Understanding of Phase Noise Squeezing Under Fractional Synchronization of a Nonlinear Spin Transfer Vortex Oscillator

R. Lebrun,[1] A. Jenkins,[1] A. Dussaux,[1,*] N. Locatelli,[1,†] S. Tsunegi,[1,2] E. Grimaldi,[1] H. Kubota,[2] P. Bortolotti,[1] K. Yakushiji,[2] J. Grollier,[1] A. Fukushima,[2] S. Yuasa,[2] and V. Cros[1]
[1]*Unité Mixte de Physique CNRS/Thales and Université Paris Sud, 1 Avenue Fresnel, 91767 Palaiseau, France*
[2]*National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan*
(Received 6 February 2015; revised manuscript received 3 April 2015; published 29 June 2015)

We investigate experimentally the synchronization of vortex based spin transfer nano-oscillators to an external rf current whose frequency is at multiple integers, as well as at an integer fraction, of the oscillator frequency. Through a theoretical study of the locking mechanism, we highlight the crucial role of both the symmetries of the spin torques and the nonlinear properties of the oscillator in understanding the phase locking mechanism. In the locking regime, we report a phase noise reduction down to −90 dBc/Hz at 1 kHz offset frequency. Our demonstration that the phase noise of these nanoscale nonlinear oscillators can be tuned and eventually lessened, represents a key achievement for targeted radio frequency applications using spin torque devices.

DOI: 10.1103/PhysRevLett.115.017201 PACS numbers: 85.75.-d, 75.40.Gb, 75.47.-m

In the last decade, there has been much anticipation as to how the rich spin transfer physics will give birth to a new generation of multifunctional spintronic devices [1]. The tunable response of spin torque devices has been presented as being crucial for several promising domains of applications such as radio frequency [2], magnonic [3], or low energy devices for information and communication technologies (ICTs). Moreover, novel opportunities relying on the fascinating properties of spin torque devices have emerged concerning the study of their stochastic and even chaotic behavior [4] with promising perspectives as neuroinspired memory devices [5]. For all of these potential applications, and notably for the corresponding microwave applications, it is essential to identify the mechanisms leading to a fine control of the phase of these spin torque devices. The nonlinear behavior of these devices gives a unique opportunity to tune their radio frequency properties [6–8], but at the cost of a large phase noise, not compatible with targeted applications [1,2]. In order to tackle these issues, one possible solution is to rely either on their synchronization to a reference signal [9–12] or on mutual synchronization [13,14] of arrays of spin torque nano-oscillators (STNOs). However, in all reported studies made in the *apparently*-locked regime of the STNOs, the phase noise, which is often measured through the estimation of the spectral linewidth recorded with a spectrum analyzer, remains large, typically in the kHz range. These large linewidths, which we associate with phase slips, highlight the complexity of the dynamical behavior of highly nonlinear oscillators and more notably their relaxation processes [10,11,15].

In this Letter, we investigate the mechanisms leading to a "pure" phase locking state (i.e., without phase slips in the 5 ms measurements) of a double vortex based STNO to an external rf current. We study the phase locking features when the source frequency F_s approaches $f_0/2$, f_0, or $2f_0$, where f_0 is the frequency of our STNO. Moreover, we succeed to elucidate the strong correlation between the oscillator parameters and the locking process through a comprehensive study combining frequency and time domain measurements as well as analytical calculations. This allows an understanding of the locking range characteristics [9,16,17], as well as the high phase coherence in the locked regime [18–20]. Our results demonstrate the specific spin transfer locking process of vortex based STNOs, and the potential for synchronizing multiple oscillators in series, which is an important breakthrough towards rf devices or associative memory applications [1].

All the presented high frequency transport measurements have been performed at room temperature (RT) on circular hybrid magnetic tunnel junctions (MTJ) (with 300 or 400 nm diameters Ø) patterned from magnetic multilayered stacks which consist of CoFe/Ru/CoFeB/MgO/NiFe(6 nm)/Cu/NiFe(20 nm). Details about the sample fabrication can be found elsewhere [8]. Each NiFe layer contains a magnetic vortex. The coupled vortex modes inside the NiFe/Cu/NiFe trilayers can be excited with a dc-current via the spin transfer torque at zero applied magnetic field [8,21,22]. In this autonomous regime, the self-sustained oscillations display a very narrow linewidth (∼100 kHz) [8,21,22]. The bottom part of the devices, i.e., the CoFe/Ru/CoFeB/MgO stack, probes the dynamics of the excited vortex core in the 6 nm NiFe layer. As a consequence, the emitted output power of the device is large as it is directly proportional to the magnetoresistive ratio of our junctions (∼80% at RT).

Here we focus our interest on the nonautonomous (or forced) regime, i.e., when the vortex oscillations are locked

 © 2015 American Physical Society

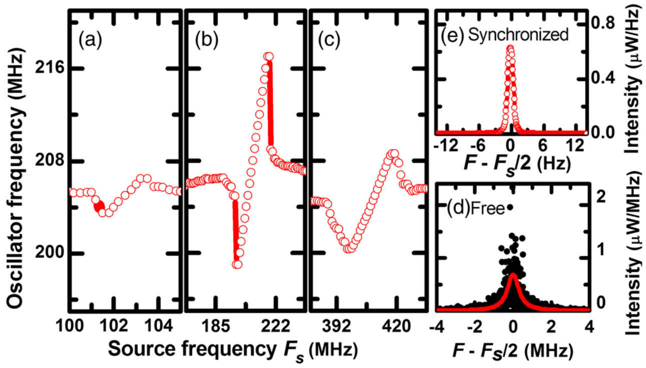

FIG. 1 (color online). Frequency of STNO vs external source frequency F_S around $f_0/2$ (a), f_0 (b), $2f_0$ (c) for $I_{rf} = 0.8$ mA (at zero applied field and $I_{dc} = +16$ mA and Ø = 400 nm). Emitted spectrum in (d) the autonomous regime without external signal and in (e) the synchronized state with a rf source at $F_s = 2f_0$.

to an external rf current. In this regime, we observe a large locking range when the frequency of the current source F_s approaches the oscillator frequency f_0 [see Fig. 1(b)]. Beyond this expected behavior, we observe that a frequency locking can be also achieved when F_S is around qf_0 with q an integer [$q = 1$ in Fig. 1(b), $q = 2$ in Fig. 1(c); see also $q = 3$ in the Supplemental Material [23]]. The mechanism of synchronization at high harmonics (q integer) [24] is usually associated with the presence of harmonics in the autonomous regime [25] with an efficiency that decreases as q increases (as the amplitude of the harmonics decreases with q).

Importantly, as displayed in Fig. 1(a), we report, for the first time in the case of an STNO, a synchronization with the external rf current even for a fraction of the oscillator frequency (f_0/q), here at F_s around $f_0/2$ (see also around $f_0/3$ in the Supplemental Material [23]). It should be noted that subharmonic phase locking in STNOs has been predicted in micromagnetic calculations [17], but never observed experimentally. Indeed, subharmonic synchronization ($1/q$) usually relies only on the nonlinear behavior of the oscillator. Indeed when an rf signal is applied at a given frequency f, it is anticipated that a nonlinear system will generate a small response at nf (where n is an integer) [26]. This explains why the locking range at $f_0/2$ is much smaller (around 1% of f_0) than the ones at f_0 and $2f_0$ (respectively, 10% and 5%) as shown in Fig. 1. Furthermore, we report a significant improvement of the spectral coherence both for *sub* and *higher* harmonic synchronization. We observe an ultrastable phase locking state with a minimum linewidth of 1 Hz [as shown in Fig. 1(e) for $F_s = 2f_0$], only limited by the resolution bandwidth of the spectrum analyzer. Note that this value is about 10^5 lower than the autonomous regime [700 kHz, Fig. 1(d)]. This strong linewidth reduction is combined with an output emitted power (integral of the intensity) increased from 0.8 μW in the autonomous regime [Fig. 1(d)] to 1.1 μW in the synchronized regime [Fig. 1(e)]. This enhanced power is associated with an increase of the radius of core gyration [23,27]. We believe that such a level of performance for spin transfer oscillators represents a breakthrough towards the actual development of new generations of injection-locked frequency dividers or multipliers.

To gain a deeper understanding of the ultralow phase noise when the oscillator is synchronized, we perform time domain measurements by recording 5 ms long output voltage time traces with a single-shot oscilloscope (for details see Ref. [27]). As already reported for other STNOs [27,28], we find that the power spectral density (PSD) of the phase noise in the autonomous regime displays a $1/f^2$ dependence from the carrier frequency that is associated to a white frequency noise (see black curves in Fig. 2). This phase noise behavior is seemingly modified when the external current I_{rf} frequency approaches f_0, $f_0/2$, or $2f_0$.

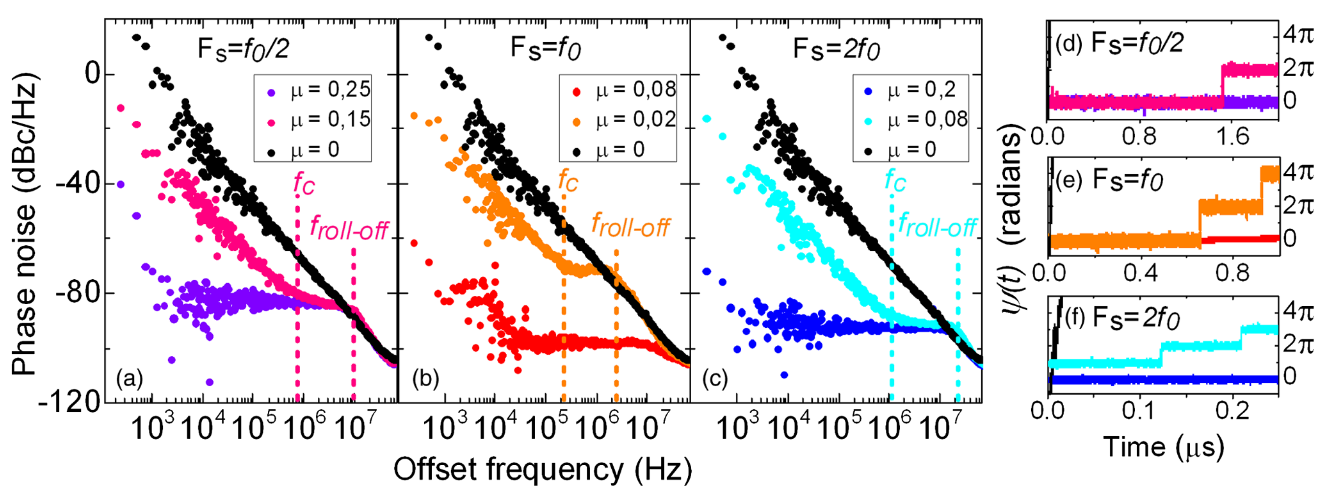

FIG. 2 (color online). Phase noise of the locked oscillator for different driving force (at zero field, $I_{dc} = +11$ mA and Ø = 300 nm) at $f_0/2$ (a), f_0 (b), and $2f_0$ (c). Associated phase deviation [$\psi = \theta(t) - \omega_0 t$] for F_s at $f_0/2$ (d), f_0 (e), and $2f_0$ (f).

When $F_s = f_0$, a significant reduction of phase noise is observed even for a low driving force $\mu = I_{rf}/I_{dc} = 0.02$ [see orange curve in Fig. 2(b)]. For such a low injection power, we observe a plateau in the phase noise from a high frequency roll-off, $f_{\text{roll-off}}$, down to a low offset frequency corner f_c [for example, for $\mu = 0.02$ at $F_s = f_0$ in Fig. 2(b), $f_c = 200$ kHz and $f_{\text{roll-off}} = 3$ MHz]. Similar behaviors with larger external rf current are obtained for an external frequency at $2f_0$ [cyan curve in Fig. 2(c) with $\mu = 0.08$] or $f_0/2$ [magenta curve in Fig. 2(a) with $\mu = 0.15$].

For an offset frequency lower than f_c, the phase noise increases because of the onset of phase slips in the dynamics of our vortex based STNOs [15]. Similar features were reported in micromagnetic simulations [29] but not clearly observed in experiments. The phase slips are associated with desynchronization-resynchronization events occurring because of the thermal fluctuations. The amplitude of these phase slips is related to the number of stable positions available over one period, which directly depends on the frequency of the current source. As a consequence, for a driving force frequency around qf_0, the phase deviation [$\psi(t) = \theta(t) - 2\pi f_0 t$ with $\theta(t)$ being the phase of the STNO] of the locked oscillator presents some phase slip events with an amplitude of $2\pi/q$. In Figs. 2(e)–(f), the phase slip amplitude is thus, respectively, 2π and π for the f_0 and $2f_0$ cases (see also the $3f_0$ case in the Supplemental Material [23]). However, when the source frequency is lower than that of the STNO, and F_s approaches f_0/q, we again observe phase slips of 2π as shown in Fig. 2(d) for F_s around $f_0/2$ (and similarly for F_s around $f_0/3$ in the Supplemental Material [23]). This result confirms that our oscillator is phase locked with an injected rf current around f_0/q because of the nonlinear oscillator behavior. The system generates a harmonic response at f_0 which permits the locking process. It can also be seen that for each locking frequency, all the phase slips present the same amplitude, which demonstrates the absence of chaotic behavior or other dynamical regimes related to multistability [4,30] in our STNOs.

For large enough driving forces [in Figs. 2(a)–(c), respectively, $\mu = 0.25$ purple curve at $f_0/2$, $\mu = 0.08$ red curve at f_0, and $\mu = 0.2$ dark blue curve at $2f_0$], a constant phase noise level from $f_{\text{roll-off}}$ to 300 Hz offset frequency (lowest value associated with our oscilloscope memory) is observed. In this ultrastable locked regime, we note the absence of phase slips. The phase deviation remains bounded below 2π with an associated resulting noise level of -90 dBc/Hz at 1 kHz from the carrier when the external frequency is at $2f_0$ [see Fig. 2(c)]. This highlights the fundamental difference between the largely reported "frequency locked state" [9–11,31] and a pure (or "real") phase locked state, which only exists in the absence of any phase slip events. Note that a similarly low phase noise is reached at f_0 [Fig. 2(b)] but the data at very low offset frequencies are hindered by the phase noise of our rf-current source.

This constant phase noise level is characteristic of a retroaction process acting on the phase of the oscillator [30]. Indeed, all thermal noise events with a characteristic frequency lower than the retroaction frequency (here indicated as the frequency roll-off $f_{\text{roll-off}}$ in Fig. 2) are strongly reduced or suppressed. It is important to stress that one of the most interesting features of STNOs is that such a retroaction process could be controlled through the different spin transfer forces [11,16,19,32].

To further analyze our experimental results, we extend the general model of the auto oscillator in the nonautonomous regime [16,27] to our case of interest, i.e., the vortex oscillator under an external rf current. In the phase locked regime, all the spin transfer forces acting directly on the phase $\theta(t)$ of the STNO through an alternative current $J_{rf}\cos(\omega_s t)$ have to be considered. In Eq. (1), we give the expression of the two active torques, i.e., the Slonczewski and fieldlike torques associated with the in-plane spin polarization arising from the magnetization of the top synthetic antiferromagnet (SAF) layer [31]:

$$\overrightarrow{F_{\text{Slon}//}} = \Lambda_{\text{SL}//} J_{rf}\cos(\omega_s t)\begin{cases}\sin\theta(t)(\overrightarrow{u_\rho})\\ \cos\theta(t)(\overrightarrow{u_\chi})\end{cases}, \quad (1a)$$

$$\overrightarrow{F_{\text{FL}//}} = \Lambda_{\text{FL}//} J_{rf}\cos(\omega_s t)\begin{cases}-\cos\theta(t)(\overrightarrow{u_\rho})\\ \sin\theta(t)(\overrightarrow{u_\chi})\end{cases}, \quad (1b)$$

where $\overrightarrow{u_\rho}$ and $\overrightarrow{u_\chi}$ are the polar vectors defined by the vortex core position [ρ, χ) [31] (with ρ the radius of oscillations and $\chi(t)$, the instantaneous angle of the vortex core position relative to the polarizer direction]. The oscillator phase $\theta(t)$ is here defined by the oscillations of magnetoresistance and through the relation $\theta(t) = \chi(t) + C\pi/2$ (with $C = \pm 1$ depending on the vortex chirality [31]). The two terms $\Lambda_{\text{SL}//}$ and $\Lambda_{\text{FL}//}$ are the respective efficiencies of Slonczewski and fieldlike in-plane torques. These two locking torques are able to drive the oscillator from the autonomous regime to a locked regime. In the first order (in the regime of small perturbations) this results in power fluctuations δp and a phase difference $\psi(t) = \theta(t) - \omega_s t$ between the source and the oscillator [16]:

$$\frac{d\delta p}{dt} = -2\Gamma_p\delta p + 2Fp_0\cos(\Psi + \Psi_{\text{st}}),$$
$$\frac{d\Psi}{dt} + \Delta\omega = +N\delta p - F\sin(\Psi + \Psi_{\text{st}}), \quad (2)$$

where Γ_p is the effective relaxation damping rate, N the nonlinear frequency shift, $F = (\Lambda_{\text{SL}//}{}^2 + \Lambda_{\text{FL}//}{}^2)^{1/2} * J_{rf}/(2GR\sqrt{p_0})$ the normalized external driving force, G the gyrotropic constant [31], R the dot radius, $\Psi_{\text{st}} = \tan^{-1}(\Lambda_{\text{FL}//}/\Lambda_{\text{SL}//})$ the phase shift of the driving force for positive bias, $\Delta\omega = \omega_s - 2\pi f_0$ the frequency detuning, and p_0 the normalized power in the autonomous regime (that is directly related to the amplitude of gyration of the vortex core [27]).

Then we can determine the stable solution as

$$\delta p = p_0 \frac{\upsilon\Delta\omega + \sqrt{(1+\upsilon^2)F^2 - \Delta\omega^2}}{(1+\upsilon^2)\Gamma_p}, \qquad (3a)$$

$$\psi_0 = \tan^{-1}(\nu) - \sin^{-1}\left(\frac{\Delta\omega}{\sqrt{(1+\upsilon^2)}F}\right) - \Psi_{\rm st}, \qquad (3b)$$

where $\upsilon = Np/\Gamma_p$ is the nonlinear dimensionless parameter [33]. These new equilibrium dynamics are valid inside the frequency locking bandwidth that depends on the strength of the locking force at the considered locking harmonic (for more details, see the Supplemental Material [23]).

In the synchronized regime, an important parameter is the phase shift ψ_0 (phase difference between source and oscillator phase). In order to increase the emitted power via synchronization of multiple oscillators [16,19], this parameter should ideally be zero. However, the dephasing parameter ψ_0 of nonlinear STNOs (i.e., with large ν) is equal to $+\pi/2$ at zero detuning ($\Delta\omega = 0$), in the absence of a driving force phase shift $\Psi_{\rm st}$ [see Eq. 3(b)] as reported in uniformly magnetized STNOs [19]. In vortex based STNOs, the locking process involves two different spin transfer forces giving a unique opportunity to tune the phase shift ψ_0 through the additional term $\Psi_{\rm st}$. In magnetic tunnel junctions, ψ_0 could reach 0 at $\Delta\omega = 0$ for a large ratio of $\Lambda_{\rm FL//}/\Lambda_{\rm SL//} = \xi R/b \gg 1$ (with ξ the efficiency of the fieldlike torque, R the dot radius, and b the vortex core radius [31]). It is important to realize that the dephasing parameter ψ_0 not only affects the locking equilibrium but also the transient synchronization regime through the decay rate of the phase and power deviations of the stationary phase locked state [19]:

$$\lambda = \Gamma_p + \frac{1}{2}F\cos\psi_0 \pm \sqrt{\left(\Gamma_p - \frac{1}{2}F\cos\psi_0\right)^2 - 2\upsilon F\sin\psi_0}. \qquad (4)$$

The decay constant of the phase fluctuations can be related to the large frequency roll-off $f_{\rm roll\text{-}off}$ displayed in Fig. 2. From Eq. (4), it can be noted that the decay constants of a synchronized nonlinear oscillator, i.e., with a large υ, have a nonreal part if ψ_0 is close to $+\pi/2$. Having imaginary decay constants leads to the presence of sidebands in the locking regime (as reported in uniformly magnetized spin-transfer nano-oscillators [19]). In Fig. 3(c), we clearly see that such sidebands are not observed for F_s close to f_0. Moreover, on the phase noise diagram [Fig. 3(b)], we note the absence of bumps or sidebands at the high frequency roll-off $f_{\rm roll\text{-}off}$. Both these features are consistent with a large $\Lambda_{\rm FL//}/\Lambda_{\rm SL//}$ ratio in our vortex based

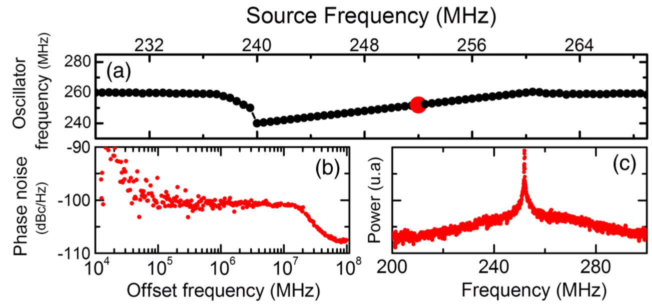

FIG. 3 (color online). Locking range at f_0 for $\mu = 0.2$ (at zero field, $I_{\rm dc} = +11$ mA and Ø $= 300$ nm) (a) Phase noise spectrum (b) and its associated emitted spectrum (c) for $F_s = 252$ MHz.

MTJs [32]. Indeed, from Eq. 3(b), we note that a large $\Lambda_{\rm FL//}/\Lambda_{\rm SL//}$ ratio involves a zero dephasing parameter ψ_0 (at $\Delta\omega = 0$) which then leads [see Eq. (4)] to real decay constants and thus to the absence of sidebands in the locked regime.

In conclusion, we succeed to demonstrate *pure* injection locking of a vortex based spin transfer oscillator on an external current with multiple integers, i.e., f_0, $2f_0$, $3f_0$ as well as half and third integer frequency $f_0/2$ and $f_0/3$. A pure phase locking state with no phase slips and a large output power (>1 μW) is observed at room temperature and zero magnetic field. It is associated with a record low phase noise down to -90 dBc/Hz at 1 kHz offset. We demonstrate that the physical mechanisms at play for the oscillator to be locked, notably in the transient regime of synchronization, are strongly correlated to the symmetry of the spin transfer locking forces. The improved understanding of the locking behavior and the fine control of the oscillator phase allows the envisaging of efficient electrical synchronization of a large number of spin transfer oscillators, which would be a real breakthrough towards applications in advanced rf devices or the novel family of neuroinspired memories.

The authors acknowledge the ANR agency (SPINNOVA ANR-11-NANO-0016) as well as EU FP7 Grant (MOSAIC No. ICT-FP7-n.317950) for financial support. E. G. acknowledges CNES and DGA for their support.

[*]Present address: INLN, Sophia Antipolis, Nice, France.
[†]Present address: IEF, CNRS, Orsay, France.

[1] N. Locatelli, V. Cros, and J. Grollier, Nat. Mater. **13**, 11 (2014).
[2] H. S. Choi, S. Y. Kang, S. J. Cho, I.-Y. Oh, M. Shin, H. Park, C. Jang, B.-C. Min, S.-I. Kim, S.-Y. Park, and C. S. Park, Sci. Rep. **4**, 5486 (2014).
[3] S. Urazhdin, V. E. Demidov, H. Ulrichs, T. Kendziorczyk, T. Kuhn, J. Leuthold, G. Wilde, and S. O. Demokritov, Nat. Nanotechnol. **9**, 509 (2014).
[4] S. Petit-Watelot, J.-V. Kim, A. Ruotolo, R. M. Otxoa, K. Bouzehouane, J. Grollier, A. Vansteenkiste, B. Van de Wiele, V. Cros, and T. Devolder, Nat. Phys. **8**, 682 (2012).

[5] N. Locatelli, A. Mizrahi, A. Accioly, R. Matsumoto, A. Fukushima, H. Kubota, S. Yuasa, V. Cros, L. G. Pereira, D. Querlioz, J.-V. Kim, and J. Grollier, Phys. Rev. Applied **2**, 034009 (2014).
[6] V. S. Pribiag, I. N. Krivorotov, G. D. Fuchs, P. M. Braganca, O. Ozatay, J. C. Sankey, D. C. Ralph, and R. A. Buhrman, Nat. Phys. **3**, 498 (2007).
[7] D. Houssameddine, U. Ebels, B. Delaet, B. Rodmacq, I. Firastrau, F. Ponthenier, M. Brunet, C. Thirion, J.-P. Michel, L. Prejbeanu-Buda, M.-C. Cyrille, O. Redon, and B. Dieny, Nat. Mater. **6**, 447 (2007).
[8] R. Lebrun, N. Locatelli, S. Tsunegi, J. Grollier, V. Cros, F. Abreu Araujo, H. Kubota, K. Yakushiji, A. Fukushima, and S. Yuasa, Phys. Rev. Applied **2**, 061001 (2014).
[9] S. Urazhdin, P. Tabor, V. Tiberkevich, and A. Slavin, Phys. Rev. Lett. **105**, 104101 (2010).
[10] M. Quinsat, J. F. Sierra, I. Firastrau, V. Tiberkevich, A. Slavin, D. Gusakova, L. D. Buda-Prejbeanu, M. Zarudniev, J.-P. Michel, U. Ebels, B. Dieny, M.-C. Cyrille, J. A. Katine, D. Mauri, and A. Zeltser, Appl. Phys. Lett. **98**, 182503 (2011).
[11] V. E. Demidov, H. Ulrichs, S. V. Gurevich, S. O. Demokritov, V. S. Tiberkevich, A. N. Slavin, A. Zholud, and S. Urazhdin, Nat. Commun. **5**, 3179 (2014).
[12] W. Rippard, M. Pufall, S. Kaka, T. Silva, S. Russek, and J. Katine, Phys. Rev. Lett. **95**, 067203 (2005).
[13] F. B. Mancoff, N. D. Rizzo, B. N. Engel, and S. Tehrani, Nature (London) **437**, 393 (2005).
[14] D. Li, Y. Zhou, B. Hu, J. Åkerman, and C. Zhou, Phys. Rev. B **86**, 014418 (2012).
[15] B. Georges, J. Grollier, V. Cros, A. Fert, A. Fukushima, H. Kubota, K. Yakushijin, S. Yuasa, and K. Ando, Phys. Rev. B **80**, 060404 (2009).
[16] N. Locatelli, V. V. Naletov, J. Grollier, G. De Loubens, V. Cros, C. Deranlot, C. Ulysse, G. Faini, O. Klein, and A. Fert, Appl. Phys. Lett. **98**, 062501 (2011).
[17] A. Hamadeh, N. Locatelli, V. V. Naletov, R. Lebrun, G. de Loubens, J. Grollier, O. Klein, and V. Cros, Phys. Rev. Lett. **112**, 257201 (2014).
[18] A. Slavin and V. Tiberkevich, IEEE Trans. Magn. **45**, 1875 (2009).
[19] D. Li, Y. Zhou, C. Zhou, and B. Hu, Phys. Rev. B **83**, 140407 (2011).
[20] M. d' Aquino, C. Serpico, R. Bonin, G. Bertotti, and I. D. Mayergoyz, Phys. Rev. B **82**, 064415 (2010).
[21] Y. Zhou, V. Tiberkevich, G. Consolo, E. Iacocca, B. Azzerboni, A. Slavin, and J. Åkerman, Phys. Rev. B **82**, 012408 (2010).
[22] A. Hamadeh, N. Locatelli, V. V. Naletov, R. Lebrun, G. De Loubens, J. Grollier, O. Klein, and V. Cros, Appl. Phys. Lett. **104**, 022408 (2014).
[23] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.115.017201 for a detailed description of the amplitude of phase slips for F_s around $3f_0$ (or $f_0/3$) and of the impact of the locking strength on the synchronized equilibrium.
[24] I. Schmideg, Proc. IEEE **59**, 1250 (1971).
[25] P. N. Skirdkov, A. D. Belanovsky, K. A. Zvezdin, A. K. Zvezdin, N. Locatelli, J. Grollier, and V. Cros, SPIN **02**, 1250005 (2012).
[26] X. Zhang, X. Zhou, B. Aliener, and A. S. Daryoush, IEEE Microwave Guided Wave Lett. **2**, 97 (1992).
[27] E. Grimaldi, A. Dussaux, P. Bortolotti, J. Grollier, G. Pillet, A. Fukushima, H. Kubota, K. Yakushiji, S. Yuasa, and V. Cros, Phys. Rev. B **89**, 104404 (2014).
[28] M. Quinsat, D. Gusakova, J. F. Sierra, J. P. Michel, D. Houssameddine, B. Delaet, M.-C. Cyrille, U. Ebels, B. Dieny, L. D. Buda-Prejbeanu, J. A. Katine, D. Mauri, A. Zeltser, M. Prigent, J.-C. Nallatamby, and R. Sommet, Appl. Phys. Lett. **97**, 182507 (2010).
[29] G. Finocchio, M. Carpentieri, A. Giordano, and B. Azzerboni, Phys. Rev. B **86**, 014438 (2012).
[30] A. Pikovsky, M. Rosenblum, and J. Kurths, *A Universal Concept in Nonlinear Sciences* (Cambridge University Press, New York, 2001).
[31] A. Dussaux, A. V. Khvalkovskiy, P. Bortolotti, J. Grollier, V. Cros, and A. Fert, Phys. Rev. B **86**, 014402 (2012).
[32] H. Kubota, A. Fukushima, K. Yakushiji, T. Nagahama, S. Yuasa, K. Ando, H. Maehara, Y. Nagamine, K. Tsunekawa, D. D. Djayaprawira, N. Watanabe, and Y. Suzuki, Nat. Phys. **4**, 37 (2008).
[33] J.-V. Kim, V. Tiberkevich, and A. N. Slavin, Phys. Rev. Lett. **100**, 017207 (2008).