequency (a) and average oscillation amplitude (b) on the reduced current  $I/I_c$  (for  $M_{\text{CoFe}} = 1800$  emu/cm<sup>3</sup>). The solid lines on both panels show the experimental data from Ref. [30].

As a general trend, we observe that smaller exchange stiffness leads to lower oscillation frequencies, as shown in Fig. 5(a). This is a natural consequence of the localization of oscillations under the CoFe nanomagnet (see maps displaying the spatial distribution of the oscillation power in Fig. 6). The frequency of such a localized mode is largely determined by the exchange stiffness of the magnetic material and hence the frequency decreases with decreasing exchange constant. We note that the dependence of the oscillation frequency on the Py exchange constant is quite strong. This feature can be used, in principle, for measurements of the exchange constant in ultrathin films by comparing the calculated  $f(I)$  curves for different values of  $A$  with the experimental data. Fig. 5(a) shows that the best

agreement between the simulated and the measured frequencies is found for  $A_{Py} = (0.6 \pm 0.65) \times 10^{-6}$  erg/cm. This result is in agreement with the value of  $A_{Py}$  obtained from our quasi-static magnetoresistance loop simulations (Fig. 3).

As we already discussed, oscillatory modes in our system are localized within the region of the Py nanowire directly under the CoFe nanomagnet because the stray field of the CoFe nanomagnet field in this region is directed roughly opposite to the external field. This situation is fully analogous to the localization of edge modes in patterned nanoelements<sup>38</sup>, where the self-demagnetizing field of the nanoelement is directed opposite to the external field, creating a potential well for the magnetization oscillations. An important distinct feature of our system is the strong asymmetry of the CoFe stray field with respect to the nanowire axis (resulting from the *C*-state of CoFe magnetization, see Fig. 4(a)) acting on the Py nanowire. This asymmetry results in the corresponding asymmetry of the mode localization pattern clearly seen in spatial power maps shown in Fig. 6.

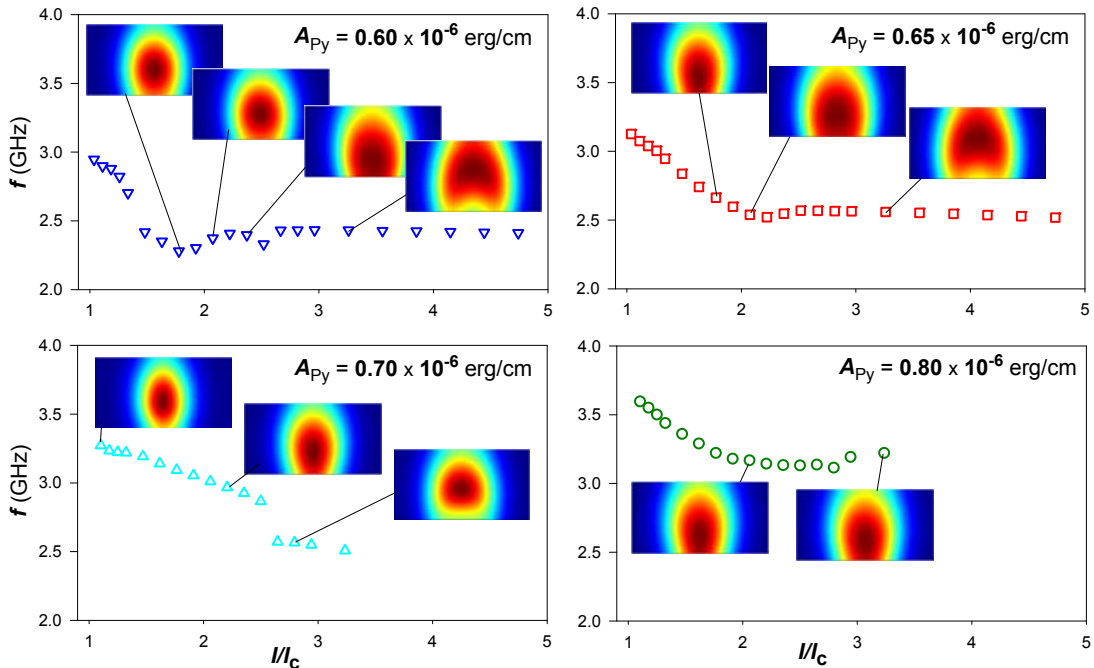


Fig. 6. (color online) Power (defined as the mean square value of the  $m_z$ -component) spatial distribution maps of the auto-oscillatory modes as a function of direct current. The area shown on all color maps corresponds to the physical size  $100 \times 50 \text{ nm}^2$ , so that all modes are localized within the Py nanowire region under the CoFe square.

For some values of the Py exchange constants, e.g.  $A_{Py} = 0.6 \times 10^{-6}$  and  $0.7 \times 10^{-6}$  erg/cm, we observe frequency jumps in the dependence of frequency on current as shown in Fig. 6. As discussed in our previous work<sup>39</sup>, these jumps are caused by the transitions between modes with different spatial localization patterns. However, the mode localization pattern may change without leading to an appreciable frequency jump. This means that the change of the mode localization type is a necessary, but not a sufficient condition to produce a jump in the dependence of frequency on current.

### C. Effect of the CoFe magnetization $M_{CoFe}$

Another important magnetic parameter affecting the current-induced dynamics is the saturation magnetization  $M_{CoFe}$  of the CoFe alloy. For this reason we also studied the influence of this parameter on the system magnetization dynamics, changing  $M_{CoFe}$  in the

interval 1600 - 1800 emu/cm<sup>3</sup>, which is a relevant range for CoFe alloys. Our simulations demonstrate that the increase of  $M_{\text{CoFe}}$  leads to a decrease of the small-amplitude Py oscillation frequency (frequency at the critical current for the onset of auto-oscillations), as shown in Fig. 7a. This effect is due to the increase of the CoFe stray field on the Py wire with increasing  $M_{\text{CoFe}}$ .

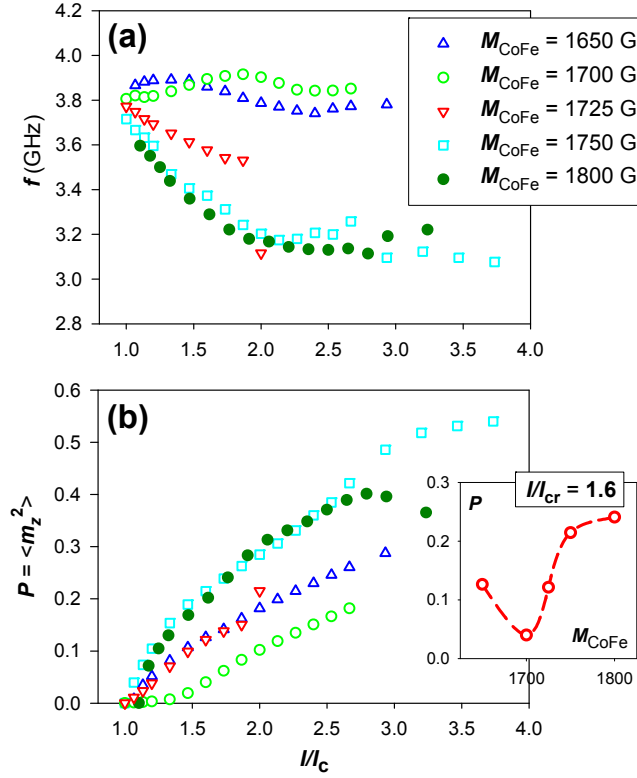


Fig. 7. (color online) Effect of the CoFe magnetization  $M_{\text{CoFe}}$  (for  $A_{\text{Py}} = 0.8 \times 10^{-6}$  erg/cm) on the oscillation frequency (a) and oscillation power (b) defined as the mean square value of the  $m_z$ -component. The inset in the panel (b) shows the non-monotonic dependence of the oscillation power on  $M_{\text{CoFe}}$ .

The most striking effect of varying  $M_{\text{CoFe}}$  is the strong and *non-monotonic* dependence of the oscillation power  $p$ , defined as the mean square value of the  $m_z$ -component, on  $M_{\text{CoFe}}$  (see the inset in Fig. 7b). The sharp non-monotonic dependence of the oscillation power on the CoFe magnetization suggests that this is a resonant effect. A possible reason for the non-monotonic dependence  $p(M_{\text{CoFe}})$  is resonant excitation of oscillations of the CoFe magnetization through *dynamic* magneto-dipolar coupling to the ST-induced oscillations of the Py magnetization. To test this hypothesis, we performed numerical simulations of the small-amplitude magnetization dynamics of our system induced by a short field pulse. Fourier analysis of the magnetization oscillations occurring after such a pulse allows us fast and accurate determination of the eigenmode oscillation frequencies of the system under study. The dependence of the oscillation frequency of two low-frequency eigenmodes of the CoFe nanomagnet on  $M_{\text{CoFe}}$  obtained from such simulations are shown in Fig. 8 together with the frequency of the ST-induced auto-oscillations. This figure demonstrates that a strong coupling between the ST-induced  $m_x$ -oscillations of Py and one of the edge modes of the CoFe nanomagnet is expected due to the frequency coincidence of these two types of oscillations. Fig. 7 demonstrates that the value of  $M_{\text{CoFe}} = 1700 - 1725$  emu/cm<sup>3</sup> gives rise to this frequency coincidence condition and the power of ST-induced Py oscillations shows a minimum. For this resonance condition, the energy supplied to the system by the dc current is

efficiently transferred to the CoFe oscillations, which decreases the amplitude of Py magnetization oscillations.

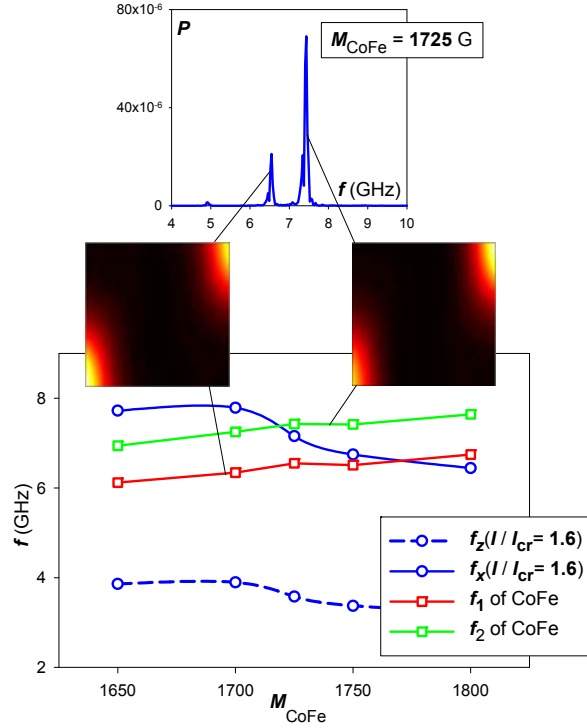


Fig. 8. (color online) Frequencies of two low-energy eigenmodes of the CoFe nanomagnet (open squares) and frequency of ST-induced auto-oscillations (open circles) as functions of the CoFe magnetization,  $M_{\text{CoFe}}$ . The upper panel shows the power spectrum of small-amplitude oscillations of magnetization of the CoFe nanomagnet induced by a sharp magnetic field pulse. Color maps display the spatial distribution of the oscillation power of the CoFe eigenmodes. The two modes are distinguished by the phase relation and by the relation of the oscillation amplitudes between the opposite corners.

Another interesting feature of the magnetization dynamics for our system is the initial blue shift of the frequency with current for  $M_{\text{CoFe}} = 1650$  and  $1700 \text{ emu/cm}^3$ , because red frequency shift is usually expected for the in-plane precession mode of magnetization excited in our system<sup>40</sup>. The observed blue shift is most probably due to the strong localization of the oscillations in the potential well created by the CoFe stray field. For currents above the critical current in the non-linear dynamics regime, the auto-oscillatory mode excited in Py nanowire becomes more localized with increasing current and the exchange stiffness shifts the frequency to a higher value.

#### D. Comparison with experiment

*Dependence of the auto-oscillation frequency on current.* Fig. 5(a) shows that our simulations are in a good agreement with the measured<sup>30</sup> dependence of frequency on current for  $A_{\text{Py}}$  between  $0.6 \times 10^{-6} \text{ erg/cm}$  and  $0.65 \times 10^{-6} \text{ erg/cm}$  (and  $A_{\text{CoFe}} = 3 \times 10^{-6} \text{ erg/cm}$ ,  $M_{\text{CoFe}} = 1800 \text{ emu/cm}^3$ ). The relatively low value of the Py exchange stiffness required to achieve this agreement is not surprising<sup>41</sup>, considering that the saturation magnetization of the alloy used in the real device is also low ( $M_{\text{Py}} = 580 \text{ emu/cm}^3$ ). Here we also note that the same low value of  $A_{\text{Py}}$  is necessary to achieve the satisfactory agreement for the magnetoresistance hysteresis loops (see Sec. III).

The experimentally observed jump of frequency as a function of current is also seen in the simulated  $f(I)$  curve for  $A_{\text{Py}} = 0.6 \times 10^{-6}$  erg/cm, albeit for a slightly different reduced current strength  $I/I_{\text{cr}}$ . As discussed in our Ref. [39], such a jump is due to transition between modes with different spatial localization patterns and as such should be sensitive to shape imperfections of the active layer. For this reason, we cannot expect the exact agreement of the simulated and measured frequencies for the jump locations.

*The critical current and the current polarization.* Our simulations show that the product of the critical current  $I_{\text{cr}}$  and the spin polarization of the current  $P$  is  $P \cdot I_{\text{cr}} \approx 0.055$  mA. Substitution of the experimental value of the threshold current  $I_{\text{cr}} \approx 1.9$  mA into this product results in the spin polarization  $P \approx 0.03$ . This polarization value is very low compared to typical values  $P \sim 0.2 - 0.4$  calculated theoretically using quantum mechanical models (see Ref. 3 and references therein) and estimated experimentally from critical currents measured for other systems. The reason for the low current polarization degree is not clear, but it might result from current spreading in the Cu spacer because the area of the spacer exceeds that of the CoFe nanomagnet (see Fig. 1 and Ref. 30). The low value of the current polarization is in agreement with the unusually high absolute value of the critical current density  $j_{\text{cr}}$  observed for the system under study. Substitution of  $I_{\text{cr}} \approx 1.9$  mA and the nominal lateral size of the CoFe nanoelement  $50 \times 50$  nm<sup>2</sup> leads to the value  $j_{\text{cr}} = 7.6 \times 10^{11}$  A/m<sup>2</sup>, which significantly exceeds  $j_{\text{cr}}$  observed in Py/Cu/Py<sup>39</sup> and Co/Cu/Co trilayers<sup>5</sup>.

The estimated current polarization increases if we assume the conductivity of CoFe to decrease near the CoFe nanomagnet edges. This spatial dependence of the conductivity can result from partial oxidation or ion mill damage of the CoFe nanoelement edges during the sample preparation. We find that if the current flows mainly through the CoFe central region, the product  $P \cdot I_{\text{cr}}$  increases leading to higher values of  $P$ . Assuming that the current density is described by  $j(x) \sim 1 - \exp(-x^2/2d^2)$ , where  $x$  denotes the distance to the nearest edge, the product  $P \cdot I_{\text{cr}}$  increases by a factor of two compared to the homogeneous current distribution.

*The upper critical current (switching current).* The current  $I_{\text{sw}}$ , at which magnetization switches from the steady-state oscillations to the 90° state (Fig. 4(b)) strongly depends on the magnetic material parameters. However, for all material parameters studied here  $I_{\text{sw}}$  is much higher than that found experimentally. Whereas the measured upper critical current is  $1.5 \cdot I_{\text{cr}}$ , the simulated  $I_{\text{sw}}$  is  $(3 - 5) \cdot I_{\text{cr}}$ . The most probable reason for this discrepancy is that thermal fluctuations are neglected in our simulations. Thermal fluctuations present in the experiment should assist the transition to the 90° state.

To better understand stability of the 90° state, we performed simulations starting from *large* current values, gradually decreasing the current to zero. For this simulation protocol, the steady-state magnetization oscillations have not been observed for any current density. When the large spin torque corresponding to a large current density was turned on, the stable 90° state shown in Fig. 4(b) was quickly achieved. As we decreased the current, the system remained in the 90° state and magnetization auto-oscillations were not observed for any current values down to  $I = 0$ . This means that for the external field  $H_x = 500$  Oe used in our simulations, the 90° state is metastable even in the absence of the spin torque. We have also verified the stability of the 90° state by simply minimizing the energy starting from this state. The 90° state is metastable due to the combined action of (i) the magnetodipolar interaction between the CoFe nanomagnet and the Py nanowire and (ii) the in-plane shape anisotropy of the CoFe nanomagnet. Hence we conclude that the 90° state is separated by an energy barrier from the initial equilibrium state and from the dynamic state of auto-oscillations. This means that  $I_{\text{sw}}$  cannot be accurately determined by simulations performed at  $T = 0$ , because the transition to the 90° state takes place when magnetization overcomes the energy barrier due to thermal fluctuations. This finding is in a very good agreement with the experiment. In the

experiment, we observed that for the largest value of the current for which the auto-oscillations have been detected, the system could spend several minutes in the oscillating state and then irreversibly switch into a static state. Such a behavior is expected for a system where a relatively high energy barrier for the transition to the  $90^\circ$  state is present. At higher currents, the switching into a static state seen in the experiment was almost instantaneous.

*Oscillation power.* The largest disagreement between the simulations and the experiment is the dependence of the oscillation power on current. In Fig. 5(b), we display the averaged oscillation amplitude (computed as the maximal angle between the Py and CoFe magnetization averaged over the vertical stacks of discretization cells) deduced from the oscillation power. This figure shows that even for the Py exchange constant  $A_{\text{Py}} = 0.65 \times 10^{-6}$  erg/cm, which provides a good agreement with the experimental oscillation frequency, the simulated power grows much slower with the current than the experimentally measured power. We verified that this discrepancy cannot be attributed to the higher conductivity of the central region of the CoFe square discussed above. Although the current confinement increases the value of the current polarization, the dependence of power on the reduced current,  $p(I/I_{\text{cr}})$ , remains nearly the same.

### E. Prospects for generating a propagating mode of auto-oscillations

Our simulations clearly show that the auto-oscillatory modes exited in our nanowire geometry for the in-plane magnetic field configuration are strongly localized. Therefore, this configuration is not suitable for phase locking of multiple ST nano-oscillators via spin waves propagating in the Py nanowire. To find a propagating mode in the geometry under study, we performed micromagnetic simulations for several other magnetic field configurations. Since the main reason for the mode localization is the stray field of the CoFe nanomagnet, we focused on ST-induced magnetization auto-oscillations in strong out-of-plane fields. In this geometry, the influence of the CoFe stray field on spin waves in the Py layer is small.

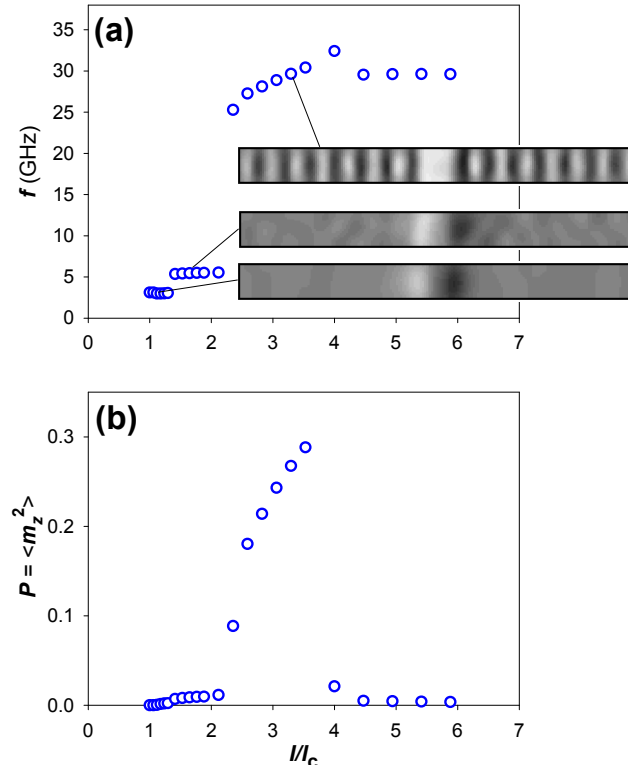


Fig. 9. (color online) Py nanowire auto-oscillation modes for out-of-plane field  $H_{\text{perp}} = 10$  kOe. Dependences of the oscillation frequency (a) and oscillation power (b) on the reduced current  $I/I_c$ . Grey-scale snapshots of the  $m_x$ -component clearly show that oscillations after the second frequency jump correspond to a spin wave mode propagating along the nanowire.

Indeed, for the out-of-plane field geometry, our simulations show a rich mode structure with several transitions between different non-linear modes with increasing current. In Fig. 9, we present a typical example of the system behavior in a strong out-of-plane field  $H_{\text{perp}} = 10$  kOe and magnetic material parameters  $A_{\text{Py}} = 0.65 \times 10^{-6}$  erg/cm,  $M_{\text{Py}} = 580$  emu/cm<sup>3</sup>,  $A_{\text{CoFe}} = 3 \times 10^{-6}$  erg/cm and  $M_{\text{CoFe}} = 1800$  emu/cm<sup>3</sup>. For currents just above the onset of auto-oscillations, we observe a localized mode with nearly spatially uniform magnetization in the mode core. After the first frequency jump another localized mode with a more complicated spatial pattern of magnetization (but still localized well inside of the nanocontact area) emerges. Finally, the second frequency jump corresponds to the transition to a large-amplitude propagating spin wave mode. Snapshots of the  $m_x$ -component in the different dynamical regimes shown in Fig. 9 (a region of the system with lateral dimensions of  $550 \times 50$  nm<sup>2</sup> surrounding the CoFe nanocontact is shown) confirm that the mode with the highest frequency is a propagating mode. Hence the out-of-plane field geometry is favorable for the generation of a propagating spin wave mode in the 1D STNO system. The properties of this mode and perspectives of using this setup for synchronization of the STNOs on a nanowire will be discussed in a future publication.

## V. CONCLUSIONS

We employed micromagnetic simulations to study magnetization dynamics induced by spin torque in a STNO system consisting of a CoFe nanomagnet current polarizer and a NiFe nanowire free layer. This system is of significant interest for studies of multiple STNO synchronization by spin waves propagating in a ferromagnetic nanowire.

Our simulations show that for the in-plane magnetic field configuration, all auto-oscillatory modes in the NiFe nanowire are localized directly under the CoFe nanomagnet. This mode localization is induced by the large stray field of the CoFe nanomagnet. We find that the oscillation frequency of the localized modes sensitively depends on the NiFe and CoFe material parameters, especially on the exchange stiffness of the NiFe nanowire. The oscillation power of these modes depends non-monotonically on the CoFe magnetization due to the resonant excitation of the CoFe nanomagnet edge modes by the oscillating magnetization of the NiFe nanowire.

The dependence of the frequency of the STNO modes on direct current bias given by our simulations is in good agreement with the experimental data for this system<sup>30</sup>. The simulations also successfully reproduce several other important features of the experimentally observed magnetization dynamics such as jumps of frequency with increasing current and metastable system behavior at high current densities. However, the dependence of the STNO power on the current bias given by the simulations is weaker than the experimentally measured dependence. Therefore, quantitative description of magnetization dynamics induced by spin transfer torque remains to be a significant challenge.

Since the in-plane magnetic field configuration yields localized auto-oscillatory modes unsuitable for synchronization of multiple STNOs via propagating spin waves, we studied magnetization dynamics in the out-of-plan field configuration. Our simulations show that an out-of-plane magnetic field sufficiently strong to saturate the NiFe magnetization perpendicular to the nanowire plane gives rise a propagating current-driven auto-oscillatory mode in the NiFe nanowire. This propagating mode holds promise for the development of 1D phase-locked STNO arrays based on multiple nanocontacts to a ferromagnetic nanowire.

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